School of Surgery and Pathology

An investigation of the dynamic angle of gait and radiographic characteristics of the first metatarsophalangeal joint in subjects with hallux limitus

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ABSTRACT

Limitation of sagittal plane dorsiflexion, or hallux limitus (HL), represents the second most commonly encountered pathomechanical disorder affecting the first metatarsophalangeal joint, after hallux valgus (HV). The kinematic role of the first metatarsophalangeal joint represents an integral component of the gait cycle. It has often been reported that for adequate leverage and propulsion to occur during normal gait, the hallux must be able to dorsiflex approximately 65° on the head of the first metatarsal. Secondary gait compensation mechanisms have often been observed clinically as a result of HL. The effect of HL on gait can be reflected in transverse plane alteration of the foot in relation to the line of progression during gait, defined as the angle of gait (AOG).

The first purpose of this study served to investigate potential differences in dynamic angle of gait AOG in subjects with HL compared to a control group. A validated technique using coloured powdered footprints was used to quantify AOG. Furthermore, it was required to establish whether the relative amount of transverse plane motion observed in the AOG was related to factors intrinsic or extrinsic to the foot. Intrinsic factors such as the amount of forefoot to rearfoot abduction was considered, and achieved by measuring the rearfoot to forefoot axis (RFA) angle using a weight bearing composite (COMP) view radiograph.

The remaining objectives of the study served to investigate other common aetiological factors associated with HL and their potential influence on AOG in subjects with HL. Characteristics of the first metatarsal associated with HL such as length and elevation were investigated. Several defined radiographic angular and linear measurements were undertaken using a validated methodology. These included first metatarsal protrusion distance (FMPD) to measure length, and lateral intermetatarsal angle (LIMA) to measure elevation of the first metatarsal.

Alternative radiographic parameters were also investigated, as a means to establish if a relationship existed between the degree of HL pathology and dynamic AOG. This involved measurement of functional first metatarsophalangeal joint dorsiflexion using lateral stressed dorsiflexion (LAT SD) radiograph, hallux abductus angle (HAA) and first intermetatarsal angle (FIMA). The final part of the investigation was to determine whether AOG was related to a specific foot type. A radiographic measurement termed the calcaneal inclination angle (CIA) was chosen to classify foot type.

Twenty-two subjects with HL consisting of 9 males and 13 females with a mean age of 54.9 years were compared to a control group, comprised of 20 subjects consisting of 8 males and 12 females with a mean age of 58.8 years. Repeated assessment indicated both dynamic AOG measurement using powdered footprints and the several angular and linear radiographic measurements were valid and reliable techniques. Results also indicated that subjects with HL did not demonstrate a significant difference in AOG compared to the control group. Furthermore, there was no significant difference in length of the first metatarsal in both groups; however there was evidence to suggest elevation of the first metatarsal was significant between the HL and control groups. Results further indicated that the amount of first metatarsophalangeal joint dorsiflexion did not appear to influence AOG in the two groups, and that AOG did not reflect the amount of forefoot to rearfoot abduction in a foot with HL compared to the control group. When comparing foot type, as indicated by CIA, it appeared AOG did not significantly alter between the HL and control groups. Finally, the results indicated AOG did not differ significantly between subjects with unilateral HL.

This thesis study indicated that with the current sample population, the wide variability in AOG prevented detection of any subtle differences that may exist in subjects with HL. Results also emphasised the need to incorporate other variables such as symptomology and foot dominance when considering the effects first metatarsophalangeal joint pathology might have on HL, such as AOG.

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DECLARATION OF ORIGINALITY

This thesis is presented for the degree of Master of Medical Science of The University of Western Australia. Studies were undertaken between May 2003 and September 2004, through the Centre for Musculoskeletal Studies, School of Surgery and Pathology, in association with the Perth Radiological Clinic, Victoria Street Radiology, Midland, Western Australia.

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.

Michael J. Taranto

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LIST OF ABBREVIATIONS

AOG:	Angle of gait
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
HL:	Hallux limitus
HR:	Hallux rigidus
HV:	Hallux valgus
LAT:	Lateral
LAT SD:	Lateral stressed dorsiflexion
LIMA:	Lateral intermetatarsal angle
RFA:	Rearfoot to forefoot axis angle

LIST OF PUBLICATIONS

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)

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CHAPTER ONE

DEVELOPMENT OF THE PROBLEM

1.0 Introduction

The first metatarsophalangeal joint represents a complex joint in both its anatomical structure and biomechanical function of the lower limb.[1] Classified as a synovial ginglymoarthroidal, or hinge joint,[2] the first metatarsophalangeal joint has an axis of motion directed primarily in the transverse plane, allowing dorsiflexion and plantarflexion of the hallux on the head of the first metatarsal.[3]

Kinematics of the first metatarsophalangeal joint represents an integral component of the gait cycle, particularly in the terminal stages of stance during propulsion.[4, 5] The required amount of dorsiflexion of the first metatarsophalangeal joint in normal gait has been noted to be less than the available motion at the joint.[6] This figure varies somewhat in the literature, ranging between 50° to 90°, with approximately 65° of first metatarsophalangeal joint dorsiflexion commonly accepted as the minimum requirement for adequate leverage and propulsion.[7]

Defined as a reduction or limitation of hallux dorsiflexion on the first metatarsal head of less than 65°, hallux limitus (HL) represents the second most commonly encountered pathomechanical disorder affecting the first metatarsophalangeal joint, with hallux valgus (HV) being the most common.[8] Characterised by a lack of dorsiflexion at the first metatarsophalangeal joint that often progresses to osteoarthritic degeneration and pain,[7] HL is representative of a multi-factorial first ray deformity associated with numerous proposed aetiologies. The most common include an elevated first metatarsal, trauma, systemic disease such as gout and rheumatoid arthritis or a long first metatarsal.[9] Attention is primarily focused on the role musculoskeletal structures have in the development and propagation of this progressive deformity.[10]

Hallux limitus often presents clinically as pain and stiffness of the first metatarsophalangeal joint.[8] Traditionally, assessment of HL has often involved the patient in a non-weight bearing position, with the clinician using qualitative techniques to assess the first metatarsophalangeal joint. Inferences are drawn from relative amounts of sagittal plane dorsiflexion and plantarflexion of the hallux and overall quality of available motion. Alteration of gait and footwear has also been a common observation in people with first metatarsophalangeal joint pathology such as HL.[8, 10] Further clinical investigation may entail radiographic assessment of the foot, generally in a non-weight bearing position, as a means to ascertain the degree of osteoarthritic degeneration present in the first metatarsophalangeal joint. Conclusions are often drawn, and treatment plans executed based on this information.

A combination of investigating skeletal parameters such as length and elevation of the first metatarsal, relative amount of functional first metatarsophalangeal joint dorsiflexion and transverse plane position of the foot during the stance phase of gait acts as the impetus for this research. An attempt will be made to quantify these parameters and assess their potential influence on HL.

Chapter one serves to introduce the reader to understand the rationale of the present investigation. Commencing with a statement of the problem, a foundation of the research is created, on which the purpose of the study is structured. In addition, significance of the study is outlined, including definition of relevant terminology, specifically related to the radiographic variables measured. Finally, the research hypotheses are outlined and a summary of the chapter is provided. Further detail on all measurement variables investigated in the study is provided in the methodology section in Chapter three.

1.1 Statement of the problem and purpose of the study

Investigation into the quantification and reporting of angle of gait (AOG) has often been a focus of research in human biomechanics. Wide variation in normal AOG parameters exists in the literature, with a notable absence of a clear definition delineating the degree of transverse plane abduction or adduction considered as abnormal, particularly in the presence of pathology. It is recognised and accepted that AOG is influenced by numerous factors extrinsic to the foot;[4] including neurological pathways, muscular and ligamentous structures, osseous ontology such as tibial and femoral torsion, hip and knee joint position.[11]

This study serves to investigate differences in dynamic AOG measurements in subjects with and without HL. Establishment of reliability and validity parameters in quantifying dynamic AOG was therefore initially required.

A second objective was to establish whether the relative amount of foot abduction in gait is related to factors intrinsic or extrinsic to the foot. Intrinsic factors, such as the amount of forefoot to rearfoot abduction was considered. This was achieved by measuring the rearfoot to forefoot axis (RFA) angle using a weight bearing composite (COMP) view radiograph.

Thirdly, to investigate the radiographic parameters of the first metatarsal as a means to establish if a relationship existed between the degree of HL pathology and dynamic AOG. Hence, to determine whether intrinsic radiographic findings were predictive of HL or AOG. This involved performing several specific weight bearing radiographic angular and linear measurements.

The final objective was to determine whether AOG was related to a specific foot type. A radiographic measurement termed the calcaneal inclination angle (CIA) was chosen to classify foot type.[12] A high CIA was indicative of a high arched or cavus foot, whereby a low CIA represented a low arched or planus foot type.[12]

Preliminary investigations established the reliability and validity parameters in measurement techniques.[13] Dynamic AOG was assessed using a comparative reliability study using powdered footprints and the EMED-SF® (novel, gmbh, Munich, Germany) force platform (Appendix 1).[13] Secondly, a reliability study was conducted measuring various radiographic angular and linear parameters of interest on a series of weight bearing radiographs (Appendix 2).[14]

1.1.1 Angle of gait pilot study

The term AOG refers to the mid-sagittal position of each foot in midstance relative to the direction of forward movement during gait.[15] The purpose of this study was twofold. The first part was to assess the inter and intra-rater reliability of measuring AOG using a modification of a previously published validated technique of powdered footprints on paper.[15, 16] The second part consisted of a simultaneous study to compare AOG from powdered footprints and foot progression angle (FPA), the equivalent form of AOG, derived from electronic EMED-SF® footprints to determine whether the two measurements were similar.

1.1.2 Radiographic pilot study

Radiographic investigation of foot disorders is commonplace in clinical practice. Whether used for assessment, diagnostic, surgical planning, or comparative purposes, radiographs provide information that may influence clinical decision-making. Frequently angular and linear measurements are undertaken in an attempt to quantify the nature of a deformity such as HL.[17-19] This study investigated reliability of several radiographic angular and linear parameters. Two uncommon weight bearing views were included, namely the LAT SD view of the first metatarsophalangeal joint and a COMP view of the foot. The remaining views consisted of measurements obtained from weight bearing dorsoplantar and lateral views.

1.2 Significance of the study

Hallux limitus has been reported to produce proximal biomechanical changes as a result of secondary gait compensatory mechanisms.[20, 21] Assessment of HL has traditionally encompassed a subjective clinical approach, often with the first metatarsophalangeal joint assessed in a non-weight bearing position.

Establishing a comprehensive approach to the functional assessment of HL represents the central component of this research study. Investigating the potential influence on dynamic AOG could represent an issue of clinical significance, particularly by better understanding the aetiology of this pathological disorder of the first metatarsophalangeal joint. Furthermore, a functional weight bearing investigation of the radiographic parameters of HL could further enhance the understanding of this condition. It is hoped this research may provide the clinician with objective measures to monitor the progression of this common deformity.

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 forward movement during gait. Clinically, this can be referred to the amount of in-toeing or out-toeing of the foot relative to the line of progression in the transverse plane.[15]

'Body Mass Index' (BMI) refers to the body weight (kg) divided by the square of the barefoot height (m).[22]

'Calcaneal inclination angle' (CIA) is a radiographic angular measurement using a weight bearing lateral view of the foot. It is the angle formed by the weight bearing plane of the foot and a line drawn from this plane through the anteroplantar margin of the calcaneal tuberosity to the plantar margin of the anterior portion of the calcaneus.[12]

'First intermetatarsal angle' (FIMA) is a radiographic angular measurement using a weight bearing dorsoplantar view of the foot and represents the angle between the longitudinal bisection of the first and second metatarsal bones.[23]

‘First metatarsal protrusion distance’ (FMPD) is a radiographic linear measurement using a weight bearing dorsoplantar view of the foot and measures the distance between the relative length of the first and second metatarsals in millimetres (mm). A positive value denotes the first metatarsal is longer than the second. Conversely, a negative value indicates the first metatarsal is shorter than the second.[23]

‘Foot progression angle’ (FPA) refers to 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® force platform.

‘Hallux’ refers to the large or great toe, incorporating both the proximal and distal phalanges.[23]

‘Hallux abductus angle’ (HAA) is a radiographic angular measurement using a weight bearing dorsoplantar view of the foot and represents the degree of lateral deviation of the hallux. It is the angle formed by the longitudinal bisection of the first proximal phalanx and the longitudinal bisection of the first metatarsus.[23]

‘Hallux limitus’ (HL) is a progressive osteoarthritic deformity affecting the first metatarsophalangeal joint characterised by a reduction or limitation of hallux dorsiflexion on the first metatarsal head of less than 65°.[8]

‘Hallux valgus’ (HV) is a deformity of the first metatarsophalangeal joint characterised by a lateral deviation and often, external rotation of the great toe, and medial displacement of the distal end of the first metatarsal.[23]

‘Lateral intermetatarsal angle’ (LIMA) is a radiographic angular measurement using a weight bearing lateral view of the foot and describes the sagittal plane angular relationship between the dorsal surfaces of the first and second metatarsals.[24]

‘Lateral stressed dorsiflexion’ (LAT SD) is a radiographic angular measurement using a weight bearing stressed lateral view of the foot. It represents the relative amount of functional first metatarsophalangeal joint dorsiflexion measured from the angle formed by the longitudinal bisection of the first metatarsal and proximal phalanx of the hallux.[12, 25, 26]

‘Rearfoot to forefoot axis’ (RFA) is a radiographic angular measurement using a weight bearing composite view of the foot. It measures the amount of intrinsic rearfoot to forefoot abduction in the foot.[27]

1.4 Research hypotheses

The following hypotheses are investigated in the study:

(i) That AOG, derived from powdered footprints, is reliable and repeatable.

(ii) That AOG, derived from powdered footprints is directly comparable to FPA derived from the EMED-SF® force platform.

(iii) That the angular and linear weight bearing radiographic measurements used in the investigation are both reliable and repeatable.

(iv) That subjects with HL have a less abducted AOG compared to the control group.

(v) That subjects with HL have a longer, shorter or elevated first metatarsal compared to the control group.

(vi) That the amount of first metatarsophalangeal joint dorsiflexion influences AOG in subjects with HL compared to the control group.

(vii) That AOG reflects the amount of forefoot to rearfoot abduction in a foot with HL compared to the control group.

(viii) That AOG becomes less abducted as the arch of the foot becomes higher in subjects with HL compared to the control group.

(ix) That AOG differs significantly between feet in subjects with unilateral HL.

1.5 Summary

The aim of this research study was to investigate the dynamic AOG in subjects with HL, and to determine whether the presence of this common first metatarsophalangeal joint deformity was associated with altered AOG. Several radiographic angular and linear parameters were also investigated in an attempt to link these findings with any potential changes in AOG. Limitations of the present study, and recommendations for further investigation will also be presented.

CHAPTER TWO

LITERATURE REVIEW

2.0 Introduction

A review of the literature was conducted to provide a comprehensive insight into the research study. An anatomical and kinematic overview of the first metatarsophalangeal joint is presented to provide a summary of its structure and function. A review of the quantification techniques of first metatarsophalangeal joint range of motion measurement and reference range values for the sagittal plane motion of dorsiflexion available at the first metatarsophalangeal joint is also provided.

A review of the deformity of HL is presented, including the aetiology, epidemiology, classification systems, and common clinical signs and symptoms of this condition affecting the first metatarsophalangeal joint.

Angle of gait is reviewed, incorporating previous methodologies of quantification, investigating variation in AOG observed in the literature.

Finally, a review of radiographic measurements is presented, outlining methodologies used to quantify both angular and linear measurements, relevant to first metatarsophalangeal joint pathology. Particular attention is focused on first metatarsophalangeal joint dorsiflexion and forefoot to rearfoot angular relationships.

2.1 Anatomy and kinematics of the first metatarsophalangeal joint

The first metatarsophalangeal joint represents a complex articulation in its anatomical structure and biomechanical function in the lower extremity during gait.[1] Classified as a synovial ginglymoarthroidal joint,[2] Wernick and Volpe[3] state, by virtue of its condylar shape, the first metatarsophalangeal joint has two axes of motion or degrees of freedom, directed in both the transverse and sagittal planes. This explains why the proximal phalanx exhibits some passive transverse and frontal plane motion of abduction and adduction, and inversion and eversion on the head of the first metatarsal, respectively. Birke et al[28] stated predominantly sagittal plane dorsiflexion and plantarflexion is observed at the first metatarsophalangeal joint.

The first metatarsophalangeal joint incorporates the articular facets of four bones within a single synovial joint capsule. These include the head of the first metatarsal, base of the proximal phalanx of the hallux and superior surfaces of the medial and lateral sesamoid bones, which are embedded in the tendon of the flexor hallucis brevis muscle (Figure 2.1).[3]

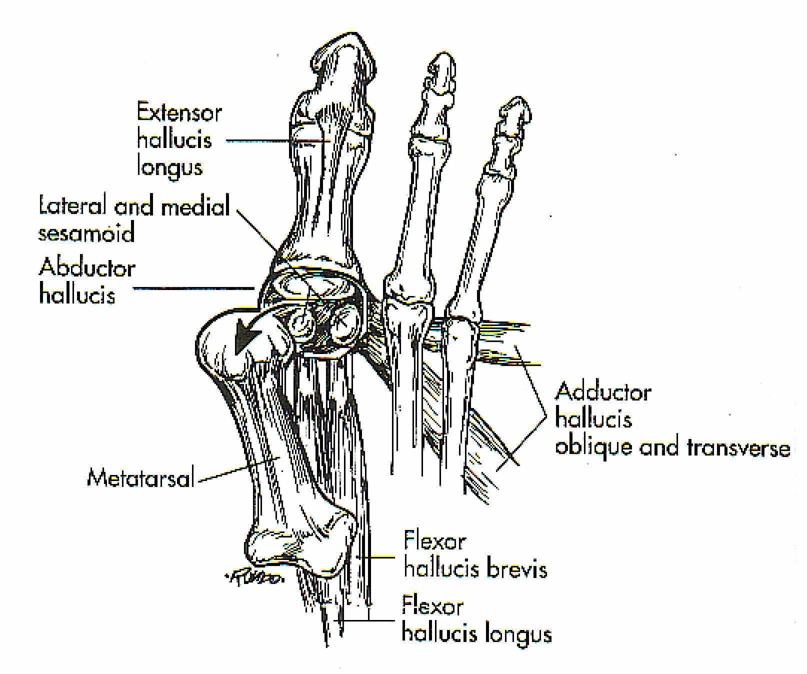

Figure 2.1 Anatomical depiction of the first metatarsophalangeal joint (adapted from Wernick and Volpe, 1996).[3]

According to Kelso et al,[29] the transverse axis of the first metatarsophalangeal joint represents an axis that changes its position with the sagittal plane motion of the joint (Figure 2.2). As a result of its ginglymoarthroidal joint classification, the first metatarsophalangeal joint demonstrates a ginglymoid or hinge-like rolling motion with the first 20° of dorsiflexion. According to Roukis et al,[19] further motion requires plantarflexion of the first metatarsal, which occurs through an arthrodial or sliding motion, thereby, allowing closed kinetic chain dorsiflexion of the first metatarsophalangeal joint beyond 20°. As this arthrodial or sliding motion of the first metatarsophalangeal joint begins at 20° of dorsiflexion, the transverse axis shifts dorsally and proximally. The vertical axis lies within the sagittal and frontal planes, therefore only transverse plane motion will occur about the first metatarsophalangeal joint.

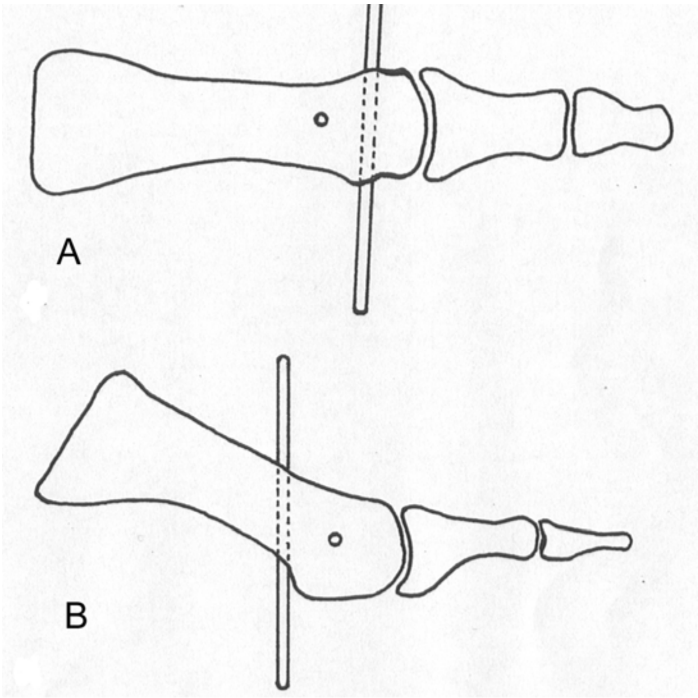

Figure 2.2 A, Dorsal view of the axes of the first metatarsophalangeal joint. B, Lateral view of the axes of the first metatarsophalangeal joint (adapted from Seibel, 1996).[30]

The theory of planal dominance outlined by Green and Carol[31] can be applied to the kinematics of the first metatarsophalangeal joint. When discussing motion in a three-dimensional environment, Green and Carol[31] noted it is important to appreciate that the axis of motion lies at the intersection or junction of the two planes perpendicular to the plane of motion. Direction of this axis is unique to the individual, therefore relative amounts of motion in all planes will occur accordingly.

Following an investigation into simulated closed kinetic motion of the first metatarsophalangeal joint, Hetherington et al[32] reported four centres of motion to exist within the first metatarsophalangeal joint, forming an arc like position (Figure 2.3). The first centre (I) near the joint surface was found to provide a rolling motion. Located near the centre of the metatarsal head, the next two centres (II) and (III) produced a movement characteristic of a sliding motion that

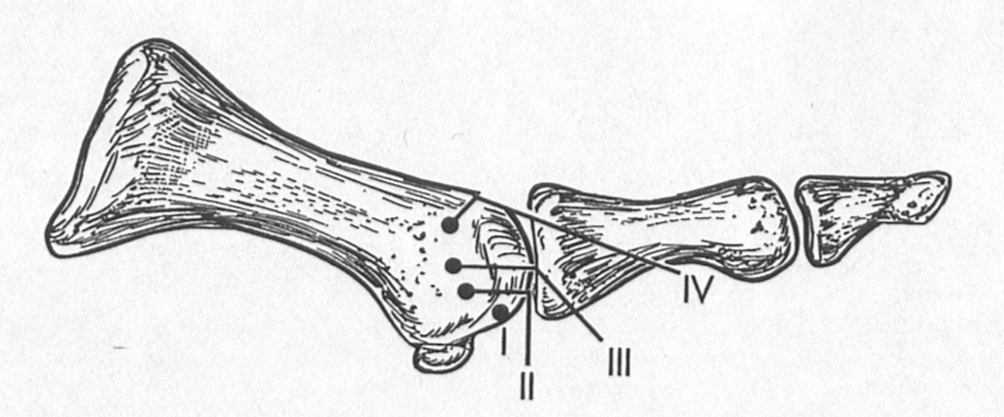

Figure 2.3 Character of motion occurring at the first metatarsophalangeal joint for each center of motion (adapted from Wernick and Volpe, 1996).[3] Refer to text for description of I-IV labels.

was believed to occur simultaneously with plantarflexion of the first ray. The final center (IV) was situated more dorsally in the metatarsal head, with its vector entering the proximal phalanx of the hallux, which was linked to a compressive force exerted at end range of motion during gait.

Conversely, the kinematics of the first metatarsophalangeal joint was studied using cadaver specimens in an open kinetic chain or non-weight bearing position. In this study, Shereff et al[33] discovered no rolling motion occurred at the first metatarsophalangeal joint. Instead, a sliding motion with compression at end range of first metatarsophalangeal joint motion occurred in normal non-weight bearing motion.

Motion of the sesamoids was also investigated in both studies, with Hetherington et al[32] concluding the sesamoids did not exhibit significant motion. Any motion observed was viewed as the first metatarsal head moving over the stationary sesamoid bones situated in the medial and lateral tendons of the flexor hallucis brevis muscle.

In contrast to this, Shereff et al[33] reported a 10mm - 12mm margin of movement of the sesamoids during normal gait in the stance phase, further noting that current understanding of first metatarsophalangeal joint motion was based on a small number of studies. According to Roukis et al,[34] this was attributed to an absence in the literature of a clear anatomical and biomechanical definition that was reliable, reproducible and demonstrated a high degree of scientific validity.

Influence of the plantar aponeurosis in controlling motion of the first metatarsophalangeal joint was presented by Hicks[35] using a model of the windlass mechanism. This model offered an explanation of the clinically determined range of motion observed at the first metatarsophalangeal joint. When the hallux was dorsiflexed during the propulsive period in the stance phase of the gait cycle, the plantar pad and aponeurosis moved distally. This effectively shortened the distance between the calcaneus, where the plantar aponeurosis was attached proximally, and first metatarsal head where it has its distal medial portion of attachment. This motion was envisaged to shorten the length of the plantar aponeurosis, or cable, of the windlass mechanism and make the arch of the foot shorter and higher.

Biossionnault and Donatelli[36] suggested first metatarsophalangeal joint dorsiflexion represented the most important motion in normal gait, and served three key functions. First, facilitation of supination of the foot converting it to a rigid lever via the windlass mechanism, making the foot mechanically efficient for propulsion. Secondly, the first metatarsophalangeal joint acted to enhance the mechanical advantage of the peroneus longus muscle via supination of the foot, whereby locking the midfoot to the rearfoot and enhancing the action of the flexor hallucis longus muscle for efficient toe-off in the terminal stage of the stance phase of gait. Finally, superficial fibers of the plantar fascia inserting into the skin, tighten, whereby allowing the plantar pad to stabilise and convert sheer forces of toe-off to the body.

According to Hopson et al,[7] the required amount of dorsiflexion of the first metatarsophalangeal joint in normal gait has been noted to be less than the available motion at the joint. This figure varied somewhat ranging from 50° to 90° (Figure 2.4).

Hopson et al[7] found a minimum of 65° of first metatarsophalangeal joint dorsiflexion was required in normal gait in the toe-off phase for adequate leverage and propulsion. According to Root et al,[6] this requirement was based on the angulation of the leg and foot to the ground in the toe-off phase of the gait cycle.

Without an adequate degree of dorsiflexion, Buell et al[25] reported abnormal biomechanical forces can be produced through the first metatarsophalangeal joint, which has been attributed to the formation of common first metatarsophalangeal joint deformities such as HL.

2.2 Measurement of first metatarsophalangeal joint range of motion

Detailed methodology in measuring first metatarsophalangeal joint range of motion in the literature has been shown to be somewhat limited with regards to

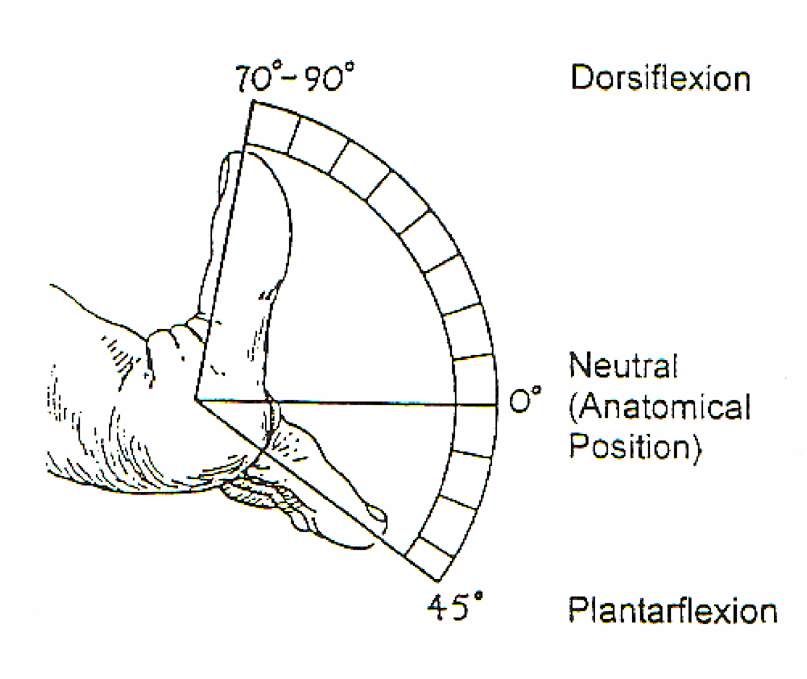

Figure 2.4 Sagittal plane first metatarsophalangeal joint range of motion (adapted from Hoppenfield, 1976).[37]

a standardised technique to quantify and reliably reproduce values given for normal range of motion.[25, 38]

Hopson et al[7] conducted a reliability study which focused on passive dorsiflexion of the first metatarsophalangeal joint, including static non-weight bearing and weight bearing measurement components. This was based on a previous study by Buell et al,[25] which investigated similar parameters. Hopson et al[7] concluded both static partial weight bearing and static weight bearing step length techniques demonstrated high intra-rater reliability.

Normal limits of first metatarsophalangeal joint dorsiflexion reported in the literature have demonstrated a large degree of variation (Table 2.1). This can be attributed to the alternative measurement techniques employed, with static measurements of first metatarsophalangeal joint dorsiflexion taken in both

Table 2.1 Reported normal ranges of sagittal plane dorsiflexion range of motion and methodology

Author	Dorsiflexion (°)	Method
Hiss[39] (1937)	45	No methodology outlined
Joseph[26] (1954)	40-100	Weight bearing lateral radiographs
Kelikian[40] (1965)	70	Non-weight bearing lateral radiographs
Sgarlato[41] (1971)	50-80	Anatomical landmarks and goniometer
Root, Orien and Weed[42] (1971)	65-75	Static weight bearing/anatomical landmarks and goniometer
Giannestras[43] (1973)	70	Non-weight bearing anatomical landmarks and goniometer
Hoppenfield[37] (1976)	70-90	Anatomical landmarks and goniometer
Bojsen-Moller and Lamoreux[44] (1979)	50-60	Electromechanical oscillator on cadaver specimens; and slow-motion film during walking
Mann[45] (1979)	70-90	Non-weight bearing anatomical landmarks and goniometer
Norkin and White[46] (1985)	70-90	Static non-weight bearing/ anatomical landmarks and goniometer
Buell et al[25] (1988)	82	Static non-weight bearing/anatomical landmarks and Weight bearing lateral radiographs
Gerhardt and Rippstein[47] (1990)	70	Non-weight bearing anatomical landmarks and goniometer
Hetherington et al[48] (1990)	65	Dynamic: Digitisation using video data
McRae[49] (1990)	65	Non-weight bearing anatomical landmarks and goniometer
Palmer and Epler[50] (1990)	90+	Anatomical landmarks and goniometer
Evans[51] (1994)	50	Non-weight bearing anatomical landmarks and goniometer
Hopson et al[7] (1995)	85-109.6	Static: weight bearing and non-weight bearing anatomical landmarks and goniometer Dynamic: Digitisation using video data
Merriman and Tollafield[11] (1995)	70-90	Tractograph/Finger goniometer
Nawoczenski et al[52] (1999)	44-58	Electromagnetic tracking device

weight bearing and non-weight bearing positions, using active and passive movement.

Buell et al[25] reported weight bearing dorsiflexion range of motion values were generally noted to be higher than non-weight bearing measurements.

Biossionnault and Donatelli[36] also noted influence of ankle joint plantarflexion and subtalar joint inversion, which occurred towards the terminal stage of the stance phase of gait, had also been associated with this observation.

Deformities associated with the first metatarsophalangeal joint such as HL have been assessed in both a weight bearing and non-weight bearing position,[25] with passive range of motion being referred to as the observer applying an external force to the hallux to determine its limit of available motion. Buell et al[25] noted this is typically several degrees lower than active range of motion.

When taking static, non-weight bearing and weight bearing range of motion measurements of the first metatarsophalangeal joint, McBride et al[1] reported subject position, limb involvement, position of the observer and instrument placement all affect the outcome of the measurement. Furthermore, McBride et al[1] noted range of motion at the first ray was effected by the position of the rearfoot. According to Buell et al,[25] placing the foot in the neutral ankle position, the amount of dorsiflexion at the first metatarsophalangeal joint was reduced. Stabilising the first metatarsal caused a reduction in range of motion, as would the degree of first ray dorsiflexion in the sagittal plane. It was further noted by Buell et al,[25] placing the foot in subtalar neutral, and a slight dorsiflexion force applied to the foot during loading, a restriction in hallux dorsiflexion was observed.

A question of the reliability and validity of figures quoted in the literature for normal range of motion in the joints of the foot had been raised.[53-55] Buell et al[25] noted establishment of a common reference point, such as the neutral position, from which measurements could be taken represented an alternative technique to address these issues.

The neutral position of the first metatarsophalangeal joint represents a functionally significant aspect of any range of motion study. This was defined as the straight line position of the joint where the hallux was in line with the longitudinal axis of the first metatarsal.[25] It was further stated by Phillips et al,[56] the neutral position of the first metatarsophalangeal joint could be found when the first metatarsophalangeal joint and subtalar joint were in their neutral position. According to Buell et al,[25] this enabled a more reproducible and reliable means of measuring non-weight bearing first metatarsophalangeal joint range of motion in the sagittal plane. This contrasted to the findings of Menz,[57] Menz,[58] and Picciano et al,[59] who reported the subtalar joint neutral position to be unreliable and was a notational rather than validated concept.

In contrast, Joseph[26] presented an alternative neutral position of the first metatarsophalangeal joint. Being one of the first studies to use radiography to measure first metatarsophalangeal joint range of motion, Joseph[26] reported the neutral position of the first metatarsophalangeal joint to be when the hallux was in a slightly dorsiflexed position whilst the joint was weight bearing and resting in a hanging position over the supporting surface.

This position has altered, with the clinical measurement of the first metatarsophalangeal joint taken with reference to the zero neutral or anatomical neutral position of the joint.[25] The resting hanging position, outlined by Joseph,[26] exhibited excessive variance in measurements between subjects and therefore the results for normal were highly variable and deemed unreliable. In addition, the study did not include women in the sample population of 50 subjects. Seeing as first ray pathology was observed in a significant number of women, normal values must include the female gender.[60-62]

Resting calcaneal stance position was also used as the position of the foot when measuring first metatarsophalangeal joint range of motion.[6, 26] According to Buell et al,[25] having the foot positioned in resting calcaneal stance was found to reduce the amount of dorsiflexion of the first metatarsophalangeal joint in the sagittal plane. This was accounted for by a plantarflexion movement of the first metatarsal, which restricted dorsiflexion of the hallux on the distal aspect of the first metatarsal head.

This was similarly noted by Shereff et al[33] in a study which investigated sagittal plane motion of the first metatarsophalangeal joint using cadaver feet. The specimens were placed in a plantargrade position and secured to only allow movement in the first metatarsophalangeal joint. Dorsiflexion and plantarflexion range of motion were concluded to be within the normal parameters quoted in the literature. These values were approaching the lower limits, which suggested the methodology used limited plantarflexion action of the first metatarsal. Other factors in the study, which may have accounted for a lower range of motion, included chemical preparation and dissection of the cadaver specimens.

According to Root et al,[6] first metatarsophalangeal joint dorsiflexion exceeding 20° to 30° required some degree of plantarflexion of the first metatarsal. A similar effect was reported by Root et al[6] when the first metatarsal was stabilised, which they suggested to be used in non-weight bearing assessment of range of motion of the first metatarsophalangeal joint. This concept however was based on theoretical modeling rather than true investigative techniques.[57]

Buell et al[25] noted to fully measure the available dorsiflexion range of motion passively, the subject was required to stress the first metatarsophalangeal joint into maximum dorsiflexion by facilitating heel lift. This initiated the windlass mechanism of the plantar aponeurosis,[35] as the heel moved into an inverted position, which according to Kidd and Kidd,[54] caused tension on the plantar fascia to increase. Hogan and Kidd[63] noted a plantarflexion moment on the first metatarsal followed, which resulted in an increased dorsiflexion range of the hallux on the first metatarsal head, similar to that noted by Roukis et al.[19]

When assessing other joints in the foot, the neutral subtalar joint position is often used as a reference point.[64, 65] Placing the foot in the neutral subtalar joint position and the ankle joint dorsiflexed to resistance when measuring first metatarsophalangeal joint range of motion non-weight bearing, is said to simulate the weight bearing foot during the stance phase of gait.[25] According to Buell et al,[25] this was believed to yield similar results as those obtained weight bearing. In addition, Lattanza et al[65] reported placing the foot in the neutral subtalar joint reference position acted to prevent the influence of pronation and supination of the foot, which was shown to affect both clinical and functional ranges of motion in other joints of the foot.

In a study by Lattanza et al,[65] which investigated non-weight bearing and weight bearing calcaneal eversion, it was concluded weight bearing measurements were greater than non-weight bearing measurements. It was further suggested by Elveru et al[64] that measurements should be conducted in weight bearing, as this was defined as the true functional position of the joint.

Clinical measurements of first metatarsophalangeal joint range of motion were traditionally conducted using dorsiflexion and plantarflexion of the hallux on the head of the first metatarsal, with the utilisation of skin bisection lines and goniometry.[53, 63] Radiographic measurement of first metatarsophalangeal joint dorsiflexion has been used as a way to reduce the amount of error associated with skin bisection line goniometry.[25, 26] Buell et al[25] further noted this would provide useful first metatarsophalangeal joint and range of motion information. In contrast, Light[66] reported radiographic measurement of sagittal plane first metatarsophalangeal joint range of motion, as outlined by Buell et al[25], was not reflective of true first metatarsophalangeal joint range of motion. This was attributed to a simplified approach to what has been described as a complex motion.

2.3 Hallux limitus

Limitation of first metatarsophalangeal joint range of motion or HL represents the second most commonly encountered pathomechanical condition affecting the medial column of the foot, with HV being the most prevalent in podiatric, orthopaedic and medical literature.[9, 10, 67] Banks and McGlamry[8] stated HL most frequently affects middle-aged and elderly individuals, males more than females, and in the United States population, occurred more often in African-Americans.

Defined as a reduction or limitation of hallux dorsiflexion on the first metatarsal head, HL was first described in the medical literature by Davies-Colley in 1887, cited by Buell et al,[25] who initially referred to the condition as hallux flexus. One year later, cited by Mann et al,[68] Cotterill coined the term ‘hallux rigidus’ (HR) to describe a stiff great toe, which effectively represented end stage ankylosis of the first metatarsophalangeal joint. Hallux rigidus can therefore be defined as a total absence of motion at the first metatarsophalangeal joint.[8]

Hallux limitus was characterised initially by a lack of dorsiflexion at the first metatarsophalangeal joint that eventually progressed to degenerative changes in the joint and subsequent pain.[7, 67] Root et al[6] stated the required amount of dorsiflexion of the first metatarsophalangeal joint in normal gait was noted to be only a small percentage of the available motion at the joint. Camasta[10] reported this figure varied somewhat in the literature, and has ranged between 50° to 90°. Hopson et al[7] stated a minimum of 65° of first metatarsophalangeal joint dorsiflexion was required in normal gait during the toe-off phase for adequate leverage and propulsion.

Hallux limitus is representative of a multi-factorial first ray deformity with numerous aetiologies accounting for the relative amount of limitation in first metatarsophalangeal joint range of motion. Aetiologic factors associated with HL are listed in Table 2.2.

In a retrospective analysis of 772 patients with HL, Grady et al[9] concluded, there was more than one aetiology present in 43% (330 patients). The primary causes of HL were noted as being trauma, metatarsus primus elevatus,

Table 2.2 Aetiologic factors associated with HL

- Acute Trauma[68]
- Ankle equinus:
  Overactivity of tibialis anterior resulting in medial column elevation and secondary hallux equinus/limitus[10]
- Arthritic degeneration of the sesamoid complex[8]
- Congenital clubfoot and talipes planovalgus:
  Intrinsic and extrinsic flexors of the hallux to attempt to stabilise the medial column[9]
- Congenitally short medial plantar fascial band[67]
- Contracture of the plantar soft tissue structures[67]
- Elevated first metatarsal:
  Intrinsic: Apex of deformity within the metatarsal shaft[69-71]
  Extrinsic: Apex of deformity proximal to the metarsocuneiform joint[69]
  Foot type:
  Forefoot rectus foot type with abnormal subtalar joint pronation[52]
  Increased pronation in midstance and toe-off[5, 52, 72]
  Functional hallux limitus and its effect on postural symptoms and gait efficiency[5, 21, 73]
- Footwear:
  High-heeled shoes[1, 74]
  Poorly fitted shoes[74, 75]
- Hypermobile first ray[6, 76]
- Iatrogenic causes following surgery[69]
- Immobilisation[76]
- Long first metatarsal[77]
- Long proximal phalanx[9]
- Arthritic conditions:
  Rheumatoid arthritis, gout, psoriatic arthritis, Reiter's syndrome, ankylosing spondylitis[10, 75]
- Neuromuscular disorders:
  Hyperactivity of the tibialis anterior or weakness of peroneus longus which leads to metatarsus primus elevatus[76]
- Neuropathic arthropathy[9]
- Obesity[43]
- Occupations requiring repeated squatting or climbing[9, 68]
- Osteochondritis dissecans of the first metatarsal head[72]
- Osteporosis[78]
- Paralytic deformities (flaccid and spastic)[9]
- Peroneal spastic flatfoot:
  Tarsal coalitions[9]
- Repetitive/Chronic trauma:
  Dancers, runners, athletes[9]
- Sesamoidal apparatus and joint capsule[67]
- Shape of metatarsal head:
  Square[10]
  Convex surface[10]
  Congenitally flattened articular surface[75]
- Short first metatarsal[77]
- Short flexor hallucis longus and brevis tendon[67, 79]

elongated first metatarsal, excessive pronation, gout, Reiter's syndrome, ankylosing spondylitis and rheumatoid arthritis.

Classification of HL has been viewed as an important factor in understanding the progression of the deformity. In the past, several classification systems had been described in the literature, primarily based on clinical or radiographic observations often considered separately.[9]

Initially, HL was classified as primary HL, which affected younger individuals between the ages of 12-15 and secondary HL, which, according to Durrant and Siepert,[67] was generally attributed to older individuals or those subject to trauma. According to Grady et al,[9] the most widely accepted classification system of HL was the one described by Regnauld in 1986. This system was based on both clinical and radiographic findings, presented in Table 2.3.

Grady et al[9] noted a criticism of Regnauld's classification system, stating it failed to address all of the radiographic findings of HL. According to Hanft et al,[80] another classification system of HL based on radiographic findings was developed further incorporating subchondral pathology and cyst formation.

According to Shereff and Bamhauer,[81] the most predominant feature of HL from a clinical perspective was pain experienced within the first metatarsophalangeal joint. However, Camasta[10] noted restriction of first metatarsophalangeal joint range of motion was not limited to the local phenomenon of joint pain. Camasta[10] further noted foot function could also alter as a compensatory outcome, which has further been described to lead to gait disturbances and postural symptoms.[21, 25, 73] Clinical signs and symptoms of HL

Table 2.3 The Regnauld classification system for HL

First Degree
- Acute/subacute pain.
- Less than 40° of dorsiflexion and 20° of plantarflexion of the hallux.
- Joint enlargement/mild dorsal spurring.
- Slight narrowing of the joint space.
- Regular, but slightly enlarged sesamoids.

Second Degree
- Intermittent pain and tingling at rest.
- Limitation of metatarsophalangeal joint motion.
- Metatarsalgia.
- Narrowing of joint space.
- Flattening of the first metatarsal and phalanx.
- Elongation and elevation of the first metatarsal.
- Hypertrophy and irregularity of sesamoids.

Third Degree
- Extensive spurring of dorsal, medial and lateral aspects of the joint.
- Flexor hallucis longus contracture.
- Severe loss of joint space.
- Hypertrophy of metatarsal, phalanx and sesamoids.
- Particular osteophytes bridge the metatarsosesamoid joint.
- Joint mice.
- Joint approaches ankylosis.

Grady et al, 2002.[9]

varied, depending on the progression of the deformity. Table 2.4 lists the common clinical symptoms reported by people with HL.

During normal gait, Murray et al[82] noted the plantar weight distribution followed a particular line of progression. The center of pressure passed from the lateral aspect of the calcaneus at heel strike and then moved towards the lateral forefoot during midstance. As the foot approached the propulsive phase of the gait cycle, the center of pressure was determined to pass between the first and second rays. In patients with HL or HR, Dananberg[21] reported there was a noticeable shift in the distal transfer of weight, whereby in late midstance and early propulsion, forces in the forefoot passed medially through the hallux and spared the first metatarsophalangeal joint. Camasta[10] reported subtle evidence

Table 2.4 Clinical signs and symptoms of HL

Signs

- Callous underlying the hallux interphalangeal joint or plantar medial aspect of the hallux[9, 10]
- Compensatory alteration in foot function can lead to gait disturbances and postural symptoms such as lateral stress loading due to lateral weight transfer, plantar fifth metatarsophalangeal joint bursitis, pericuboid joint overload with effusion of the metatarsal-cuboid or calcaneal cuboid joint[9, 21, 68, 73, 83]
- Dermal hyperpigmentation from chronic shoe pressure[74]
- Dorsal first metatarsophalangeal joint osseous hypertrophy resulting in footwear irritation and secondary skin and soft tissue irritation[8, 68]
- Dorsal-medial prominence of the first metatarsophalangeal joint[9, 79]
- Focal first metatarsophalangeal joint calor with an active effusion or acute exacerbation of an arthritic joint[81]
- Hyperextension of the hallux interphalangeal joint with associated interphalangeal sesamoids[76]
- Limitation/restriction of first metatarsophalangeal joint range of motion[77, 81]
- Localised first metatarsophalangeal joint oedema, erythema and guarding secondary to acute pain[67, 72]
- Non-weight bearing resting position of the hallux held in equinus relative to lesser digits[84]
- Periarticular erythema[10]
- Subungual exostoses, onycholysis and paronychia resulting from hallux interphalangeal joint hyperextension[9]
- Synovial effusion[68]
- Visible joint enlargement[78]

Symptoms

- Burning sensation due to irritation of the proper dorsal digital branch of the medial dorsal cutaneous nerve which supplies the dorsal medial quadrant of the hallux[81]
- Deep ache associated with ambulation both within the joint and dorsally[79]
- Exacerbation of symptoms when in bare feet, high heeled or flexible athletic footwear[9]
- Pain beneath the hallux interphalangeal joint[9, 10]
- Pain within the first metatarsophalangeal joint[9, 10, 76]
- Paraesthesia distally to the site resulting from neuropraxia of the proper dorsal digital branch of the medial dorsal cutaneous nerve due to chronic irritation[10, 69]
- Tonic spasms or cramps of the extensor hallucis longus[68, 76]

---

of this occurred in examination of shoe wear patterns, noted particularly under the second metatarsophalangeal joint and hallux interphalangeal joint. There has also been reported a noticeable angulation of the shoe break in the upper of the shoe at the metatarsophalangeal joint level, instead of being transverse in a normally functioning foot.[21, 73]

Dananberg[21] further reported the effect of HL on postural symptoms such as gait, and was referred to in the literature as functional hallux limitus. Described as the functional inability of the proximal phalanx of the hallux to extend on the first metatarsal head during gait, Dananberg[21] stated this momentary block in sagittal plane motion of the first metatarsophalangeal joint occurred late in stance phase. Payne et al[5] further noted as heel lift was initiated, the first metatarsophalangeal joint was unable to provide an adequate range of dorsiflexion. This resulted in compensatory mechanisms to occur such as early heel lift, abductory twist secondary to lateral deviation of the centre of pressure and excessive pronation at the midtarsal joint.[20, 21, 73, 83]

Furthermore, according to Bingold,[79] an apropulsive gait could develop as a consequence of HL, particularly as it progressed towards ankylosis. Unilateral involvement is most common in females with a wide age distribution, with an average age range from 12 years[85] to 60 years.[68] Camasta[10] believed evidence of these gait characteristics and footwear patterns usually preceded the onset of joint symptoms in patients by several years duration. Therefore the question must be asked whether the onset or progression of HL is the result of adopting a particular gait pattern or variation of gait occurs as a result of the deformity?

2.4 Angle of gait

Human gait represents a highly complex dynamic event involving anatomical, physiological, biomechanical and neurological processes, which are both intrinsic and extrinsic to the lower limb.[16] Although the literature proposes abnormal biomechanics as a risk factor in the development of foot deformities such as HL,[5, 20, 21, 73] the direct relationship between AOG and HL has not been investigated.

The term ‘angle of gait’ refers to the mid-sagittal position of each foot in midstance relative to the direction of forward movement during gait (Figure 2.5).[15] Normal dynamic AOG had been variously reported in the literature. It has been said to range between 5° to 9°[7, 61, 82] and 7.5° to 10° abducted from the midline of forward progression.[86]

According to Holden et al,[87] there are numerous factors which can influence AOG. Included are hip joint position and motion, influence of supporting soft tissue ligamentous and muscular structures, degree of femoral, tibial and malleolar torsion, amount of abduction and adduction of the whole foot to the body of the talus and neurological mechanisms.[4, 88, 89]

Alternatively, musculoskeletal pain can also be a significant contributing factor influencing AOG as a result of compensatory mechanisms.[20, 73] In addition to this, footwear can influence AOG characteristics as a result of materials, last design and manufacturing.[10]

Additionally, Murray et al[61, 82] reported factors such as walking speed and gender can influence AOG. Morton[90] stated race and genetic traits can also influence AOG and contribute to its variable nature. Dominant leg and walking substrate have also been reported as additional factors which can influence gait, according to Clarkson,[91] resulting from potential tactile sensations during barefoot ambulation.

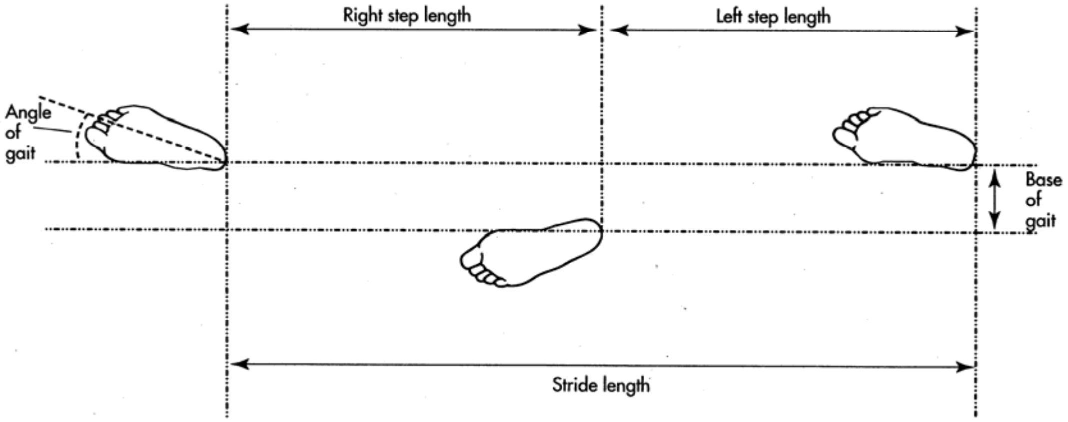

Figure 2.5 Angle of gait in relation to stride length, step length and base of gait (adapted from Wernick and Volpe, 1996).[3]

According to Sutherland et al,[4] several significant changes occur to the dynamic transverse plane position of the foot during normal walking (Figure 2.6). In the initial phase of the gait cycle, a relatively constant degree of abduction occurs. Between opposite foot strike and toe-off, or the period of second double support, adduction occurs. At commencement of toe-off, the foot abducts as it simultaneously dorsiflexes to clear the foot during swing phase.

There have been numerous techniques outlined in the literature to obtain and measure AOG (Table 2.5). These range from manual methods using static and dynamic footprint impressions, employing mediums such as ink or talcum powder on paper, to more advanced techniques incorporating computer intensive digital technology. Although the manual techniques are relatively inexpensive, they require a great degree of time and input.

In later studies, more advanced techniques were used to quantify AOG. Lee et al[92] conducted a three-dimensional study which investigated forefoot abduction

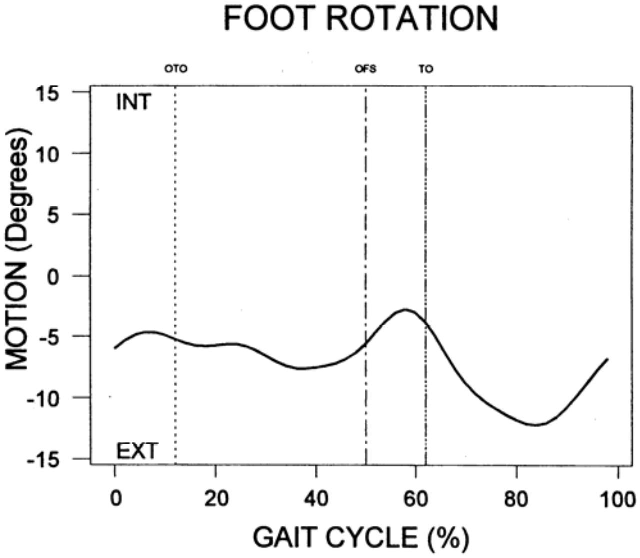

Figure 2.6 Amounts of internal (adduction) and external (abduction) rotation of the foot during normal gait (adapted from Sutherland et al, 1994).[4]

and adduction relative to the rearfoot. Video data were collected from reflective markers affixed to the ends of Steinmann pins positioned in vitro to the tibia, calcaneus, cuboid and first and fifth metatarsal bones. Katoh et al[93] used a piezoelectric force plate and digitised video footage to investigate dynamic foot function during gait.

Those investigations conducted by Lee at al[92] and Katoh et al[93] included two and three-dimensional gait analysis systems, similar to those used by Cappozzo et al.[94] Kinematic three-dimensional analysis has also been used to investigate gait parameters such as AOG.[95-99] Alternatively, Carson et al[100] and Gilchrist and Winter[101] presented mathematical based models of multi-segment foot model kinematic analysis as an alternative means to investigate AOG.

Table 2.5 Reported methodologies used to measure AOG

Author	Year	Methodology
Fukushima[102]	1955	Powdered plaster of paris
Ogg[103]	1963	Paper, corn pads, ink and felt-tip markers
Scrutton and Robson[104]	1968	Talcum powder and linoleum
Murray et al[61]	1970	Reflective markers and interrupted light photography
Burnett and Johnson[105]	1971	Gauze injected with ink and paper
Chodera[106]	1974	Thin aluminium foil and magnetic tape
Boenig[107]	1977	Moleskin, ink and paper
Shores[108]	1980	Paper and paint
Clarkson[91]	1983	Moistened absorbent paper
Katoh et al[93]	1983	Forceplate analysis and foot-switch contact patterns
Kippen[109]	1983	Paper and ink
Levangie et al[110]	1983	Moleskin, water based ink and paper
Rose-Jacobs[111]	1983	Paper, corn pads, ink and felt-tip markers
Rutherford[112]	1983	Glass plates and mirrors
Bertoti[113]	1986	Moleskin impregnated with water based ink and paper
Gaudet et al[114]	1990	Ink pads, reflective marker and video analysis
Cappozzo et al[94]	1996	Reflective markers and digital videofluoroscopy
Freychat et al[27]	1996	Radiograph, forceplate analysis system
Gilchrist and Winter[101]	1996	Mathematical based mulit-segmental foot model
Keenan and Bach[115]	1996	Video analysis with reflective markers
Zejie et al[99]	1996	Three-dimensional kinematic trajectory acquisition and analysis with digital orthogonal integration phase detection
Wilkinson and Menz[16]	1997	Transparent grid, laundry markers, metal rulers, alcohol swabs, white cardboard, coloured talcum powder, artists' fixative and lamination
Beischer et al[95]	1999	Clinical and radiological assessment with kinematic and kinetic three-dimensional gait analysis
Lee et al[92]	1999	In vitro Steinmann pins, reflective markers and video data analysis
Ho et al[116]	2000	Motion analysis system
Wu et al[98]	2000	Computerised motion analysis system
Carson et al[100]	2001	Stereophotogrammetry and retroreflective markers
Nester et al[96]	2001	Three-dimensional video gait analysis
Ounpuu et al[97]	2002	Three-dimensional video gait analysis

Several studies have looked at the inter-rater and intra-rater reliability of measuring specific gait characteristics such as AOG.[15, 16] A reliability study conducted by Kippen[109] investigated measuring specific gait parameters, one of which was AOG, from static and dynamic ink footprints. A significant quantifiable ratio between dynamic and static footprint data was reported.

Wilkinson and Menz[16] identified specific methodological limitations in the study by Kippen.[109] These related to identification of a reproducible reference point on the curve of the heel, and restriction of the use of the particular methodology to barefoot individuals. Favourable measurement outcomes reported were also questioned, suggesting they may have resulted from the single subject design of the reliability study conducted by Kippen,[109] whereby the examiners may have demonstrated memory bias.

Following this, Wilkinson et al[15] and Wilkinson and Menz[16] investigated the measurement of several gait parameters, also including dynamic AOG using footprints. The research conducted by Wilkinson and Menz[16] stemmed from the lack of consensus in the literature as to how footprint data should be derived and interpreted. In addition to this, a corresponding lack of investigation into the reliability of footprint evaluation lead Wilkinson and Menz[16] to develop a reliable and valid manual method of measuring dynamic AOG. A high inter and intra-rater reliability was reported,[16] which has now been utilised in subsequent gait research as it demonstrated a high degree of reliability and validity.[13] Limitations of this technique, as with other similar methodologies, is its labour intensive and time-consuming nature.

Most AOG studies have involved measurement relative to a line through the middle of a walkway, as described by Holden et al.[87] Wilkinson et al[15] believed this was not reflective of normal walking, under the assumption the line of progression changed during the gait cycle. Other studies, such as Freychat et al,[27] calculated the line of progression by using ipsilateral footprints, however

Wilkinson et al[15] believed this may not have accounted for the variability in the line of progression caused by the contralateral foot.

The footprint method of assessing gait parameters has been shown to be easy, reliable, valid, inexpensive and clinically feasible.[27, 91, 107, 108, 110] A recent study by Kennedy et al[117] investigated the variability in outlines of barefoot inked footprints for forensic purposes, and showed large variability between-subjects and a high degree of similarity for multiple impressions from the same subject. Kennedy et al[117] examined variability between subjects from an identification viewpoint, specifically with regard to foot dimensions, and concluded inked footprints were highly individual.

Few studies have investigated the simultaneous collection of footprint data. One such study by Urry and Wearing[118] compared ink footprints to electronic footprints as a means to assess differences in geometric parameters. Significant differences were found to exist in several geometric indexes investigated, with the conclusion that electronic footprints derived from the pressure platform were not representative of the equivalent ink footprints.

In contrast, Mathieson et al[119] reported intra-rater reliability of geometric analysis of electronic footprints to be high. According to Chu et al,[120] potential problems associated with electronic footprints are they were poorly delineated. Urry and Wearing[118] further noted irregular borders and inadequate contact area were the result of low equipment sensitivity.

The EMED-SF® force platform analysis system is an instrument used for recording and evaluating static and dynamic pressure distribution on flat surfaces.[121] According to Graf,[121] numerous parameters of foot function can be investigated using this system. Hughes et al[122] has previously established reliability parameters of the EMED-SF® force platform analysis system, however validation in terms of plantar foot pressures being representative of dynamic foot motion would require further investigation.

The EMED-SF® platform produces a maximum pressure image, 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 (FPA), defined as the angle between the mid-axis of the foot and the direction of travel during data collection using a plantar pressure distribution image of the foot (Figure 2.7).

2.5 Radiographic investigation and measurement

Radiographic investigation of the foot and lower limb represents an important component in patient assessment by the treating practitioner, and often contributes significantly to the clinical decision making process.[123] Numerous studies have investigated radiographic measurements in first ray deformities of the foot, with HV being the principal focus of attention.[18, 62, 123-132]

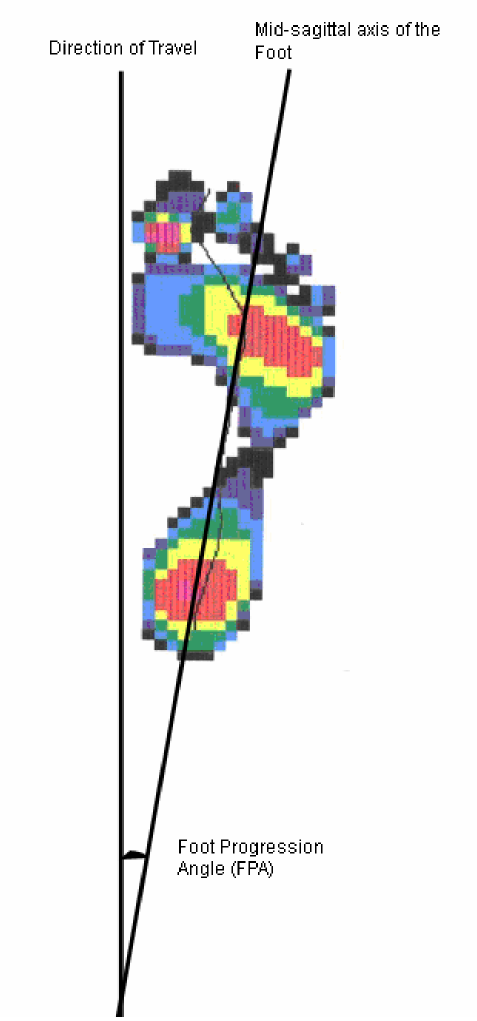

Figure 2.7 EMED-SF® maximum pressure image depicting the foot progression angle (FPA); defined as the angle formed between the direction of travel and the mid-sagittal axis of the foot.

Factors considered in these studies included weight bearing and non-weight bearing position, and gender influence as investigated by Tanaka et al,[62] as well as inter-rater and intra-rater reliability of measurements which were reported by Kilmartin et al.[127] Inter-rater and intra-rater reliability of most radiographic measurements of the foot have been found to be reasonably good, with Bryant et al[133] reporting that intra-rater reliability improved with experience.

In a study which investigated measurement reliability using subjects with HV, Resch et al[130] reported a high inter-rater error when investigating standard radiographic measurements, with an average inter-rater error of up to 6.4° for the HAA and 5.4° for the FIMA.

According to Camasta et al,[134] there are numerous potential sources of error when considering radiographic measurements. These commence with the initial stages of taking and developing the radiograph. Subject position and distance in relation to the film and the position and distance of the x-ray tube, are factors that influence magnification. Camasta et al[134] noted this to rarely be an influencing factor in foot radiographs, since most radiograph machines use a fixed source to film distance.

In addition to magnification effects, placement of the subject or source at an angle to the film will cause a degree of distortion to occur. Common foot types such a pes planus and pes cavus, therefore may significantly influence this relationship, based on the degree of severity of the foot type.[134]

According to Schneider and Knahr,[131] alternative sources of error in radiographic measurements included choosing anatomical landmarks and constructing lines. Saltzman et al[123] reported reading of the measurement instrument and over-exposure of the radiograph as another source of potential error, while Bryant[135] and Resch et al[130] noted foot positioning and relationship of the foot to the central ray and radiograph cassette accounted for error. McRae[49] reported arch height in relation to declination of the metatarsals as a significant factor in error associated with measuring radiographs, primarily as a result of the effect of distortion.

According to Bryant,[86] weight bearing radiographs are considered to be an accurate representation of both structural and functional relationship of the foot. Camasta et al[134] further reported individual variation existed between radiographers in several areas, including patient positioning, placement of the central ray, focal distance, and equipment variability, including exposure and development processes.

Weight bearing and non-weight bearing position of the subject was demonstrated to have a significant influence on joint position, as reported by Bryant.[86] Weight bearing views were reported to demonstrate the foot in a locked and static position, and hence simulates a functional foot position. According to Bryant et al,[133] this provided a more representative impression of the osseous and soft tissue structures under weight bearing stress, which is more reflective of human bipedal function than non-weight bearing foot radiographs.

An attempt to demonstrate this was conducted by Perlman et al[136] using standard static weight bearing lateral radiographs in subjects normal angle and base of gait, and compared these findings to dynamic gait utilising fluoroscopy. It was concluded a high reliability of the measurement process and high correlation between radiographic and fluoroscopic results existed, indicating value in taking weight bearing angle and base of gait lateral radiographs.

Methods of measuring radiographs also differ, including the most common and clinically applied technique using a lightbox, chinagraph pencil and standard manual tractograph of one-degree increments. Although a universally accepted measurement technique, limitations such as being unreliable and time consuming were identified.[137] An alternative technique was investigated by Beasley et al,[137] which used a digital radiograph analyser and digitising software. Greater speed and smaller measurement error was observed when comparing this method to the traditional manual technique, however the methodology and statistical analysis were poorly defined.

An elevated first metatarsal or metatarsus primus elevatus has been implicated as one of the major aetiological factors in HL.[69] Radiographic assessment of this position has been attempted in the past by Drago et al.[76] This was performed by bisecting the first metatarsal on a weight bearing lateral view. A line divergent to the talar bisection was termed to remain consistent with metatarsus primus elevatus.[76]

An alternative technique to quantify elevation of the first metatarsal, and hence involvement in HL, was introduced by Bryant et al.[24] Termed the lateral intermetatarsal angle or LIMA, Bryant et al[24] defined this as a measurement of the sagittal plane angular divergence between the dorsal cortices of the first and second metatarsals from lateral weight bearing foot radiographs.

The LIMA measurement of metatarsus primus elevatus was proposed by Bryant et al[24] in favour of that described by Drago et al[76] for the primary reason that the talus may be in a plantarflexed position, thereby giving a false positive measure of metatarsus primus elevatus. Results of the investigation by Bryant et al[24] demonstrated good reliability in measuring elevation of the first metatarsal, with significant differences reported with increased first metatarsal elevation in subjects with HL compared to a control group.

Measurement of first metatarsophalangeal joint dorsiflexion using radiographs had been previously investigated.[25, 26] Buell et al[25] reported the average dorsiflexion range of motion at the first metatarsophalangeal joint was lower in the group with first ray pathology compared to the normal group. Average unassisted and assisted dorsiflexion was 77° and 82°, respectively, for the control group, and 51.4° and 55° for the group demonstrating first ray pathology. Further evaluation by Buell et al[25] demonstrated a decrease in first metatarsophalangeal joint range of motion with increasing age.[25]

Buell et al[25] concluded clinical versus radiographic unassisted and assisted first metatarsophalangeal joint dorsiflexion demonstrated very close correlation. This conclusion, however, was derived by comparing average values, rather than reporting statistical analyses of the data. Furthermore, failure to include subject demographics and definition of inclusion criteria for the study was absent, particularly those with first ray pathology.

Reliability of the composite (COMP) view[138] in measuring the RFA angle has not been previously established in the literature. The advantage of the COMP view is it allows the entire skeletal anatomy of the foot to be viewed, however has not been used extensively in clinical practice or research. In a study conducted by Freychat et al,[27] determination of the forefoot to rearfoot axis using a radiograph was described, whereby the radiographic axis of the foot using a COMP view was transferred onto footprints generated from a force platform. This subsequently reduced potential sources of error such as location of anatomical landmarks and soft tissue influence.

The suggested relevance of the RFA is that the forefoot and rearfoot may act somewhat independently, and foot position is influenced by mobility around the transverse tarsal joint, as proposed by Bojsen-Moeller.[139] Using this theory, the forefoot to rearfoot axis, may allow static measurements to reflect dynamic function, such as pronation and supination of the foot, as outlined in a study by Dahle et al.[140] Additionally, it provides a transverse plane measurement of the forefoot to rearfoot relationship.

Stacoff et al[141] proposed the complex triplanar motion of pronation and supination of the foot can be influenced by movement of the forefoot on the rearfoot. Foot pathologies such as adult acquired flatfoot and tibialis posterior tendon dysfunction, resulting in excessive pronation, are thought to contribute to compensatory forefoot abduction.[142-144] In addition to acting as a plantarflexor and invertor, the tibialis posterior muscle itself can also function as an adductor of the forefoot at the midtarsal joint, opposing the action of peroneus brevis.[143] Additionally, forefoot abduction has relevance with regard to tightness of the plantar aponeurosis, indicating a more abducted or open foot type.[145] Subsequently, measurement of the forefoot to rearfoot axis, using the COMP view, may be indicated in future research relating to transverse plane pathomechanics.

2.6 Summary

The literature has highlighted multiple aetiologies associated with the development and progression of HL.[9, 10, 76] Common aetiologies reported with HL included excessive length and elevation of the first metatarsal. In association with these, others such as trauma, gout, and importantly the biomechanical function of the foot, have been implicated. Specifically characterised by abnormal subtalar and midtarsal joint pronation, leading to first ray elevation and progression of HL.

An association between abnormal foot function and the development of HL has long been reported in the literature. This, however, has equally been met with controversy, primarily with regard to a notable lack of valid measurement techniques to quantify biomechanical parameters of the foot, such as pronation and supination. Representative of a complex triplanar motion, quantification of a movement that occurs simultaneously in all three cardinal body planes and varies between and within individuals proves a difficult task.

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

Given the established relationship between excessive supination and foot adduction, assessment of transverse plane motion, specifically AOG, may be important in providing further insight and understanding of the complex nature of the aetiology of HL. Gait analysis using footprint impressions is a simple and inexpensive method of obtaining valuable information relating to foot dynamics.

Radiographic measurements of foot parameters provide an objective assessment of foot structure and function in HL, reducing sources of error and subjectivity associated with clinical observation. In contrast, radiographic measures can also simultaneously introduce alternative sources of error in measure such as visual parallax error and aberrations associated with magnification.[134] Of the radiographic parameters reviewed, two groups of variables important for assessment of HL have emerged. The first group comprised those variables considered causative or that provide value in monitoring the progression of the HL deformity. Specifically, these were LAT SD, FMPD, and LIMA. The second group consisted of those factors capable of influencing AOG, specifically RFA angle. The variable CIA was considered important in both groups, given its aetiological implication as a potential predictor of foot type, as well as its capability of influencing AOG and the subsequent amount of pronation or supination occurring during gait.

Therefore, in this study, radiographic measures were utilised to assess both the progression of HL and the relationship between structural features and AOG.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

This chapter outlines the methodology used in the research study. The study design is presented, along with an outline of the research questions investigated. A summary of the participant demographics and methods of recruitment are also outlined, including both inclusion and exclusion criteria. Ethical considerations are then presented, along with general subject demographic data collection procedures. Reliability and validity issues are addressed for measurement of AOG and radiographic measurements, which are presented as a brief summary of the pilot studies that were designed and conducted. Further details of the pilot studies are presented in Appendix 1 and Appendix 2 respectively. A detailed description of data collection procedures for AOG and the radiographic angular and linear measurements investigated are presented, along with a summary of the statistical methods used for data analysis.

3.1 Study Design

A prospective observational quasi-experimental case-control study design was used.

3.2 Participants

Participants in the study were grouped into two study groups. This comprised of subjects with HL (n=22 subjects) and a control group (n=20 subjects).

3.3 Recruitment

All subjects involved in the study were recruited from the author's private practice podiatry clinic in the Perth metropolitan area using a sample of convenience. Subjects deemed suitable for participation were screened by the researcher for inclusion criteria. Once the inclusion criteria were satisfied, the potential subject was sent an information and consent form (Appendix 3). Once the subject information and consent form was signed and returned to the researcher, the subject was referred to the designated radiology clinic for a standardised radiographic series.

3.4 Inclusion criteria

HL Inclusion Criteria:

- Have read, comprehended and completed the subject information and consent to participate document.
- Have reached skeletal maturity as determined by radiographic examination and be a minimum age of 18 years of age.
- Have a radiographic measured limitation of first metatarsophalangeal joint dorsiflexion on a stressed lateral radiograph of less than 65°.[7]

Control subjects inclusion criteria:

- Have read, comprehended and completed the informed consent document.
- Have reached skeletal maturity as determined by radiographic examination and be a minimum age of 18 years of age.
- Have a radiographic measured limitation of first metatarsophalangeal joint dorsiflexion on a stressed lateral radiograph of 65° or more.[7]

3.5 Exclusion criteria

Subjects demonstrating HL and control subjects would be excluded from the study if they had any of the following:

- A history of any condition likely to affect gait, such as lower limb surgery, trauma, neurological disorders, walking aids, a history of congenital hip dysplasia, systemic disease, for example sero-negative or sero-positive pathology, or any hypermobility syndromes such as Ehlers Danlos or Marfan's Syndrome.

3.6 Ethical considerations

All subjects participating in the study were required to read, understand and sign a subject information and freedom of consent form prior to any participation in the research project (Appendix 3). This document acted to inform the subject of any associated risks of the research and indicated the research would be conducted in a form acceptable to the National Health and Medical Research Committee (NHMRC). It further informed the subject if they declined or withdrew from participating in the study, their treatment status would remain unaffected. The Human Research Ethics Committee of the University of Western Australia approved the study.

All participants involved in the study were not subjected to any invasive procedures. All subjects were alphanumerically coded in a form known only to the principle researcher, with all data and documentation to be kept securely in the Centre for Musculoskeletal Studies, University of Western Australia, for a period of five years. Data were saved on a Microsoft Excel® spreadsheet on the hard drive of the researchers personal computer, which had password security capabilities. These data, a 256MB PenDrive® external memory stick and 750MB re-writable CD, acting as two forms of electronic data back-up, were stored in a lockable filing cabinet.

Radiographic examination of subjects with HL is an integral component of the usual comprehensive podiatric assessment of the deformity. As subjects with HL were sourced from the author's private practice, obtaining radiographs for this group did not represent an ethical issue. Based on the safety parameters relating to x-ray exposure, and a previous related study.[86] The NHMRC (2002) stated "*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 five millisievert*" (2002:23).[86]

Considering the radiographic views and equipment required for the study, a skin entrance dose per exposure of 160-212 microgray was anticipated. Each subject participating in the study would have no more than five views taken bilaterally with a total of 12 exposures, making the total skin entrance exposure dose per subject 1920-2544 microgray. This was the equivalent to 1.92-2.54 millisievert. This amount of x-ray radiation was below the recommended yearly effective dose equivalent of five millisievert for volunteer studies. It was further noted radiographs of feet were considered very safe due to the low radiation exposure and ability to protect all body organs from scatter radiation.[86] The researcher ensured the radiographers used appropriate screening measures to protect subjects.

3.7 Data collection protocol

All data were collected by the same researcher, with data recorded in an identical manner for each subject. Once the subject arrived at the private practice clinic of the principle researcher at the designated appointment time for data collection, the researcher checked the subject information and consent to participation form had been signed and returned. Opportunity was provided for discussion to answer any questions raised by the participant to ensure full comprehension of the document that was signed.

Once participation was confirmed, the subject was then examined regarding exclusion criteria previously outlined. Demographic data including full name, gender, date of birth, weight (kg) and height (m) were collected and recorded into the data collection spreadsheet on the principle researcher's laptop computer, with the subject then being assigned an alphanumeric code for identification purposes. Weight was recorded using a single set of electronic scales and recorded to the nearest 0.1 kilogram. The subject's height was recorded using the same wall mounted height tape measure and recorded to the nearest 0.1 centimeter.

Only one subject was assessed at any one time for the purpose of reducing the chance of data confusion and to ensure a degree of quality control. The principle researcher measured and recorded all data to reduce double handling the data and hence possibility of data entry error. To account for any potential discrepancies in data entry, the principle researcher randomly crosschecked raw data and spreadsheet entries for any processing errors prior to data analysis.

3.8 Angle of gait pilot study (Appendix 1)

The term AOG refers to the mid-sagittal position of each foot in midstance relative to the direction of forward movement during gait.[15] The purpose of this study was twofold. Firstly, to assess the intra and inter-rater reliability of measuring AOG using an existing validated technique of powdered footprints on paper.[15, 16] Secondly, to compare AOG from powdered footprints and foot progression angle (FPA), the equivalent form of AOG, derived from electronic EMED-SF® footprints to determine whether a relationship existed.

3.9 Radiographic pilot study (Appendix 2)

Radiographic investigation of foot disorders is commonplace in clinical 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,[17, 18] such as HL. This study investigated reliability of several radiographic angular and linear parameters. Two uncommon weight bearing views were included, namely the LAT SD view of the first metatarsophalangeal joint and a COMP view of the foot. The remaining views consisted of measurements obtained from weight bearing dorsoplantar and lateral views.

3.10 Angle of gait measurement procedure

Footprint data was obtained using 10m lengths of white paper (80gsm) measuring 91.5cm in width. The test environment remained identical for all subjects. The paper was laid out over a level, flat, 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 of 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 a depth of approximately 4cm in the plastic container, which was placed at the base of the chair at one end.

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 instructed to rise from the chair and walk normally to the other end, looking straight ahead, commencing with the right foot. On reaching the other end, the subject was instructed to sit down on the other chair. Following this, artist 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 and allowed 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, so as to allow for effects of acceleration and deceleration. 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 lockable cupboard for the interim period prior to AOG measurements, which would be undertaken at a later stage.

Measurement of AOG using the 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®) was used to draw lines, and angles were measured using a transparent plastic 15cm protractor (Celco®) with increments of one degree which allowed data to be recorded to 0.5° 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 line of the grid was transferred to the paper and labelled 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 labelled 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 (LOP) (Figure 3.1).

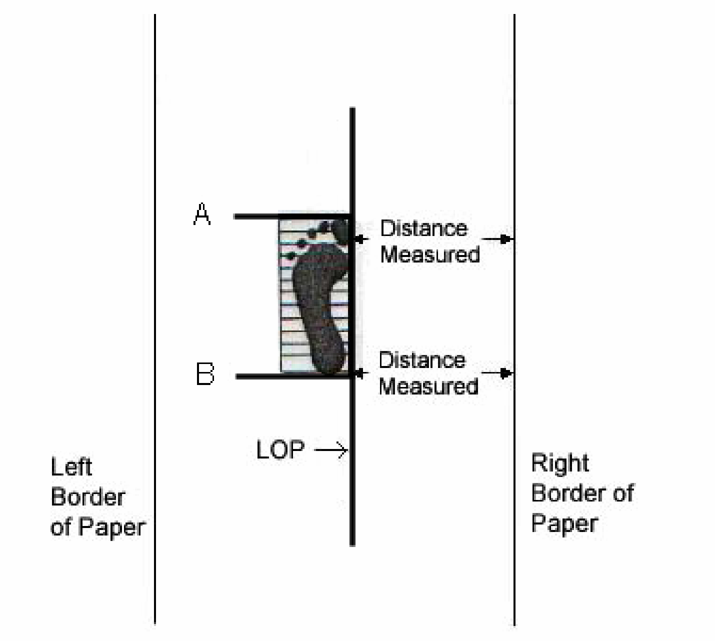

Figure 3.1 Placement of transparent grid to ensure parallel lines representing the apex of the hallux (A) and posterior border of the heel (B) and equal distances between the vertical border of the grid and the right edge of the paper (LOP = line of progression) (adapted from Taranto et al, 2004).[13]

The footprint was then divided into thirds by measuring the distance between line (A) and line (B). A further sub-division of the proximal third into half was performed forming lines (C), (D) and (E) respectively (Figure 3.2). This was undertaken because the proximal third of the footprint did not 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 line (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).

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, 2004).[13]

The line corresponding to the medial side of the forefoot originally marked on the paper (line of progression) was extended to the point of intersection of line (FX). The angle formed was termed the AOG and was measured in degrees.

This process was repeated a total of four times per subject to give AOG measurements for two consecutive strides. Data was recorded in the data recording sheet for AOG, which had the subjects alphanumeric coded, placed in a specified file for AOG measurement raw data recording sheets and stored in the lockable filing cabinet for data entry into the spreadsheet for a later date.

3.11 Radiographic views

Three radiographers from the same radiology clinic (Perth Radiological Clinic, Victoria Street Radiology, Midland, Western Australia) were used to take the specified radiographic views 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 (Shimadzu Gen Unit). Radiographic views were all weight bearing and included dorsoplantar (DP), lateral (LAT), lateral stress dorsiflexion of the first metatarsophalangeal joint (LAT SD) and composite (COMP) views. The radiographic cassette used in all exposures was an extremity Dupont® MV with Agfa® mammary HT film.

For the DP view, 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, each foot was exposed separately using a lead shield to cover the other half of the x-ray film.[12] Table 3.1 outlines specific parameter settings for the DP view.

In the LAT view, 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.[12] Table 3.1 outlines specific parameter settings for the lateral view.

The LAT SD view of the first metatarsophalangeal joint was taken as per the lateral view, however the subject was instructed to place the foot not being imaged parallel to, and in front of the other foot, keeping the leg straight. The knee on the contralateral side was flexed at approximately 40° and the heel was raised off the ground to the point where the first metatarsophalangeal joint was in maximum dorsiflexion, without obvious frontal or transverse plane movement[12]. The radiograph was taken with parameters outlined in Table 3.1.

For the COMP view[138], 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 3.3a). The central ray was centered over the anterior aspect of 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). The radiographs for both exposures were taken with parameters outlined in Table 3.1.

3.12 Radiographic measurement procedure

Radiographic measurements were conducted using a radiograph light box in a darkened room. Acetate transparencies were placed over each radiograph and secured on all four corners using clear adhesive tape (3M Scotch Tape®). Using a fine (0.5mm) water-soluble overhead projection marker (Artline® 803 Fine), various angular and linear measurements were made on the radiographs. Data were recorded in the data recording sheet for radiographic measurements, which was coded with the subject's alphanumeric allocation, placed in a specified file for radiographic measurement raw data and stored in the lockable filing cabinet for data entry into the spreadsheet for analysis at a later time.

Table 3.1 Radiographic parameters of angular and linear radiograph measurements

View	Focal Film Distance	Position and Angle of Central Ray	Exposure
DP	90cm	20° from the vertical directed at base of third metatarsal	5kKV, 100mA, 0.04 sec
LAT	90cm	90° from the vertical directed at the cuboid	54kV, 100mA, 0.04 sec
LAT SD	90cm	90° from the vertical directed at the first MPJ	54kV, 100mA, 0.04 sec
COMP	90cm	Position 1: Central ray vertical over the ankle joint. Position 2: X-ray tube not displaced, central ray through posterior aspect of ankle joint	62kV, 125mA, 0.05 sec 62kV, 125mA, 0.05 sec

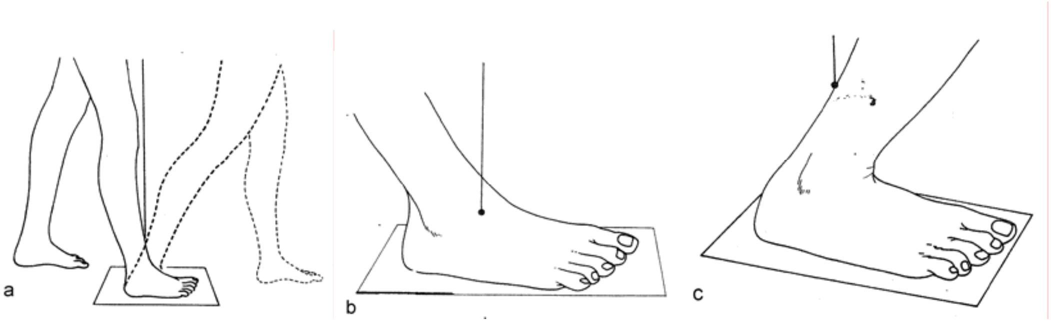

Figure 3.3 Radiographic technique for COMP view; (a) Plantar aspect of the foot in contact with the film; (b) Central ray centered over the anterior aspect of the ankle for first exposure; (c) Central ray centered over the posterior aspect of the ankle for the second exposure (adapted from Montagne et al, 1981).[138]

After each measurement, the transparencies were wiped clean of any marks and removed from the radiograph. Other items used included a transparent plastic 30cm ruler (Linex®), which was used to draw lines, and angles were measured using a transparent plastic 15cm protractor (Celco®) with increments of one degree which allowed data to be recorded to 0.5° resolution, a calculator (Canon® F-800 Scientific Statistical Calculator), and a data recording sheet (Appendix 5).

For each subject, seven measurement variables were obtained for the left and right feet (14 per subject). These included calcaneal inclination angle (CIA), lateral intermetatarsal angle (LIMA), hallux abductus angle (HAA), first intermetatarsal angle (FIMA), first metatarsal protrusion distance (FMPD), lateral stressed first metatarsophalangeal joint dorsiflexion (LAT SD) and rearfoot to forefoot axis angle (RFA).

The CIA provided an indication of calcaneal pitch and height of the foot framework.[12] 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 margin of the anterior portion of the calcaneus. (Low: 0°-10°, Medium: 10°-20°, High: 20°-30°).[12] Using the LAT view, a line was drawn representing the weight bearing surface of the foot. From the anteroplantar margin of the calcaneal tuberosity another line was drawn extending through the plantar margin of the anterior portion of the calcaneus. The angle formed was termed the CIA (Figure 3.4).

The LIMA describes the sagittal plane angular relationship between the first and second metatarsals.[24] Using the LAT view, the central region of the dorsal cortex of the first metatarsal shaft was marked. Similarly, the same was repeated for the second metatarsal shaft. The resultant angle formed by the intersection of these two lines represented the LIMA (Figure 3.4).

The HAA represented the degree of lateral deviation of the hallux, and is the angle formed by the longitudinal axis of the first proximal phalanx and the longitudinal axis of the first metatarsal. Using the DP view, the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft was identified, and bisected. Similarly, this was repeated for the proximal phalanx of the hallux. The angle formed by these intersecting lines was measured and termed the HAA (Figure 3.5).

The FIMA is the angle between the longitudinal axis of the first and second metatarsal bones. Using the DP view, the medial and lateral margins of the proximal and distal thirds of the first metatarsal shaft was identified, and bisected. Similarly, this was repeated for the second metatarsal. The angle formed by these intersecting lines was measured and termed the FIMA (Figure 3.5).

The FMPD is the distance between the relative length of the first and second metatarsals. Using the DP view, placing a compass at the intersection of the FIMA, a line was drawn tangential and parallel to the central articulating surface of the first metatarsal head. This line was extended so that it intersected with the second metatarsal head. A line parallel to the first line, tangential to the central articulating surface of the second metatarsal head was also drawn. The distance between these two lines was measured and recorded in millimetres (mm). A positive value denoted the first metatarsal was longer than the second.

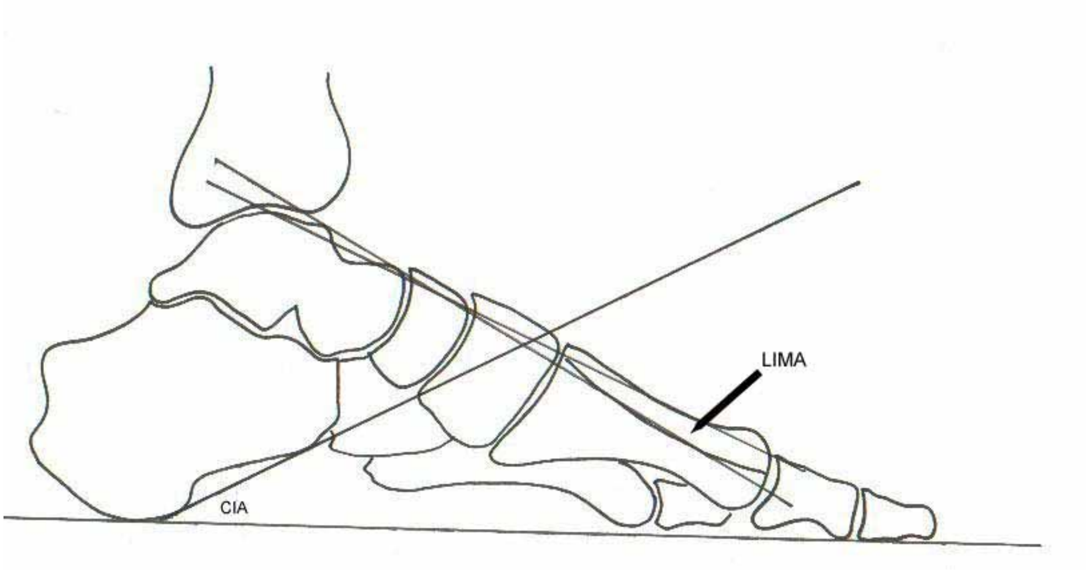

Figure 3.4 Measurement of CIA and LIMA using a weight bearing lateral radiograph (adapted from Taranto et al, 2004).[14]

Conversely, a negative value indicated the first metatarsal was shorter than the second (Figure 3.5).

The LAT SD is a reflection of the weight bearing or functional dorsiflexion of the first metatarsophalangeal joint. Using the LAT SD radiograph, the dorsal and plantar cortices of the proximal and distal thirds of the first metatarsal shaft was identified, and bisected. Similarly, this was repeated for the proximal phalanx of the hallux. The angle formed by the intersection of these two lines was termed the amount of first metatarsophalangeal joint dorsiflexion or LAT SD (Figure 3.6).

The RFA angle represents the amount of intrinsic rearfoot to forefoot abduction[27]. Using the composite view, the posterior sclerotic margin of the calcaneus was bisected to obtain the point representing the rear extremity of

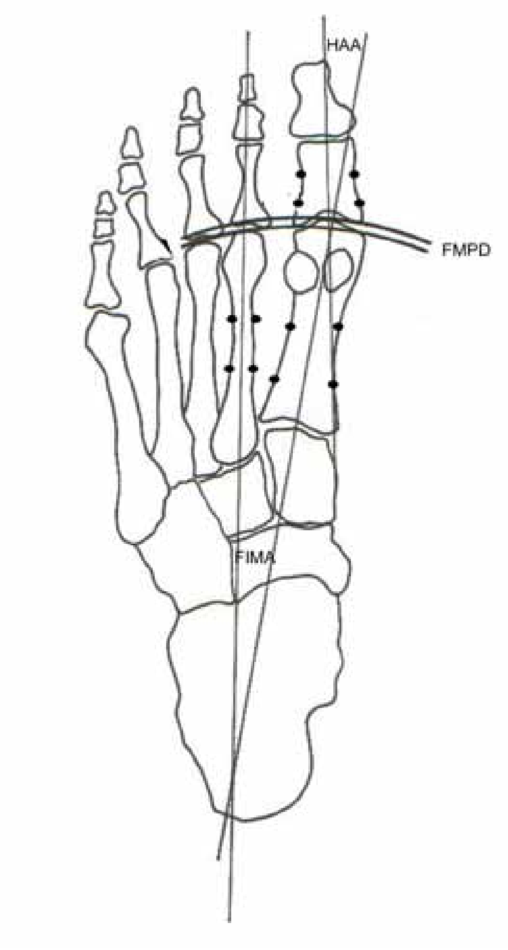

Figure 3.5 Measurement of HAA, FIMA and FMPD using a weight bearing DP radiograph (adapted from Taranto et al, 2004).[14]

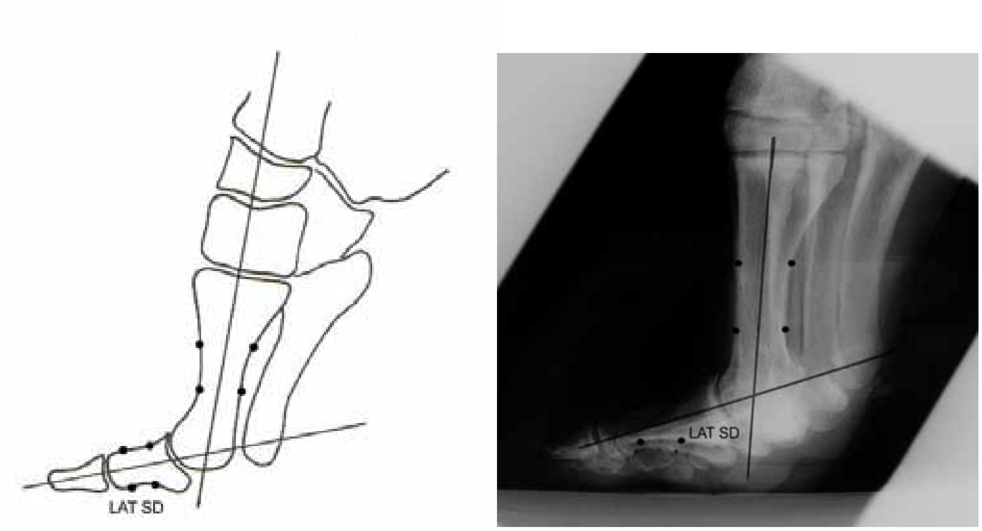

Figure 3.6 Measurement of weight bearing first metatarsophalangeal joint dorsiflexion using a weight bearing LAT SD radiograph (adapted from Taranto et al, 2004).[14]

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 3.7).

3.13 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 as the criterion representing meaningful differences.

Most statistical analysis was undertaken in terms of number 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. According to Menz,[146] 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 may occur with

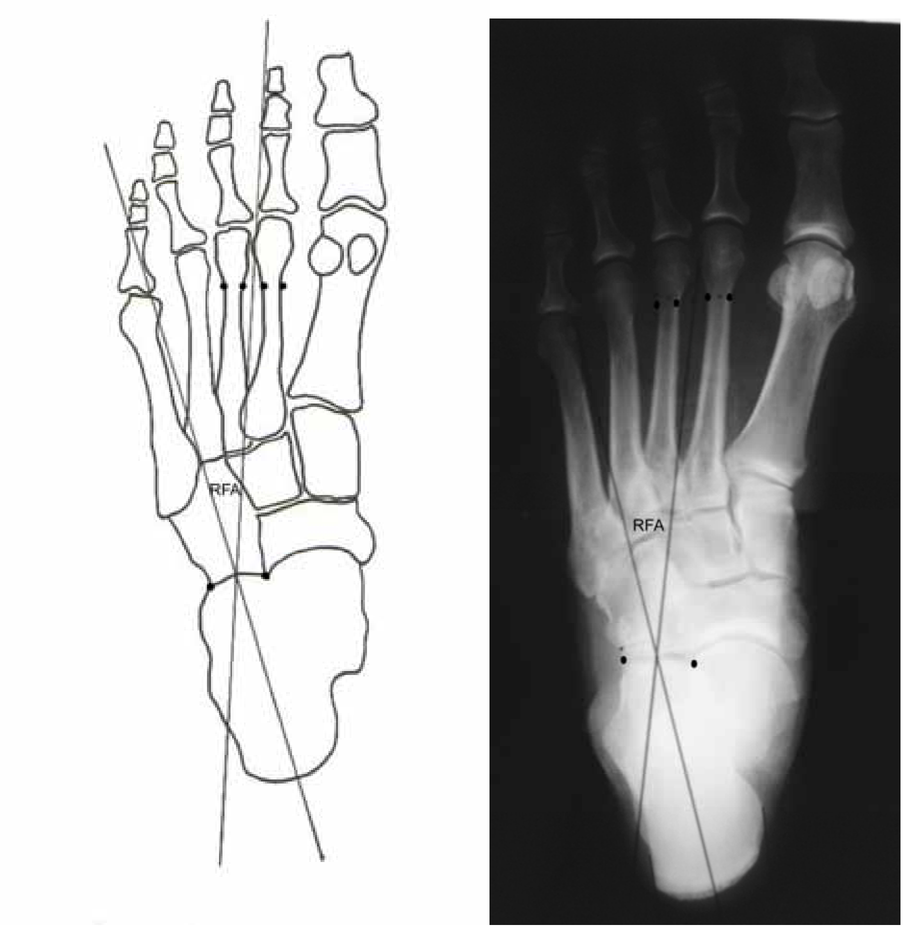

Figure 3.7 Measurement of RFA using a weight bearing composite radiograph (adapted from Taranto et al, 2004).[14]

combining left and right foot data.

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 (Allison GA 2004, written communication, 2nd August). In order to prevent the possibility of such errors caused by increasing the sample size secondary to use of numbers of feet rather than number of subjects, some analysis was undertaken in terms of number of subjects. Specifically this related to comparison of the subjects who exhibited bilateral HL with the control group.

Of those subjects who had a unilateral HL deformity (six had right HL, four had left HL), 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.

3.13.1 Normality

The complete data set (HL and control groups combined) and the subgroups (HL and control groups separately) were assessed for normality using Kolmogorov-Smirnov non-parametric unpaired two-group analysis. To ensure normality of the dependent variables was not influenced by an increased sample size due to using numbers of feet, normality of the data was undertaken in terms of numbers of subjects.

3.13.2 Laterality

Of those subjects who exhibited bilateral HL (12 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 HL subjects (n=12) out of a total of 22 subjects with HL 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 LAT SD.

The control group (20 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 HL deformity, even though the contralateral foot without the deformity was excluded from the overall data analysis.

3.13.3 Associations

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

3.13.4 Group differences

In order to detect differences of the dependent variables between groups (all HL subjects and all control subjects), unpaired t tests were undertaken. 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.[147]

The variability of normal values of LAT SD found in the literature provided the rationale for undertaking a tertile analysis which enabled exclusion of subjects with LAT SD values close to the LAT SD threshold used for allocation into HL or control groups. Comparison of lower and upper tertiles of LAT SD was undertaken. Specifically, this involved rank analysis according to LAT SD threshold whereby LAT SD values between 60°-70° degrees were excluded. Due to the subsequent reduction in sample size, the non-parametric Mann Whitney U statistic was used.

CHAPTER FOUR

RESULTS

4.0 Introduction

This study investigated AOG characteristics of the feet in a population with and without HL, as determined by degree of LAT SD. 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 HL, unilateral HL 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 7. Descriptive statistics

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

	n	No. of feet (R, L)	Gender M, F	Age (yrs) (SD) (Range)	Weight (kg) (SD)	Height (m) (SD)	BMI (SD)
HL	22	34 (18,16)	9, 13	54.9 (12.0) (47)	73.2 (12.8)	1.6 (0.1)	26.6 (3.6)
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; R: right, L: left; M: male, F: female

for each dependent variable under investigation excluding AOG are presented for both the HL and control groups in Tables 4.2 and 4.3 respectively. Descriptive statistics of the main variable of interest, AOG, between the HL 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 (40 feet) that could be used in the study as both feet needed to meet inclusion criteria for normal values of LAT SD. The HL group consisted of 22 subjects (34 feet) made up of 12 subjects with bilateral HL and ten subjects with unilateral HL. Of the ten subjects with unilateral HL, six had HL on the right foot, and four had HL on the left foot.

4.2 Normality

Both the subgroups (HL and control groups) and entire sample showed statistical evidence of normality, with all p values obtained from Kolmogorov-Smirnov analysis being above $p > 0.05$, as presented in Table 4.5. All three groups reported identical p values for the dependent variables with the exception of LIMA (L), FIMA (L) LAT SD (R) and AOG (R), which were still all normally distributed but showed differences in p values between the groups.

Table 4.2 The mean, standard deviation (SD), minimum, maximum and range of dependent variables for the HL group

	LEFT		**RIGHT**	
Dependent Variable	**Mean (SD)**	**Min - Max (Range)**	**Mean (SD)**	**(Min, Max) (Range)**
CIA	25.1 (5.2)	17.0 - 34.0 (17.0)	24.6 (5.0)	(17.0, 35.0) (18.0)
LIMA	3.6 (2.2)	0 - 9.0 (9.0)	4.4 (2.7)	(0.5, 12.0) (11.5)
HAA	11.6 (5.1)	3.5 - 20.0 (16.5)	12.4 (5.2)	(5.0, 23.5) (18.5)
FIMA	8.9 (2.2)	6.0 - 13.0 (7.0)	9.2 (3.6)	(0, 15.5) (15.5)
FMPD	0.8 (3.0)	-5.0 - 6.0 (11.0)	2.1 (4.6)	(-4.5, 11.0) (15.5)
LAT SD	50.0 (14.4)	11.0 - 64.0 (53.0)	50.0 (14.5)	(14.0, 64.0) (50.0)
RFA	17.8 (7.5)	5.0 - 28.0 (23.0)	16.7 (6.7)	(5.0, 25.0) (20.0)

L: left foot; R: right foot; Min: minimum; Max: maximum (number of subjects = 22, number of feet = 34, 16 left and 18 right, made up of 12 subjects with bilateral HL and ten subjects with unilateral HL. Of the ten subjects with unilateral HL six had right HL and four had left HL)

Table 4.3 The mean, standard deviation (SD), minimum, maximum and range of dependent variables for the control group

	L		R	
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	19.1 (6.9)	(9.0, 35.0) (26.0)	17.5 (7.1)	(5.5, 35.0) (29.5)

L: left foot; R: right foot; 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 HL and control groups

		AOG (L)		AOG (R)	
	No. of subjects (No. of feet)	Mean (SD) (°)	(Min, Max) (Range) (°)	Mean (SD) (°)	Min, Max (Range) (°)
HL	22 (34)	9.4 (5.1)	(0, 16.0) (16.0)	13.2 (5.2)	(3.0, 25.3) (22.3)
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

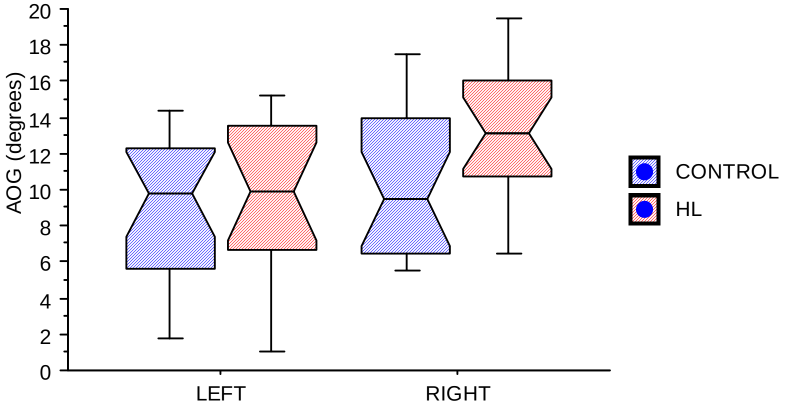

Figure 4.1 Box plot of left and right foot AOG for HL and Control groups.

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

Dependent Variable	**Entire Sample (n=36 subjects) p value**		**HL (n=16 subjects) p value**		**Control (n=20 subjects) p value**	
	L	**R**	**L**	**R**	**L**	**R**
CIA	-	-	-	-	-	-
LIMA	0.34	-	-	-	0.17	-
HAA	-	-	-	-	-	-
FIMA	0.74	-	-	-	-	-
FMPD	-	-	-	-	-	-
LAT SD	-	-	-	0.74	-	-
RFA	0.99	-	-	-	-	-
AOG	-	0.74	-	-	-	-

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

4.3 Laterality

A paired t test revealed no significant difference of the AOG between left and right feet for the 12 subjects in the group with bilateral HL (t= -1.98, p=0.07) as demonstrated in Figure 4.2. The 20 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 HL group with unilateral HL (t=1.48, p=0.17).

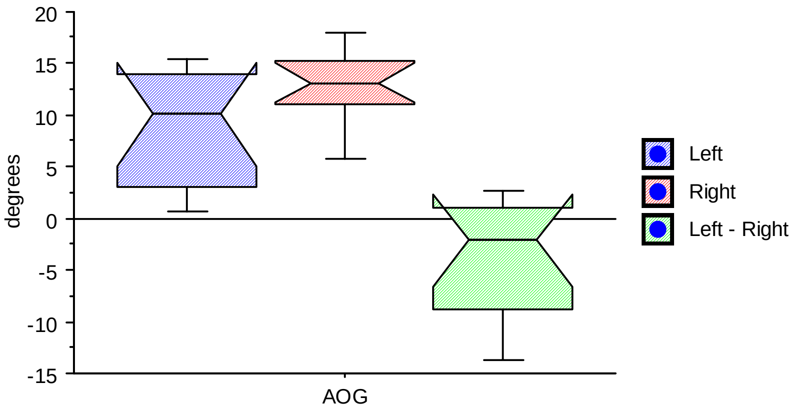

Figure 4.2 Box plot showing AOG between left and right feet and distribution of the difference between left and right sides of AOG for the twelve subjects with bilateral HL.

An unpaired t test showed no significant difference in AOG of the left foot (t=-0.02, p=0.99) and right foot (t=1.33, p=0.20) between the subjects who exhibited bilateral HL (n=12 subjects) and the control group (n=20 subjects).

Pearson's product moment correlation between the groups that exhibited bilateral HL and the control group showed no association between AOG and LAT SD (*r*: -0.05, 95% CI: -0.30, 0.19).

4.4 Associations

Results of Pearson's product moment correlations for the subgroups and entire sample are presented in Appendix 8. Table 4.6 highlights the significant associations found for each subgroup and the entire sample.

Table 4.6 Significant Pearson's product moment correlations between dependent variables for HL group, control group and entire sample

Association	Correlation	95% lower CI	95% upper CI
HL Group	0.42	0.10	0.67
CIA & RFA	-0.52	-0.73	-0.22
LIMA & FIMA	0.62	0.36	0.79
LIMA & FMPD	-0.64	-0.80	-0.39
LIMA & LAT SD	-0.36	-0.62	-0.03
HAA & LAT SD	-0.36	-0.62	-0.02
HAA & RFA	-0.38	-0.64	-0.05
HAA & AOG	0.34	0.002	0.61
FIMA & LAT SD	0.45	0.13	0.68
LAT SD & RFA			
Control Group	0.32	0.004	0.57
CIA & LAT SD	0.38	0.83	0.62
CIA & AOG	-0.33	-0.58	-0.02
LIMA & FIMA	0.33	0.02	0.58
HAA & FIMA	-0.39	-0.62	-0.08
FIMA & FMPD			
Entire Sample	0.24	0.02	0.45
CIA & RFA	-0.40	-0.58	-0.19
LIMA & FIMA	0.43	0.22	0.60
LIMA & FMPD	-0.35	-0.54	-0.13
LIMA & LAT SD	-0.23	-0.44	-0.001
LIMA & RFA	0.29	0.07	0.49
HAA & FIMA	-0.28	-0.48	-0.52
HAA & LAT SD	-0.30	-0.50	-0.08
FIMA & FMPD			

4.5 Group differences

Unpaired t tests between the HL and control groups are presented in Table 4.7. Significant differences ($p<0.0001$) between groups were found bilaterally for the dependent variable LAT SD. The results of tertile assessment using Mann Whitney U statistic in which LAT SD between 60°-70° were excluded are presented in Table 4.8. The significant difference in LAT SD was expected, given it was the dependent variable used to classify the rank analysis.

Table 4.7 T values, p values, 95% lower and upper confidence intervals (CI), and mean difference for dependent variables between HL and control groups

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	0.03	-0.13	0.98	0.90	-3.44	-3.64	3.54	3.20	0.05	-0.22
LIMA	1.25	0.62	0.22	0.54	-0.50	-1.35	2.30	2.52	0.80	0.59
HAA	1.51	1.12	0.14	0.27	-0.86	-1.51	5.81	5.23	2.48	1.86
FIMA	0.36	0.76	0.72	0.45	-1.41	-1.17	2.01	2.55	0.30	0.69
FMPD	-0.27	0.73	0.79	0.47	-2.69	-1.68	2.06	3.56	-0.31	0.94
LAT SD	-7.21	-7.72	-	-	-33.94	-35.55	-19.02	-20.75	-26.48	-28.15
RFA	-0.57	-0.33	0.57	0.74	-6.27	-5.33	3.52	3.82	-1.38	-28.15
AOG	0.22	1.71	0.83	0.10	-2.98	-0.54	3.71	6.26	0.36	2.86

L: left foot; R: right foot; “-“: p<0.0001; n=16 left feet and 18 right feet in HL group, 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	0.88 (-0.15)	0.73 (-0.34)
LIMA	0.12 (-1.57)	0.06 (-1.90)
HAA	0.16 (-1.42)	**0.06 (-1.91)**
FIMA	0.48 (-0.69)	0.71 (-0.37)
FMPD	0.88 (-0.15)	0.65 (-0.45)
LAT SD	**<0.0001 (-7.38)**	**<0.0001 (-6.27)**
RFA	0.77 (-0.29)	0.56 (-0.58)
AOG	0.12 (-1.57)	0.18 (-1.34)

No tertile assessment: no exclusion of LAT SD threshold, n=34 HL feet, 40 control feet; Tertile assessment: LAT SD threshold exclusion 60°-70°, n=24 HL feet in upper tertile, 30 control feet in lower tertile; significant values are presented in bold

CHAPTER 5

DISCUSSION

5.0 Introduction

Abnormal foot biomechanics have been attributed to a wide degree of pathology affecting the lower limb.[6, 42] The consequence of these pathomechanics on the medial column of the foot has remained a focus of interest in the literature, specifically related its effect on the first metatarsophalangeal joint.[8, 21, 83]

Hallux limitus, represents the second most commonly encountered pathomechanical condition affecting the first metatarsophalangeal joint, with HV being the most prevalent in scientific literature.[9, 10] Representative of a multi-factorial aetiology, HL is primarily defined by progressive osteoarthritic degeneration and subsequent limitation of first metatarsophalangeal joint range of motion in the sagittal plane.[8]

A degree of agreement exists in the literature, predominantly as a result of anecdotal evidence and clinical observation, that abnormal foot biomechanics are associated with the development and progression of HL.[10] This study was undertaken in an attempt to determine whether certain AOG characteristics existed between subjects with HL, compared to control subjects without HL. The literature has identified considerable variability in the normal reference range of AOG, primarily as a result of its complex and highly interactive nature with both intrinsic and extrinsic variables associated to the human body.[11]

Prior to commencing a discussion of the results derived from this research, assessment of normality for the dependent variables investigated in the study population was undertaken. Following this, presentation of the individual hypotheses initially outlined in Chapter one will be discussed in relation to the results.

Reliability of measurements are initially discussed, with specific reference to the reliability of AOG derived from powdered footprints. Following this, measurement of AOG using powdered footprints compared to FPA, the equivalent of AOG, derived from the EMED-SF® force platform is then addressed in the discussion. The radiographic angular and linear parameters previously outlined are then discussed, specifically in relation to characteristics of the first metatarsal. These include length and elevation of the first metatarsal and first metatarsophalangeal joint dorsiflexion. Angular relationship of the forefoot and rearfoot with regard to relative degree of forefoot abduction, foot framework structure and unilateral pathology will also be discussed.

Following this, the statistically significant dependent variables are discussed. Finally, limitations of the study and recommendations for further investigation are presented.

5.1 Normality

There was statistical evidence using the Kolmogorov-Smirnov analysis to support normal distribution in the entire sample and subgroups. The dependent variables LIMA, FIMA, RFA and AOG, demonstrated differences in the probability of ensuring normality for the entire sample. The results also indicated there was less probability that LAT SD were normally distributed in the HL group. This result was expected for the dependent variable LIMA and LAT SD, as these two variables have been strongly associated with the development and clinical observation of HL in the literature.[10, 24, 69-73] This was further anticipated for LAT SD, as this was the specific dependent variable used to classify the HL and control groups.

5.2 Hypotheses

The hypotheses previously outlined in Chapter one are grouped into reliability of measurements, AOG, radiographic characteristics of the first metatarsal, first metatarsophalangeal joint dorsiflexion, rearfoot to forefoot abduction, foot structure and finally unilateral pathology. These hypotheses are presented and discussed in relation to the results and previously reported literature.

5.2.1 Reliability of measurements

(i) That AOG, derived from powdered footprints, is reliable and repeatable.

(ii) That AOG, derived from powdered footprints is directly comparable to FPA derived from the EMED-SF® force platform.

(iii) That the angular and linear weight bearing radiographic measurements used in the investigation are both reliable and repeatable.

To address the first three hypotheses, two independent pilot studies were conducted prior to the commencement of the study and data collection. The first pilot study[13] (Appendix 1) established reliability in the methodology of measuring AOG used in the study, addressing the first hypothesis. It was further demonstrated that this methodology was reliable, repeatable and comparable to the FPA, or equivalent of AOG, derived electronically from the EMED-SF® force platform, thereby confirming the second hypothesis.

To address the third hypothesis for measurement reliability, a second pilot study[14] was conducted (Appendix 2). Reliability in the radiographic measurement methodology was established for the several weight bearing angular and linear measurements used in the study. Measurements derived from this pilot study were deemed reliable and repeatable.

5.2.2 Angle of gait

(iv) That subjects with HL have a less abducted AOG compared to the control group.

Prior to addressing this hypothesis, an investigation was undertaken to determine whether any differences existed between left and right sides when examining AOG in the same subject. When looking at the 12 subjects with bilateral HL, a non-significant difference of AOG was identified between left and right feet (t= -1.98, p=0.07), with the right foot being slightly more abducted than the left. When examining the control group, there was no significant difference in AOG between the left and right feet in the 20 subjects (t=-1.13, p=0.27).

When the 12 subjects with bilateral HL were compared with the 20 control subjects there was no significant difference between left (t=-0.02, p=0.99) and right (t=1.33, p=0.20) feet for AOG.

When considering the subtle difference in AOG between left and right feet in subjects with bilateral HL, issues of dominance could potentially be related to observations of asymmetry. Effects of dominance have previously been investigated by Baum and Spencer[148] and Herring,[149] however in the context of this current study, the potential effect of foot dominance remains speculative as information relating to dominance was not included in the subject profile and is an issue identified for further study.

In cases of bilateral HL, differences in the observed AOG between left and right sides can be attributed to compensatory gait effects. Limited or reduced first metatarsophalangeal joint dorsiflexion during the propulsive phase of the gait cycle has been associated with postural disturbances and secondary pathology.[5, 20, 21, 73] It therefore appears reasonable to expect reduction in sagittal plane dorsiflexion at the first metatarsophalangeal joint, secondary to HL, to result in asymmetry observations in AOG in subjects with bilateral HL. Adequate first metatarsophalangeal joint dorsiflexion during the terminal stage of stance, as the foot approaches the propulsive phase of the gait cycle, has been previously demonstrated as an integral component in the normal biomechanical functioning of the foot and leg.[5, 21, 36]

An alternative comparison of subjects with HL compared to control subjects was whether AOG compensated as the level of the HL deformity progressed. When comparing subjects with bilateral HL to the control subjects, no association was identified between AOG and worsening HL deformity. That is, AOG did not appear to change significantly as LAT SD decreased, with LAT SD used as a measure of worsening or progressing HL (*r*: -0.05, 95% CI: -0.30, 0.19).

It has often been suggested that as HL progressively worsens, and the relative degree of first metatarsophalangeal joint dorsiflexion reduces, AOG subsequently alters as a secondary mechanism. Camasta[10] and Dananberg[20, 21, 73] have speculated that as the relative amount of functional first metatarsophalangeal joint dorsiflexion reduces, secondary to the progression of the HL deformity, AOG may subsequently change.

Chapman[83] similarly proposed that with the forward transfer of body weight during the terminal stage of midstance, a lateral shift in body weight occurs to ensure adequate sagittal plane motion of the foot. Furthermore, an abducted (out-toe) or adducted (in-toe) toe-off can subsequently occur. It is believed the observed gait compensation occurs as a result of the subject's predisposition to a more abducted or adducted gait, or simply, the tendency of the body's biomechanics to take the path of least resistance.[83]

This possibly contributes to explaining why there was no association identified between AOG and worsening HL deformity. Identification of a subject's predisposition to adopt an in-toe or out-toe gait was not included in the subject profile of the current study, and would be difficult to objectively assess in the clinical setting. Therefore, whilst the association between HL and AOG has continued to be speculative, this has yet been adequately demonstrated. Reasons as to the absence of a sound explanation perhaps will remain largely theoretical.

5.2.3 First metatarsal radiographic characteristics

(v) That subjects with HL have a longer, shorter or elevated first metatarsal compared to the control group.

Results of this study identified an association between LIMA and LAT SD in the HL group (*r*: -0.64, 95% CI: -0.80, -0.39) and combined sample (*r*: -0.35, 95% 95% CI: -0.54, -0.13). This indicated that the more elevated the first metatarsal was, less dorsiflexion was observed at the first metatarsophalangeal joint. This finding remained consistent with the literature,[8, 10, 24, 69-73] however some authors have reported no such relationship to exist.[133, 150]

Differences in findings could be attributed to measurement techniques used to quantify elevation of the first metatarsal. Specifically, Meyer et al[150] measured elevation of the first metatarsal as the linear difference (in millimeters) between the height of the first and second metatarsal shafts, whilst Bryant et al[133] measured first metatarsal declination angle using a longitudinal bisection of the metatarsal shaft, with both studies using weight bearing lateral radiographs. Both Meyer et al[150] and Bryant et al[133] reported no significant difference to exist in elevation of the first metatarsal between subjects with HL and control subjects.

In contrast, Bryant et al,[24] in a later study, identified a significant difference between the angular divergence of the dorsal cortices of the first and second metatarsal shafts between people with HL and a control group. Referred to as the lateral intermetatarsal angle or LIMA, this measurement technique was used in the current study as a measure of first metatarsal elevation. As a measure of first metatarsal elevation and its role in the development of HL, LIMA was a more reliable measure of first metatarsal elevation and remained consistent with the current findings.

Additionally, an association was identified between LIMA and FMPD in the HL group (*r*: 0.62, 95% CI: 0.36, 0.79) and combined sample (*r*: 0.43, 95% CI: 0.22, 0.60), indicating that as elevation of the first metatarsal measured with LIMA increased, the length of the first metatarsal increased, as measured with FMPD.

One possible explanation for this significant finding is that a longer first metatarsal may be mechanically predisposed to elevation as a result of a combination of a greater lever arm effect and first ray hypermobility.[6, 76] This observation remained consistent with the literature, which listed a long and hypermobile first metatarsal as aetiological factors in the development of HL.[6, 76, 79, 151] In contrast, Bryant et al[133] reported no relationship between first metatarsal protrusion distance and the presence of HL, as was also reported by Villadot.[152]

An interesting finding was that FIMA was associated with LIMA in all three groups, namely the HL group (*r*: -0.52, 95% CI: -0.73, -0.22), control group (*r*: -0.33, 95% CI: -0.58, -0.02) and combined sample (*r*: -0.40, 95% CI: -0.58, -0.19). That is, as FIMA increased, LIMA decreased.

A possible explanation for this association can be a geometrical effect as a result of the lateral radiograph. The LIMA is measured on a weight bearing lateral radiograph, using the dorsal cortices of the first and second metatarsal shafts as the lines of reference.[24, 153] Metatarsals on the lateral projection are effectively superimposed on each other, which creates the possibility that as the distance between the first and second metatarsal increases in the transverse plane, measured by FIMA, the LIMA, which is a sagittal plane measurement, may decrease. This can occur as a result of optical geometry and normal metatarsal declination angle on a radiograph which has osseous landmarks superimposed, as outlined by Green and Green.[154]

5.2.4 First metatarsophalangeal joint dorsiflexion

(vi) That the amount of first metatarsophalangeal joint dorsiflexion influences AOG in subjects with HL compared to the control group.

The literature supported the view that first metatarsophalangeal joint pathology, such as secondary osteoarthritic degeneration, is directly associated with HL and subsequent reduction in sagittal plane first metatarsophalangeal joint dorsiflexion.[8, 10, 28, 79]

An interesting result was the association between HAA and LAT SD, which was identified in the HL group (*r*: -0.36, 95% CI: -0.62, -0.03) and combined sample (*r*: -0.28, 95% CI: -0.48, -0.52). This finding indicated that as HAA increased, the amount of first metatarsophalangeal joint dorsiflexion measured by LAT SD decreased.

An increased HAA of greater than 20° is associated with HV,[23] therefore the results indicated that as the HV deformity worsened, there was less sagittal plane first metatarsophalangeal joint dorsiflexion available. Osteoarthritic degeneration of the first metatarsophalangeal joint is a recognised secondary consequence of HV.[62, 155, 156] It has previously been demonstrated that subject's with HL have a reduced amount of first metatarsophalangeal joint dorsiflexion, as measured by LAT SD. Descriptive statistics of LAT SD highlight this, with the HL group demonstrating a mean LAT SD of 50.0° for left and right feet, and a mean of 77.4° for the control group. From this information, it could be argued that as HAA increases, the relative amount of secondary osteoarthritic degeneration and, as a consequence, a concurrently developing HV deformity can occur. Osteoarthritic degeneration of the first metatarsophalangeal joint that can occur leads to a reduced range of motion in the sagittal plane, particularly dorsiflexion, as indicated by LAT SD in the current study.

5.2.5 Forefoot to rearfoot abduction and foot structure

(vii) That AOG reflects the amount of forefoot to rearfoot abduction in a foot with HL compared to the control group.

(viii) That AOG becomes less abducted as the arch of the foot becomes higher in subjects with HL compared to the control group.

Excessive pronation has been identified in the literature as a potential aetiological factor in the development of HL.[5, 6, 52, 72] Radiographic measures used in this study that relate to foot pronation were CIA and RFA. Prior to determining whether excessive pronation was related to HL, CIA and RFA was investigated to determine their association with AOG.

Gamble and Yale[12] noted the angle of inclination of the calcaneus, as measured by the CIA, establishes the height of the foot framework. The range of calcaneal inclination was reported as 0° - 10° indicating low, 10° - 20° medium, and 20° - 30° indicating a high calcaneal inclination. In clinical terms of foot framework structure, a low CIA was associated with an excessively pronated or low arched foot, medium CIA with a normal arched foot and high CIA indicating an excessively supinated or high arched foot.[12] Wearing et al,[157] however believe although calcaneal pitch, as indicated by CIA, may be used as an indicator of rearfoot position, biomechanical classification of foot types and subsequent inferences on dynamic foot function requires further investigation.

If excessive pronation, as indicated by a low CIA, was related to HL, then it would be expected that as CIA increased and the arch or foot framework became higher, then AOG would decrease. This association was not apparent in subjects with HL, however an association between AOG and CIA was identified in the control group. This association was identified as statistically significant, however demonstrated a weak correlation (*r*: 0.38, 95% CI: 0.83, 0.62). While this result may question the previously identified association in the literature between HL and an excessively pronated foot type, it could also imply that CIA should not be used as an indicator of pronation and supination, as reported by Wearing et al.[157]

Pronation and supination of the foot is a complex triplanar movement of the foot, which is determined by the axis of the subtalar joint that is directed in all three cardinal body planes.[42] It appears the complex triplanar motion of pronation and supination of the foot cannot be simplified into a single dimension sagittal plane measurement of one bone in the entire skeletal anatomy of the foot, namely the calcaneus. Furthermore, it remains possible that a decrease in arch height may not be directly associated with abduction of the entire foot in relation to the leg. Instead, Bojsen-Moller[139] suggested that it may result in abduction of the forefoot in relation to the rearfoot. In addition, Neylon et al[158] further demonstrated arch collapse without excessive abduction of the forefoot.

Another concept to assist in this observation can be explained in terms of compensation. Using the planal dominance model presented by Green and Carol,[31] motion and associated compensatory mechanisms, will take place in the plane with the most available motion for that individual foot. This theory suggests that each individual exhibits their own unique axes of motion, that consequently reflects different directions of motion, available in a particular plane. Chapman[83] further adds to the planal dominance theory of Green and Carol[31] by describing that secondary gait compensation occurs towards the path of least biomechanical resistance.

There was no association found between RFA and AOG. This suggests the amount of forefoot abduction in relation to the rearfoot, as measured by the RFA angle, was not associated with AOG. An alternative explanation also exists, whereby the RFA angle measurement, which demonstrated a small value, may not contain the inherent sensitivity to detect variations in AOG. The large variability in AOG has previously been reported, particularly as a result of the numerous extrinsic multi-factorial determinants that greatly influence the net observed AOG.[11]

An association between CIA and RFA (*r*: 0.42, 95% CI: 0.10, 0.67) was identified in the HL group (*r*: 0.42, 95% CI: 0.10, 0.67) and combined sample (*r*:

0.24, 95% CI: 0.02, 0.45). This indicated that as CIA increased, the amount of forefoot to rearfoot abduction increased. Although this association was significant, the correlation was weak.

5.2.6 Unilateral pathology

(ix) That AOG differs significantly between feet in subjects with unilateral HL.

The observation that AOG was not affected by the degree of HL was 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 HL deformity (t=1.48, p=0.17).

5.3 Variability of sagittal plane dorsiflexion of the hallux

The relative amount of sagittal plane dorsiflexion of the hallux, as measured by LAT SD, was the dependent variable used in the classification of subjects with HL. The literature has defined 65° of hallux dorsiflexion on the first metatarsal head as the required amount for normal gait to occur.[6-8]

Results of this study demonstrated similar normal values of first metatarsophalangeal joint dorsiflexion, measured by LAT SD, based on the control group. The LAT SD for the left foot ranged from 66.0° - 87.0° with a mean of 76.5° and the right foot ranged from 66.0° - 90.0° with a mean of 78.2°. Mean values of LAT SD in the control group remained consistent with the reported values of adequate first metatarsophalangeal joint dorsiflexion for normal gait.[6, 7, 25, 32, 48]

Mean values of LAT SD in the HL group similarly remained consistent with the literature.[7, 8] The LAT SD for the left foot ranged from 11° - 64° with a mean of 50.0° and the right foot ranged from 14° - 64° with a mean of 50.0°. Hopson et al[7] stated the required amount of dorsiflexion of the first metatarsophalangeal joint in normal gait has been noted to be a small percentage of the available motion at the joint. The measured values of the control group in the study by Hopson et al[7] varied from 50° to 90°, suggesting that 65° of hallux dorsiflexion on the first metatarsal head may not be the required minimum amount of dorsiflexion for normal gait. The results of LAT SD and its influence on AOG in people with HL could indicate the almost arbitrarily defined 65° or less of hallux dorsiflexion, which was used to classify subjects in the HL group, may be too high to detect significant differences in the study population. This was investigated using the Mann Whitney U rank analysis with a tertile assessment using a threshold exclusion of 60° - 70°. Excluding values in the analysis ±5° from the defined 65° dorsiflexion for HL group classification was designed to address this issue. Results were similar to the rank analysis without tertile assessment, in that there was no significant difference between LAT SD and AOG in the HL group. This finding could further be interpreted that the minimum requirement of first metatarsophalangeal joint dorsiflexion is even less than 60° for normal gait, therefore explaining why there was no significant difference even using the tertile assessment demonstrating threshold exclusion.

5.4 Variability of Angle of Gait

The current study demonstrated a large variation in 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. The range of AOG in the control group was very large, from 0° - 21.5°. The observed AOG range in the current study was greater than that reported in the literature from 5° - 13°.[3, 11, 61, 82, 135] In addition, AOG in the HL group was large, with a mean (±SD) of 9.4 (±5.1) for the left foot and 13.2° (±5.2) for the right foot. The range of AOG in the HL group was similarly large, from 3.0° - 25.3°. As can be observed, the mean AOG between the control and HL group did not differ considerably, and was reflected in the statistical analysis.

It could be suggested that such a large variability in AOG, as demonstrated in the study population, could account for the lack of significant differences identified in the HL and control groups.

5.5 Significant findings of dependent variables

When examining the results of the unpaired t tests for the dependent variables between the HL and control groups, a significant difference ($p<0.0001$) was identified for left and right LAT SD. Numerous questions are often raised via the interpretation of clinical based findings or observations. Based on the assumption that extreme values of HL, may have been required to see differences clinically, a tertile analysis was used, excluding LAT SD values between 60°-70°. The Mann Whitney U rank analysis interpretation was used and identified LAT SD as a significant finding ($p=0.0001$). This supported the concept that the radiographic variable LAT SD was the most indicative dependent variable of HL and the best predictor.

5.6 Limitations and Recommendations for Further Study

Some limitations were identified in the process of conducting this study. These have acted to provide further recommendations for future investigation, not only specifically related to this research topic, but other studies that are investigating similar variables.

The primary limitation of the study was the relatively small sample size and technique used. Whilst statistical power and integrity of the results were attained, a larger number of subjects in the HL and control groups would have been advantageous with respect to external validity factors, particularly when using a sample of convenience. This would be particularly applicable to those dependent variables investigated that demonstrated a wide variability such as AOG.

From the findings in this study, it appeared the range of normal values of AOG was larger than reported in the literature. As previously stated, the reference range of AOG in this study was very wide. Therefore, to identify any differences in AOG between the HL and control groups would remain difficult to detect, particularly when considering the sample size. One way to address this would be to increase the sample size of the study population and increase the number of further studies related to AOG. This would contribute to the reference range of statistical data associated with AOG and begin to clarify some of these potential confounding issues. Conducting cross-sectional and longitudinal studies may be used to capture these data.

Another limitation was the inherent variable nature of AOG. Inclusion criteria for the study was specified and adhered to, taking care to identify and exclude any subject with potential soft tissue, osseous or torsional abnormalities and secondary changes at the ankles, knees, hips, or any other potential influencing factor as previously outlined in the exclusion criteria.

Another possible limitation of the study was the assumption that ranges of motion were equal between genders. To establish gender differences of soft tissue, osseous and torsional changes that occur at the ankle, leg, knee and hip was beyond the scope of the current study. Despite the purpose of this study to compare AOG in a population with HL compared to a control group, it was not the intention or goal of the study to determine what specifically was causing the relative degree of foot abduction or adduction, given the possibility and combination of the numerous extrinsic factors that can influence AOG.

A further limitation identified in this study, following analysis of the data, was the issue of foot dominance. One of the findings of the study was the significant difference identified between left and right feet, indicating asymmetry. It appeared that the mean degree of abduction was greater on the right side compared to the contralateral side. Unfortunately, this observation cannot be commented on in context of the current study as foot dominance was not available to include in statistical analysis.

The small number of subjects exhibiting a unilateral HL deformity represented another limitation. The final hypothesis was to determine if AOG significantly differed between feet in subjects with unilateral HL. No significant difference was identified in AOG for the ten subjects with unilateral HL. To address this limitation, an increase in the sample population of subjects demonstrating both unilateral and bilateral HL pathology would be required.

Absence of information related to symptomology was another limitation and is a recommendation to include for future investigations. In a clinical setting, the primary factor that prompts a person to address first metatarsophalangeal joint pathology such as HL is pain. Pain can either present localised to the first metatarsophalangeal joint, or as symptoms in an alternative location as a direct result of secondary gait compensation mechanisms.[20, 21, 73] From this, the question can be asked whether people who are experiencing symptoms would exhibit different characteristics in terms of AOG compared to those who are asymptomatic? A plausible explanation for this prospect is increased abduction noted in subjects with HL which could be the result of a compensatory mechanism for pain rather than the physical deformity itself. While quantifying pain is subjective by nature, incorporating a pain analogue scale into the study would introduce an acceptable measurement variable into data analysis.[159, 160]

Another alternative explanation for increased abduction noted clinically in subjects with worsening first metatarsophalangeal joint pathology such as HL is the possible increased requirement for stability during gait as a secondary consequence.

Limitations in methodology were also identified. In particular those related to radiographic data. Firstly, a reliability trial was not undertaken to establish inter and intra-rater reliability of the three radiographers used in the study. Although a standardised protocol of taking the radiographic views was used, actual variation between views taken of the same foot at different time intervals was not considered, both within and between the three radiographers used in the study. This issue represented a significant limitation to reliability in measures of radiographic views, which could be more fundamental and precedes in importance the previously established reliability of repeated angular and linear radiographic measures on the same view. This was particularly relevant to the LAT SD and COMP views, which represent two uncommon radiographic views of the foot and are rarely used in clinical practice.

Secondly, walking speed was not controlled during data collection for AOG measurements, which was a factor Murray et al[61, 82] identified as a potential influence on AOG. Subjects were instead instructed to walk at their normal walking speed, which could be argued is reflective of the individuals usual gait. A recommendation for footprint data collection for AOG measurements was to have the subject familiarise themselves with the process of walking on paper with their feet coated with the coloured talcum powder. Although the subject familiarised themselves with walking along the length of the paper prior to having their feet coated in coloured talcum powder, different tactile sensations have previously been demonstrated to influence gait.[87, 91]

An alternative technique in footprint data collection used to measure AOG could incorporate an electronic gait analysis system such as the RS Scan® (RS Scan International, Olen, Belgium), or the EMED Pedar System® (novel, gmbh, Munich, Germany), which allows subjects to familiarise themselves for a period of time prior to data collection. Other advantages of these systems include simultaneous data collection of other variables such as force and pressure time integrals, angle and base of gait and cadence. Another major advantage of utilising such an electronic system is ease of data collection and reduction in labour input that was required to derive measurements such as AOG using the powdered footprint method used in this study.

The final limitation identified in the study focused on the fact that AOG measurements, which represented a dynamic measurement, were compared to static angular and linear radiographic measurements. Interpretation of the results in terms of function therefore remained difficult.

CHAPTER SIX

CONCLUSION

From the study the following conclusions were made:

(i) AOG derived from powdered footprints was reliable and repeatable.

(ii) AOG derived from powdered footprints was comparable to FPA derived from the EMED-SF® force platform.

(iii) The angular and linear weight bearing radiographic measurements used in the investigation were reliable and repeatable.

(iv) Subjects with HL did not demonstrate a significant difference in AOG compared to the control group.

(v) Subjects with HL have an elevated first metatarsal, however do not have a longer first metatarsal compared to the control group.

(vi) The amount of first metatarsophalangeal joint dorsiflexion does not influence AOG in subjects with HL compared to the control group.

(vii) Angle of gait does not reflect the amount of forefoot to rearfoot abduction in a foot with HL compared to the control group.

(viii) Angle of gait does not become less abducted as the arch of the foot becomes higher in subjects with HL compared to the control group.

(ix) Angle of gait does not differ between feet in subjects with unilateral HL.

REFERENCES

1. McBride, I., Wyss, U., Cooke, D., Murphy, L., Phillips, J., Olney, S. First metatarsophalangeal joint reaction forces during high heeled gait. Foot and Ankle.11(5):282-288, 1991.
2. Sarrafian, S. Anatomy of the foot and ankle. 2nd ed. Philadelphia: JB Lippincott Company; 1993.
3. Wernick, J., Volpe, R. Lower extremity function and normal mechanics. In: Valmassy R, ed. *Clinical Biomechanics of the Lower Extremities*. St Louis: Mosby; 1996:1-59.
4. Sutherland, D., Kaufman, K., Moitoza, J. Kinematics of normal human walking. In: Rose J, Gamble J, eds. *Human walking*. 2nd ed. Baltimore: Williams and Wilkins; 1994:23-44.
5. Payne, C., Chuter, V., Miller, K. Sensitivity and specificity of the functional hallux limitus test to predict foot function. Journal of the American Podiatric Medical Association.92(5):269-271, 2002.
6. Root, M., Orien, W., Weed, J. *Normal and abnormal function of the foot: clinical biomechanics.* Vol 2. Los Angeles: Clinical Biomechanics Corporation; 1977.
7. Hopson, M., McPoil, T., Cornwall, M. Motion of the first metatarsophalangeal joint: Reliability and validity of four measurement techniques. Journal of the American Podiatric Medical Association.85(4):198-204, 1995.
8. Banks, A., McGlamry, E. Hallux limitus and rigidus. In: McGlamry E, Banks A, Downey M, eds. *Comprehensive textbook of foot surgery.* Vol 1. 2nd ed. Baltimore: Williams and Wilkins; 1992:600-616.

9. Grady, J., Xe, T., Zager, E., Sheldon, L. A retrospective analysis of 772 patients with hallux limitus. Journal of the American Podiatric Medical Association.92(2):102-108, 2002.

10. Camasta, C. Hallux limitus and hallux rigidus: Clinical examination, radiographic findings and natural history. Clinics in Podiatric Medicine and Surgery.13(3):423-448, 1996.

11. Tollafield, D., Merriman, L. Assessment of the locomotor system. In: Merriman L, Tollafield D, eds. *Assessment of the lower limb*. New York: Churchill Livingstone; 1995:139-190.

12. Gamble, F., Yale, I. *Clinical foot roentgenology*. 2nd ed. New York: The Williams and Wilkins Company; 1975.

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

14. Taranto, M., Taranto, J., Bryant, A., Singer, K. Radiographic investigation of angular and linear measurements including first metatarsophalangeal joint dorsiflexion and rearfoot to forefoot axis angle. Journal of Foot and Ankle Surgery.Submitted for publication 2004.

15. Wilkinson, M., Menz, H., Raspovic, A. The measurement of gait parameters from footprints. The Foot.5:84-90, 1995.

16. Wilkinson, M., Menz, H. Measurement of gait parameters from footprints: A reliability study. The Foot.7:19-23, 1997.

17. Bryant, A., Singer, K. Review of radiographic measurements following austin bunionectomy. Journal of the American Podiatric Medical Association.88(6):290-294, 1998.

18. Schneider, W., Csepan, R., Kasparek, M., Pinggera, O., Knahr, K. Intra- and inter-observer repeatability of radiographic measurements in hallux surgery: Improvement and validation of a method. Acta Orthopaedica Scandinavia.73(6):670-673, 2002.

19. Roukis, T., Jacobs, P., Dawson, D., Erdmann, B., Ringstrom, J. A prospective comparison of clinical, radiographic, and intraoperative features of hallux rigidus. The Journal of Foot and Ankle Surgery.41(2):76-95, 2002.

20. Dananberg, H. Gait style as an etiology to chronic postural pain: part 1. Functional hallux limitus. Journal of the American Podiatric Medical Association.83(8):433-441, 1993.

21. Dananberg, H. Functional hallux limitus and its relationship to gait efficiency. Journal of the American Podiatric Medical Association.76(11):648-652, 1986.

22. Van De Graaff, K., Fox, S. *Concepts of human anatomy and physiology*. 2nd ed. Iowa: WM.C.Brown Publishers; 1989.

23. Landers, P. Introduction and evaluation of hallux abducto valgus. In: McGlamry E, Banks A, Downey M, eds. *Comprehensive textbook of foot surgery.* Vol 1. 2nd ed. Baltimore: Williams and Wilkins; 1992:459-468.

24. Bryant, A., Mahoney, B., Tinley, P. Lateral intermetatarsal angle: A useful measurement of metatarsus primus elevatus? Journal of the American Podiatric Medical Association.91(5):251-254, 2001.

25. Buell, T., Green, D., Risser, J. Measurement of the first metatarsophalangeal joint range of motion. Journal of the American Podiatric Medical Association.78(9):439-449, 1988.

26. Joseph, J. Range of movement of the great toe in men. Journal of Bone and Joint Surgery.36-B(3):450-457, 1954.

27. Freychat, P., Belli, A., Carret, J. P., Lacour, J. Relationship between rearfoot and forefoot orientation and ground reaction forces during running. Medicine and Science in Sports and Exercise.28(2):225-232, 1996.

28. Birke, J., Cornwall, M., Jackson, M. Relationship between hallux limitus and ulceration of the great toe. The Journal of Orthopaedic and Sports Physical Therapy.10(5):172-176, 1988.

29. Kelso, S., Richie, D., Cohen, I., Weed, J., Root, M. Direction and range of motion of the first ray. Journal of the American Podiatric Medical Association.72:600-605, 1982.

30. Seibel, M. *Foot function: a programmed text*. Baltimore: Williams and Wilkins; 1988.

31. Green, D., Carol, A. Planal dominance. Journal of the American Podiatric Medical Association.74(2):98-103, 1984.

32. Hetherington, V., Carnelt, J., Patterson, B. Motion of the first metatarsophalangeal joint. Journal of Foot and Ankle Surgery.28:13-19, 1989.

33. Shereff, M., Bejjani, F., Kummer, F. Kinematics of the first metatarsophalangeal joint. The Journal of Bone and Joint Surgery.68-A(3):392-398, 1986.

34. Roukis, T., Scherer, P., Anderson, C. Position of the first ray and motion of the first metatarsophalangeal joint. Journal of the American Podiatric Medical Association.86(11):538-546, 1996.

35. Hicks, J. The mechanics of the foot. II. The plantar aponeurosis and the arch. Journal of Anatomy.88(1):25-30, 1954.

36. Biossionnault, W., Donatelli, R. The influence of hallux extension on the foot during ambulation. The Journal of Orthopedic and Sports Physical Therapy.5(5):240-242, 1984.

37. Hoppenfield, S. *Physical Examination of the Spine and Extremities*. Norwalk: Appleton-Century-Crofts; 1976.

38. Allen, K. Dorsiflexion at the first metatarsophalangeal joint: a comparison of measurement by tractograph and digital biometer. British Journal of Podiatry.February:25-32, 1998.

39. Hiss, L. *Foot disorders*. Los Angeles: Los Angeles University Press; 1937.

40. Kelikian, H. *Hallux valgus, allied deformities of the forefoot and metatarsalgia*. Philadelphia: W.B. Saunders Company; 1965.

41. Sgarlato, T. *A compendium of podiatric biomechanics*. San Francisco: California College of Podiatric Medicine Press; 1971.

42. Root, M., Orien, W., Weed, J. *Biomechanical examination of the foot: clinical biomechanics.* Vol 1. Los Angeles: Clinical Biomechanics Corporation; 1971.

43. Giannestras, N. *Foot disorders: medical and surgical management*. Philadelphia: Lea and Febiger; 1973.

44. Bojsen-Moller, F., Lamoreux, L. Significance of free-dorsiflexion of the toes in walking. Acta Orthopaedica Scandinavica.50(4):471-479, 1979.

45. Mann, R., Hagy, J. The function of the toes in walking, jogging and running. Clinical Orthopaedics and Related Research.142:24-29, 1979.

46. Norkin, C., White, D. *Measurement of Joint Motion: A Guide to Goniometry*. Philadelphia: F.A. Davis; 1985.

47. Gerhardt, J., Rippstein, J. *Measuring and recording of joint motion: instrumentation and techniques*. Toronto: Hogrefe and Huber; 1990.

48. Hetherington, V., Johnson, R., Albritton, J. Necessary dorsiflexion of the first metatarsophalangeal joint during gait. Journal of Foot and Ankle Surgery.29(3):218-222, 1990.

49. McRae, R. *Clinical orthopedic examination*. 3rd ed. Edinburgh: Churchill Livingstone; 1990.

50. Palmer, M., Epler, M. *Clinical assessment procedures in physical therapy*. Philadelphia: J.B. Lippincott; 1990.

51. Evans, R. *Illustrated essentials in orthopedic physical assessment*. St. Louis: Mosby; 1994.

52. Nawoczenski, D., Baunhauer, J., Umberger, B. Relationship between clinical measurements and motion of the first metatarsophalangeal joint during gait. The Journal of Bone and Joint Surgery.81-A(3):370-376, 1999.

53. Kidd, R. An examination of the validity of some of the more questionable corner stones of modern chiropodial diagnosis. Journal of British Podiatric Medicine.46(8):172-173, 1991.

54. Kidd, R., Kidd, R. The role of abnormal collagen synthesis in the pathomechanics of the diabetic foot: A re-evaluation of the paradigm of neuropathy in podiatric practice. Australian Podiatrist.27:97-101, 1993.

55. McPoil, T., Hunt, G. Evaluation and management of foot and ankle disorders: Present problems and future directions. Journal of Orthopaedic Sports and Physical Therapy.21(6):381-388, 1995.

56. Phillips, R., Law, E., Ward, E. Functional motion of the medial column joints of the foot during propulsion. Journal of the American Podiatric Medical Association.86(10):474-486, 1996.

57. Menz, H. Clinical hindfoot measurement: A critical review of the literature. The Foot.5:57-64, 1995.

58. Menz, H. Alternative techniques for the clinical assessment of foot pronation. Journal of the American Podiatric Medical Association.88(3):119-129, 1998.

59. Picciano, A., Rowlands, M., Worrell, T. Reliability of open and closed kinetic chain subtalar joint neutral positions and navicular drop tests. Journal of Orthopaedic and Sports Physical Therapy.18(4):553-558, 1993.

60. Kusumoto, A., Suzuki, T., Kumakura, C., Ashizawa, K. A comparative study of feet morphology between filipino and japanese women, with reference to the significance of a deformity like hallux valgus as a normal variation. Annals of Human Biology.23(5):373-385, 1996.

61. Murray, M., Kory, R., Sepic, S. Walking patterns of normal women. Archives of Physical Medicine and Rehabilitation.51(11):637-650, 1970.

62. Tanaka, Y., Takakura, Y., Takaoka, T., Akiyama, K., Fujii, T., Tamai, S. Radiographic analysis of hallux valgus in women on weightbearing and non-weightbearing. Clinical Orthopaedics and Related Research.336:186-194, 1997.

63. Hogan, D., Kidd, R. The reliability and validity of goniometers when measuring the first metatarsophalangeal joint in stance. Australasian Journal of Podiatric Medicine.35(1):19-22, 2001.

64. Elveru, R., Rothstein, J., Lamb, R., Riddle, D. Methods for taking subtalar joint measurements: a clinical report. Physical Therapy.68(5):678-682, 1988.

65. Lattanza, L., Gray, G., Kantner, R. Closed versus open kinematic chain measurements of subtalar joint eversion: Implications for clinical practice. The Journal of Othopedic and Sports Physical Therapy.9(9):310-314, 1988.

66. Light, M. Dynamics and function of the first metatarsophalangeal joint. In: Kominsky S, ed. *Advances in Podiatric Medicine and Surgery.* Vol 2. St Louis: Mosby-Year Book; 1996:41-65.

67. Durrant, M., Siepert, K. Role of soft tissue structures as an etiology of hallux limitus. Journal of the American Podiatric Medical Association.83(4):173-180, 1993.

68. Mann, R., Coughlin, M., DuVries, H. Hallux rigidus: A review of the literature and a method of treatment. Clinical Orthopaedics and Related Research.142,:57-63, 1979.

69. Cicchinelli, L., Camasta, C., McGlamry, E. Iatrogenic metatarsus primus elevatus. Etiology, evaluation, and surgical management. Journal of the American Podiatric Medical Association.87(4):165-177, 1997.

70. Camasta, C. Radiographic evaluation and classification of metatarsus primus elevatus. In: Camasta C, Vickers N, Ruch J, eds. *Reconstructive Surgery of the Foot and Leg-Update 1994*. Tucker Georgia: The Podiatry Institute; 1994:122-127.

71. Horton, G., Park, Y., Myerson, M. Role of metatarsus primus elevatus in the pathogenesis of hallux rigidus. Foot and Ankle International.20(12):777-780, 1999.

72. McMaster, M. The pathogenesis of hallux rigidus. The Journal of Bone and Joint Surgery.60-B(1):83-87, 1978.

73. Dananberg, H. Gait style as an etiology to chronic postural pain part 2. Postural compensatory process. Journal of the Podiatric Medical Association.83(11):615-624, 1993.

74. Bonney, G., McNab, I. Hallux valgus and hallux rigidus: A critical survey of operative results. Journal of Bone and Joint Surgery.34-B(3):366-385, 1952.

75. Cohn, I., Kanat, I. Functional limitation of motion of the first metatarsophalangeal joint. The Journal of Foot Surgery.23(6):477-484, 1984.

76. Drago, J., Oloff, L., Jacobs, A. A comprehensive review of hallux limitus. The Journal of Foot Surgery.23(3):213-220, 1984.

77. Evans, R., Averett, R., Sanders, S. The association of hallux limitus with the accessory navicular. Journal of the American Podiatric Medical Association.92(6):359-365, 2002.

78. Regnauld, B. Hallux limitus. In: Regnauld B, ed. *The Foot: Pathology, Aetiology, Seminology, Clinical Investigation and Treatment*. New York: Springer-Verlag; 1986:335-350.

79. Bingold, A., Collins, D. Hallux rigidus. Journal of Bone and Joint Surgery.32-B(2):214-222, 1950.

80. Hanft, J., Mason, E., Landsman, A., Kashuk, K. A new radiographic classification for hallux limitus. Journal of Foot and Ankle Surgery.32(4):397-404, 1993.

81. Shereff, M., Baumhauer, J. Hallux rigidus and osteoarthrosis of the first metatarsophalangeal joint. The Journal of Bone and Joint Surgery.80-A(6):898-908, 1998.

82. Murray, P., Drought, B., Kory, R. Walking patterns of normal men. The Journal of Bone and Joint Surgery.46-A(2):335-360, 1964.

83. Chapman, C. Functional hallux limitus-the essentials. British Journal of Podiatry.2(2):40-44, 1999.

84. Rzonca, E., Levitz, S., Lue, B. Hallux equines: The stages of hallux limitus and hallux rigidus. Journal of the American Podiatry Association. 74(8):390-393, 1984.

85. Kessel, I., Bonney, G. Hallux rigidus in the adolescent. Journal of Bone and Joint Surgery.40-B:668, 1958.

86. Bryant, J. *Reliability of derived measures from foot radiographs* [Masters]. Perth, Western Australia, Curtin University of Technology; 1997.

87. Holden, J., Cavanagh, P., Williams, K., Bednarski, K. Foot angles during walking and running. In: Winter D, Norman R, Wells R, Hayes K, Patla A, eds. *Biomechanics IX-A*. 0 ed. Champaign: Human Kinetics Publishers; 1985:451-456.

88. Sutherland, D., Olshen, R., Cooper, L., Woo, S. The development of mature gait. The Journal of Bone and Joint Surgery.62-A(3):336-353, 1980.

89. Skinner, S. Development of gait. In: Rose J, Gamble J, eds. *Human walking*. 2nd ed. Baltimore: Williams and Wilkins; 1994:123-138.

90. Morton, D. The angle of gait: A study based upon the examination of the feet of central african natives. Journal of Bone and Joint Surgery.4-A(14):741-754, 1932.

91. Clarkson, B. Absorbent paper method for recording foot placement during gait. Physical Therapy.63:3-4, 1983.

92. Lee, S., Muller, C., Stefanyshyn, D., Nigg, B. Relative forefoot abduction and its relationship to foot length in vitro. Clinical Biomechanics.14:193-202, 1999.

93. Katoh, Y., Chao, E., Laughman, R., Schneider, E., Morrey, B. Biomechanical analysis of foot function during gait and clinical applications. Clinical Orthopaedics and Related Research.177:23-33, 1983.

94. Cappozzo, A., Catani, F., Leardini, A., Benedetti, M., Della Croce, U. Position and orientation in space of bones during movement: experimental artefacts. Clinical Biomechanics.11(2):90-100, 1996.

95. Beischer, A., Brodsky, J., Pollo, F., Peereboom, J. Functional outcome and gait analysis after triple or double arthrodesis. Foot and Ankle International.20(9):545-553, 1999.

96. Nester, C., Hutchins, S., Bowker, P. Effect of foot orthoses on rearfoot complex kinematics during walking gait. Foot and Ankle International.22(2):133-139, 2001.

97. Ounpuu, S., DeLuca, P., Davis, R., Romness, M. Long-term effects of femoral derotation osteotomies: an evaluation using three-dimensional gait analysis. Journal of Pediatric Orthopaedics.22:139-145, 2002.

98. Wu, W., Su, F., Cheng, Y., Huang, P., Chou, Y., Chou, C. Gait analysis after ankle arthrodesis. Gait and Posture.11:54-61, 2000.

99. Zejie, Y., Yanming, Y., Qihang, W., Wenlian, L. A new system for three-dimensional kinematic trajectory acquisition and analysis I: The application of an ultrasonic technique to human gait analysis. Medical Engineering Physics.18(5):420-426, 1996.
100. Carson, M., Harrington, M., Thompson, N., O'Connor, J., Theologis, T. Kinematic analysis of a multi-segment foot model for research and clinical applications: A repeatability analysis. Journal of Biomechanics.34:1299-1307, 2001.
101. Gilchrist, L., Winter, D. A two-part, viscoelastic foot model for use in gait simulations. Journal of Biomechanics.29(6):795-798, 1996.
102. Fukushima, T. Angle and distance between steps. Journal of Bone and Joint Surgery.37-A:1311, 1955.
103. Ogg, H. Measuring and evaluation the gait patterns of children. Physical Therapy. 43:717-720, 1963.
104. Scrutton, D., Robson, P. The gait of 50 normal children. Physiotherapy. 54:363-368, 1968.
105. Burnett, C., Johnston, E. Development of gait in childhood: Part one - method. Developmental Medicine and Child Neurology.13:196-206, 1971.
106. Chodera, J. Analysis of gait from footprints. Physiotherapy.60:179-181, 1974.
107. Boenig, D. Evaluation of a clinical method of gait analysis. Physical Therapy.57:795-798, 1977.
108. Shores, M. Footprint analysis in gait documentation. Physical Therapy.60:1163-1167, 1980.

109. Kippen, S. A preliminary assessment of recording the physical dimensions of an inked footprint. The Journal of British Podiatric Medicine.48:74-80, 1983.

110. Levangie, P., Brouwer, J., McKeen, S., Parker, K., Shelby, K. The effects of the standard rolling walker and two posterior rolling walkers on gait variables of normal children. Physical and Occupational Therapy in Pediatrics.4:19-31, 1989.

111. Rose-Jacobs, R. Development of gait at slow, free, and fast speeds in 3- and 5-year-old children. Physical Therapy.63:1251-1259, 1983.

112. Rutherford, A. Footprints. Journal of Audiovisual Media in Medicine.6:80-88, 1983.

113. Bertoti, D. Effect of Short leg casting on ambulation in children with cerebral palsy. Physical Therapy.66:1522-1529, 1986.

114. Gaudet, G., Goodman, R., Landy, M., Russell, G., Wall, J. Measurement of step length and step width: A comparison of video tape and direct measurement. Physiotherapy Canada.42:12-15, 1990.

115. Keenan, A., Bach, T. Video assessment of rearfoot movements during walking: A reliability study. Archives of Physical Medicine and Rehabilitation.77:651-655, 1996.

116. Ho, C., Lin, C., Chou, Y., Su, F., Lin, S. Foot progression angle and ankle joint complex in preschool children. Clinical Biomechanics.15:271-277, 2000.

117. Kennedy, R., Pressman, I., Chen, S., Petersen, P., Pressman, A. Statistical analysis of barefoot impressions. Journal of Forensic Sciences.48(1):55-63, 2003.

118. Urry, S., Wearing, S. A comparison of footprint indexes calculated from ink and electronic footprints. Journal of the American Podiatric Medical Association.91(4):203-209, 2001.

119. Mathieson, I., Upton, D., Birchenough, A. A comparison of footprint parameters calculated from static and dynamic footprints. The Foot.9:145-, 1999.

120. Chu, W., Lee, S., Chu, W., Wang, T., Lee, M. The use of arch index to characterize arch height: a digital image processing approach. IEEE Transactions on Biomedical Engineering.42(11):1088-1093, 1995.

121. Graf, P. The EMED system of foot pressure analysis. Clinics in Podiatric Medicine and Surgery.10(3):445-454, 1993.

122. Hughes, J., Pratt, L., Linge, K., Clark, P., Klenerman, L. Reliability of pressure measurements: the EMED F system. Clinical Biomechanics.6(1):14-18, 1991.

123. Saltzman, C., Brandser, E., Berbaum, K., et al. Reliability of standard foot radiographic measurements. Foot and Ankle International.15(12):661-665, 1994.

124. Chi, T., Davitt, J., Younger, A., Holt, S., Sangeorzan, B. Intra- and inter-observer reliability of the distal metatarsal articular angle in adult hallux valgus. Foot and Ankle International.23(8):722-726, 2002.

125. Condon, F., Kaliszer, M., D, C., O'Donnell, T., Shaju, A., Masterson, E. The first intermetatarsal angle in hallux valgus: An analysis of measurement reliability and error involved. Foot and Ankle International.23(8):717-721, 2002.

126. Coughlin, M., Freund, E. The reliability of angular measurements in hallux valgus deformities. Foot and Ankle International*.*22(5):369-379, 2001.

127. Kilmartin, R., Barrington, R., Wallace, W. The x-ray measurement of hallux valgus: An inter- and intra- observer error study. The Foot*.*2:7-11, 1992.

128. Laporta, G., Melillo, T., Olinsky, D. X-Ray evaluation of hallux abducto valgus deformity. Journal of the American Podiatry Association*.*64(8):544-566, 1974.

129. Petje, G., Steinbock, G., Schiller, C. Radiographic analysis of metatarsus primus varus. 45 feet followed 15 months after distal metatarsal osteotomy and lateral soft-tissue release. Acta Orthopaedica Scandinavica*.*68(6):567-570, 1997.

130. Resch, S., Ryd, L., Stenstrom, A., Johnsson, K., Reynisson, K. Measuring hallux valgus: A comparison of conventional radiography and clinical parameters with regard to measurement accuracy. Foot and Ankle International*.*16(5):267-270, 1995.

131. Schneider, W., Knahr, K. Metatarsophalangeal and intermetatarsal angle: Different values and interpretation of postoperative results dependent on the technique of measurement. Foot and Ankle International*.*19(8):532-536, 1998.

132. Talbot, K., Saltzman, C. Assessing sesamoid subluxation: How good is the AP radiograph? Foot and Ankle International*.*19(8):547-554, 1998.

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

134. Camasta, C., Pontious, J., Boyd, R. Quantifying magnification in pedal radiographs. Journal of the American Podiatric Medical Association.81(10):45-548, 1991.

135. Bryant, J. A comparison of radiographic foot measurements taken in two different positions. Journal of the American Podiatric Medical Association.95(5):234-239, 2001.

136. Perlman, P., Dubois, P., Siskind, V. Validating the process of taking lateral foot x-rays. Journal of the American Podiatric Medical Association.86(7):317-321, 1996.

137. Beasley, B., Grambart, S., King, J. X-ray evaluation using the X-PODite digital radiograph analyzer a preliminary study. Clinics in Podiatric Medicine and Surgery.19:477-482, 2002.

138. Montagne, J., Chevrot, A., Galmiche, J. *Atlas of foot radiology*. Paris: Masson Publishing; 1981.

139. Bojsen-Moeller, F. Calcaneocuboid joint and stability of the longitudinal arch of the foot at high and low gear push off. Journal of Anatomy.129:165-176, 1979.

140. Dahle, L., Mueller, M., Delitto, A., Diamond, J. Visual assessment of foot type and relationship of foot type to lower extremity injury. Journal of Orthopaedic Sports and Physical Therapy.14:70-74, 1991.

141. Stacoff, A., Kaelin, X., Stuessi, E., Segesser, B. The torsion of the foot in running. International Journal of Sport and Biomechanics. 5:375-389, 1989.

142. Mosier, S., Pomeroy, G., Manoli, A. Pathoanatomy and etiology of posterior tibial tendon dysfunction. Clinical Orthopaedics and Related Research.365:12-22, 1999.

143. Yeap, J., Singh, D., Birch, R. Tibialis posterior tendon dysfunction: a primary or secondary problem? Foot and Ankle International.22(1):51-55, 2001.

144. Greisberg, J., Hansen, S., Sangeorzan, B. Deformity and degeneration in the hindfoot and midfoot joints of the adult acquired flatfoot. Foot and Ankle International.24(7):530-534, 2003.

145. Viale, F., Dalleau, G., Freychat, P., Lacour, J., Belli, A. Leg stiffness and foot orientations during running. Foot and Ankle International.19(11):761-765, 1998.

146. Menz, H. Two feet, or one person? Problems associated with statistical analysis of paired data in foot and ankle medicine. The Foot.14(1):2-5, 2004.

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

148. Baum, I., Spencer, A. Limb dominance. Its relationship to foot length. Journal of the American Podiatric Medical Association.70(10):505-507, 1980.

149. Herring, K. Injury prediction among runners. Preliminary report on limb dominance. Journal of the American Podiatric Medical Association.83(9):523-528, 1993.

150. Meyer, J., Nishon, L., Weiss, L., Docks, G. Metatarsus primus elevatus and the etiology of hallux rigidus. The Journal of Foot Surgery.26(3):237-241, 1987.

151. Nilsonne, H. Hallux rigidus and its treatment. Acta Orthopaedica Scandinavia.1:295, 1930.

152. Villadot, A. Metatarsalgia due to biomechanical alteration of the forefoot. Orthopedic Clinics of North America.4:165, 1973.

153. Schuberth, J., Reilly, C., Gudas, C. The closing wedge osteotomy: a critical analysis of first metatarsal elevation. Journal of the American Podiatry Association.74(1):13-24, 1984.

154. Green, S., Green, H. The influence of radiographic projection on the appearance of deformities. Orthopedic Clinics of North America.25(3):467-474, 1994.

155. Glasoe, W., Allen, M., Saltzman, C. First ray dorsal mobility in relation to hallux valgus deformity and first intermetatarsal angle. Foot and Ankle International.22(2):98-101, 2001.

156. Mann, R., Coughlin, M. Hallux valgus: Etiology, anatomy, treatment and surgical considerations. Clinical Orthopaedics and Related Research.157:31-41, 1981.

157. Wearing, S., Urry, S., Pearlman, P., Dubois, P., Smeathers, J. Serial measurement of calcaneal pitch during midstance. Journal of the American Podiatric Medical Association.89(4):188-193, 1999.

158. Neylon, T., Johnson, B., Laroche, R. Use of the lapidus bunionectomy in first ray insufficiency. Clinics in Podiatric Medicine and Surgery.18(2):365-375, 2001.

159. Wolfe, F. Pain extent and diagnosis: development and validation of the regional pain scale in 12,799 patients with rheumatic disease. Journal of Rheumatology.30(2):369-378, 2003.

160. Scrimshaw, S., Maher, C. Responsiveness of visual analogue and McGill pain scale measures. Journal of Manipulative & Physiological Therapeutics.24(8):501-504, 2001.

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 (95% 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 (95% 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.

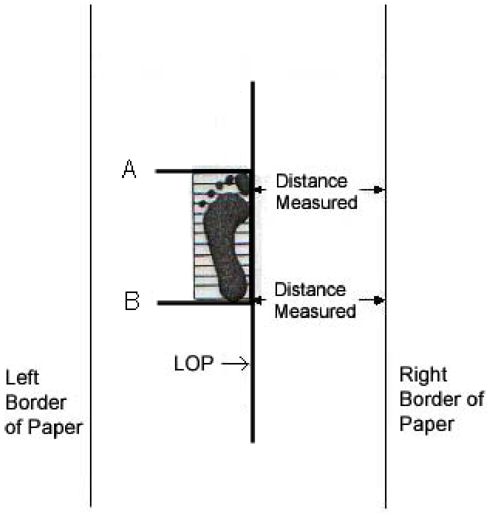

Figure 1. Placement of transparent grid to ensure parallel lines representing the apex of the hallux (A) and posterior border of the heel (B) and equal distances between the vertical border of the grid and the right edge of the paper (LOP = line of progression) (adapted from Taranto et al, 2004).

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).

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.

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 (95% 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				

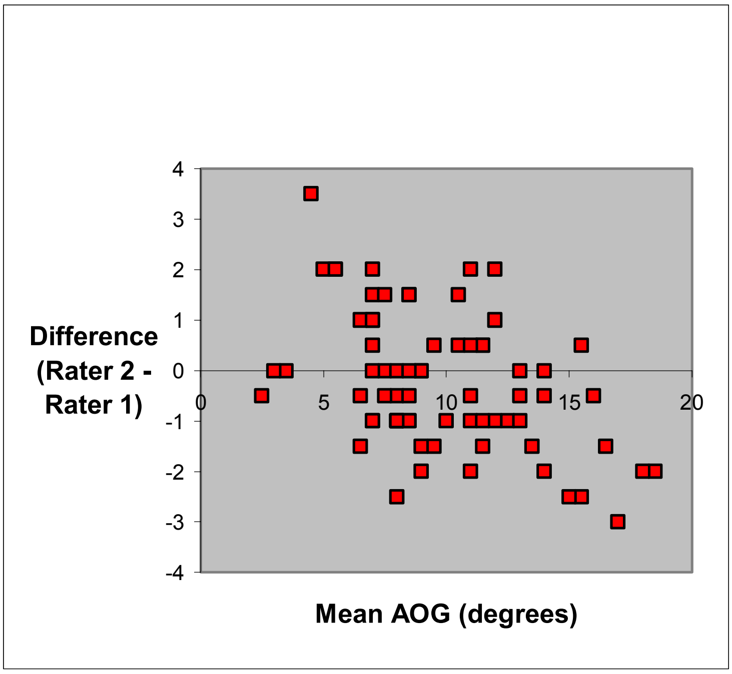

Figure 3. Differences between rater one and rater two for AOG calculation from powdered footprints.

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 (95% CI: -0.54, 0.59), indicating no significant difference (*t* = 0.09, p = 0.93). A Pearson's product moment correlation of 0.98 (95% 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

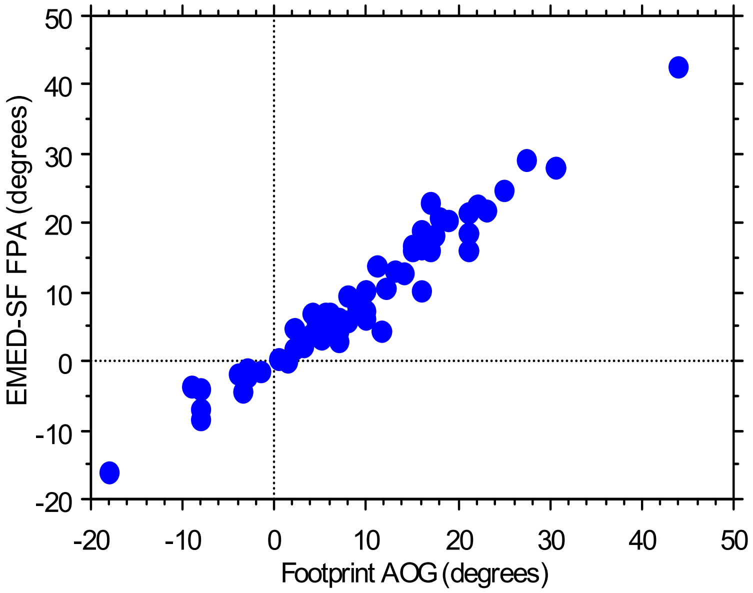

Figure 4. Scattergram between AOG from powdered footprints and FPA from EMED-SF®.

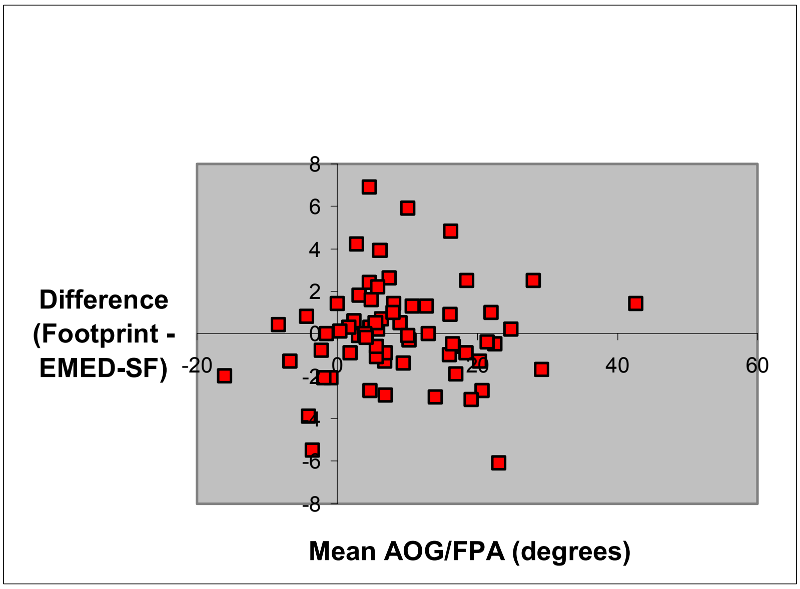

Figure 5. Differences between AOG from powdered footprints and FPA from EMED-SF®.

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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REFERENCES

1. Wilkinson, M., Menz, H., Raspovic, A. The measurement of gait parameters from footprints. The Foot.5:84-90, 1995.
2. Murray, M., Kory, R., Sepic, S. Walking patterns of normal women. Archives of Physical Medicine and Rehabilitation.51(11):637-650, 1970.
3. Murray, P., Drought, B., Kory, R. Walking patterns of normal men. The Journal of Bone and Joint Surgery.46-A(2):335-360, 1964.
4. Hopson, M., McPoil, T., Cornwall, M. Motion of the first metatarsophalangeal joint: Reliability and validity of four measurement techniques. Journal of the American Podiatric Medical Association.85(4):198-204, 1995.
5. Bryant, J. A comparison of radiographic foot measurements taken in two different positions. Journal of the American Podiatric Medical Association.95(5):234-239, 2001.
6. Clarkson, B. Absorbent paper method for recording foot placement during gait. Physical Therapy.63:3-4, 1983.
7. Holden, J., Cavanagh, P., Williams, K., Bednarski, K. Foot angles during walking and running. In: Winter D, Norman R, Wells R, Hayes K, Patla A, eds. *Biomechanics IX-A*. 0 ed. Champaign: Human Kinetics Publishers; 1985:451-456.
8. Gaudet, G., Goodman, R., Landy, M., Russell, G., Wall, J. Measurement of step length and step width: A comparison of video tape and direct measurement. Physiotherapy Canada.42:12-15, 1990.
9. Fukushima, T. Angle and distance between steps. Journal of Bone and Joint Surgery.37-A:1311, 1955.
10. Ogg, H. Measuring and evaluation the gait patterns of children. Physical Therapy. 43:717-720, 1963.

11. Scrutton, D., Robson, P. The gait of 50 normal children. Physiotherapy. 54:363-368, 1968.
12. Wilkinson, M., Menz, H. Measurement of gait parameters from footprints: A reliability study. The Foot.7:19-23, 1997.
13. Burnett, C., Johnston, E. Development of gait in childhood: Part one - method. Developmental Medicine and Child Neurology.13:196-206, 1971.
14. Boenig, D. Evaluation of a clinical method of gait analysis. Physical Therapy.57:795-798, 1977.
15. Bertoti, D. Effect of Short leg casting on ambulation in children with cerebral palsy. Physical Therapy.66:1522-1529, 1986.
16. Levangie, P., Brouwer, J., McKeen, S., Parker, K., Shelby, K. The effects of the standard rolling walker and two posterior rolling walkers on gait variables of normal children. Physical and Occupational Therapy in Pediatrics.4:19-31, 1989.
17. Katoh, Y., Chao, E., Laughman, R., Schneider, E., Morrey, B. Biomechanical analysis of foot function during gait and clinical applications. Clinical Orthopaedics and Related Research.177:23-33, 1983.
18. Rutherford, A. Footprints. Journal of Audiovisual Media in Medicine.6:80-88, 1983.
19. Ho, C., Lin, C., Chou, Y., Su, F., Lin, S. Foot progression angle and ankle joint complex in preschool children. Clinical Biomechanics.15:271-277, 2000.
20. Freychat, P., Belli, A., Carret, J. P., Lacour, J. Relationship between rearfoot and forefoot orientation and ground reaction forces during running. Medicine and Science in Sports and Exercise.28(2):225-232, 1996.
21. Shores, M. Footprint analysis in gait documentation. Physical Therapy.60:1163-1167, 1980.
22. Kennedy, R., Pressman, I., Chen, S., Petersen, P., Pressman, A. Statistical analysis of barefoot impressions. Journal of Forensic Sciences.48(1):55-63, 2003.
23. Urry, S., Wearing, S. A comparison of footprint indexes calculated from ink and electronic footprints. Journal of the American Podiatric Medical Association.91(4):203-209, 2001.
24. Mathieson, I., Upton, D., Birchenough, A. A comparison of footprint parameters calculated from static and dynamic footprints. The Foot.9:145-, 1999.
25. Chu, W., Lee, S., Chu, W., Wang, T., Lee, M. The use of arch index to characterize arch height: a digital image processing approach. IEEE Transactions on Biomedical Engineering.42(11):1088-1093, 1995.
26. Graf, P. The EMED system of foot pressure analysis. Clinics in Podiatric Medicine and Surgery.10(3):445-454, 1993.
27. Meyers-Rice, B., Sugars, L., McPoil, T., Cornwall, M. Comparison of three methods for obtaining plantar pressures in non-pathologic subjects. Journal of the American Podiatric Medical Association.84(10):499-504, 1994.
28. Bryant, A., Tinley, P., Singer, K. Normal values of plantar pressure measurement determined using the EMED-SF system. Journal of the American Podiatric Medical Association.90(6):295-299, 2000.
29. Hughes, J., Pratt, L., Linge, K., Clark, P., Klenerman, L. Reliability of pressure measurements: the EMED F system. Clinical Biomechanics.6(1):14-18, 1991.
30. Bryant, A., Singer, K., Tinley, P. Comparison of the reliability of plantar pressure measurements using the two-step and midgait methods of data collection. Foot and Ankle International.20(10):656-650, 1999.
31. Wearing, S., Urry, S., Smeathers, J., Battistutta, D. A comparison of gait initiation and termination methods for obtaining plantar foot pressures. Gait and Posture.10:255-263, 1999.
32. Bland, J., Altman, D. Statistical methods for assessing agreement between two methods of clinical measurement. The Lancet.8:307-310, 1986.

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 (95% 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 (95% 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.

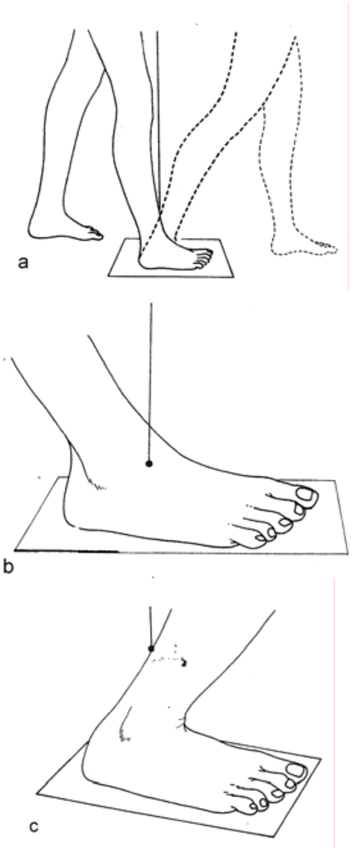

FIGURE 1 Radiographic technique for COMP view showing position of subject and central ray (adapted from Montagne et al[26], 1981).

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**.**

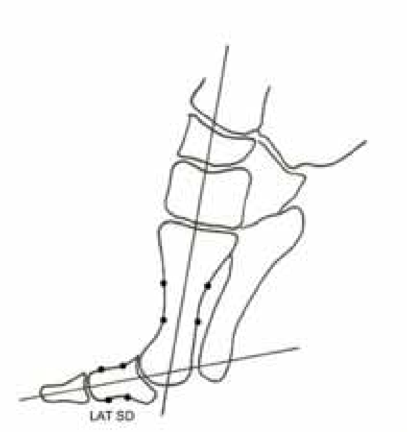

FIGURE 2 Calculation of LAT SD from weight-bearing LAT SD view.

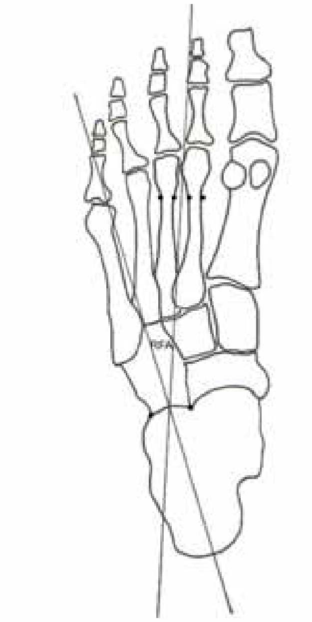

FIGURE 3 Calculation of RFA angle from weight-bearing composite view.

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.

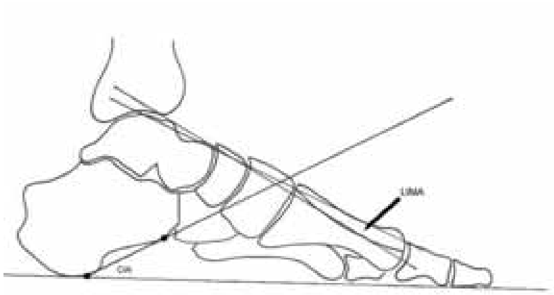

FIGURE 4 Calculation of CIA and LIMA from weight-bearing LAT view.

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.

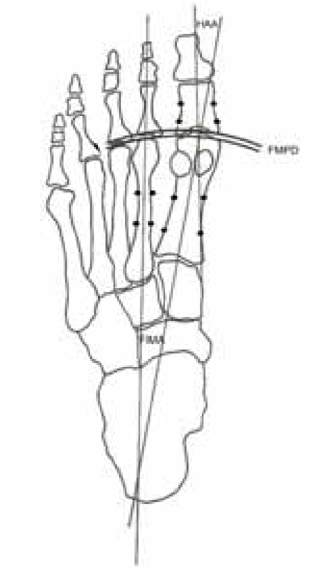

FIGURE 5 Calculation of HAA, FIMA and FMPD from weight-bearing DP view.

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 (95% 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 (95% 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.

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References

1. Bryant, A., Singer, K. Review of radiographic measurements following austin bunionectomy. Journal of the American Podiatric Medical Association.88(6):290-294, 1998.
2. Schneider, W., Csepan, R., Kasparek, M., Pinggera, O., Knahr, K. Intra- and inter-observer repeatability of radiographic measurements in hallux surgery: Improvement and validation of a method. Acta Orthopaedica Scandinavia.73(6):670-673, 2002.
3. Kilmartin, R., Barrington, R., Wallace, W. The x-ray measurement of hallux valgus: An inter- and intra- observer error study. The Foot.2:7-11, 1992.
4. Coughlin, M., Freund, E. The reliability of angular measurements in hallux valgus deformities. Foot and Ankle International.22(5):369-379, 2001.
5. Bryant, A., Tinley, P., Singer, K. A comparison of radiographic measurements in normal, hallux valgus, and hallux limitus feet. The Journal of Foot and Ankle Surgery.39(1):39-43, 2000.
6. Cavanagh, P., Morag, E., Boulton, A., Young, M., Deffner, K., Pammer, S. The relationship of static foot structure to dynamic foot function. Journal of Biomechanics.30(3):243-250, 1997.
7. Bojsen-Moeller, F., Lamoreux, L. Significance of free-dorsiflexion of the toes in walking. Acta Orthopaedica Scandinavia.50(4):471-479, 1979.
8. Kelikian, H. *Hallux valgus, allied deformities of the forefoot and metatarsalgia*. Philadelphia: W.B. Saunders Company; 1965.
9. Joseph, J. Range of movement of the great toe in men. Journal of Bone and Joint Surgery.36-B(3):450-457, 1954.
10. Buell, T., Green, D., Risser, J. Measurement of the first metatarsophalangeal joint range of motion. Journal of the American Podiatric Medical Association.78(9):439-449, 1988.
11. Allen, K. Dorsiflexion at the first metatarsophalangeal joint: a comparison of measurement by tractograph and digital biometer. British Journal of Podiatry.February:25-32, 1998.
12. Evans, R. *Illustrated essentials in orthopedic physical assessment*. St. Louis: Mosby; 1994.
13. Gerhardt, J., Rippstein, J. *Measuring and recording of joint motion: instrumentation and techniques*. Toronto: Hogrefe and Huber; 1990.
14. Giannestras, N. *Foot disorders: medical and surgical management*. Philadelphia: Lea and Febiger; 1973.
15. Hoppenfield, S. *Physical examination of the spine and extremities*. Norwalk: Appleton-Century-Crofts; 1976.
16. Hopson, M., McPoil, T., Cornwall, M. Motion of the first metatarsophalangeal joint: Reliability and validity of four measurement techniques. Journal of the American Podiatric Medical Association.85(4):198-204, 1995.
17. Mann, R., Coughlin, M., DuVries, H. Hallux rigidus: A review of the literature and a method of treatment. Clinical Orthopaedics and Related Research.142,:57-63, 1979.
18. McRae, R. *Clinical orthopedic examination*. 3rd ed. Edinburgh: Churchill Livingstone; 1990.
19. Tollafield, D., Merriman, L. Assessment of the locomotor system. In: Merriman L, Tollafield D, eds. *Assessment of the lower*

limb. Edinburgh: Churchill Livingstone; 1995.

20. Norkin, C., White, D. *Measurement of Joint Motion: A Guide to Goniometry*. Philadelphia: F.A. Davis; 1985.
21. Palmer, M., Epler, M. *Clinical assessment procedures in physical therapy*. Philaddelphia: J.B. Lippincott; 1990.
22. Root, M., Orien, W., Weed, J. *Biomechanical examination of the foot: clinical biomechanics.* Vol 1. Los Angeles: Clinical Biomechanics Corporation; 1971.
23. Sgarlato, T. *A compendium of podiatric biomechanics*. California: California College of Podiatric Medicine; 1971.
24. Hetherington, V., Johnson, R., Albritton, J. Necessary dorsiflexion of the first metatarsophalangeal joint during gait. Journal of Foot and Ankle Surgery.29(3):218-222, 1990.
25. Nawoczenski, D., Baunhauer, J., Umberger, B. Relationship between clinical measurements and motion of the first metatarsophalangeal joint during gait. The Journal of Bone and Joint Surgery.81-A(3):370-376, 1999.
26. Montagne, J., Chevrot, A., Galmiche, J. *Atlas of foot radiology*. Paris: Masson Publishing; 1981.
27. Freychat, P., Belli, A., Carret, J. P., Lacour, J. Relationship between rearfoot and forefoot orientation and ground reaction forces during running. Medicine and Science in Sports and Exercise.28(2):225-232, 1996.
28. Bojsen-Moeller, F. Calcaneocuboid joint and stability of the longitudinal arch of the foot at high and low gear push off. Journal of Anatomy.129:165-176, 1979.
29. Menz, H. Clinical hindfoot measurement: A critical review of the literature. The Foot.5:57-64, 1995.
30. Umberger, B., Nawoczenski, D., Baumhauer, J. Reliability and validity of first metatarsophalangeal joint orientation measured with an electromagnetic tracking device. Clinical Biomechanics.14:74-76, 1999.
31. Schneider, W., Knahr, K. Metatarsophalangeal and intermetatarsal angle: Different values and interpretation of postoperative results dependent on the technique of measurement. Foot and Ankle International.19(8):532-536, 1998.
32. Saltzman, C., Brandser, E., Berbaum, K., et al. Reliability of standard foot radiographic measurements. Foot and Ankle International.15(12):661-665, 1994.
33. Bryant, J. A comparison of radiographic foot measurements taken in two different positions. Journal of the American Podiatric Medical Association.95(5):234-239, 2001.
34. Resch, S., Ryd, L., Stenstrom, A., Johnsson, K., Reynisson, K. Measuring hallux valgus: A comparison of conventional radiography and clinical parameters with regard to measurement accuracy. Foot and Ankle International.16(5):267-270, 1995.
35. McCrea, J., Clark, D., Fann, T., Venson, J., Jones, C. Effects on Radiographic technique on the metatarsophalangeal joints. Journal of the American Podiatry Association.67(12):837-840, 1977.
36. Camasta, C., Pontious, J., Boyd, R. Quantifying magnification in pedal radiographs. Journal of the American Podiatric Medical Association.81(10):45-548, 2003.
37. Green, S., Green, H. The influence of radiographic projection on the appearance of deformities. Orthopedic Clinics of North America.25(3):467-474, 1994.
38. Perry, M., Mont, M., Einhorn, T., Walter, J. The validity of measurements made on standard foot orthoroentgenograms. Foot and Ankle.13(9):502-507, 1992.
39. Coughlin, M., Saltzman, C., Nunley, J. Angular measurements in the evaluation of hallux valgus deformities: a report of the ad hoc committee of the American Orthopaedic Foot and Ankle Society on angular measurements. Foot and Ankle International.23(1):68-74, 2002.
40. Gamble, F., Yale, I. *Clinical foot roentgenology*. 2nd ed. New York: The Williams and Wilkins Company; 1975.
41. Root, M., Orien, W., Weed, J. *Normal and abnormal function of the foot: clinical biomechanics.* Vol 2. Los Angeles: Clinical Biomechanics Corporation; 1977.
42. Schuberth, J., Reilly, C., Gudas, C. H. The closing wedge osteotomy: a

criticalanalysis of first metatarsal elevation. Journal of the American Podiatry Association.74(1):13-24, 1984.

43. Meyer, J., Nishon, L., Weiss, L., Docks, G. Metatarsus primus elevatus and the etiology of hallux rigidus. The Journal of Foot Surgery.26(3):237-241, 1987.

44. Christman, R., Flanigan, K., Sorrento, D., Stanich, C. Radiographic Analysis of Metatarsus Primus Elevatus: A Preliminary Study. Journal of the American Podiatric Medical Association.91(6):294-299, 2001.

45. Bryant, A., Mahoney, B., Tinley, P. Lateral intermetatarsal angle: A useful measurement of metatarsus primus elevatus? Journal of the American Podiatric Medical Association.91(5):251-254, 2001.

46. Roukis, T., Jacobs, P., Dawson, D., Erdmann, B., Ringstrom, J. A prospective comparison of clinical, radiographic, and intraoperative features of hallux rigidus. Journal of Foot and Ankle Surgery.41(2):76-95, 2002.

47. Horton, G., Park, Y., Myerson, M. Role of metatarsus primus elevatus in the pathogenesis of hallux rigidus. Foot and Ankle International.20(12):777-780, 1999.

48. Landers, P. Introduction and evaluation of hallux abducto valgus. In: McGlamry E, Banks A, Downey M, eds. *Comprehensive textbook of foot surgery.* Vol 1. 2nd ed. Baltimore: Williams and Wilkins; 1992:459-468.

49. Karasick, D., Wapner, K. Hallux valgus deformity: preoperative radiologic assessment. American Journal of Radiology.155:119-123, 1990.

50. Piggott, H. Natural history of hallux valgus in adolescent and early life. Journal of Bone and Joint Surgery.42B:749-760, 1960.

51. Griffiths, T., Palladino, S. Metatarsus adductus and selected radiographic measuremtns of the first ray in normal feet. Journal of the American Podiatric Medical Association.82(12):616-622, 1992.

52. Hardy, R., Clapham, J. Observations on hallux valgus based on a controlled series. Journal of Bone and Joint Surgery.33-B(3):376-389, 1951.

53. Antrobus, J. The primary deformity in hallux valgus and metatarsus primus varus. Clinical Orthopaedics and Related Research.184:251-255, 1984.

54. Houghton, G., Dickson, R. Hallux valgus in the younger patient. Journal of Bone and Joint Surgery.61B:176-177, 1979.

55. Smith, R., Reynolds, C., Stewart, M. Hallux valgus assessment: Report of research committee of American orthopaedic foot and ankle society. Foot and Ankle International.5(2):92-103, 1984.

56. Duke, H., Newman, L., Bruskoff, B., Daniels, R. Relative metatarsal length patterns in hallux abducto valgus. Journal of the American Podiatry Association.72(1):1-5, 1982.

57. Laporta, G., Melillo, T., Olinsky, D. X-Ray evaluation of hallux abducto valgus deformity. Journal of the American Podiatry Association.64(8):544-566, 1974.

58. Brage, M., Bennett, C., Whitehurst, J., Getty, P., Toledano, A. Observer reliability in ankle radiographic measurements. Foot and Ankle International.18(6):324-329, 1997.

59. Condon, F., Kaliszer, M., D, C., O'Donnell, T., Shaju, A., Masterson, E. The first intermetatarsal angle in hallux valgus: An analysis of measurement reliability and error involved. Foot and Ankle International.23(8):717-721, 2002.

60. Judge, M., LaPointe, S., Yu, G., Shook, J., Taylor, R. The Effect of Hallux Abducto Valgus Surgery on the Sesamoid Apparatus Position. Journal of the American Podaitric Medical Association.89(11/12):551-559, 1999.

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Appendix 3:

Investigation of dynamic angle of gait and radiographic characteristics of the first metatarsophalangeal joint in subjects with hallux limitus

Michael Taranto, Dr. Kevin Singer and Dr. Alan Bryant

Subject Information

Limited movement of the big toe joint (hallux limitus) is a common foot condition. Several causes have been linked to the development of this problem, including length and position of particular bones in the foot and the angle people place their foot on the ground when walking. This investigation will look at these causes by measuring these bones in foot x-rays and footprints obtained using coloured talcum powder and paper.

You are invited to participate in this study, as your foot demonstrates this condition of interest (or it may represent a comparison foot type known as a control). Involvement in this study will involve 5 x-ray views taken of the left and right feet 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 Michael 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, Michael Taranto can be contacted on 9250 1676 or 0419 990 789 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, realizing 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:

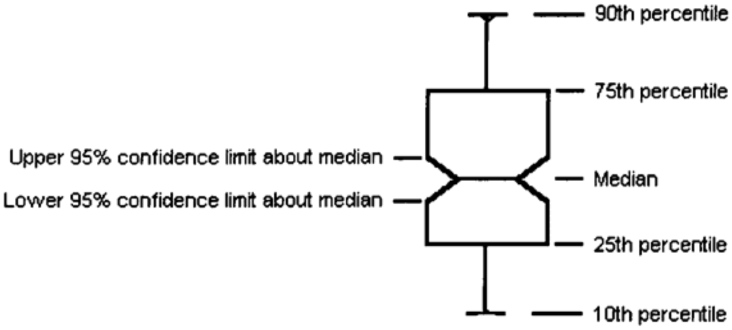
Radiographic Measurements Data Recording Sheet

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



Appendix 7:

Hallux Limitus 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)
1HL	34.000	26.000	0.000	0.500	9.000	15.000	11.000	14.000	0.000	-2.500	64.000	63.000	22.500	24.000
2HL	28.000	33.000	5.000	7.000	14.500	15.000	6.000	6.000	1.500	3.000	59.000	32.000	25.000	25.000
3HL	17.000	19.000	2.000	4.000	8.000	12.000	8.000	6.500	-2.000	2.000	82.000	55.000	14.000	19.500
4HL	30.000	27.000	6.500	5.000	8.000	13.500	8.000	9.500	6.000	7.000	64.000	86.500	21.000	18.500
5HL	22.000	24.000	7.000	5.000	13.000	12.000	9.500	9.500	10.000	11.000	80.000	58.000	21.500	23.000
6HL	26.000	24.000	8.000	5.500	6.500	23.500	12.500	15.500	10.000	11.000	68.000	47.000	4.500	10.000
7HL	21.000	18.500	9.000	5.000	17.000	19.000	8.000	9.000	3.500	5.000	11.000	30.000	5.000	5.000
8HL	24.000	20.500	6.000	6.000	20.000	10.000	9.500	4.500	0.000	3.500	37.000	61.000	9.000	9.000
9HL	23.000	25.000	4.000	3.000	12.000	14.000	6.000	8.000	5.000	6.000	57.000	67.000	16.000	15.000
10HL	27.500	27.000	2.000	12.000	16.500	10.000	6.000	0.000	4.000	8.500	36.000	14.000	6.000	10.000
11HL	26.500	25.000	2.000	3.000	5.000	13.000	8.000	10.000	-5.000	-5.000	54.500	69.000	28.000	20.000
12HL	19.000	17.500	2.000	2.000	3.500	6.000	10.500	10.000	-2.000	-3.000	45.500	64.000	8.000	6.000
13HL	27.000	26.000	0.500	1.000	11.000	8.500	10.500	10.500	-2.000	-3.000	70.000	64.000	23.500	18.000
14HL	22.000	27.000	2.000	3.000	12.000	18.500	10.500	12.000	-5.500	-4.500	69.000	56.000	7.000	11.000
15HL	29.000	29.000	4.000	6.000	7.500	16.500	9.000	12.000	-2.000	0.000	47.000	37.000	20.000	17.500
16HL	23.000	22.000	3.000	4.500	9.500	6.500	13.000	12.000	3.000	2.000	64.000	48.000	16.500	22.500
17HL	17.000	17.000	4.000	3.000	12.000	18.000	10.000	9.000	2.500	1.000	38.000	37.000	18.000	16.000
18HL	27.000	25.500	2.000	1.500	19.000	10.000	13.000	11.500	-1.000	-1.500	59.500	62.000	14.000	15.500
19HL	24.000	23.000	3.000	6.000	15.500	8.000	7.000	8.000	3.000	4.000	69.000	64.000	16.000	24.000
20HL	17.000	23.000	3.000	3.000	16.500	15.000	8.000	7.500	-2.500	-2.000	58.000	78.000	25.000	27.000
21HL	23.000	28.000	3.000	3.000	9.000	5.000	8.000	7.000	1.000	1.000	44.000	53.000	23.000	20.000
22HL	33.000	35.000	2.500	4.000	7.000	9.000	8.000	8.500	-1.000	1.000	61.000	55.000	27.000	25.000

Hallux Limitus Raw Data (Continued)

ID	AOG (L1)	AOG (R1)	AOG (L2)	AOG (R2)	GENDER	DOB	X-RAY DATE	AGE (yrs)	WEIGHT (kgs)	HEIGHT (m)	HEIGHT (cm)	BMI	INCLUSION	NO. OF FEET
1HL	4.000	2.000	5.000	4.000	F	3/03/1954	31/10/2003	49	60.000	1.625	162.500	22.722	B	2
2HL	0.000	12.500	0.000	12.000	F	23/05/1942	24/10/2003	61	58.500	1.602	160.200	22.795	B	2
3HL	1.000	5.500	8.000	7.000	F	15/04/1950	9/12/2003	53	74.000	1.674	167.400	26.407	R	1
4HL	10.000	7.000	10.500	4.000	F	1/03/1941	27/11/2003	62	50.500	1.607	160.700	19.555	L	1
5HL	8.000	16.500	6.500	17.000	M	18/08/1970	27/11/2003	33	65.000	1.670	167.000	23.307	R	1
6HL	4.000	10.000	3.500	10.000	M	12/03/1947	26/11/2003	56	84.000	1.721	172.100	28.361	R	1
7HL	0.000	14.000	2.000	14.000	F	26/10/1934	28/11/2003	69	71.200	1.575	157.500	28.702	B	2
8HL	8.000	12.000	10.000	9.500	M	29/09/1944	3/12/2003	59	77.500	1.704	170.400	26.691	B	2
9HL	10.000	23.000	9.000	15.000	M	14/06/1974	4/12/2003	29	78.000	1.730	173.000	26.062	L	1
10HL	10.000	12.500	7.500	10.500	F	18/05/1944	9/12/2003	59	70.000	1.585	158.500	27.864	B	2
11HL	11.000	7.000	7.000	7.500	F	20/03/1941	15/12/2003	62	75.000	1.616	161.600	28.720	L	1
12HL	14.000	14.500	15.000	17.000	M	21/04/1947	11/02/2004	57	90.500	1.790	179.000	28.245	B	2
13HL	7.000	9.000	10.000	12.500	F	14/06/1964	10/12/2003	39	61.000	1.504	150.400	26.967	R	1
14HL	17.000	17.000	14.000	15.000	F	7/05/1946	19/12/2003	57	70.500	1.640	164.000	26.212	R	1
15HL	14.000	7.000	11.000	7.000	F	12/05/1947	9/01/2004	57	63.000	1.612	161.200	24.244	B	2
16HL	10.500	11.500	12.000	16.000	M	13/03/1967	7/01/2004	37	74.000	1.767	176.700	23.701	B	2
17HL	16.000	16.000	11.000	9.000	F	27/05/1928	14/01/2004	76	81.500	1.543	154.300	34.231	B	2
18HL	0.000	18.000	3.000	16.000	F	15/05/1952	2/01/2004	52	66.500	1.658	165.800	24.191	B	2
19HL	14.500	25.000	13.000	25.500	F	28/12/1954	4/12/2003	49	63.500	1.618	161.800	24.256	R	1
20HL	13.000	15.000	14.000	14.500	M	12/05/1949	2/02/2004	55	93.500	1.782	178.200	29.444	L	1
21HL	16.000	13.000	16.000	16.500	M	12/07/1940	28/01/2004	64	106.000	1.730	173.000	35.417	B	2
22HL	16.000	20.000	14.500	21.000	M	4/12/1932	2/02/2004	72	77.000	1.700	170.000	26.644	B	2

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

Control Raw Data (Continued)

ID	AOG (L1)	AOG (R1)	AOG (L2)	AOG (R2)	GENDER	DOB	X-RAY DATE	AGE (yrs)	WEIGHT (kg)	HEIGHT (m)	HEIGHT (cm)	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	160.000	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	159.500	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	157.200	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	168.400	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	169.800	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	159.500	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	175.200	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	153.500	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	164.000	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	153.500	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	160.500	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	177.500	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	149.000	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	174.000	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	159.000	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	181.600	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	175.200	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	164.800	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	175.200	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	181.200	28.020	B	2

Appendix 8:

Pearson’s Product Moment Correlations for Hallux Limitus Group

	CIA	LIMA	HAA	FIMA	FMPD	LAT SD	RFA	AOG
CIA	1.000							
LIMA	-0.116	1.000						
HAA	0.037	-0.003	1.000					
FIMA	-0.061	-0.403	0.291	1.000				
FMPD	-0.001	0.430	0.224	-0.301	1.000			
LAT SD	0.131	-0.351	-0.278	0.076	-0.156	1.000		
RFA	0.243	-0.229	-0.148	0.005	-0.041	0.205	1.000	
AOG	0.154	-0.130	-0.128	-0.120	0.084	-0.060	0.129	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