Using surface markers to describe the kinematics of the medial longitudinal arch in a longitudinal study of flexible flat feet and health-related quality of life

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by
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Declaration

I declare that this thesis is entirely my own work, and except where otherwise stated, describes my own research.

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Jerneja Uhan, Alpesh Kothari, Amy Zavatsky, Julie Stebbins

Abstract

Flexible flat foot (FFF) is a condition which, despite being commonly seen in the clinical setting, has no clear consensus on its aetiology, prognosis, or management plan. This thesis aimed to observe the natural development of the medial longitudinal arch (MLA) from childhood into adulthood in in FFF and compare it with neutral feet (NF). This is the first known longitudinal study of FFF. To conduct this study, it was initially necessary to develop a measure to characterise the MLA accurately and reliably in both static and dynamic stances. This entailed the comparison of eight configurations of motion-capture markers on the foot. Each configuration used varying combinations of real and virtual foot marker coordinates to enable measurement of the MLA angle. The optimal MLA measure was selected based on quantitative and qualitative Multi Criteria Decision Analysis, criteria for which were determined through a Delphi study. The measure which used real markers on the heel, navicular, and first and fifth metatarsal heads, was determined as the best choice for assessing the MLA. Initially, it was applied to participants with cerebral palsy, to observe if it could characterise the MLA in feet with complex deformity and variable walking patterns. This demonstrated good alignment with established measures of the foot, as well as with clinical observation of foot behaviour. Therefore, it was deemed suitable for comparing the static foot posture and walking patterns of participants with FFF and NF between childhood and adulthood. In addition, the effect of FFF in childhood on quality of life (QofL) in adulthood was assessed, to help decide which feet should be treated. Overall, the MLA for the FFF group did not improve over time, suggesting these feet do not spontaneously resolve. There was some evidence to suggest children with FFF may have poorer QofL outcomes in adulthood. In particular, limitations in forefoot supination and hindfoot dorsiflexion may be predictors of poorer QofL in adulthood.

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Abbreviations

AHI- Arch Height Index

AI- Arch Index

CGA- Clinical Gait Analysis

CP- Cerebral Palsy

FFF- Flexible Flat Feet

FHSQ- The Foot Health Status Questionnaire

FPI- Foot posture Index

GC- Gait Cycle

LLA- Lateral Longitudinal Arch

MCDA- Multi Criteria Decision Analysis

MLA- Medial Longitudinal Arch

MSFMs- Multi Segmented Foot Models

NF- Neutral feet

OFM- Oxford Foot Model

OGL- Oxford Gait Laboratory

OXAFQ-C - The Oxford Ankle Foot Questionnaire for Children

QofL - Quality of Life

RM- Rizzoli Model

ROM- Range of Motion

SD- standard deviation

STJ- Subtalar Joint

TA- Transverse Arch

VAS- Visual Analog Scale

I. Introduction

This chapter outlines the rationale for the main aspects of this thesis, including the development of an optimal measure to assess the Medial Longitudinal Arch (MLA) and the need to prospectively assess flexible flat feet (FFF) from childhood into adulthood. An overview of the remaining chapters of this thesis is also provided here.

1.1 Rationale

Flexible flat foot is a condition that is commonly seen in the clinical setting, typically due to parental concerns about the appearance of their children's feet or reports of foot pain by the children themselves [1–6]. Despite affecting many individuals, there is currently no clear agreement on management pathways. Clinicians often advise that children will naturally outgrow this condition, but it is clear that this is not always the case. Such lack of consensus regarding management can be attributed to two primary reasons. Firstly, there are no longitudinal studies to track the development of FFF from childhood to adulthood. Without this information, it becomes challenging to understand how FFF evolves over time and whether it is likely to remain unchanged or resolve spontaneously. This is particularly important, given that it has been shown to be associated with poorer quality of life (QofL) outcomes in childhood [7,8]. Secondly, there is no definitive way to measure the MLA in both static and dynamic situations, in a manner that has been validated specifically for a paediatric FFF population. In the clinical setting, the static MLA is typically assessed to gauge the severity of FFF. However, this does not account for the functional aspect of this condition, for which a reliable and direct dynamic MLA assessment method is required.

The aims and objectives of this thesis were formulated to address these gaps in knowledge and provide an evidence base to help inform FFF management.

1.2 Aims and objectives

The main objectives of this thesis are objectives 2-4. However, to be able to achieve these objectives, addressing objective 1 was initially required.

Objective 1: To define the optimal way to assess the MLA during static situations, as well as during walking, and to develop a method for remote assessment of foot posture.

Objective 2: Use the outcome of objective 1 to investigate changes in static foot posture from childhood into adulthood in those with flexible flat feet compared to those with neutral foot postures.

H0 There will be no significant change in static foot posture in adulthood compared to childhood, regardless of initial foot type.

Objective 3: Use the outcome of objective 1 to investigate change in dynamic foot motion during walking from childhood into adulthood in those with flexible flat feet compared to those with neutral foot postures.

H0 There will be no significant change in dynamic foot motion during walking in adulthood compared to childhood, regardless of initial foot type.

Objective 4: To investigate the relationship between foot posture and walking patterns in childhood and quality of life in adulthood.

H0 Foot posture and walking patterns in childhood are not associated with quality of life in adulthood.

1.3 Thesis overview

Chapter one of this thesis presents the overall aims and rationale for the study. It sets the foundation for the subsequent chapters, by establishing the context and importance of the research. Building upon the introductory chapter, chapter two delves into a review of the literature on foot and ankle anatomy. It further explores the biomechanics of the foot and ankle during gait, enhancing understanding of the mechanical principles underlying foot function. Chapter three then transitions to the specific topic of FFF. It provides a comprehensive overview of this condition, including how it is distinguished from other types of flat feet. The chapter delves into the prevalence, prognosis, and various treatment pathways of FFF, alongside the range of available treatment options for its management. Chapter four focuses on the available clinical assessment methods for evaluating FFF. This chapter covers both static and dynamic measures, to give a comprehensive understanding of the tools and techniques used in clinical practice. With a base of knowledge from the current literature established, chapter five details the material and methods used in this study to achieve its research objectives. It specifically focuses on the development of eight configurations for assessing the MLA. Chapter six involves the application of the MLA measures, to assess the MLA in a variety of weightbearing and non-weightbearing movement tasks. Additionally, it highlights the selection process that led to identifying the optimal measure, based on multi-criteria decision analysis (MCDA). Chapter seven explores the use of the selected optimal measure on individuals with cerebral palsy (CP). This chapter explores how the measure performs in this unique population and provides valuable insights into its clinical applicability. Chapter eight addresses a contemporary challenge, by discussing the development and validation process of a remote data collection method. This method allows for remote assessment of the arch height index (AHI) and arch index (AI) when in-person data collection is not feasible, such as during the COVID-19 pandemic. Chapter nine presents the methodology of a longitudinal study on FFF spanning a follow-up period of 7-8 years. Chapter ten examines changes in foot posture across the longitudinal study, while chapter eleven does so for walking patterns. Chapter twelve evaluates quality of life

from childhood to adulthood and provides valuable insights into the long-term impact of FFF. Lastly, chapter thirteen provides an overview of the newly discovered outcomes of this thesis.

2 Foot anatomy and biomechanics

This chapter describes the fundamental structures that form the foot's anatomy, together with the principles of how the foot behaves during locomotion, within the context of the gait cycle (GC). Such information provides a knowledge base on the form and function of a typically developed foot, to enable appreciation of foot pathologies which may differ in the characteristics outlined here.

2.1 Basic anatomical terminology

The human foot is a complex structure comprising 26 bones, 33 synovial joints and over 100 ligaments, tendons and muscles [9–12]. It has evolved its form and bone structure through the necessity of supporting and resisting mechanical stresses across various tasks such as walking, turning and running [13,14]. In order to perform such tasks, it is necessary to change the shape of the foot through the movement of synovial joints, supported or restricted by ligaments and tendons and controlled by muscles [10,11,14]. Therefore, for the purpose of evaluating foot function, an understanding of the foot's anatomy, including the terminology used to describe the positioning of its composite structures, is required.

The standard anatomical position is the reference from which the spatial relationships between anatomical structures are defined. In this position, a person stands upright and faces forward with their feet parallel and hip width apart, and toes pointing forward. The upper limbs are by the sides, with the palms facing forward, resulting in the thumb being lateral (Figure 1) [11,12,14,15]. In this manner, terms are correspondingly used to describe positioning between two structures relative to each other. In most instances, the positioning is defined according to three planes - sagittal, coronal and transverse (Table 1) [11,12,14,15]. In addition, movements occurring between regions

within the foot can be described using specific terminology. Descriptions of general anatomical movements in the planes are presented in Table 1, while descriptions of movements that are specific to the foot and ankle region are presented in Table 3.

Anatomical plane	**Description of anatomical plane**	**Direction of movement in the plane**	**Direction of movement in lay terms**
Sagittal plane	A vertical plane passing through the body in the anatomical position, that divides the body into right and left parts.	Superior Inferior Anterior Posterior	Towards the top Towards the bottom Towards the front Towards the back
Coronal plane	A vertical plane passing through the body in the anatomical position, that divides the body into front and back parts.	Superior Inferior Medial Lateral	Towards the top Towards the bottom Towards the midline of the body Away from the midline of the body
Transverse plane	A horizontal plane passing through the body in the anatomical position, that divides the body into upper and lower parts.	Anterior Posterior Medial Lateral	Towards the front Towards the back Towards the midline of the body Away from the midline of the body

Table 1: The descriptions of the internationally accepted terminology for anatomical planes and positioning, together with the corresponding planes from which they are defined [11,12,14,15].

Anatomical positioning	Definition of anatomical positioning
Ipsilateral	On the same side
Contralateral	On the opposite side
Proximal	Closer to the point of origin or the trunk of the body
Distal	Further from the point of origin or the trunk of the body

Table 2:The internationally accepted terminology for anatomical positioning that is not specific to a plane [11,12,14,15]

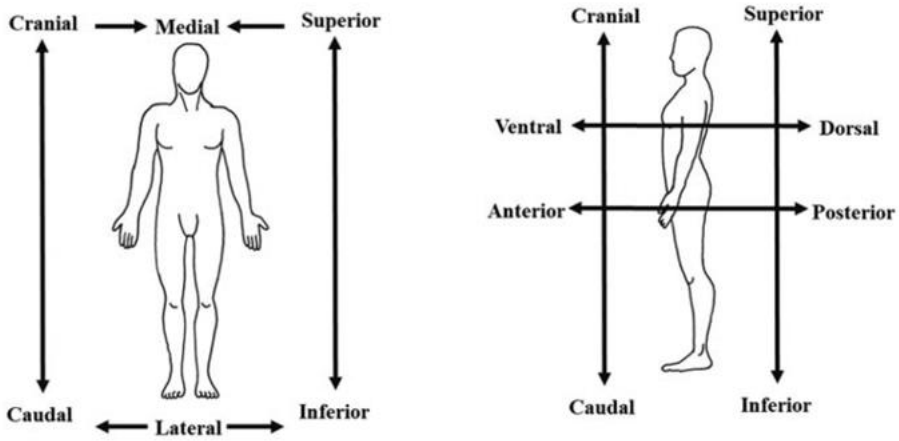


Figure 1: The anatomical position and anatomical directions, adapted from Ledoux et al. [12]

Movement	Plane of movement	Direction of movement
Plantarflexion	Sagittal	Towards caudal side
Dorsiflexion	Sagittal	Towards cranial side
Abduction	Transverse	Away from the midline
Adduction	Transverse	Towards the midline
Inversion	Frontal	Towards the midline
Eversion	Frontal	Away from the midline
Pronation	Frontal/Sagittal/Transverse	Subtalar eversion + dorsiflexion + abduction Movement of foot up and away from centre of body
Supination	Frontal/Sagittal/Transverse	Subtalar inversion + plantarflexion + adduction Movement of foot down and towards centre of body

Table 3: The movements that occur in the foot and ankle [11,12,14,15]

2.2 Bones of the foot

The foot can be divided into three regions that are determined by their composite bones – the hindfoot, the midfoot and the forefoot (Table 4 and Figure 2) [11,12,14,15]. The grouping of bones into these specific regions is generally accepted due to the relation between foot structure and function.

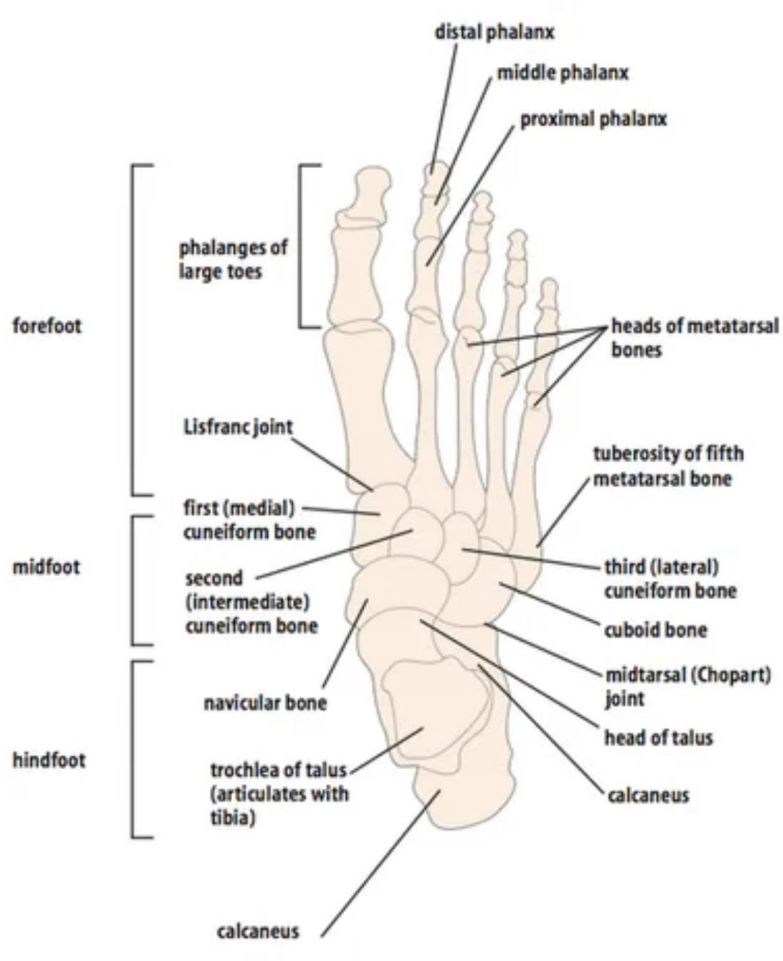


Figure 2: The bones and regions of the foot Moore [16]

Foot region	Composite bones
Forefoot	5 proximal phalanges, 5 distal phalanges, 4 middle phalanges, 2 sesamoid bones
Midfoot	Medial cuneiform, intermediate cuneiform, lateral cuneiform, navicular, cuboid
Hindfoot	Talus, calcaneum

Table 4: The composite bones for each foot region [11,12,14,15]

2.3 Joints of the foot

2.3.1 Hindfoot region

2.3.1.1 Talocrural joint

The talocrural joint, also known as the ankle joint, can be classified as a synovial hinge joint formed by the talus articulating with both the distal tibia and fibula [17]. The axis of this joint's motion was initially investigated in an anthropometric study by Isman and Inman [18], and defined as an oblique axis of rotation. Since the medial malleolus lies slightly anterior and superior to the lateral malleolus, the oblique joint axis results in abduction and eversion accompanying dorsiflexion; and adduction and inversion with plantarflexion [11,14]. Over time, the single axis model has been investigated and adapted. Leardini et al. [19] conducted a comprehensive literature review on ankle motion and concluded that the concept of the ankle joint being a hinge joint was an oversimplification [19]. Rather, it was suggested that ankle joint movements occur through rolling and sliding. In addition, it was proposed that the ankle joint may have two rotational axes - one plantarflexion axis and one dorsiflexion axis. The motion of the ankle joint has also been reported as an instantaneous helical axis that is altered throughout the joint's motion [19].

With respect to the movements occurring in the sagittal plane, ranges of motion of 23-56° in plantarflexion and 13-33° in dorsiflexion have been reported [19]. Other estimates in typically developed feet, describe clinical consensus values of 18° for dorsiflexion and 48° for plantarflexion [20]. In addition, studies have observed notable motion in the other two planes, with mean range of motion (ROM) values reported in two studies of 8.1° and 15.3° in the frontal plane, and 7.8° and 10.0° in the transverse plane [21,22].

2.3.1.2 Subtalar joint

The hindfoot is formed by the talus and calcaneum bones [11,14,23]. The convex posterior facet of the calcaneum articulates superiorly with the concave facet of the talus and anteriorly with the navicular to form the subtalar joint (STJ) [24–26]. Collectively, the anterior facets of the calcaneum articulate to form a concavity for the ovoid talus head and a triple faceted area in the inferior surface of talus articulation, thereby acting similarly to a ball and socket joint [11,12,14,15]. The STJ can be approximated as a single hinge joint, with an oblique axis of rotation that runs from the posterior lateral plantar surface to the anterior dorsal medial aspect of the talus [18,27–30]. The motion of this joint is not as clearly defined as that of the ankle joint, due its uneven and variable shape, alongside having minimal external landmarks to visualise it. This joint's movement has been regarded as either rotation, translation or a combination of both [25,26].

Several studies have obtained an insight on STJ motion, where the joint was initially found to have a helical movement with which the talus advanced 1.5 mm for every 10° of rotation around the joint axis [29]. This concept was elaborated upon by Van Langelaan et al. [31] who determined the presence of multiple helical axes rather than one, in their cadaveric fluoroscopic study. Such rejection of the view of single axis joint rotation has been corroborated, with evidence of parallel translation of the joint axis obtained by Lundberg and Svensson [32,33] and verified in a cadaveric study by Leardini et al [34].

STJ motion is complex due to the presence of these multiple joint axes, together with the variability of the shape of articulations and soft tissues restraints. The reported range of STJ motion varies from 10° to 50° [29,35–37]. When clinically assessed, such motions can be expected to range between 20° of eversion and 30° of inversion in typically developed adult feet [20].

From a functional perspective, the importance of STJ motion has been debated. It has been reported in some instances that the ankle joint contributes more to transverse plane motion, and

that coronal plane motion of the ankle exceeds that of the STJ in some cases [35,38]. Therefore, assessing individual joints that form the hindfoot may be of limited value, in comparison to assessing the hindfoot as a whole [39].

2.3.2 Midfoot region

2.3.2.1 Midtarsal joint

The midtarsal or transverse tarsal joint is formed by two distinct joints - the calcaneocuboid joint on the lateral aspect and the talonavicular joint on the medial aspect [40]. The calcaneocuboid joint is a saddle joint between the calcaneum and cuboid bones. The talonavicular joint involves articulation between the talus of the hindfoot and navicular of the midfoot. The navicular is a small boat-shaped bone with two crests oriented in a dorsoplantar position, which divide it into medial, intermediate, and lateral articular surfaces [11,12,14,15]. The medial articular surface, which is the largest and convex with a triangular-shaped surface, articulates with the medial cuneiform bone. The intermediate articular surface, which also has a triangular-shaped surface but is flat, articulates with the intermediate cuneiform bone that is located between the medial and lateral cuneiform bones [6,7]. The lateral articular surface is the smallest among the three. It has a quadrangular surface and articulates with the lateral cuneiform bone. There are three wedge-shaped cuneiform bones and one square-shaped cuboid bone which articulate with the forefoot. The cuboid lies lateral to the lateral cuneiform bone [11,14,23].

The two composite joints of the midfoot combine to form a joint line, at which movements occur along longitudinal (Figure 3A) and oblique axes (Figure 3B). At the longitudinal axis, which is located approximately 15° superior to the horizontal plane and 10° medial to the longitudinal plane, the main movements are inversion and eversion [29]. As for the oblique axis, this is located approximately 52° superior to the horizontal plane and 57° from the midline and is the axis about which flexion and extension occur [29]. The functional significance of this joint pertains to the midtarsal joint locking mechanism. This is initiated by STJ inversion, which leads to an alignment of the aforementioned axes, enabling the foot to become a rigid liver to propel the body forward during mid to late stance [11,41].

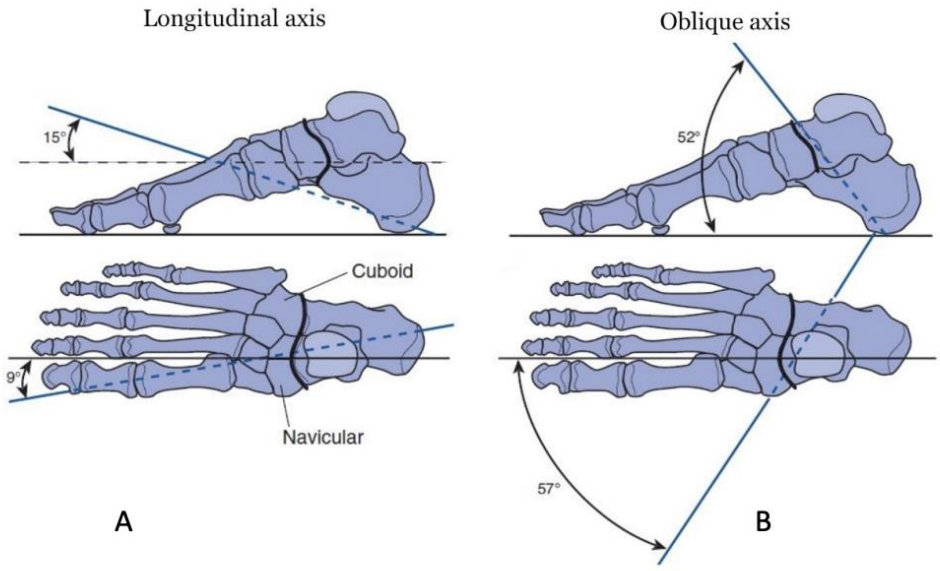


Figure 3: The two-axis representation of the midtarsal joint motion, the longitudinal axis (A) and the oblique axis (B), adapted from Nordin & Frankel [30]

2.3.2.2 Intertarsal and tarsometatarsal joints

The intertarsal joints are formed by the three cuneonavicular joints, the intercuneiform joints, the cuboideonavicular joints, and the cuneocuboid joint [192]. Due to the compact positioning and restricted movement of these joints, there is limited information pertaining to their range of motion [14,23]. The tarsometatarsal or Lisfranc joint, which is technically a boundary between the forefoot and midfoot bones rather than a joint, is stabilised by the thick, fibrous Lisfranc ligament [14,23,42]. In a cadaveric study, the joints at this landmark have demonstrated significantly lower ROM of 3.5° and 0.6° respectively in the cuneiform-first and second metatarsals, in comparison to 9.6° and 10.2° respectively in the cuboid-fourth and fifth metatarsals [43]. Given their compact characteristics, both intertarsal and tarsometatarsal joints typically cannot have their range of motion measured during gait assessment [10,11].

2.3.3 Forefoot region

2.3.3.1 Metatarsophalangeal joints

The most distal aspect of the forefoot consists of the toes, which are formed by consecutive articulations between the proximal, middle and distal phalanges; except for the first toe which only comprises an articulation between the proximal and distal phalanges [11,14,23]. There are five proximal phalanges which articulate with five metatarsals, to form five condyloid metatarsophalangeal joints in each foot [11,12,14,15]. Each metatarsal presents with a convex head, which articulates with one of five corresponding concave phalanges [12,14,23]. Furthermore, there are two sesamoid bones which lie around the articulation between the first metatarsal and first proximal phalanx within the flexor hallucis brevis tendon [12,14,23]. At each of these articulations, a gliding motion of the phalanges in the sagittal plane is facilitated by the convex metatarsal head [12,14,23]. All the metatarsophalangeal joints have two axes which allow for sagittal plane motion in the form of dorsiflexion and plantarflexion, and transverse plane motion in the form of abduction and adduction [10–12,14,23]. The sagittal plane motion of the second to the fifth metatarsophalangeal joints is limited by joint capsules and plantar plates [12,14,23]. As for the transverse plane motion of all the metatarsophalangeal joints, these are limited by collateral ligaments [12,14,23]. This motion is small and bears no functional significance in gait. The sagittal plane ROM in the first metatarsophalangeal joint is greater than the rest, with an average of approximately 111° [44]. From a functional perspective, the first metatarsophalangeal joint enables transmission of the bodyweight force upon propulsion, alongside the activation of the windlass mechanism which elevates the MLA [11,12,14,23].

These joints directly allow movements of the foot, in conjunction with the surrounding soft tissues to achieve this. These soft tissues, including ligaments and muscles, have the vital role of facilitating efficient and effective load-bearing activities.

2.4 Soft tissues

The soft tissues of the feet include over 100 ligaments, 19 intrinsic muscles and 10 extrinsic muscles that control movement [12,14,16]. An in-depth description of all these structures is beyond the scope of this thesis, but awareness of certain key structures is required to understand how the foot and ankle complex fulfils its role in unloaded and load-bearing activities.

2.4.1 Ligaments

From over 100 ligaments in the foot, the short and long plantar ligaments and the plantar calcaneonavicular or spring ligament will be outlined due to their implications in FFF [11,23,45]. The long plantar ligament extends from the under-surface of the calcaneum to the base of the second to fourth metatarsals, passing over the tuberosity of the cuboid [12,14,16]. Beneath it lies the short plantar ligament, which runs from the anterior calcaneal tubercle to the cuboid [12,14,16]. The spring ligament is a wide band of thick fibres that extends from the anterior margin of the sustentaculum tali of the calcaneum to the under-surface of the navicular bone [12,14,16]. In addition to connecting these two bones, it also forms a sling that supports the talar head in the acetabulum pedis. These plantar ligaments provide static support to the MLA of the foot [12,14,16].

2.4.2 Intrinsic and extrinsic muscles

Intrinsic and extrinsic muscles of the foot can be differentiated by their roles and anatomical positions (Table 5). Intrinsic muscles originate and terminate within the foot, serving to stabilise the foot and maintain arch height [10–12]. They are assembled in four layers. In contrast, extrinsic muscles originate from the leg and extend into the foot through tendons, holding the role of moving the foot and ankle [10–12]. The roles of pertinent foot muscles that are important in context of the MLA are outlined in Table 5.

It is apparent that soft tissue support is an important variable for maintaining the integrity of the MLA. This is evidenced in cadaveric studies, which found the plantar fascia to be the main

contributor of arch stability, ahead of the long and short plantar ligaments and spring ligament [46,47]. In addition, the tibialis posterior muscle specifically has been reported to hold an important role in supporting the foot arch. Specifically, it functions as an ankle invertor and plantarflexor, thereby preventing excessive pronation and eversion which could lead to arch collapse [48–50].

Muscle	Origin	Insertion	Action
Anterior compartment			
Extensor hallucis longus	Interosseous membrane and middle half of the anterior surface of the fibula	Distal phalanx of the great toe	Extends the hallux, and dorsiflexes and inverts foot
Extensor digitorum longus	Anterior surface of the fibula and lateral portion of the interosseous membrane	Dorsum of the second-fifth toes via extensor expansions	Extends proximal, middle and distal interphalangeal joints, dorsiflexes the foot
Tibialis anterior	Lateral upper surface of the tibia	Medial surface of the medial cuneiform and first metatarsal	Dorsiflexes and inverts the foot
Peroneus tertius	Distal part of the anterior surface of the fibula	Dorsum of the shaft of the fifth metatarsal	Everts the foot
Lateral compartment			
Peroneus brevis	Lower third of the lateral surface of the fibula	Base of the fifth metatarsal	Plantarflexes and everts the foot
Peroneus longus	Proximal two thirds of the lateral fibular surface	Tendon passes medially across the plantar surface of the foot and inserts into the medial cuneiform and base of the first metatarsal	Plantarflexes the first ray, plantarflexes and everts the foot
Posterior compartment			
Flexor digitorum longus	Middle half of the posterior surface of the tibia	Bases of the distal phalanges of the second-fifth toes	Flexes the proximal, middle and distal interphalangeal joints of the second-fifth toes and plantarflexes the foot
Flexor hallucis longus	Lower two thirds of the posterior surface of the fibula	Distal phalanx of the big toe	Flexes the metatarsophalangeal and proximal interphalangeal joints of the great toe, plantarflexes the foot
Tibialis posterior	Interosseous membrane of the posteromedial surface of the fibula and posterolateral surface of the tibia	Passes via the navicular, inserting into the under-surface of medial cuneiform and second-fourth metatarsals	Plantarflexes and inverts the foot, elevates medial longitudinal arch
Gastrocsoleus	Distal femur (gastrocnemius), Posterior surface of the tibia (soleus)	Posterior aspect of the os calcis via the Achilles tendon	Plantarflexion and inversion of the foot

Table 5: The intrinsic and extrinsic muscles of the foot that play an important role in context of the MLA. Adapted from [3,4,6,7,43]

2.4.3 Arches of the foot

Having discussed the soft tissues that support them, the foot arches will now be discussed. The foot comprises three arches: the medial longitudinal arch (MLA) (Figure 4A), lateral longitudinal arch (LLA) (Figure 4B) and transverse arch (TA) (Figure 4C) [11,12,14,15,51]. These arches can be defined by the physical arrangement of their constituent bones, which form convex structures.

The MLA is formed by the calcaneum, talus, navicular, medial cuneiform, and first three metatarsals [11,12,14,15,52]. As for the LLA, this is made up of the calcaneum, cuboid, and lateral two metatarsals, and normally has contact with the ground when in the standing position. The transverse arch can be divided into two entities - the proximal and distal transverse arches. The proximal transverse arch spans the cuboid bone laterally and the three cuneiform bones medially. The distal transverse arch is relatively shallower, being formed by the metatarsal heads [11,12,14,15,52].

Of these arches, it is the MLA that holds an integral role in stabilising the foot and transmitting load during gait [10,11,53]. This stability is achieved through mechanisms that were described by Hicks [54] using beam and truss models, in which the MLA acts as a multi-segment beam on which weight is distributed between the forefoot and hindfoot. Consequently, the dorsal surface of the MLA is under compression and the plantar surface under tension. To prevent collapse of the arch, the MLA acts as a truss, on which compressive forces from weightbearing are counteracted by an increase in the tensile force of the plantar fascia through the windlass mechanism, where extension of the hallux causes tightening of the plantar fascia [11,55,56].

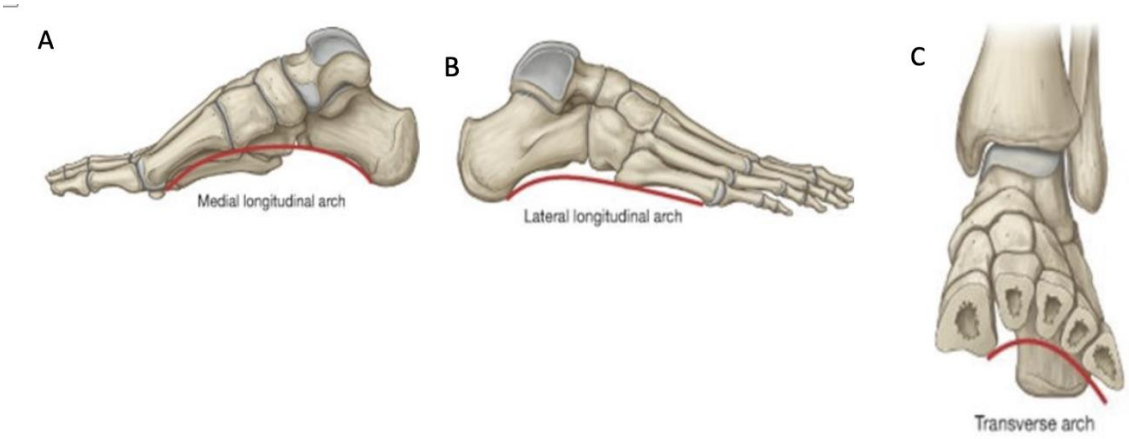


Figure 4:The three arches: a) medial longitudinal arch, b) lateral longitudinal arch and c) transverse arch, adapted from Drake et al. [15]

2.5 Foot and ankle biomechanics during gait

With the foot and ankle anatomy having been outlined, it is now important to address their function, with a focus on walking gait. The process of human locomotion can be described in terms of the gait cycle (GC) [10,11,57–59]. The GC is defined as the interval between two consecutive foot contact events of the same foot. It can be separated into two distinct phases: the stance phase when the foot is in contact with the floor, and the swing phase when the foot is swinging through the air [10,39,60]. The stance phase can be further subdivided into initial foot contact, midstance and toe-off, while the swing phase can be divided into follow-through, forward swing and foot descent (Figure 5) [10,39,60]. The stance phase accounts for 55 to 62% of one total gait cycle, while the swing phase makes up the remaining 38 to 45% [61]. The phases of the gait cycle describe the key events during locomotion. While these events occur in both feet, there is a discrepancy in timing, where one foot will be in the stance phase while the other is either on the ground or in the swing phase and vice versa. The precise timing of each phase varies in each individual, based on their physical characteristics and walking speed [62]. In this thesis, the conventional description of GC events and phases will be described as presented by Levine et al. [39] and Baker et al. [60].

The stance phase begins with initial foot contact, where the heel touches the ground [63]. Once the foot contacts the ground, the loading response period begins. During this phase, the subtalar joint pronates, and the ankle and knee slightly flex to allow the foot to adapt to the ground surface [10,39]. In this period, which is known as the heel or first rocker, muscles mostly work eccentrically to assist in the absorption of ground reaction forces (GRFs) and break the forward momentum of the body when lowering the foot to the ground [10,39]. When the foot is flat on the ground, the midstance phase is reached, during which the opposite foot is in swing phase and passes the stance phase foot. Next, the body moves forward over the stance limb with assistance from the lower extremity muscles that are now working mostly concentrically. This is represented by the transition of ankle plantarflexion to dorsiflexion, which defines the ankle or second rocker. This anterior movement leads to the terminal stance phase, where the bodyweight is shifted to the forefoot [10,39,64]. Subsequently, the heel lifts off the ground, following which the ankle plantarflexes and tibial external rotation and forefoot supination occur prior to toe-off. These movements define the toe or third rocker. Toe-off is the last part of the stance phase, where the foot pushes off the ground to propel the body forward. Immediately after toe-off, the swing phase of the GC begins, where the hip joint flexes to bring the thigh forward and upwards, and the knee flexes to allow the lower leg to swing forward. In addition, the ankle dorsiflexes to aid in clearing the foot off the ground. The hip joint reaches its maximum level of flexion, and the knee continues to flex in the mid-swing phase, at which time the foot passes under the body towards the opposite foot. Following this, there is the terminal swing phase, where the hip and knee extend to straighten the knee joint to prepare the leg for the next stance phase [10,39,64].

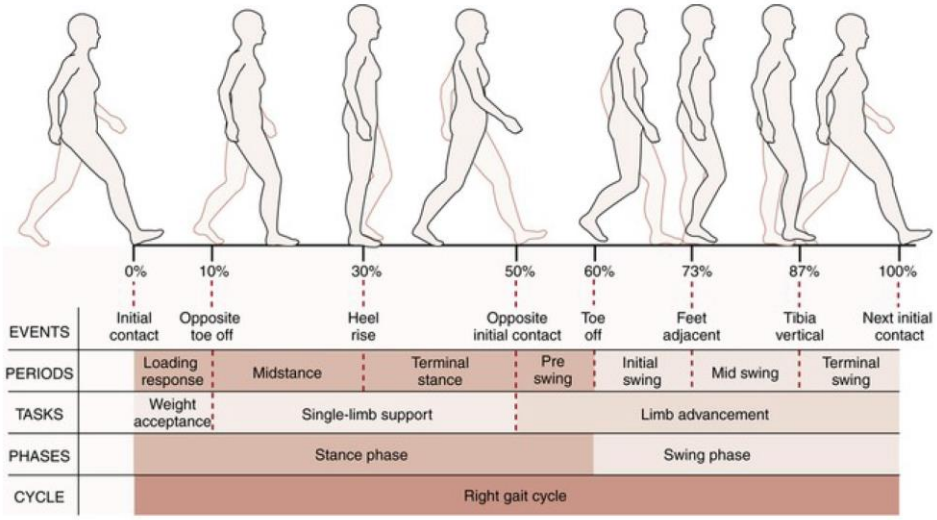


Figure 5: The gait cycle and its events during locomotion for the right foot only, adapted from Neumann et al. [17]

This chapter has outlined the complexity of the foot in terms of its composite structures of bones, joints, muscles and ligaments, which function together as a unit to enable locomotion. It is no surprise that Leonardo Da Vinci described the foot as a masterpiece of engineering and a work of art. Many foot pathologies can lead to dysfunction and compensatory mechanisms during walking. One such pathology that bears importance in this matter is FFF, which will now be explored.

3 What is flexible flat foot?

Flat foot, also known as pes planus or planovalgus is an umbrella term that refers to deformities of the medial longitudinal arch (MLA), where its height is reduced [8,65,66]. Such feet tend to display similar morphological features such as forefoot abduction, prominence of the navicular, and medial curving of the Achilles tendon [8,67,68]. However, their underlying pathology can be starkly different. Therefore, the American College of Foot and Ankle Surgeons (ACFAS) has defined flat feet using four subcategories: rigid flat foot, flexible flat foot (FFF), skew flat foot, and "other" flat foot [69]. This thesis focuses on FFF; therefore, other types of flat foot will not be explored further.

3.1 Flexible flat foot

FFF is characterised by a flattened MLA on weightbearing, but “normal” MLA on non-weight bearing or upon extension of the big toe; either passively or with the subject standing on their toes [65,67]. In contrast to the rigid flat foot, this presentation is typically assumed to hold no specific underlying pathological process and may be asymptomatic or symptomatic [8,70–75].

3.2 Developmental flat foot

It is important to define developmental flat foot, which can be characterised by the presentation of a flattened MLA from birth, that is typical in all children. This is regarded as a normal phase of development, and therefore not a cause for concern [2,67,76]. In fact, children below the age of 6 years can be reassured that their flat foot is normal and unlikely to persist into adulthood [2,67,76]. Studies which have assessed MLA development in the early years of life have reported that the primary ossification centres of the calcaneum, talus, cuboid and metatarsals are present in-utero. In contrast, primary ossification of the navicular bone, which holds a crucial role in MLA formation, starts between 3 and 5 years of age [77–84]. As for the onset of secondary ossification centres, with which the bones acquire their final form, this occurs at varying stages for each foot bone,

ranging from 3 to 8 years of age. Therefore, the arch would not be expected to be fully developed in these early years of life [77–84]. In addition, the foot bones are protected by a thick fatty pad at the bottom of the foot during the ossification process, which can exacerbate the flat appearance of the foot [85–87]. The completion of MLA development has been demonstrated to typically fall in the range of 6 to 8 years (Table 6).

Based on these physiological principles, it is apparent that FFF is only potentially problematic if it persists beyond the completion of foot development. While reasonably well-defined protocols are present for the management of rigid flat feet, the management of FFF remains unclear and problematic, leading to the need for the research conducted in this thesis.

Author (year)	**Sample size**	**Sample age range (years)**	**Assessment method**	**Arch height development findings**
Pfeiffer et al. [81]	835	3-6	Laser surface scanner	The arch completes development between 4 and 5 years of age
Onodera et al. [80]	391	3-10	Footprints	
Forriol and Pascual et al. [82]	1676	3-17	Footprints	The arch is developed by the age of 6 years, with minimal changes thereafter
Bosch et al. [88]	36	1-10	Plantar pressure measurements	
Sadeghi-Demneh et al. [89]	667	7-14	Footprints and Arch Height Index	
El et al. [90]	579	6-12	Footprints	
Volpon et al. [79]	672	0-15	Footprints	Rapid development between the ages of 2 to 6 years
Gilmour et al. [91]	272	5-7	Arch Index and navicular height	The arch stays stable between the ages of 7 to 9 years
Tong and Kong et al. [92]	437	7-8	Footprints	
Chen et al. [93]	1024	5-13	A 3D coordinate measuring probe, a digital tape measure, and a Harris and Beath mat imprint	The foot arch becomes flatter between 7 and 8 years, followed by a reversal to a higher arch between 8 and 9 years of age
Chang et al. [94]	2083	7-12	*Footprints*	

Table 6: This table presents the ages of MLA development cited across the literature

3.3 Incidence of flexible flat feet

From the previous section, it is apparent that the prevalence of FFF can vary due to the variation in foot bone development. This is reflected by the relatively greater prevalence of FFF of 21%-57% in the early ages of two to six years, prior to the completion of arch development, in contrast to 0.6-28% thereafter which would be reflective of non-developmental FFF (Table 7) [74,90,95–103]. Despite being a concern for a sizable portion of individuals, FFF remains poorly understood in the context of childhood, as well as its development over time [8,67,76,104–110]. Consequently, there is no clear consensus on its management, evidenced by discrepancies within the research and clinical settings on whether and how treatment should be instigated [8,73,104,111–116].

Author (year)	Sample size	Sample age range (years)	Prevalence of flexible flat foot	Assessment method
Lin et al. [95]	377	2-3	41%	Visual classification
		3-4	39%	
		5-6	22%	
Bordin et al. [96]	243	8-10	16.4% (18.1 males, 14.6% females)	Cole index, a photo-podoscopic examination
Abtahian et al. [97]	400	12-18	3.4%	Clinical examination and toe standing test
Mansoor et al. [98]	714	6-10	14.8% (16.4% bilateral, 23.6% unilateral)	Clinical examination and toe standing test
Echarri et al. [99]	1851	3-4	Most children have Paediatric Flexible Flat Feet	Footprints
		5-12	10-20%	
El [90]	579	6-12	17.2% (moderate or severe) 82.8% (normal or mild)	Footprints
Chang et al. [74]	2083	7-12	58.7%	Harris and Beath mat and footprints
Aneumapali [100]	500	18-21	13.6% (12.8% males, 14.4% females)	Navicular drop test
Rose et al. [101]	237	5-12	9.9%	Physical examination and footprints
Didia et al. [102]	990	5-14	0.60% (bilateral), 2.2.% (unilateral)	Footprints
Bordin et al. [96]	243	8-10	2.7%	Footprints
Tenenbaum et al. [103]	825 964	17-21	12.4% (mild), 3.8% (severe)	Clinical examination

Table 7: The prevalence of FFF across different ages. The general trend demonstrates a decreased prevalence of FFF with increased age.

3.3.1 Aetiology of flexible flat feet

Although the precise reasons why FFF persists beyond completion of foot development is not known, several aetiological factors may be explanatory. These explanations stem from observed differences in prevalence between demographics, alongside differences in biomechanics and morphological characteristics in comparison to neutrally aligned feet.

3.3.2 Gender

The role of gender in the pathogenesis of FFF is currently inconclusive. Some studies have reported a significantly increased prevalence of FFF in boys compared to girls by margins ranging from 4.6 to 18% [74,81,103]. In contrast, other studies have noted an increased prevalence of FFF in girls compared to boys [90,100]. Although, one of these studies, by Aenumulapalli et al. [100], reported only a marginal difference of 1.6% and assessed young adults rather than children. In addition, other studies have suggested no association between FFF and gender [95,117]. However, the study by Lin et al. [95] grouped neutral feet and mild flexible flat feet together and made comparisons against moderate/severe flexible flat feet, when assessing associations with gender. [118]

3.3.3 Body mass index (BMI)

The consensus from studies is suggestive of a greater likelihood of FFF as BMI increases. Many studies have evidenced this, with records of increased FFF problems in both overweight and obese children compared to those of normal weight [74,81,103,117]. Although, it must be acknowledged that such clear trend has not always been demonstrated. For instance, Lin et al. [95] found its combined group of neutral feet and mild FFF to be significantly heavier than the moderate/severe flat feet group. In addition, Kothari et al. [5] found no difference in BMI between neutral feet and FFF in their study. With regards to why a higher BMI is associated with greater likelihood of FFF, there are two main suggestions: The observed foot flatness in such individuals may be due to a thicker foot fatty pad in response to a greater weight bearing force being exerted or as a direct

consequence of such weight bearing on the foot structure resulting in its flattening [74]. Further studies that address these distinct theories are required.

3.3.4 Genetics

The influence of genetics on FFF is underpinned by its presentation in children with parents that also present with such foot morphology. In addition, a higher incidence of FFF in Afro-Caribbean populations in comparison to Caucasians has been reported, suggestive of ethnicity having potential involvement in FFF [119,120]. Beyond such patterns of heritability, genetics can also affect other aetiological factors such as flexibility.

3.3.5 Flexibility

As suggested by its name, it would be expected for FFF to be strongly associated with increased general flexibility. However, there has been minimal research on this matter. Within the limited literature available, there appears to be unanimous support in favour of hypermobility being linked to both the presence and extent of FFF [90,95]. This can be explained by the notion that greater flexibility can be the result of a genetic change, where changes in protein conformation occur, which can affect the soft tissues surrounding the MLA. If these soft tissues are too flexible, they may not be able to adequately support and maintain the MLA, particularly when resisting a weight bearing force [121].

3.3.6 Lower limb alignment

The association between lower limb alignment and FFF must be addressed with caution. Several findings including increased hindfoot eversion [122], external tibial torsion and resultant foot-bimalleolar angle, and increased knee valgus have all been observed in FFF compared to neutral feet [123]. Further research is needed to understand whether these alignments contribute to the development of FFF or if they occur as a consequence of this foot type.

3.3.7 Bone morphology

The impact of foot bone morphology on FFF is underpinned by its structural implications. A cadaveric study by Harris and Beath [106] alluded to this, suggesting that a malformed sustentaculum tali leads to FFF, due to its inability to effectively support the head of the talus. Consequently, upon bodyweight exertion, there is adduction and plantarflexion of the talus alongside eversion of the calcaneum. Such effects were not observed in a strong, stable subtalar joint. In addition, bone morphology may also affect the predisposition to foot flattening by virtue of increasing joint mobility. Specifically, Bruckner et al. [124] suggested that subtalar joints with two articular facets would exhibit greater mobility, in comparison to those with three articular facets. However, it must be noted that these studies were conducted on cadaveric bones, and therefore cannot definitively determine their relationship with FFF. In contrast, an in-vivo study in a cohort of children by Kothari [109] demonstrated absent anterior subtalar articulation ($p < 0.001$) and increased flexibility to be significant predictors of a low arch height index. Nevertheless, given the limited base of in-vivo evidence for this, further studies are required to conclusively determine how subtalar morphology is implicated in FFF.

3.3.8 Patho-mechanic theory

As well as abnormal foot bone structure and alignment in FFF, the dysfunctional movements that are associated with these are essential to address. These can be understood through two patho-mechanic theories, including the midfoot joint locking mechanism and the change of joint axis of rotation.

The first patho-mechanic theory of the midfoot locking mechanism described by Inman et al. [125] and Harris and Beath [109] involves two main functional modes that characterise the alignment of the foot bones: locked and unlocked. In optimal gait, during the push off phase, dorsiflexion of the toes leads to tightening of the plantar fascia and ligaments. This enables the midfoot locking

mechanism, in which the constituent bones are stabilised to create a rigid structure. Therefore, the midfoot can act as a rigid lever for propelling the body forward [10,11,106,125–127]. However, FFF presents with excessive hindfoot valgus, where the talus is deviated plantar medially to the calcaneum. This altered anatomical positioning leads to a change in the joint axes' orientations, where the midfoot joint axes become parallel to each other (Figure 6) [10,11,126,128,129]. The calcaneocuboid joint axis is positioned closer to the insertion of the peroneus longus, which reduces the efficacy of its function of plantarflexing the first ray and everting the foot [11,126,129]. Such impaired function of this lever can result in inadequate midfoot locking via eversion of the cuboid, leading to the calcaneocuboid joint and both the fourth and fifth metatarsals remaining in an open packed position [11,128–130]. This results in the inability to stabilise the first ray and inadequate lifting and eversion of the lateral column of the foot with the aid of the peroneus brevis [11,116,129,131]. Therefore, with such impaired locking mechanism, there is increased demand on the surrounding tissues to provide stability and balance. With such strain exerted on the structures around the foot, it is suggested that it may predispose to worsening of the condition, alongside symptoms of pain and fatigue [10,11,104,116,128,132].

The second patho-mechanic theory, described by Harris and Beath [109] and Blackwood et al.[128], refers to lateral changes in the subtalar joint axis due to excessive hindfoot valgus. Theoretically, this axis change further stretches the Achilles tendon, making it weaker and resulting in the gastrocnemius needing to function as an invertor of the foot, beyond its typical role as a plantarflexor and evertor [10,11,106,127]. In addition, the excessive hindfoot valgus observed in FFF impairs plantarflexion by the Achilles. This impairs the midfoot locking mechanism and results in ineffective toe-off [10,11,106,126,128].

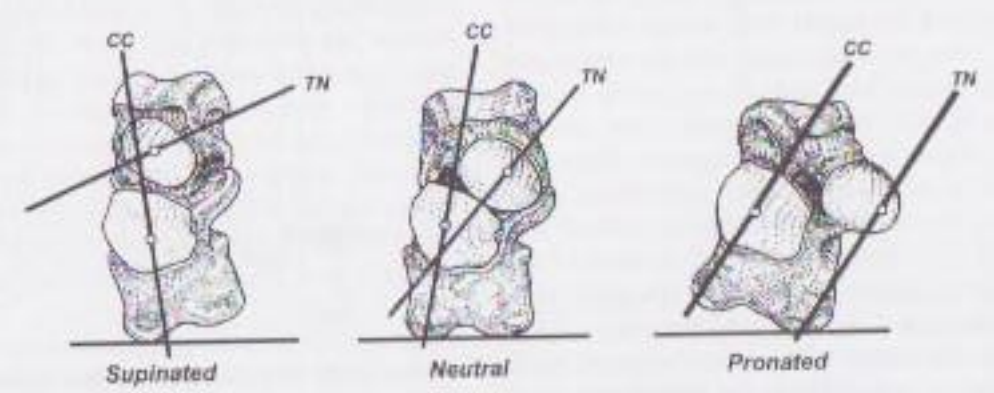


Figure 6: The anterior view of the right talus and calcaneus in three different foot types, adapted from Michaud [11]

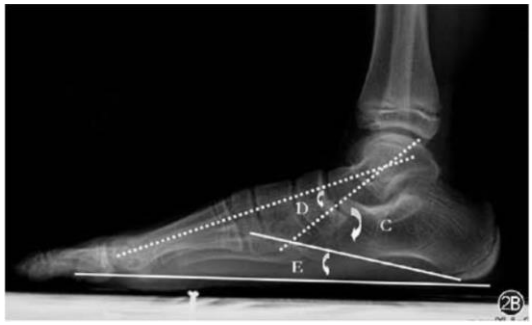
3.4 Why are only some cases of FFF symptomatic?

Having addressed the aetiology and pathophysiology through which FFF manifests, there remains the need to understand why differences in symptoms exist in this condition. The specific elements of FFF may provide some insight into whether a child may develop symptoms. In addition, factors pertaining to limb alignment and gait pattern may also provide insight into the risk of experiencing symptoms with this condition.

The impact of foot alignment in FFF on symptoms can be appreciated in studies which used radiological techniques to measure angles of bony alignment in the foot and compared them between those with and without symptoms [133–135]. In this regard, significantly greater antero-posterior view talonavicular coverage angles (Figure 7A) [133,134] and lateral view talo-first metatarsal angles (Figure 7B)[134,135] have been reported in symptomatic FFF in comparison to asymptomatic FFF. The talonavicular coverage angle represents medial uncovering of the talar head, through lateral deviation of the navicular in relation to the talus. Upon lateral deviation of the navicular, the ability of the talonavicular joint to transmit load from the hindfoot to the forefoot is impaired. Therefore, the presence of greater talonavicular coverage angles in symptomatic FFF may be explained by impaired load transmission [133].



A



B

Figure 7: The x-rays illustrating the antero-posterior view talonavicular coverage angle (7A) and the lateral view talo-first metatarsal angle (7B) marked by the letter D, adapted from [133,134]

In addition, variations in lower limb kinematics within cases of FFF, with respect to movements at the hip, knee and foot, can provide insight into the predisposition of having symptoms. Specifically, significantly greater forefoot abduction (Figure 8) has been noted throughout the entire stance phase in symptomatic FFF compared to asymptomatic FFF [136]. In addition, symptomatic FFF participants demonstrated significantly lower hip flexion at foot strike, significantly greater knee flexion during midstance and significantly greater hindfoot-tibial internal rotation and knee flexion at toe-off in comparison to asymptomatic FFF [136]. On the other hand, a study by Hosl et al. [137] found no overall kinematic discrepancies between asymptomatic and symptomatic paediatric FFF. It must be noted that the classification of FFF symptomology in these studies was binary, where groups were made based on the absence or presence of symptoms. Therefore, it did not account for the variability and diversity of symptoms experienced.

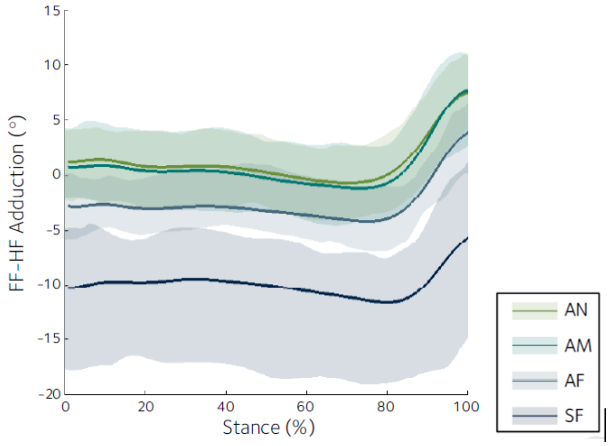


Figure 8: The kinematic graph presenting the difference in forefoot abduction pattern between symptomatic and asymptomatic FFF, where the black line represents symptomatic FFF (SF) and the blue line represents asymptomatic FFF (AF), adapted from [136]

A variety of symptoms have been associated with FFF. Pain has been reported to affect 65.3% of children 10-14 years with FFF, and functional limitations have been reported in 68.3% of the same demographic [138]. The most commonly reported areas of pain are the knee [69,139,140], lower back [69,139–141], leg [141] and foot [142]. In addition, FFF has been known to affect quality of life (QofL), which is a measure that reflects psychosocial and physical aspects of life among other things, and also accounts for symptoms such as pain. In adults with FFF aged 20-40 years, mean total disability percentages of 34%, 37% and 37% with respect to pain and stiffness, activity limitation and social domains respectively have been reported [143]. Interestingly, although QofL accounts for symptoms, the overall score may not align with the presence or absence of them, due to influence of the other aforementioned factors. This was demonstrated in studies by Kothari et al. [7] and Žukauskas et al. [8], in which lower QofL was reported in children with FFF compared to NF, irrespective of the presence of symptoms.

It is apparent that FFF holds a variety of implications beyond abnormal structural characteristics. This emphasises the need to treat this condition with a holistic approach. Given that most evidence

on the consequences of FFF in terms of structure, symptoms and QofL is cross-sectional, there is the need for prospective studies to gain a thorough insight into its long-term effects. This can provide evidence as to when to instigate treatment to mitigate negative consequences in the future.

3.5 Treatment for flexible flat feet

Unfortunately, there is currently no consensus on the management of FFF [8,73,104,111–113,144]. This results in varied management plans based on each clinician's preference being implemented [1,116,145,146]. Attempts to harmonise management pathways have been made by the American College of Foot and Ankle Surgeons (ACFAS) [69], by stratifying paediatric flat feet into subtypes of FFF, rigid foot, skewfoot, and "other" (including neurological, muscular, genetic and collagen conditions). In current practice, plans for deciding FFF treatment are initiated by taking a medical history, specifically that of symptoms, trauma and age. As per the ACFAS guidelines, treatment should not be initiated in cases of asymptomatic FFF (Figure 9). This contrasts to treatment pathways for the rigid foot, where treatment is typically instigated irrespective of the presence of symptoms [69].

Therefore, it is apparent that the presence of current symptoms is seemingly the only factor that is taken into consideration for instigating treatment in FFF [84], although, this has been disputed in the literature. Halabachi et al. [67] suggested both symptomatic and asymptomatic FFF should be seen by a specialist for consideration of conservative treatment, including strengthening exercises. In addition, Halabachi et al.[67] has countered the current trend of clinical FFF management, by suggesting that children with asymptomatic FFF aged below eight years should be observed and provided with education on footwear, and children aged above eight years together with all symptomatic FFF children should be reviewed with imaging (radiography, CT, MRI), and those with no abnormal findings should be referred to a sports medicine specialist for non-surgical

interventions. As for cases of symptomatic FFF with abnormal imaging results, referral to an orthopaedic surgeon was recommended [67].

The major limitation of all current FFF management strategies is that they are focused only on current presentations and do not account for future possibilities. In particular, FFF that is asymptomatic in childhood may become problematic in adulthood and would therefore potentially miss out on the benefits gained from early intervention. In contrast, FFF that is symptomatic in childhood but self-resolves in adulthood would undergo unnecessary treatment which can have its own drawbacks. Unfortunately, as there is no current evidence base pertaining to the prognosis of children with FFF, there may be difficulty in justifying going against the current treatment recommendations. Therefore, it would be useful to gain insight into the nature of changes in FFF over time to help inform such decisions.

Despite variability in the choice and timing of intervening in FFF, the same types of conservative treatment options are commonly used and will now be outlined in more detail.

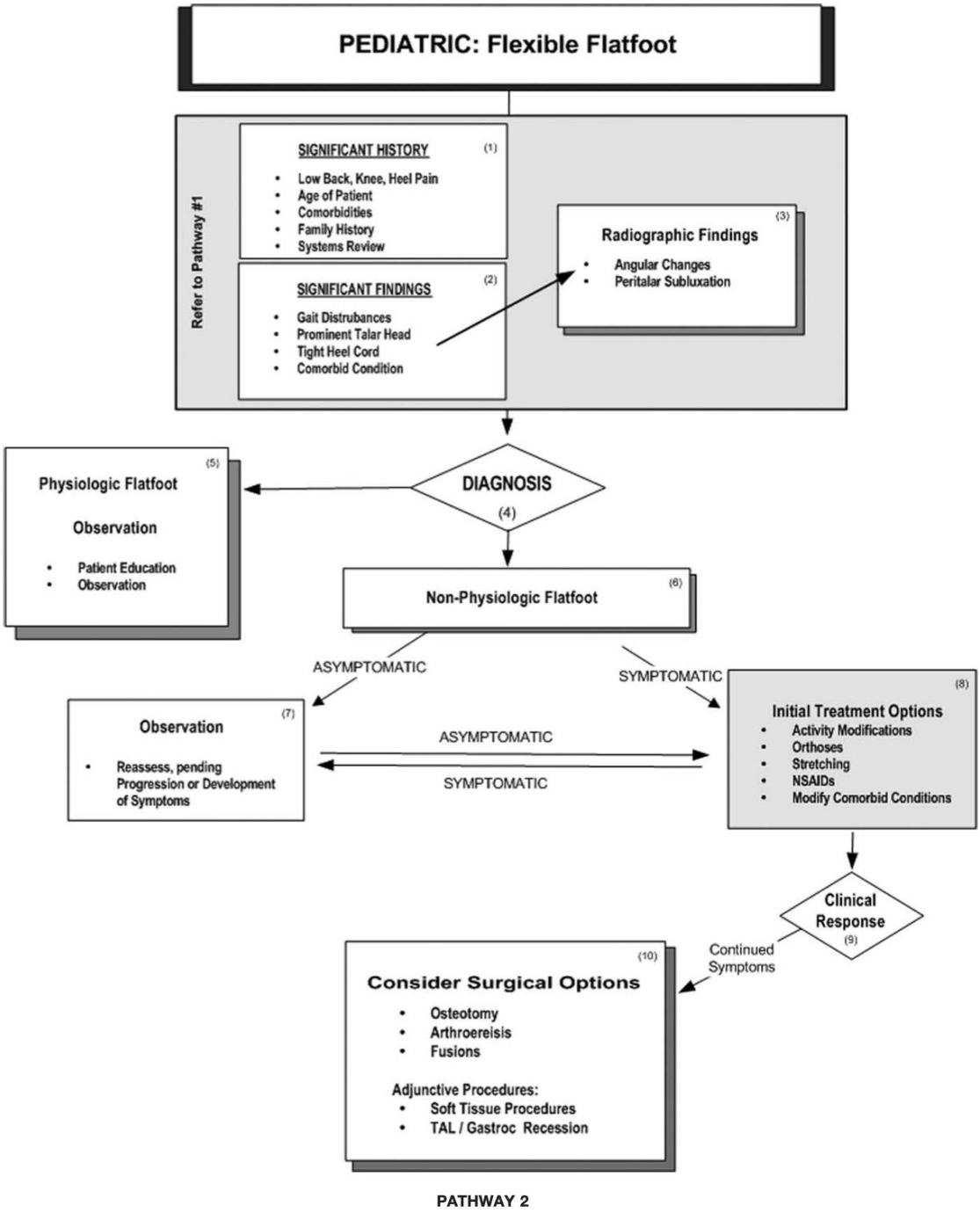


Figure 9: The FFF management pathway outlined by ACFAS [69]

3.5.1 Orthotics

Orthotics are a form of treatment which addresses FFF by theoretically altering foot posture to resemble “neutral” feet, with the talus equidistant from the medial and lateral malleoli [111,147]. Usually, they come in the form of off-the-shelf orthotics, which can be modified in accordance with personal requirements [148–150]. They can also be custom-made [148,149]; traditionally designed using a negative cast (plaster of Paris) and more contemporarily using a foam box or 2D/3D scanners [149,151,152]. Their effectiveness can be evaluated by their impact on structure, gait kinematics and symptoms associated with FFF.

With regards to impact of orthotics on foot structure, the measure of the resting calcaneal stance position has been utilised, which was demonstrated by two studies to be significantly improved from baseline following the use of orthotics in FFF [153,154]. Other studies have suggested that use of orthotics in managing FFF should be limited [155,156] to rare scenarios, under instructions of an orthopaedic surgeon, possibly due to being implicated in weakening the foot muscles [156]. The impact of orthotics on managing FFF has been questioned by several studies. A key argument for this is underpinned by a systematic review by Choi et al. [157], which advocated against orthotics use in FFF on the basis that FFF improvement in children occurred with growth irrespective of its use. Although, the comprised studies evaluated children with mean ages ranging from 2 to 10 years, thereby including many with developmental FFF which would eventually correct itself, as opposed to the more problematic non-developmental FFF that would persist in older age. However, a study on children aged 10-11 years also concluded that orthotics are not necessary for managing FFF, upon assessment of radiographic improvements in both medial arch support insole and control groups in their study [158]. Moreover, an even stronger stance against orthotics use was made by Staheli et al. [159] and Camurcu et al. [4], who stated that alongside being ineffective, it can lead to lowered self-esteem into adulthood due to embarrassment from their use. Although

this study used a definition of FFF that pertained to developmental FFF, a distinction to FFF that persists beyond the arch development phase was not made.

As for their impact on gait and kinematics, orthotics generally have been depicted to exhibit positive effects. Improvements in coordination [160,161], lower limb alignment [162–164] and lower limb kinematic parameters [162,165,166] have been observed with the use of orthotics in children with FFF. Specifically, the kinematic changes of decreased foot eversion and forefoot, knee and hip abduction and hip flexion peak moments at 6 months and 12 months upon using orthotics were reported during walking [166]. Beyond these studies which evaluated lower limb motion, acute effects of foot orthoses on the ground reaction forces in male children with FFF during walking were evaluated by Alavi-Mehr [164] and Dars et al. [167], who found the beneficial effects of lower forces with the use of orthotics. The former study noted reduced medio-lateral ground reaction force values in non-dominant limbs, in walking with orthotics compared to without. In a systematic review by Dars et al. [153], beneficial reductions in centre of pressure displacement and maximum force and plantar pressures, alongside increased foot contact area were noted. From a functional perspective, orthotics have been observed to reduce the occurrence of falls and improve balance in children with symptomatic FFF [168].

The effects of orthotics in relation to FFF symptoms have generally been evaluated by changes in pain, commonly using Visual Analogue Scale (VAS) measurements. Three studies noted significant improvements in pain levels in FFF, following the use of orthotics [142,168,169]. In addition, from a systematic review by Dars et al. [153], all five included studies which assessed pain demonstrated improvement with orthotics; although this was only statistically significant in three of them.

Overall, there is still uncertainty on whether orthotics are an effective form of FFF treatment. Amidst the aforementioned positive effects, there are other factors such as the possibility of weakened intrinsic foot muscles due to reduced workload, psychological impacts of

embarrassment and lowered self-esteem from wearing orthotics and monetary costs, that must also be considered [4].

3.5.2 Physical therapy

Physical therapy is a form of primary conservative FFF treatment, with the underlying principle of strengthening and stretching the muscles of the lower extremity. Despite being strongly recommended by the literature and in clinical settings, evidence of the effectiveness of this therapy is limited [170].

Nevertheless, physical therapy has been empirically shown to improve aspects including foot structure and balance. In fact, studies have demonstrated physical therapy, in the form of a rehabilitation programme, to be more effective than orthotics in improving the severity of FFF in children [171–173]. In addition, physical therapy as a stand-alone intervention [173] has also demonstrated the positive effect of improved balance in FFF [173–175].

Overall, it is apparent that exercise has beneficial effects on FFF [173]. However, there is a limited base of evidence for this intervention, and ACFAS clinical guidance only advocates for it to be done under specialist supervision [69]. Therefore, it is possible that it may have been overlooked in wider clinical practice.

3.5.3 Taping

Kinesio taping is an intervention that theoretically alleviates pain, by reducing pressure and irritation on the neural and sensory receptors. The positive effects of taping have been observed in the form of improvements in foot muscle tone in the context of FFF [176,177]. However, it must be acknowledged that the evidence base of the mechanism of these beneficial effects has thus far been limited to the placebo effect. Associations of taping with mechanisms including improved muscle contractility through the support of weakened muscles, decreased inflammation through increased lymphatic and blood flow, and increased joint range of motion through the adjustment

of misaligned muscle fibres, have not been evidenced in the literature and therefore remain speculative.

3.5.4 Footwear – special shoes

Modified footwear serves as another conservative treatment option for FFF. The main accessible types of footwear for this purpose include commercial footwear that is available in shops and custom-made prescription orthopaedic footwear.

An optimal form of footwear has not been clearly defined for the treatment of FFF. Some research recommends the use of wider shoes with hard thick soles, to provide structural and functional support to the FFF [67,115,178]. Other studies report that a wider shoe with a flexible sole is more appropriate, as this makes the foot muscles work harder in order to stabilise the foot, thereby helping to support the arch in the long-term [179–181].

There is limited evidence for the effectiveness of orthopaedic footwear on FFF. Orthopaedic shoes have been demonstrated to be inferior to orthotics, based on measures of gait symmetry and walking speed [182]. With such unclear consensus on which option is ideal, the current solution involves accounting for the child's preferences and individual requirements [73,111,115,155]. However, if the footwear is used in conjunction with in-shoe orthotics, a harder sole is deemed more beneficial as it would support the function of the orthotics. Lace-up shoes are considered to be more appropriate than slip-ons, possibly due to the additionally required involvement of flexor muscles (flexor digitorum longus, flexor hallucis longus and tibialis posterior) upon wearing slip-on footwear. Clear advice on which type of footwear is most suitable for FFF has not yet been provided.

Across the different treatment options for FFF, some beneficial effects on symptoms, gait and function have been demonstrated. However, there is uncertainty on whether FFF should be treated irrespective of symptoms, together with a lack of clear guidance on which treatment approach is

optimal. To aid in handling such uncertainty, an understanding of FFF prognosis beyond childhood is vital.

3.6 Prognosis of flexible flat foot in childhood

All children are born with FFF, with typically developing feet expected to grow in length and develop an adult-like arch over time [183,184]. This is facilitated by changes in tissue properties and changes which occur in response to increasing loads and activity, which directly influence foot morphology [92,94,183,184]. This includes the growth and increased force production capability of muscles, and reduction in size of the fatty pad that underlies the heel, toes and foot arch [87,184]. In addition, foot length increases rapidly by approximately two millimetres per month until the age of 3 years, followed by relatively slower growth of around one millimetre per month between the ages of 3 and 5 years [183,184]. Furthermore, there are intrinsic differences that distinguish adult feet from those of young children, where the latter have fewer cross-links between the collagen fibres within their tendons and ligaments. This increases tissue elasticity and flexibility, thereby increasing joint ROM [92,94]. Given the lack of knowledge from cross-sectional studies on the development of FFF from childhood to adulthood, it can be anticipated that there may be the possibility of shared characteristics in FFF between these time points. Although, the extent of this overlap is difficult to predict without longitudinal evidence.

To conclude this chapter, it is apparent that there is a lack of understanding of the symptomology associated with FFF and the manner through which it changes over time. This poses many problems in terms of deciding if and when to start treatment and how best to do so. Therefore, further information, that is ideally acquired from prospective cohort studies, is desirable to provide evidence to help guide management that can maximally benefit individuals with FFF throughout their lives. To gather such information, a thorough and detailed longitudinal assessment of FFF is important.

4 Clinical assessment of Flexible Flat Feet

This chapter will explore the various methods for characterising FFF and for assessing the structure of the MLA. There are static (radiographic, footprint and clinical assessments) and dynamic (biomechanical assessment) methods. Such methods can be used to enable clinicians to detect FFF as well as characterise the severity of it via MLA height or otherwise [73,111,113,144].

4.1 Radiographic assessment

Radiographs enable static, two-dimensional characterisation of FFF using geometric measurements that are taken from plain film views. These can be manually measured by drawing lines on the film or automatically using computer software [185,186]. From the literature, the measurements that have been used in the context of assessing FFF from the anteroposterior (AP) view are the talocalcaneal angle, talus-second metatarsal angle, and talo-navicular coverage angle; from the dorsoplantar view the talocalcaneal angle, hallux metatarsophalangeal angle and first intermetatarsal angle; and from the lateral view the calcaneal inclination angle, calcaneal first metatarsal angle, talocalcaneal angle, talohorizontal angle, Costa Bertani angle, talometatarsal angle, talonavicular angle, tibiotalar angle, and talus plantarflexion angle (Table 8)[67,76,185–189]. However, differing selections of these measurements have been used in each study, with no clear consensus on the optimal combination of measurements for assessing FFF. Some studies have provided specific criteria for distinguishing FFF from neutral feet. FFF has been defined as an angle of ≥4° in heel valgus during the resting calcaneal stance position, together with at least one of the following measurements: AP talocalcaneal angle >30°, lateral view talocalcaneal angle >45°, lateral view talometatarsal angle >4°, and calcaneal inclination angle <20° [189–191]. In addition, Aharonson et al. [192] used the criteria of an AP talocalcaneal angle >25°, talus plantarflexion angle >23° and calcaneus dorsiflexion angle <20° to classify FFF.

Radiographic measurements have shown only minimal association with the symptoms of FFF [135]. In a study by Moraleda et al. [133], only one of 13 radiographic measurements was correlated with FFF symptoms. This suggests that the measurements are limited in their ability to characterise symptoms and pain [73,76]. Furthermore, Böhm et al. [193] denoted that static radiographic assessment, in context of FFF, could only explain a small amount of variance foot kinematics during walking.

A major advantage of radiography is its ability to provide direct visualisation of the foot bones [194]. However, there are limitations pertaining to the techniques used to capture radiographic images. Even upon successful image capture, due to the static posture adopted and two-dimensional image generated from plain radiographs, they cannot characterise variations in foot kinematics that occur during walking or depict the true, three-dimensional form of the foot [195]. Although this limitation is mitigated through the use of weight-bearing cone beam CT scans, this modality is relatively less accessible and more expensive. Moreover, even plain radiographs are costly and still less accessible in community clinical settings. Radiographs also pose risks from ionising radiation exposure to the subject [76]. Measurement repeatability may be reduced due to variations in foot positioning, and accuracy may be affected by image distortion caused by difficulty in adopting the required stance by subjects such as children [187]. Therefore, radiological assessment may not always be appropriate or indicated [147].

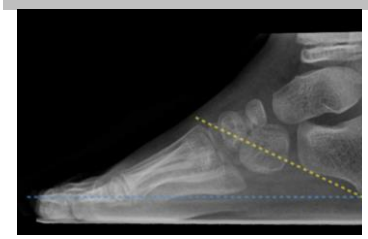
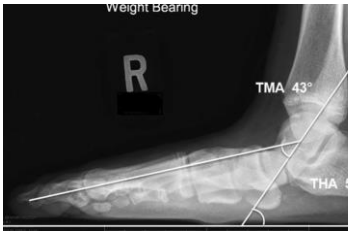
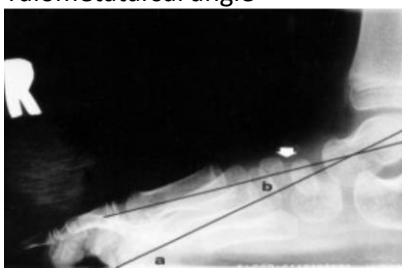
Anteroposterior (AP)/ Dorsoplantar view				
				
Talocalcaneal angle	Talus-second metatarsal angle	Talonavicular coverage angle	First metatarsophalangeal angle	First intermetatarsal angle
Lateral view				
				
Calcaneal inclination angle	Calcaneal first metatarsal angle	Talocalcaneal angle		
				
Talohorizontal angle	Costa Bertani angle	Talometatarsal angle		
				
Talonavicular angle	Tibiotalar angle	Talus plantarflexion angle (a)		

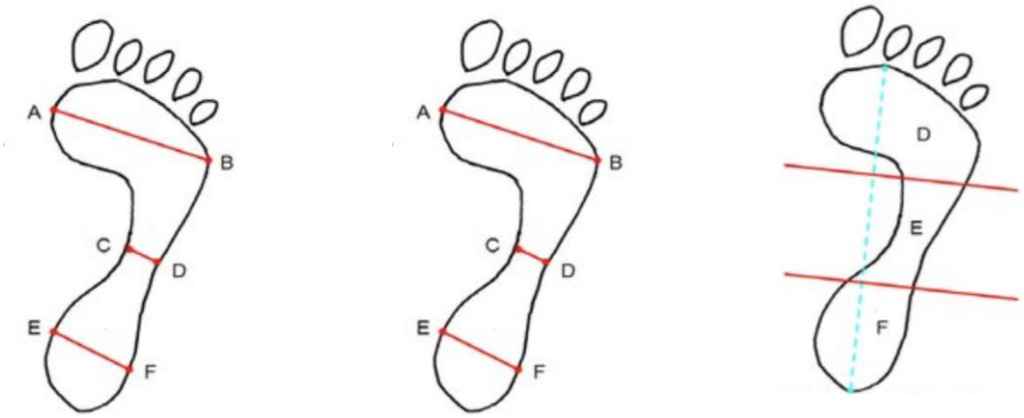
Table 8: Radiographic images demonstrating the various angles used to characterise feet, adapted from [196]

4.2 Footprint assessment

Another static form of indirect MLA assessment involves the use of footprints [197–199]. Physical footprints can be captured traditionally by using ink and paper, or more recently using inkless paper techniques [197–199]. Electronically generated footprints can be captured using electronic pedobarographic systems that measure the plantar pressure distribution [197]. While the ink and paper physical method is inexpensive and simple to undertake, it is less practical to conduct in wider clinical settings. Therefore, the inkless paper technique is preferable, while also avoiding the need for technical equipment.

Upon generating footprints using any of the aforementioned techniques, assessment can be conducted using geometric measurements. Quantitative analysis of the MLA is most commonly assessed using the Arch Index (AI), Chippaux-Smirak Index and Staheli Index (Figure 10) [76,112,200,201]. The AI is calculated by dividing the midfoot area by the total area of the foot (excluding the toes). As for the Staheli Index, the minimum width of the midfoot is divided by the maximum hindfoot width [200]. This is similar to the Chippaux-Smirak Index, which divides the minimum midfoot width by the maximum forefoot width [200]. From these indices, only the AI is capable of distinguishing between high arches of varying degrees, which would have minimal or no contact in the midfoot region [112,202].

Since each of these indices evaluate the MLA using different algorithms, the cut-off values to indicate a flat foot posture vary. For the AI, values ≥0.26 have been predominantly cited as flat feet [201,203]. As for the Chippaux-Smirak Index, there has been greater variability across the literature, with flat foot cut-offs ranging from ≥45 to >62.7% [76,202]. Similarly, the Staheli Index has exhibited differences regarding flat foot definitions, with cut-offs ranging from ≥0.89 to ≥1.28 [76].



Chippaux-Smirak Index = CD/AB

Staheli Index= CD/EF

Arch Index= E/(D+E+F)

Figure 10: The calculation process of Chippaux-Smirak Index, Staheli Index and Arch Index, adapted from Ozer and Barut [204]

Despite such variability in their defined cut-off values, all three indices have demonstrated excellent repeatability. For the AI, intra-rater ICCs of 0.924 [205] and 0.971 [206], and inter-rater ICCs of 0.957 and 0.892 have been reported. Both the Chippaux-Smirak Index and Staheli Index elicited similar intra-rater ICCs of 0.914 and 0.970, and 0.914 and 0.970 respectively. In addition, their inter-rater ICCs were also similar, of 0.961 and 0.971, and 0.963 and 0.975 respectively. Upon being validated against the clinical assessment measure of navicular height, all three indices elicited moderate correlations with clinical classification, ranging from -0.609 to -0.645 [205].

Specifically in context of FFF, the AI has also been used as a screening method of recruiting children with this condition for research studies, using the commonly cited cut-off value of ≥0.26 [207]. This value contrasts with measurements in neutral feet, which have been recorded in numerous studies in the range of 0.20-0.24 in pre-school children [182,208]. These mean AI values across the literature strongly support the notion of ≥0.26 being an adequate cut-off value for detecting FFF [208]. Such a trend has also been noted with the use of the Staheli Index. Here, a significantly lower mean index of 0.67 was noted in primary school children with either a neutral foot or mild FFF, in comparison to a mean index of 1.12 in those with moderate and severe FFF [90].

However, there are also some limitations to these indices. The AI may be skewed by the presence of the fatty pad on the plantar surface of the foot that is present in young children [74,209]. In addition, it is restricted in its ability to differentiate between the severities and types of flat foot deformities [112]. Furthermore, given it is only a static foot posture measure, it may not be truly reflective of the MLA form during walking [11]. Therefore, the recommendation would be to accompany the AI with dynamic assessment methods, along with hands-on clinical assessment methods, as this mitigates these limitations by palpating the fatty pad and visualising the arch directly in three-dimensions [209].

4.3 Clinical assessment

Clinical assessment is a method that is widely used for assessing the static MLA structure, by taking measurements based on anatomical foot landmarks [76,111]. The measurements used in the literature for characterising FFF include the Arch Height Index (AHI), Foot Posture Index (FPI) and navicular drop test [113,144].

4.3.1.1 Arch Height Index

The AHI was developed by Williams and McClay, to quantify arch height using callipers [53]. This method involves dividing the foot (arch) height at the 50%-foot length position, by the truncated foot length (excluding the toes) (Figure 11). Cut-off values to classify high arched, neutral and flat feet have not been defined, although the mean AHI values from sampled cohorts of 0.340 [210] and 0.316 [53] provide some indication of what a neutral AHI may be. In the context of FFF, the AHI has been used to classify the foot posture of children, with a cut-off AHI value of <0.31 to indicate FFF [211].

The AHI has exhibited strong repeatability, with an intra-rater ICC range of 0.94-0.98 and inter-rater ICC range of 0.81-0.85, when used to assess young adults [53]. A similar level of repeatability has

also been demonstrated in children, with intra- and inter-rater repeatability ICCs exceeding 0.76 in both standing and sitting measurements [212].

This measure can be considered a clinical gold standard, as it has been validated against radiographic measurements, with a strong ICC of 0.85 between the clinical calliper and radiographic measurements [53]. However, accuracy may be affected by the type of equipment being used to conduct measurements, and the presence and extent of deformities in the feet being assessed [213].

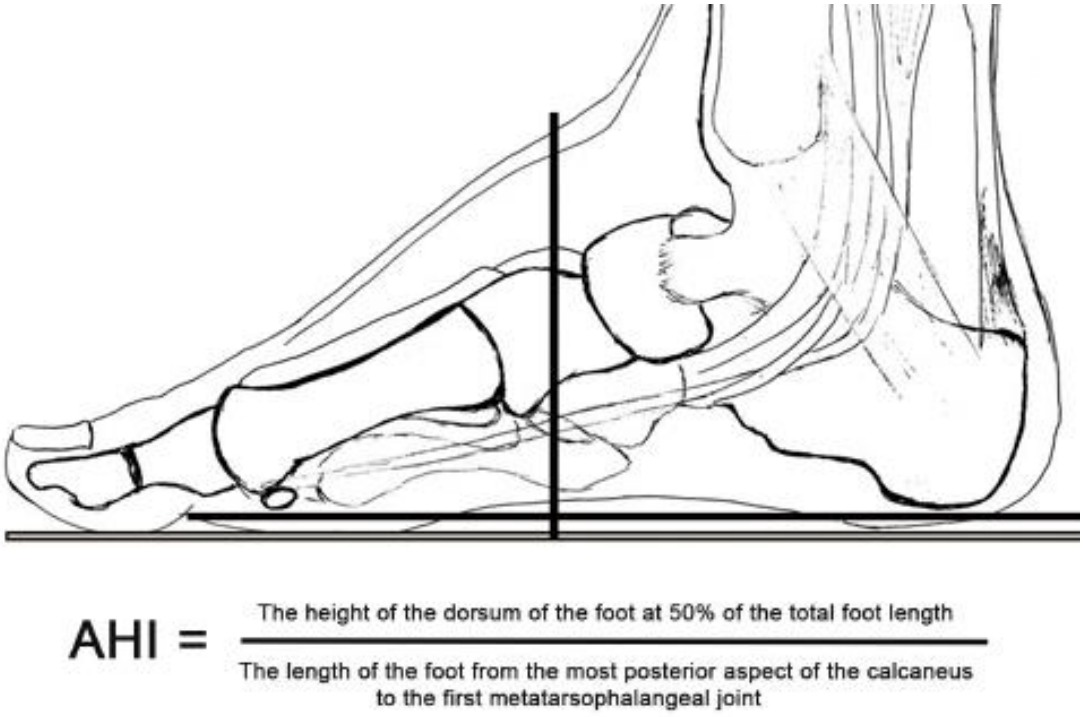


Figure 11: A diagram presenting the process of calculating the AHI, created by the author of this thesis

4.3.1.2 Foot Posture Index

The foot posture index (FPI) has been commonly used in the clinical setting, with some clinicians recognising it as a gold standard for assessing static foot posture. It is an efficient assessment method which requires no equipment and involves visual assessment of the foot to score against defined criteria [113]. The original FPI had 8 criteria (Figure 12) but was modified to remove two criteria due to limited repeatability and clinical utility, to form the FPI-6 that is currently more commonly used (Figure 12)[214,215]. For each criterion, a score ranging from -2 to 2 is given, and then a total score ranging from -12 to 12 is calculated. A foot with a total score of 6-9 is considered pronated, and 10-12 highly pronated [214]. Specifically, in the context of FFF, Evans et al. [216] determined a cut-off score of ≥ 6 to identify this condition in children. it must be noted that it is possible for examiners to achieve similar overall FPI scores which would denote a similar foot type, despite giving different scores in each of the criteria [216].

FPI-6
- (1) talar head palpation
- (2) curves above and below the malleoli
- (3) inversion/eversion of the calcaneus
- (4) bulge at the region of the talonavicular joint
- (5) congruence of the medial longitudinal arch
- (6) abduction/adduction of the forefoot on rearfoot.

FPI-8
- (7) congruence of the lateral border of the foot
- (8) Helbings sign

Figure 12: The FPI-6 and FPI-8 criteria

The FPI-6 has been reported to demonstrate very strong intra-rater repeatability with an ICC of 0.96 ($p<0.001$) in children aged 6-18 years [217]. It has also shown strong intra-rater repeatability with ICCs ranging from 0.928 to 0.937 in adults [218]. Furthermore, inter-rater repeatability ICCs of 0.62 and 0.74 in children and adolescents respectively have been reported [218,219]. The FPI-8 has shown slightly lower repeatability in adults, with intra-rater repeatability ICCs ranging from 0.72 to 0.86 and an inter-rater repeatability ICC of 0.58 [219]. Despite such promising results, examiner

experience must be considered [219]. Novice examiners have been reported to demonstrate poor inter-rater repeatability when using the FPI-6, with an ICC as low as 0.17 [219]. The ICC is also highly sensitive to subject variability, which can be encountered from heterogenous samples of foot postures, which can skew the strength of repeatability demonstrated [220].

The FPI has also been demonstrated to have moderate diagnostic accuracy for identifying FFF. This was concluded upon evaluating the FPI-6 in individuals with known foot postures identified through radiological imaging and using the area under the curve measure (reported to be 0.82; 95% CI (0.78–0.85) [217]. This tool has also been validated for assessing general foot posture in adults, demonstrating significant correlations ($p<0.01$) with all radiographic measures, ranging in strength from -0.36 to -0.59 [221]. When used on children aged 3-10 years, the FPI was deemed to have poor sensitivity in detecting MLA changes and to be minimally accurate in differentiating between varying severities of a given foot posture deformity in this cohort [80]. This relates to the subjective nature of the tool, which requires considerable examiner experience in children's feet to effectively detect structural changes [80].

4.3.1.3 The navicular drop test

The navicular drop test is a pseudo-static foot assessment tool, which was described by Brody [80] in 1982, as an indicator of foot pronation. It measures the change in navicular height between neutral and relaxed foot positions [222]. It involves the examiner marking the navicular tuberosity of the subject during standing, and then placing the subtalar joint in neutral while the subject's foot is 50% weight bearing. Alternatively, the subject can sit in a manner to achieve 50% weight bearing of the foot [222]. The height of the marked point is recorded as the first measurement. Subsequently, the measured leg is placed in a relaxed stance, and the height of the marked point is recorded again as the second measurement. The navicular drop is calculated as the difference between the first and second measurements [223,224].

A navicular drop of <10 mm is considered normal, with measurements exceeding 15 mm considered abnormal [222]. In relation to FFF, a cut-off of ≥ 10 mm has been used to identify those with FFF [100,222]. The navicular drop test has demonstrated discrepancies in repeatability, dependent on examiner experience. Upon assessment of a healthy population, more experienced examiners obtained an intra-rater ICC of 0.83, compared to less experienced examiners who obtained ICCs ranging from 0.61 to 0.79 [225]. A possible variable underlying such disparity between experience levels is the poor repeatability of subtalar joint neutral positioning [157, 159]. Across other studies which used this measurement, intra-rater ICCs ranged from 0.37 to 0.95 [224]. Inter-rater repeatability of this measurement has also demonstrated considerable variability, with ICCs ranging from 0.72 to 0.94 [39,83,75]. However, the clinical navicular drop assessment method has been successfully validated against radiographic navicular drop measurements, with significant positive correlations in weight bearing (r=0.885) and non-weight bearing (r=0.880) stances reported [247].

A notable implication outlined by this measure pertains to the importance of dynamic assessment, due to the changes observed with variations in subtalar joint positioning across weightbearing and non-weightbearing stances. To capture the dynamic form of the foot, the navicular drop can be modified to increase measurement repeatability using a marker-based system with stereophotogrammetric equipment [227]. However, if such equipment were readily available in the clinical setting, full standard clinical gait analysis might be preferred.

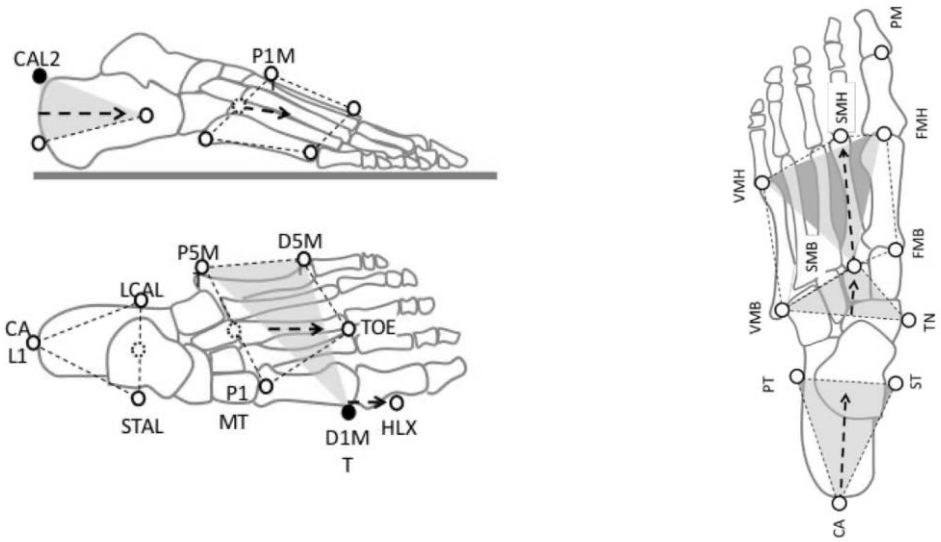
Overall, static clinical assessments have demonstrated good inter- and intra-rater repeatability, provided they are conducted by an experienced clinician, with some of them having been used on populations with FFF. They all offer an important advantage regarding feasibility, as they can be conducted in any setting without the need for specialist equipment. However, none of these assessments are capable of evaluating the deformation of the arch during walking [228,229]. It

must be emphasised that obtaining accurate measurements in the paediatric population is particularly important due to the wide variability in foot size and posture. Therefore, dynamic measures such as clinical gait analysis (CGA) may provide a more detailed assessment of MLA function during activities and offer valuable information for guiding treatment decisions.

4.4 Biomechanical assessment

Clinical gait analysis (CGA) is a method used to measure the kinematics of lower extremity joints in different planes [163,230,231]. It involves the placement of small markers on the skin in specific positions on the body, usually representing bony landmarks [230–233]. The trajectories of these markers are then used to obtain kinematic data during walking, through use of mathematical models which represent the body as a number of segments. Multi-segment foot models (MSFMs) can provide information on motions that occur within the foot itself, unlike single-segment models that display the motion of the foot as a whole [231,232].

The Oxford Foot Model (OFM) [231,234–238] and the Rizzoli Model (RM) [231,239–245] are the two most commonly used multi-segment foot models that have been validated for use in children and adults (Figure 13). The OFM is reported to provide measurements closer to those provided using bone pins than the RM in some planes, and vice versa in other planes [246].



A B

Figure 13: The marker placement and segments of the a) Oxford Foot Model and b) Rizzoli Model [247]

While both models track the tibia, rearfoot, and forefoot, a notable difference is the direct ability to track the midfoot and MLA, which is only present in the RM, although limited to a two-dimensional representation [248,249]. Rather, the OFM indirectly assesses the midfoot, by calculating the distance of the base of the first metatarsal from the plane of the forefoot (metatarsals). This may pose limitations when evaluating conditions that affect the midfoot, such as FFF, which may benefit from direct assessment of this structure.

Both the OFM and RM have demonstrated good repeatability. Upon assessment of children with foot deformities, the intra-rater measurement variability of the OFM was mostly between 3° and 5°, while the inter-rater variability was always under 4° [235]. Similar repeatability of the OFM was observed in typically developing children, with intra-rater variability ranging from 0.9 - 8.6° [236]. As for OFM repeatability in adults, intra-rater repeatability ICCs ranging from 0.71 - 0.97 and inter-rater repeatability ICCs ranging from 0.53- 0.97 have been reported [237,238]. As for the RM, mean intra-rater variability ranging from 0.9- 1.7° and inter-rater variability ranging from 2.7 - 11.5° were reported upon evaluation of adults [240]. Interestingly, the repeatability of the RM has been

deemed to be greater than the OFM when assessing adults, but similar when assessing children [246].

The OFM has been used to demonstrate differences in gait between individuals with FFF and those with neutral feet (NF) [139,250]. Also, it has been used to correlate the kinematics in FFF to the presence of symptoms. When compared to both asymptomatic FFF and NF, increased forefoot abduction throughout the stance phase was observed in symptomatic FFF [136]. Kothari et al. [141] reported no kinematic parameter associated with a flat foot posture to be related to increased proximal joint symptoms. However, these discrepancies in outcomes may be explained by methodological differences across the two studies. The symptomatic feet in Kerr et al. [136] predominately included foot and ankle pain, while Kothari et al. [141] exclusively investigated hip, knee, and back pain. Furthermore, Kerr et al. [136] included participants below the age of eight years, who would theoretically not have completed foot arch development; unlike Kothari et al. [141], whose sample was entirely eight years and above.

It is apparent that the OFM holds many strengths, of which some are shared by the RM. However, they are both limited by the lack of accurate, three-dimensional portrayal of the MLA. Tracking this structure is important in evaluating FFF, since it is the morphology of the MLA that is altered in this condition. To address this, refinement of the OFM to include a component that enables direct, three-dimensional MLA tracking is required. This may potentially provide important details on differences in gait that occur in FFF, alongside possible kinematic explanations for the presence of symptoms in this condition.

4.5 Conclusion

From the FFF and MLA assessment methods outlined, it is apparent that each exhibits a range of advantages and disadvantages. However, it is clear that a dynamic assessment measure is most desirable for evaluating the MLA from a functional perspective. While the discussed CGA methods do conduct such assessment, they require modifications to optimise their use in the specific context of evaluating FFF. Therefore, creating an adjunct to enable detailed analysis of MLA as a means of characterising FFF would be a valuable addition to current assessment methods.

5 Developing dynamic and static measures of MLA

The previous chapters have outlined the need to understand the development of FFF over time (Chapter 3). In addition, they have emphasised the need for an optimal dynamic measure of the MLA, which will be the focus of this chapter. The design process of the newly developed MLA measure included a preliminary study and a clinical case study in the context of cerebral palsy (CP) to demonstrate its range of use. The general methods and materials used to collect and process the biomechanical motion data used throughout the thesis are presented here. Study-specific techniques and statistical analyses unique to each study will be described within the relevant chapters.

5.1 Ethical Considerations

Existing motion capture data on subjects with neutral feet (NF) and flexible flat feet (FFF) were used for the retrospective part of this study on investigating the eight newly developed MLA measures as the first step of the validation process. These data were collected as part of the doctoral studies of Mr Alpesh Kothari, who gained the approval of the National Research Ethics Service (REC reference: 12/SC/0334, Oxford - South Centre B Committee). To enable additional data collection for the purpose of validating the newly developed MLA measures, through the use of a range of unique marker placement protocols, Central University Research Ethics Committee (CUREC 2) ethical approval was obtained from the Medical Sciences Interdivisional Research Ethics Committee, University of Oxford (reference: R74434/RE002) prior to the study. To enable further assessment of the use of the MLA measures on pathological populations, a case study on cerebral palsy participants was conducted, for which ethical approval was gained (reference: 21/LO/0426).

5.2 Participants and recruitment

Study 1 included a prospectively recruited set of 30 participants (60 feet) with a mean age of 20 years (age range 8-25 years, 12 male and 17 female). Recruitment was facilitated by advertisement in the Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences (NDORMS) and Engineering Science departmental newsletters and posters around the campus of the University of Oxford. In addition, an email was sent to all undergraduate and postgraduate colleges at Oxford to notify their students and staff (for recruitment of their children) of this study (Figure 14). Potential participants who expressed interest in the study were emailed an invitation letter, which included a questionnaire with the study's exclusion criteria.

The inclusion criteria for screening prospective participants were the following:

1. Age of 8-25 years.
2. No previous/current surgeries or significant injuries to legs or feet.
3. No foot deformity (upon clinical assessment by a trained podiatrist).

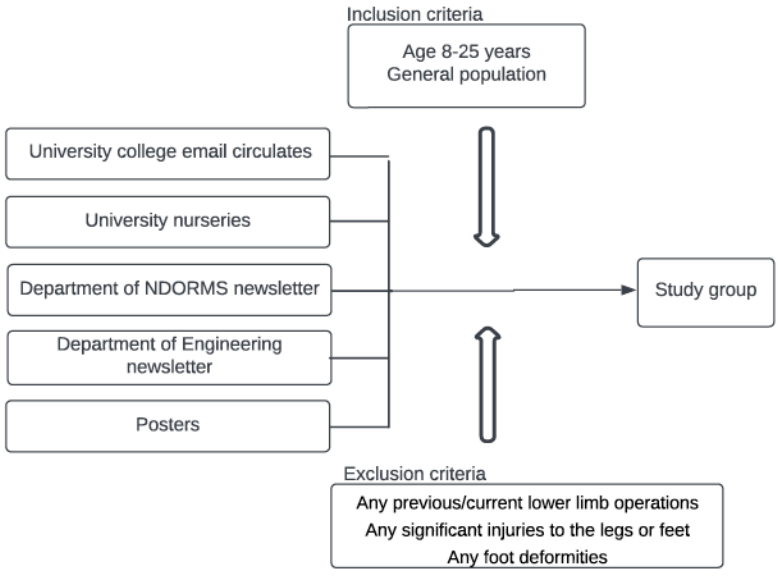


Figure 14: The selection criteria and route of entry of participants into study 1- the validity study

For study 2, the data from the baseline study on FFF undertaken by Mr Alpesh Kothari was used. While initially, data from 95 children were collected, Study 2 only utilised data from 42 children. This was because, either the navicular marker was not used on the remaining participants, which is necessary for the reconstruction of some of the eight MLA measures; or the required data for the validation study could not be extracted. These 42 children (84 feet) had a mean age of 11 years (age range of 8-15 years), comprising 50 NF and 34 FFF. Recruitment was mainly conducted through advertisement in clinical practice. For more detailed information on this study's recruitment process and inclusion criteria, please refer to Figure 15, that was extracted from the doctoral thesis of Mr Alpesh Kothari [252]

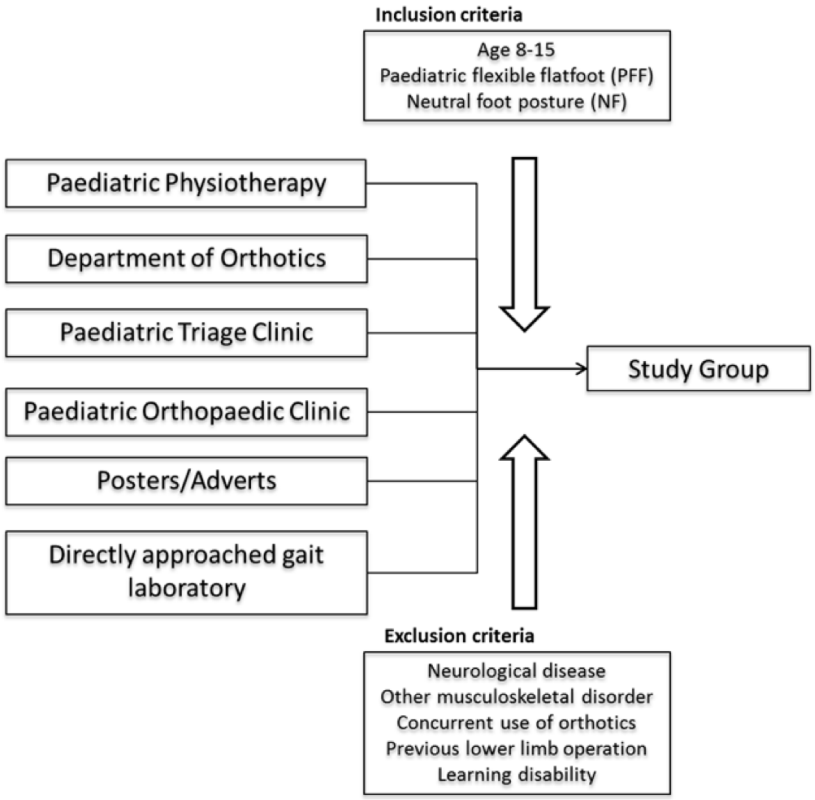


Figure 15: The selection criteria and route of entry of children into study 2- the baseline study of flexible flat feet.

For study 3, data was collected on cerebral palsy patients who attended the Oxford Gait Laboratory (OGL). This case study included 4 participants with a mean age of 24.5 years (age range of 9-56). Participants were referred to the gait laboratory by their orthopaedic consultant. The inclusion criterion was a diagnosis of CP with the presence of foot deformity.

Overall, in Chapter 6, the included participants from study 1 and 2 were 72 healthy participants with no known lower limb or foot injuries, deformities, or surgical history according to a self-reported survey. Collectively, these participants represented all three foot arch types (75 neutral, 10 flat and 23 high arch). In addition, there were 34 participants diagnosed with FFF in childhood. For study 3, which is presented in Chapter 7, 4 participants with cerebral palsy were included. For details on the characteristics of each study's participants, see Table 9.

	Study 1 **Validity study**	**Study 2** **Baseline study on flexible flat feet**	**Study 3** **Case study on cerebral palsy**
Number of participants (feet)	30 (60)	42 (84)	4 (8)
Mean age (years)	20	11	25
Age range (years)	8-25	8-15	9-56
Gender (n)	F17 M13	F 17 M 25	F1 M3
Arch type frequency (based on AHI) and proportion of total feet (%)	High 23 (38.3) Neutral 25 (41.7) Flat 12 (20.0)	FFF 34 (40.5) Neutral 50 (59.5)	Planovalgus 5 (62.5) Planus 3 (37.5)
Mean height (cm) (SD)	164 (20)	153 (12)	159 (19.5)
Mean bodyweight (kg) (SD)	61 (18)	44 (13)	73 (41.8)

Table 9: presents the anthropometric characteristics including mean and standard deviation (SD) values of all participants included in studies 1, 2 and 3

5.3 Equipment

In all three studies, motion data was captured using 10 millimetre retro-reflective passive markers attached directly onto the anatomical locations of interest using hypoallergenic, double-sided tape. Sixteen infra-red Vicon MX-T40 cameras (Vicon Motion Systems, Oxford, UK) were used to track the instantaneous positions of the markers, sampling at a rate of 100 Hz with a resolution of four megapixels (Figure 16A). To identify gait events (foot contact and foot off time points) and measure the ground reaction force, two AMTI OR6-6-1000 and one OR6S6 (Advanced Mechanical Technology Inc., MA, USA) force-plates were used (Figure 16B). Data from the force-plates was collected at a rate of 1000 Hz and synchronised with the motion analysis data.



Figure 16: a) an example of an infra-red Vicon MX-T40 camera and b) an example of the force-plates used in this study [253,254].

5.4 Gait Analysis Data Collection

Gait analysis was undertaken in the Oxford Gait Laboratory (OGL) at the Nuffield Orthopaedic Centre in Oxford. The OGL is one of only 15 gait laboratories in England that is accredited by the Clinical Movement Analysis Society UK and Northern Ireland (CMAS) [255]. An institution can achieve accreditation through adherence to the quality, standards and training outlined by the CMAS [256]. In the field of gait analysis, this is paramount, as the integrity of data is highly dependent on consistency and accuracy of the methods used [257].

Prior to allowing the commencement of independent data collection, extensive training was undertaken under the supervision of Dr Julie Stebbins, the clinical scientist and manager of the OGL. This included training on laboratory calibration, marker placement, data collection and data processing. Only after supervised marker placement and gait laboratory operation protocols were conducted, was independent data collection permitted to take place. In cases of technical difficulties, there was always a clinical scientist present, who could ensure data of high quality could be collected.

To capture three-dimensional gait data, an experimental protocol was developed. It was based on the OGL protocol of capturing walking data, together with recommendations from the latest literature on developing dynamic measures of the MLA, multisegmented foot models and gait analysis methodology [239,244,248,258–264].

5.5 Systems Calibration

Prior to collecting data from the participants, system calibration was conducted in accordance with manufacturer guidelines. Following this, verification of the calibration was undertaken using a T-shaped calibration wand (Figure 17) and a bespoke device developed in the OGL to assess force plate outputs and synchronisation between the force plates and camera system [265]. The

calibration residual errors were less than 0.1 millimetre for the motion capture system (calibration was repeated if any errors exceeded this). The force plateerror tolerance was less than 2% of the known weight and the marker position error was no more than 2 millimetre. The time synchronisation threshold between the cameras and force plates was 5 frames (0.05 seconds). Data capture was only undertaken if the calibration and verification checks were within these tolerances.



A B

Figure 17: a) The T-shaped calibration wand for camera calibration and b) a 10 kg weight for force plate checking.

5.6 Subject Preparation

Prior to motion capture, informed consent was undertaken and anthropometric measurements (height, weight, inter-ASIS distance, knee-width and ankle-width) were taken as required by the gait analysis models adopted for each of the studies; these are the Plug-in-Gait (PiG) model [266,267] and the Oxford Foot Model (OFM) [234,235]. The following anthropometric foot measurements were obtained in addition to the aforementioned measurements for study 1 and 2 only. These were foot height at the 50% of foot length, truncated foot length and total foot length; all during both standing and sitting. See Appendix A for the subject measurement sheet.

Following this, 56 retro-reflective markers (10 mm in diameter) were attached to specific, predefined anatomical landmarks and other points of interest on the lower limbs using double-sided hypoallergenic tape, in accordance with the standardised OGL marker placement protocol. As the OFM does not directly capture midfoot function, an additional navicular (NAV) marker was added on each foot. This facilitated the assessment of the eight newly developed dynamic MLA measures. Furthermore, in order to provide more detailed assessment of the forefoot, and in acknowledgement of the work completed by Dr Po-Hsiang Chan, two additional markers on the head of the fourth metatarsal (D4M) and the base between second and third metatarsal (PXM) were added [268]. These two additional markers were only applied in study 1. This, more complex model of the forefoot, was not used as part of this study. Therefore, a total of 62 retro-reflective markers were used for data collection in study 1 and 58 in each of studies 2 and 3. For further details on the markers used, see Figure 18 and Table 10.

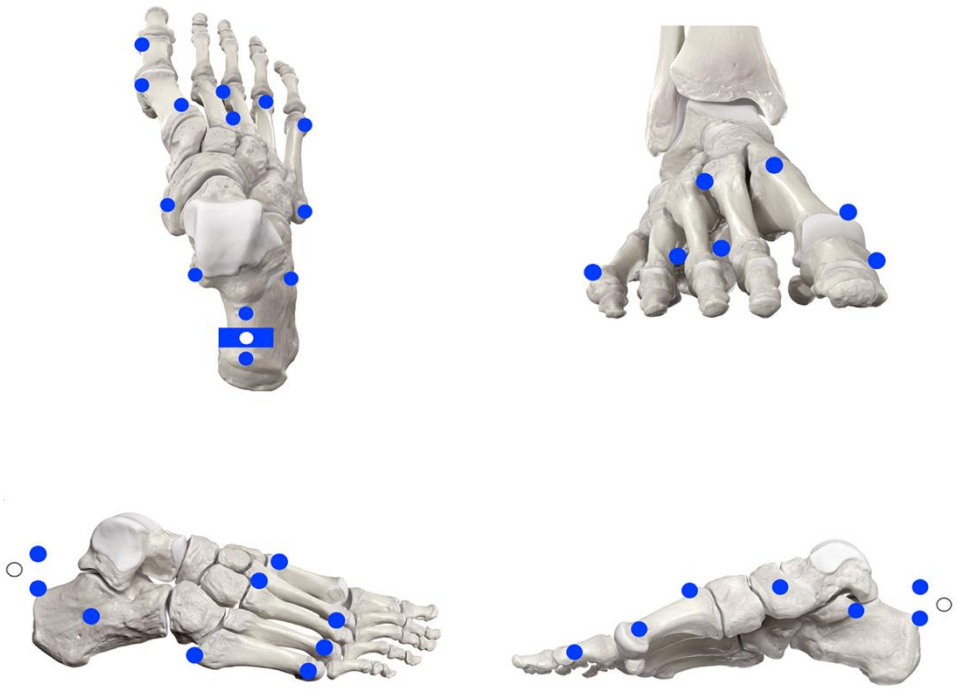


Figure 18: The full marker set for data collection



Marker Number	*Name of the marker*	*Marker Position*	*Description*	*Study 1 Validity study*	*Study 2 Baseline study on flexible flat feet*	*Study 3 Clinical case studies*
HINDFOOT MARKERS						
13	**RCPG**	Right posterior calcaneum wand marker	Between RPCA and RHEE and in line with RPCA and RHEE, in line with the coronal orientation of the hindfoot	X	X	X
11	**RPCA**	Right proximal calcaneum	Posterior aspect of calcaneum, proximal end of midline in sagittal plane	X	X	X
10	**RLCA**	Right lateral calcaneum	Lateral aspect of calcaneum at same distance from RHEE as RSTL and at same level from plantar surface of the foot as RSTL	X	X	X
14	**RSTL **&*****	Right sustentaculum tali	Sustentaculum tali	X	X	X
12	**RHEE**&*****	Right heel marker	Middle of the calcaneum, same height as the TOE marker	X	X	X
MIDFOOT MARKER						
9	**RNAV*&*****	Right navicular tuberosity	Inferomedial aspect of navicular bone, in the area directly anteroinferior to the medial malleolus, at the most prominent point of navicular tuberosity	X	X	X

FOREFOOT MARKERS AND HALLUX						
3	**RP1M **&*****	Right base of first metatarsal	Proximal head of first metatarsal, just medial to the extensor hallucis longus tendon (palpated by asking participant to dorsiflex hallux)	X	X	X
8	**RP5M *****	Right base of fifth metatarsal	Laterally, over the base of the fifth metatarsal	X	X	X
2	**RD1M**** &***	Right head of first metatarsal	Medially, on the head of the first metatarsal	X	X	X
7	**RD5M**	Right head of fifth metatarsal	Laterally, on the head of the fifth metatarsal	X	X	X
1	**RHLX**	Right base of hallux	Medial side of the proximal phalanx of the hallux, mid-way between the dorsal and plantar surfaces	X	X	X
4	**RTOE**	Right between second and third metatarsal heads	Dorsum, between the heads of the second and third metatarsals	X	X	X
6	**RD4M***	Right head of fourth metatarsal	Dorsum, on the head of the fourth metatarsal	X		
5	**RPXM***	Right base between second and third metatarsals	Dorsum, between the bases of the second and third metatarsals	X		

Table 10: Descriptions of individual markers for the right foot (similar markers placed on the left foot)

*Indicates markers in addition to the original OFM

** indicates markers that are projected onto the floor in addition to non-projected combinations

*** indicates marker used in the newly developed measure of the MLA

5.7 Experimental Protocol

Once consent was obtained from the participants, or their legal guardian if they were aged below 16 years, all the anthropometric measurements were taken, and the markers were placed (Table 10). All the trials were recorded barefoot. No markers were removed at any time during the data collection for study 1. In studies 2 and 3, the D1M, PCA and MMA markers were removed after the static trial to minimise gait impediment; they were virtually recreated in software during post-processing, in line with the normal procedure for calculating OFM angles.

Participants were then asked to perform a number of tasks (Table 11). A static trial was collected first. Participants were positioned on the force plate and asked to stand in a natural position with their arms crossed and hands positioned on opposite shoulders. Care was taken to ensure that the knees were not hyperextended, as this can lead to erroneous definition of the knee joint axes, which would in turn alter the subsequent kinematic and kinetic output.

After this, participants performed the tasks of sitting on a chair (non-weightbearing), then upon standing performed the heel lift and Jack's test with the aid of a researcher. Care was taken to ensure the tests were performed correctly, with emphasis on ensuring the activation of the windlass mechanism. During the seated trial, care was taken to ensure the participant's knees were flexed to 90°.

For the walking trials, the participant was instructed to walk in their usual way along a 10-metre walkway at a self-selected pace. Walking trials were repeated until at least six trials with clean force plate strikes for both the left and right feet were collected. In addition, functional knee movement tasks were also completed, in line with the standardised OGL protocol. However, this data was not used, as it was deemed incompatible with the data used in the baseline study, due to differences in model compatibility. Dynamic plantar pressure data were collected from each foot, with

implementation of a three-step technique to capture the data [269]. A total of six trials for each foot, with a complete footprint, were recorded. To optimise the quality of the data, if it was observed that the participant had altered their stride pattern for a specific trial, the trial was discarded.

Static pressure data were also collected, where participants were asked to step a single foot onto the pressure-plate, while keeping the opposite foot resting on the floor, adjacent to the pressure-plate. This enabled the capture of single support, partial weightbearing foot pressure data. To acquire full weightbearing pressure data, participants were asked to stand and balance on one foot. Care was taken with participant positioning, by having them stand precisely in the middle of the pressure plate. Following these tests, a second static trial was recorded as a quality control measure and to provide a marker record to use in cases where any markers needed reapplication during data collection

Task	*Description of the task*	*Study 1*	*Study 2*	*Study 3*
AHI weightbearing	The measurements of full foot length, truncated foot length and dorsum height at 50%-foot length were taken using callipers and standing on graph paper, with the participant standing on both legs with full weightbearing.	X	X	
AHI non-weightbearing	The same process as that described for acquiring weightbearing AHI was conducted, but with the participant sitting on a chair with both feet flat on the floor, but only touch weight-bearing.	X		
*Standing static **	The participant stood still with their feet about 10 centimetres apart, in a natural position, with their arms crossed and hands positioned on opposite shoulders, while standing on the force plate.	X	X	X
*Jack's test **	The participant stood still on the force plate, with their feet shoulder width apart and bodyweight equally distributed between both feet. In this stance, a researcher passively dorsiflexed their toe to activate the windlass mechanism and held it in this position for 10 seconds.	X		
*Heel rise**	The participant stood with their feet about 10 centimetres apart. In this position, the participant slowly raised their heels off the floor as far as possible, while keeping their knees straight. They were asked to hold this position for a count of 8 and then slowly lower their heels to the floor.	X		
*Sitting **	The participant sat on a stool, with their arms crossed, hands positioned on opposite shoulders and knees flexed to 90°. Their feet were placed on the force plate to check that minimal weight was through the feet.	X	X	X
*Dynamic knee flexion/ extension **	The participant remained seated on a chair with their limbs relaxed. A researcher supported their limbs by placing one hand under the participant's knee and the other hand below the participant's foot. In this stance, the researcher performed flexion and extension of their knee, for 6 trials with each knee, to obtain a functional knee axis.	X	X	X
*Dynamic walking trials**	The participant walking across a 10 metre walkway within the capture volume at a self-selected speed.	X	X	X
*static semi-weightbearing foot pressure**	The participant stood with their feet shoulder width apart, next to the pressure plate. This was followed by placing the foot that was closest to the pressure plate onto it and keeping the other foot adjacent to the pressure plate.	X		
*static weightbearing foot pressure**	The participant stood behind the pressure plate, with their feet shoulder width apart. One foot was placed onto the pressure plate and the other foot lifted off the ground. This process was repeated on the other foot.	X	X	
*dynamic foot pressure **	The participant stood three steps behind the pressure plate, then 6 pressure measurements per foot were captured.	X	X	

*Table 11: Details of the tasks conducted for data collection *Trials completed with 3D motion tracking*

5.8 Data Processing

5.8.1 Kinematic Data Processing

Data collection and post-processing of the kinematic data was performed by Jerneja Uhan with the use of Vicon, Nexus software version 2.12 (Vicon Motion Systems, Oxford, UK) and subsequently reviewed by Dr Julie Stebbins.

All markers were manually labelled for the static trials and labelled through an automated process (auto-labelling function within Nexus) for all the dynamic trials. Gait events (heel-strike and toe-off) were detected using the force plate, which marks the start and finish of a full stance phase. If the gait events could not be detected in this manner, they were identified manually.

In the literature, various signal processing methods have been advocated for movement analysis data [270–272]. These include means of filtering the data, such as spline smoothing, Woltring filtering [273] and using a double Butterworth filter which holds the beneficial ability of processing data with unequal sampling intervals. In this study, gaps in marker trajectories below 5 frames (0.05 seconds) were filled using the 'spline-fill' interpolation function embedded within Nexus. For gaps larger than 5 frames, depending on the location and timing during the gait cycle, other gap-filling algorithms were chosen in accordance with the OGL Gap Filling Protocol v1.2. Trials with gaps larger than 15 frames were discarded. The kinematic data and kinetic data and marker trajectories were exported in a c3d file format [274], along with information on anthropometric parameters and gait events.

5.8.2 Model Computation

The PlugInGait (PiG) model [266,267], also known as the Helen Hayes Model or the Conventional Gait Model, is a popular validated model used widely in both CGA and biomechanical research [275]. In this study, a modified version of the PiG model was used to compute pelvis, hip and knee kinematics. Pelvic angles were calculated in accordance with Baker et al. [276], hip joint centres were calculated in accordance with Harrington et al. [277], and knee axes were determined using a functional calibration technique [278]. For the initial data collection in study 1, knee axes were optimised using the approach outlined by Baker et al. [279]. The lower limb model was used in conjunction with the OFM [234,235] to estimate foot kinematics and provide a framework and reference to which the newly defined MLA angle was compared.

5.9 The Oxford Foot Model

The original OFM is a three-segment MSFM developed by Carson et al. [234] in 2001, that is composed of the hindfoot, forefoot and hallux (and shank). This was subsequently modified by Stebbins et al. [235] to make the model more applicable to children with deformed feet. It also improved the tracking and repeatability of the model, through positioning of the markers to optimise visibility and practicality.

In the OFM, the hindfoot segment is formed by the calcaneum and talus, the forefoot segment is composed of all five metatarsals, and the hallux segment is solely the proximal phalanx. A total of eighteen markers for each foot are required. In principle, stereophotogrammetry only requires three markers to define and track each rigid segment. However, the presence of one extra marker per segment creates redundancy, if any of the required three are missing due to technical reasons such as occlusion. Moreover, additional markers are used in the static trial to define the anatomical frames. Once static calibration is completed, these extra markers can be removed and reconstructed as virtual markers in the dynamic trials.

To date, the OFM remains one of the most widely used MSFMs. Such common use can be attributed to the extensive number of validation studies it has undergone and its implementation in the Vicon motion capture software [254]. Additionally, the repeatability of the OFM kinematic output has been reported for different age groups [236], pathological conditions [280], motion tasks [281,282] and different laboratories [283] .

Despite this, the OFM has been critiqued, with a main aspect being the lack of a midfoot segment [232,239,284–286], resulting in the MLA being tracked indirectly rather than directly. This could potentially hinder the utility of investigations pertaining to foot conditions, such as FFF and midfoot break, where the assessment of the MLA holds an important role [287] .

The current method of tracking the MLA in the original OFM entails obtaining the arch height and foot length. Arch height is obtained by calculating the perpendicular distance between the marker on the base of the first metatarsal, and the forefoot plane which is formed by the first and fifth metatarsal heads and base of the fifth metatarsal. The foot length, which is used to normalise the arch height measurement, is obtained by calculating the distance between the heel and second toe markers. It must be noted that this is not the standard way of measuring arch height and that the measurement patterns observed upon using this method anecdotally do not fit the patterns observed from CGA across the literature.

5.10 The new measure of MLA

The development of the new MLA measure was underpinned by principles derived using the literature and anatomical knowledge. This led to the creation of eight potential geometric definitions of the MLA (Figure 19). All eight MLA definitions aimed to mimic the Moreau-Costa-Bertani angle [288] and the angle between rearfoot inclination and first metatarsal inclination as described by Saltzman et al. [289]. In addition, in four of the eight definitions, the first metatarsal and either the heel or sustentaculum tali markers were projected onto the floor, as this has been demonstrated to provide a superior method of tracking the MLA by Caravaggi et al. [248] in the Rizzoli foot model due to its greater repeatability [237,290].

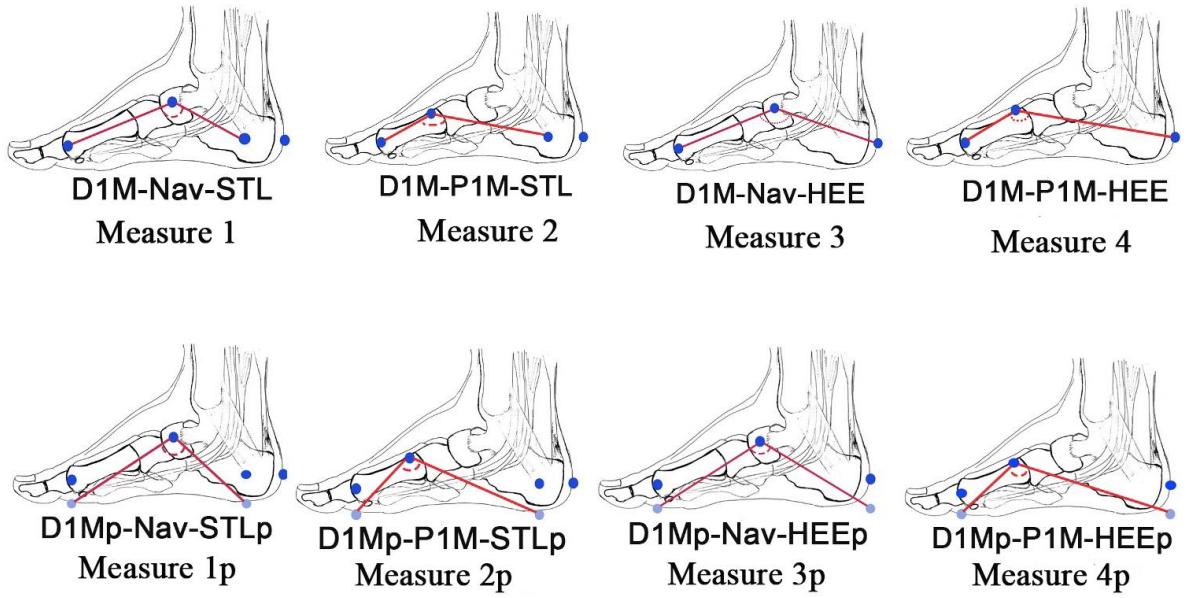


Figure 19: The eight measures reflecting distinct MLA angle definitions. D1M- head of first metatarsal, Nav- navicular tuberosity, P1M – proximal first metatarsal, STL- sustentaculum tali, HEE-posterior middle of the calcaneus. The subscript p indicates that the marker is projected to the floor to create a virtual marker.

Notably, the new methods outlined here allow for three-dimensional assessment of the MLA during walking. For each measure in Figure 19, the MLA angle was calculated as the angle between the unit normal vectors of two planes ('anterior' and 'posterior'). Each plane was defined by three points: one at the apex of the arch (either NAV or P1M), one at P5M, and one other. For the anterior plane, the third point was D1M. For the posterior plane, the third point was either HEE or STL. For measures 1p, 2p, 3p and 4p, the most proximal and distal markers were projected to the floor (z component assumed to be zero in standing). For detailed descriptions of the marker configurations making the anterior and posterior planes for each of the eight model definitions, please refer to Table 12.

Model	Anterior plane composite markers	Posterior plane composite markers	Apex marker
1	1) First metatarsal head (D1M) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	1) Sustentaculum tali (STL) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	Navicular (NAV)
1p	1) First metatarsal head projected to floor (D1Mp) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	1) Sustentaculum tali projected to floor (STLp) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	Navicular (NAV)
2	1) First metatarsal head (D1M) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	1) Sustentaculum tali (STL) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	First metatarsal base (P1M)
2p	1) First metatarsal head projected to floor (D1Mp) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	1) Sustentaculum tali projected to floor (STLp) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	First metatarsal base (P1M)
3	1) First metatarsal head (D1M) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	1) Heel (HEE) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	Navicular (NAV)
3p	1) First metatarsal head projected to floor (D1Mp) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	1) Heel projected to floor (HEEp) 2) Navicular (NAV) 3) Fifth metatarsal base (P5M)	Navicular (NAV)
4	1) First metatarsal head (D1M) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	1) Heel (HEE) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	First metatarsal base (P1M)
4p	1) First metatarsal head projected to floor (D1Mp) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	1) Heel projected to floor HEEp) 2) First metatarsal base (P1M) 3) Fifth metatarsal base (P5M)	First metatarsal base (P1M)

Table 12: Detailed descriptions of the derivations of the 3D MLA angles in relation to the placement of the markers.

5.11 Conclusion

This chapter has outlined the general methodology utilised in this thesis to collect, process, and analyse the biomechanical data required to conduct this research. The following chapter will focus on the study to define the optimal method for tracking the MLA during dynamic activities.

6 Defining the optimal method for using surface markers to describe the kinematics of the medial longitudinal arch

This chapter presents how the optimal method for defining the MLA using surface markers was identified, by evaluating the eight MLA representations formulated based on recommendations from the literature. Parts of this chapter have been published in the journal *Gait and Posture* [291].

6.1 Background

Static and dynamic evaluation of clinical foot and ankle disorders is regularly performed with three-dimensional gait analysis, including the use of marker-based multi-segment foot models (MSFMs). Over forty MSFMs have been reported in the literature and used across multiple pathologies [232] to inform and evaluate treatment options and management in clinical practice [232,292]. The modelling approach across these models can be variable, at least in part, because they are often designed for specific purposes or populations.

Such differences in modelling approach are particularly evident when considering the midfoot. In some MSFMs, the midfoot is represented as a single rigid three-dimensional segment, with Euler angles used to describe its orientation in relation to other segments [3–4, 6]. However, it is questionable whether this is the best approach, as the midfoot is composed of multiple, cube-shaped bones in which it is not easy to define anatomically or kinematically meaningful axes. Another approach, such as in the OFM, is to output the linear distance between the apex of the MLA and the forefoot plane. The main limitation of this method is the translation into clinical applicability. The most important element for understanding midfoot function is obtaining an insight on dynamic changes in the shape, deformation and reconstitution of the MLA [228,229]. This is in fact the structure that is most frequently assessed in relation to lower limb complaints [1,2]. Therefore, to provide detailed

insight on pathologies pertaining to the midfoot, direct MLA measurement would hold greater utility than assessment of the midfoot segment as a whole.

To characterise the MLA, an understanding of its anatomy is essential. One approach is to approximate the arch as a triangle when viewed medially, with two points forming the base of the MLA and the other the apex. This principle has been used in previous studies, where these three points have been used to calculate the MLA angle [249]. Furthermore, to improve measurement repeatability, the incorporation of virtual markers projected to the floor was introduced by Caravaggi et al. [249]. Of the midfoot bones, the navicular is generally accepted to form the apex of the MLA. However, there is a lack of evidence for deciding what other two points should be used, meaning a single optimal method has not been identified in the literature.

An approach to aid decision making that has been used in several healthcare fields is multiple-criteria decision analysis (MCDA) [295]. MCDA defines the desired properties and incorporates these into a decision model to rank the options using multiple criteria [295]. In context of this study assessing MLA measurement, the desired properties were divided into quantitative and qualitative aspects. The quantitative properties pertained to accuracy and repeatability of MLA measurement. Accuracy can be defined as demonstrating the known biomechanical principles of MLA deformation when exposed to the bodyweight and other forces, resulting in flattening of the arch. Therefore, comparisons of static and dynamic tasks in which there are varying levels of bodyweight force exerted on the foot should elicit differences in MLA angles [296]. In addition, MLA measurement accuracy can be demonstrated by comparing it against a known gold standard. Currently, radiographic measurements are deemed the gold standard due to facilitating direct visualisation of anatomy [228]. Validated clinical methods such as the AHI can also be used as comparators [297], particularly given that exposure to ionising radiation is problematic.

The qualitative properties relate to versatility and practicality. Versatility pertains to the ability of the marker set to be utilised on feet of all shapes, sizes and pathologies. Practicality focuses on the ease of marker placement and facilitation of data extraction, analysis and interpretation.

6.2 Aim

To define the optimal way to assess the MLA during walking using MCDA.

6.3 Objective

To use qualitative and quantitative elements of MCDA to rank various methods of MLA representation using motion capture of surface markers on the foot during different activities.

6.4 Methods

6.4.1 Participants

The 30 participants and their recruitment process, outlined in Chapter 5 under Study 1, were used in this study.

6.4.2 Development of MLA measures

Eight measures were implemented using markers on the head of the first metatarsal (D1M), the proximal first metatarsal (P1M), the navicular tuberosity (NAV), the proximal fifth metatarsal (P5M), the sustentaculum tali (STL), and the posterior middle of the calcaneum (HEE) (all but P5M shown in Figure 20). Of these, four MLA measures (Measure 1, Measure 2, Measure 3, Measure 4) were established using real markers only, to reflect radiographically derived angles. Another four MLA measures (Measure 1p, Measure 2p, Measure 3p, Measure 4p) were created using a combination of real and virtual markers (projected to the ground during static standing). Caravaggi et al. [248] advocated the latter type of measures to improve repeatability in the vertical position of the markers. For each measure, the MLA angle was calculated as described in Section 5.10.

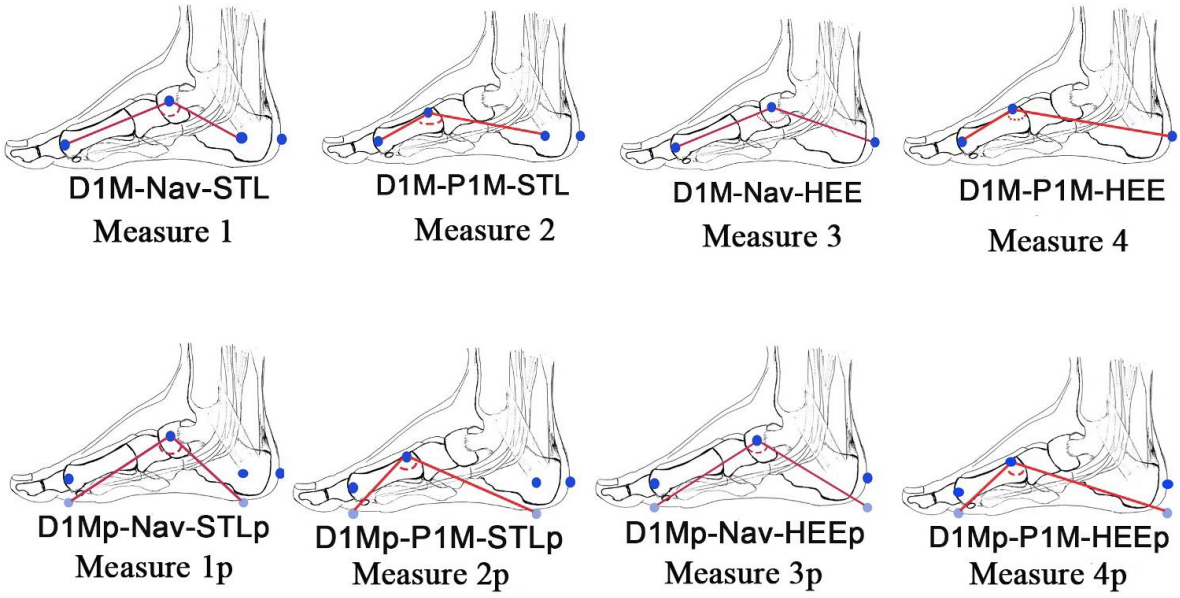


Figure 20: The eight measures reflecting distinct MLA angle definitions. D1M- head of first metatarsal, Nav- navicular tuberosity, P1M – proximal first metatarsal, STL- sustentaculum tali, HEE-posterior middle of the calcaneus. The subscript p indicates that the marker is projected to the floor to create a virtual marker.

6.4.3 Multi-criteria decision analysis

MCDA was used to objectively define the optimal MLA measure [298,299]. The criteria for MCDA were first proposed via a consensus meeting of 15 participants including orthopaedic surgeons, a podiatrist, physiotherapists, biomechanical engineers and clinical scientists, which was held at the OGL. Upon initial proposition of desired characteristics of the MLA measure based on experiences from using the current OFM, followed by input from the multidisciplinary team on what they considered to be clinically desirable traits, a preliminary questionnaire was developed. This comprised of 36 questions, that were later tested by two rounds of online questionnaires. This led to a selection of 26 questions being taken to the national meeting of the Clinical Movement Analysis Society of UK and Ireland (CMAS) for further testing through Delphi work, where two rounds of questionnaires were undertaken and resulted in the determination of 18 criteria (Table 13). Later, these criteria were divided into qualitative and quantitative aspects.

To conduct the quantitative MCDA, relative ranking scores for each measure for each criterion were calculated. The measures were scored based on the mean difference in MLA angle across set tasks (a1 – a6), correlation with AHI (b1-b2) and the mean difference in MLA angle between the repeated measurement attempts (c1). The best measure in each instance scored 8 and the worst 1. Scores were awarded irrespective of the statistical significance of each result (see Table 16). The measure with the most points in total was deemed to be the best. No weightings were applied, as there were no clear criteria for making one criterion more important than another.

To evaluate qualitative MCDA criteria (d1-2), observational evaluation of whether the markers were appropriately placed across the different foot sizes and shapes in the quantitative analysis sample was conducted by an experienced researcher. For criteria (e1-5), two additional online questionnaires (Table 14 and Table 15) were sent to five clinicians and three clinical scientists. Questionnaires focused on the practicality (specifically the ease of use) of the measure. All questions were multiple-choice, to provide objective and quantifiable responses. In the same manner as the quantitative aspects, no weightings amongst the qualitative aspects were applied. For two of the three areas of the foot at which markers were placed to measure the MLA angle, there were two anatomical landmark choices. These paired choices were compared against each other. As for the evaluation of criterion related to clinical utility (Table 13 - f1), this will be explored in the next chapter.

An information session was held initially, where an experienced clinician presented the study's aims, objectives, and outcomes to all clinicians who agreed to complete the questionnaire. In addition, a practical session was conducted to demonstrate the techniques for placing the markers that were included in the eight MLA measures. All markers from the eight measures, except the navicular marker, are part of the OFM set that is used in the OGL. Therefore, the practical session mainly focused on palpating the navicular and placing the marker. To minimise result bias, clinicians were given three

weeks to familiarise themselves with navicular marker placement on their clinical patients, before completing the questionnaire presented in Table 14.

Before distributing the clinical scientist questionnaire for answering the MCDA (e3-5), another session was held, dedicated to demonstrating data processing and extraction for the new MLA measures. After this, the data processing protocol was shared with the clinical scientists to attempt independently, prior to answering the questionnaire presented in Table 15.

Desired property		Criterion
Sensitivity to characterising MLA shape - which measure can best detect changes in the shape of the MLA that are known to occur in specific stances/movements	a1	Ability of the measure to detect a flatter arch (greater MLA angle) while standing with the feet flat on the floor compared to during Jack's test (in accordance with the windlass mechanism).
	a2	Ability of the measure to detect a flatter arch (greater MLA angle) while standing with the feet flat on the floor compared to during the heel lift test (in accordance with the windlass mechanism).
	a3	Ability of the measure to detect a flatter arch (greater MLA angle) during Jack's test compared to during the heel lift test (in accordance with the windlass mechanism).
	a4	Ability of the measure to detect a flatter arch (greater MLA angle) while standing with the feet flat on the floor compared to when seated with the feet flat on the floor but with minimal load through them (reflecting the change in MLA when loaded compared to unloaded)
	a5	Ability of the measure to be able to detect a flatter arch (greater MLA angle) at midstance (50% stance), in comparison to initial contact - foot strike (0-3% of the gait cycle), as expected in typically developed feet.
	a6	Ability of the measure to be able to detect a flatter arch angle (greater MLA angle) at toe-off (62% of GC) in comparison to midstance (50% stance), as expected in typically developed feet.
	a7	Ability of the measure to be able to detect differences between the maximum and minimum arch angle values.
	a8	Ability of the measure to distinguish between populations with different arch types, by detecting a greater MLA angle while standing with feet flat on the floor in children/adults with flat feet compared to those with typically developed feet, as expected.
Alignment with known MLA assessment methods	b1	Correlation between the measure's static standing MLA angle and the Arch Height Index during static standing.
	b2	Correlation between the measure's MLA angle at 50% stance and the Arch Height Index static standing.
Repeatability	c1	Strength of intra-rater repeatability of measurement.
Alignment with known MLA assessment methods	d1	Adaptability of the measure for use on different foot sizes (adults, children aged 8-16 and children under the age of 8 with small feet).
	d2	Adaptability of the measure for use on different foot arch types (rigid flat foot, flexible flat foot, cavus).
Ease of use	e1	Level of ease of marker placement, with emphasis on ensuring ease of palpation of any new markers added to the already existing OFM set.
	e2	Ability to facilitate timely marker placement, thereby ensuring that if new markers are added to the already existing OFM set, their placement does not extend the current marker placement time.
	e3	Level of ease of implementation, with emphasis on ensuring analysis and the interpretation of the collected data can be conducted without the need for additional software or extensive alteration from the existing OFM data analysis protocol.
	e4	Ability to facilitate timely data processing and data extraction, thereby ensuring that their data processing does not extend the current processing time.
	e5	Ability to facilitate ease of interpretation of the results, in a manner that is comparable to the already existing OFM set.
Clinical utility	f1	Ability to generate data output that can be interpreted and applied to clinical practice.

Table 13: The MCDA criteria; the greyed-out area was assessed in chapter 7

Questions for ease of use	Response
Q1 Which do you find easier to place, the navicular marker or the base of the first metatarsal marker?	NAV/P1M
Q2 Which marker do you have more confidence in how accurately you can place, the navicular marker or the base of first metatarsal marker?	NAV/P1M
Q3 Which do you find easier to place, the sustentaculum tali marker or the heel marker?	STL/HEEL
Q4 Which marker do you have more confidence in how accurately you can place it, the sustentaculum tali or heel marker?	STL/HEEL
Q5 In your opinion, has the alternative option for measuring the medial longitudinal arch increased the total marker placement time?	Yes/no
Q6 If yes, please state the length of the additional total marker placement time? Please report in seconds.	Seconds

Table 14: The clinician questionnaire for assessing ease of use

Questions for ease of data processing	Response
Q1 How easy/difficult did you find it to process the data with the additional calculation for the medial longitudinal arch?	Easy/ Moderate/Difficult
Q2 In your opinion, does the method for defining the medial longitudinal arch require extensive alteration from the existing OGL protocol?	Yes/No
Q3 In your opinion, has the time required for data processing when including the method for defining the medial longitudinal arch been extended or stayed roughly the same?	Extended/Same

Table 15: The clinical scientist questionnaire for assessing ease of data processing

6.4.4 Statistical analysis

Since this study evaluated a novel method for characterising the MLA, with no previous data available, a formal *a priori* sample size calculation could not be performed. However, the sample size used in this study (60 feet from 30 participants) is in alignment with comparable studies in the literature [249,300–302].

Statistical Package for Social Sciences (SPSS) version 27 was used to perform the statistical tests. The data was assessed for normality using the Shapiro-Wilk test, following which all datasets were deemed to be parametric. Z-scores were calculated to identify outliers.

MLA angle change detection was presented in the form of mean differences between the compared tasks (e.g. sitting and standing), which were assessed for significance using repeated measures ANOVA. The data was also examined with box and whisker plots. Correlation of the static (standing) and dynamic (50% stance phase) movement tasks with the AHI, for all MLA measures, was assessed

by calculating Pearson correlation coefficients. Repeatability of each of the measures during the static standing task was presented in the form of mean differences between the two measurement sessions.

For the qualitative part of the MCDA, frequency analysis was used. This involved calculating the proportion of feet from the total sample where all markers were able to be reliably tracked, without any overlapping or merging together, to assess criteria (d1-2). For criteria (e1-5), closed responses to each of the criteria were collated and tallied. The frequencies of selected responses were evaluated in relation to the MLA measures they corresponded to.

6.5 Results

6.5.1 Quantitative MCDA results

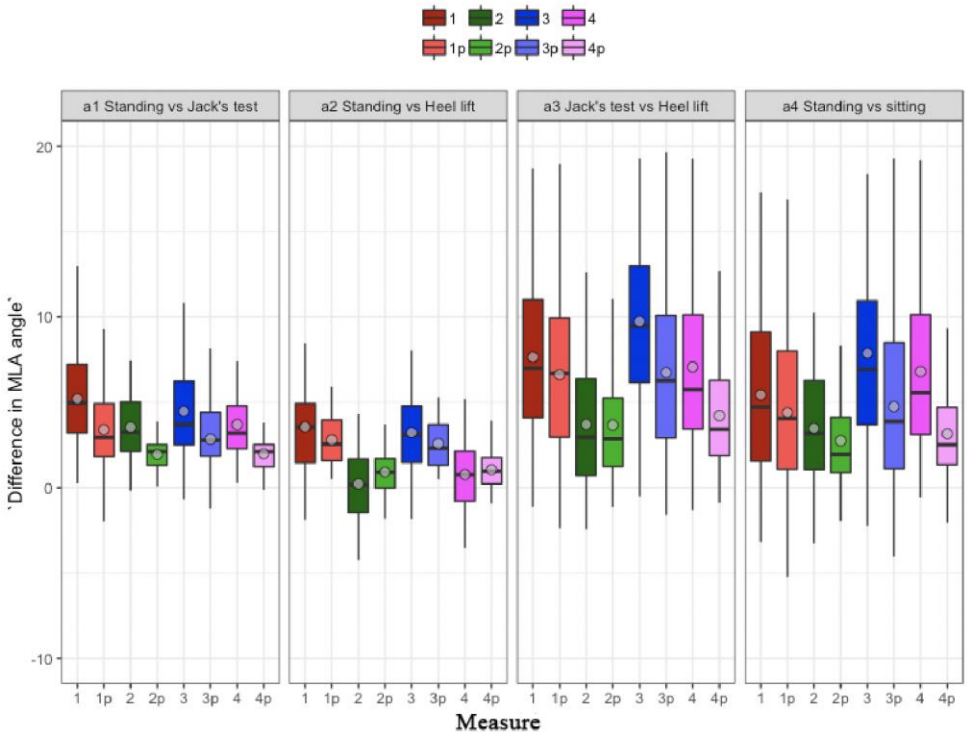
The total scores from the quantitative MCDA (Table 16) were collectively greater in the measures which exclusively used real markers, in comparison to the measures which used a combination of real markers and markers projected to the floor. In terms of overall performance, Measure 3 was deemed to be the optimal method, by virtue of having the highest overall score.

Desired property	Criterion	MLA measure scores							
		1	**1p**	**2**	**2p**	**3**	**3p**	**4**	**4p**
MLA change detection	a1 standing vs Jack's test	8	**6**	1[NS]	**2**	7	**5**	3	**4**
	a2 standing vs heel lift	7	**6**	2	**1**	8	**5**	4	**3**
	a3 Jack's test vs heel lift	6	**5**	3	**1**	8	**4**	7	**2**
	a4 standing vs sitting	8	**4**	5	**1**	7	**3**	6	**2**
	a5 foot strike vs 50% stance	4	**5**	1[NS]	**6**	3	**7**	2	**8**
	a6 50% stance vs toe-off	7	**6**	1	**2**	8	**5**	4	**3**
	a7 max vs min value in GC	6	**8**	1	**2**	7	**5**	4	**3**
Alignment	b1 correlation AHI vs static	7	**5**	1	**3**	8	**6**	2	**4**
	b2 correlation AHI vs 50%stance	7	**4**	1	**3**	8	**6**	2	**5**
Repeatability	c1 intra-rater repeatability	4	**6**	3	**1**	7	**8**	5	**2**
	Total score	**64**	**54**	**19**	**22**	**71**	**54**	**39**	**36**

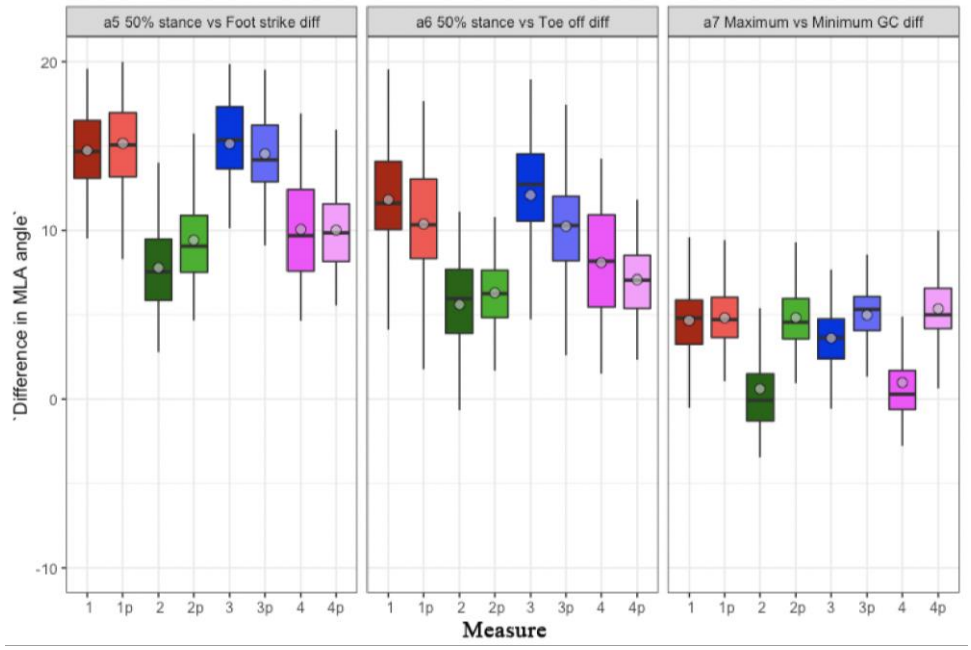
Table 16: The scores for each measure based on the MCDA criteria.

NS indicates the result is not significant

Differences in MLA angle between tasks were detected by all measures (Figure 21). Amongst the static tasks of standing, sitting, Jack's test and heel lift, significant mean differences were found in all measures, except for Measure 2 during comparison of standing with Jack's test. The largest mean difference in MLA angle between standing and each of sitting and Jack's test was detected by Measure 1. For comparisons in MLA angle between heel lift and each of standing and Jack's test, Measure 3 demonstrated the largest mean difference.



a)



b)

Figure 21: The differences in MLA angles across a) static and b) dynamic tasks. The box represents the interquartile range, the tails represent the minimum and maximum values without outliers, the thick black line in the middle of the box represents the median and the circle in the middle of the box represents the mean.

Among the measurement points of foot strike and 50% GC, alongside the minimum and maximum MLA angles during stance phase, significant mean differences were found in all measures, except for Measure 2 upon comparison of foot strike with 50% stance phase. The largest mean difference in MLA angle was observed in Measure 4p for the difference between foot strike and 50% stance phase, Measure 3 for between 50% stance phase and toe-off, and Measure 1p for between the minimum and maximum MLA angles within the GC.

There were significant inverse correlations between the standing MLA angle and AHI across all MLA measures (Table 17). However, high inverse correlations, defined as 0.7 or greater [303], were only observed in Measures 3, 1 and 3p, with the highest in Measure 3. Between the 50% GC MLA angle and AHI, there were significant inverse correlations across all MLA measures. However, high inverse correlations were only observed in Measures 1 and 3, with the highest in Measure 3.

Measure	**1**	**1p**	**2**	**2p**	**3**	**3p**	**4**	**4p**
Standing vs AHI correlation (r) – MCDA b1	-0.71*	-0.65*	-0.48*	-0.59*	-0.73*	-0.70*	-0.56*	-0.64*
50% stance vs AHI correlation (r) – MCDA b2	-0.70*	-0.64*	-0.50*	-0.61*	-0.71*	-0.68*	-0.57*	0.66*

*Table 17: The correlations between AHI and each of standing and 50% stance MLA angles across the measures; significant correlations are marked with **

Measure	**1**	**1p**	**2**	**2p**	**3**	**3p**	**4**	**4p**
Mean MLA angle difference as attempt 1 -attempt 2 (°)	- 1.5	2.6	-10.1*	-6.0*	1.3	-1.2	-9.7*	-5.2*

*Table 18: The difference in MLA angles between repeated standing measurements across the measures; significant differences between attempt 1 and attempt 2 are marked with **

6.5.2 Qualitative MCDA results

The assessment of versatility (d1-2) of the measures was conducted on 10 flat feet, 23 high arched feet and 25 neutral feet, which ranged from 23-30 centimetres in size, and yielded 100% of markers being confirmed as visible and able to be tracked without merging of markers. Therefore, it was observed that all measures demonstrated adequate versatility for use on a variety of feet.

The MCDA criteria (e1-5) evaluating the practicality of the measures encompassed two parts. Criteria (e1-2) were evaluated by five clinicians, while criteria (e3-5) were evaluated by three clinical scientists. The former criteria (e1-2), pertaining to the confidence and accuracy of marker placement, demonstrated that three clinicians preferred using the base of the first metatarsal marker and the sustentaculum tali marker, while two clinicians opted for the navicular and heel markers. Given the relatively even split of clinicians choosing each of the paired options, there was no clear preference of marker choice established. Three clinicians reported that adding a navicular marker to the existing marker set only minimally increased their overall time for marker placement - with additional placement time ranging from 5 to 180 seconds.

Regarding the ability to process and analyse data (e3-5), there was unanimous agreement amongst the clinical scientists, who reported that data processing was easy and required no additional time or extensive alterations to the existing OGL protocol.

From the results, it is apparent from the quantitative aspect, that Measure 3 held superiority by being comparatively the best in most of the criteria. Since all measures were deemed similar from the qualitative aspect, the quantitative scores determined the overall optimal choice. Therefore, Measure 3, by virtue of having the highest quantitative score, was concluded as optimal for measuring the MLA (Table 16). It must be noted that this result does not account for criterion f1 (clinical utility), which will be explored in the next chapter (Chapter 7).

6.6 Discussion

The purpose of this study was to determine which measure most meaningfully and reliably characterised the MLA angle across static and dynamic tasks. From this study's quantitative MCDA criteria, the results demonstrated that the use of real markers is preferred in terms of measurement accuracy, and Measure 3 (D1M-NAV-HEE) was the best of the eight measures for characterising the MLA, based on static and dynamic MLA arch angle assessments. From the qualitative assessment, all measures of MLA assessment were acceptable, with no measure demonstrating clear superiority over the others. Overall, when combining the results from the quantitative and qualitative aspects, Measure 3 was deemed the optimal method.

This was the first study to incorporate the use of quantitative and qualitative MCDA to facilitate objective decision-making for determining the optimal method for MLA assessment in gait tasks. The conclusion of Measure 3 being optimal is strengthened by the evidence that it consistently obtained the highest scores in each of the desired properties, alongside having the greatest average score. Nevertheless, for the property of repeatability, Measure 3p which incorporated projected markers was superior. Therefore, depending on the relative importance of accuracy and repeatability to the research application, the optimal choice may be different.

From this study's results on MLA change detection, it can be observed that most of the static task comparisons yielded significant differences irrespective of the MLA measure used. The standing MLA angles were significantly greater than the sitting angles across all eight measures, due to comparatively greater bodyweight force exertion on the foot, resulting in a flatter arch with a larger MLA angle. For the tasks of heel lift and Jack's test, each had lower MLA angles in comparison to standing, which may be explained by the activation of two mechanisms to elevate the MLA – the windlass and calcaneocuboid locking mechanisms. Jack's test involves passive dorsiflexion of the big toe, which activates the windlass mechanism due to increased tension in the plantar aponeurosis,

leading to the pulling of the calcaneum towards the metatarsal heads, culminating in an upward force in the MLA that elevates it [296]. As for the heel lift, this causes supination of the foot, which leads to convergence of the talonavicular and calcaneocuboid joint axes, resulting in locking of the transverse tarsal joint and elevation of the MLA in a process known as the calcaneocuboid locking mechanism [304]. Additionally, plantarflexion at the ankle joint and dorsiflexion of the toe which occur during the heel lift also activate the windlass mechanism, thereby providing an extra form of foot stabilisation to elevate the MLA [305].

In the dynamic tasks, the MLA angle at 50% stance phase was significantly greater than both foot strike and toe-off angles. Relatively greater bodyweight force would be exerted onto the MLA to flatten it to a greater extent in the former task than the latter tasks, as this point represents single limb support. At toe-off, foot supination and toe dorsiflexion with the shifting of the bodyweight force forward to the contralateral leg activates the calcaneocuboid locking and windlass mechanisms, to elevate the MLA [11]. Upon comparison between foot strike and the 50% stance phase, it was noticed that Measure 3 did not detect as large differences as the measures with projected markers. This is likely due to small changes in the MLA angle between these two time points, resulting in only small differences between the measures.

Furthermore, the MLA angles were correlated against clinically assessed AHI, as this comparator has been previously validated against radiographic measurements [297]. All MLA measures showed significant inverse correlations with AHI for both standing and 50% stance. However, there was notable disparity in the correlation strengths. Interestingly, MLA measures 3, 1 and 3p which sequentially had the strongest correlations between standing and AHI, also had the highest respective correlations between 50% stance and AHI. A similar trend for standing and 50% stance phase was also noted for the lowest correlations with AHI, namely Measures 2, 2p and 4. This suggests the accuracy

to which a measure assesses the MLA during static tasks may be indicative of its ability to assess the structure during dynamic ones as well.

It is well recognised that the navicular plays a key role in the anatomy and function of the MLA. Several other studies have reported the use of the navicular marker as a useful means of characterising the MLA in MSFMs [244,249,263,306]. This is due to the natural anatomical position of the navicular marker and the particular role it holds in MLA function [11]. It is also known to have a low rate of measurement error, including marker misplacement and soft tissue artifacts [302]. Additionally, the use of the navicular marker for representing the MLA has been confirmed in studies using plain x-rays [248] and biplanar fluoroscopy [307,308]. Therefore, together with the results from this study's MCDA, it can be suggested that using a measure with a navicular marker is an optimal way of characterising the MLA.

The incorporation of projected markers onto the floor was based on the study by Caravaggi et al. [248], which suggested that projection of the metatarsal bone marker helps to increase repeatability. The results of this study corroborate this finding, with Measure 3p holding the best MCDA score for the repeatability property. Although, it must also be acknowledged that Caravaggi et al. [248] used the Rizzoli foot measure in contrast to the modified OFM used in this study, and that different types of static and dynamic tasks were conducted between the studies. Therefore, the results cannot be directly compared or used interchangeably.

With regards to the versatility of the measures' application, this is underpinned by their ability to assess various types of feet. Feet can vary based on their size and shape, which are dependent on a multitude of factors including stage of development and the presence of pathology. Foot growth and development is normally completed by the age of 16 years [74,90,95–103,108,184,309]. Therefore, it can be assumed that this measure is applicable on all feet where the arch is fully developed (around 8 years of age), given the sample included participants beyond this age. In addition, to evaluate its

clinical applicability in context of being able to assess feet with pathologies, a case study on four participants with cerebral palsy will be presented in the next chapter (Chapter 7).

When addressing the practicality of the measures, there are several factors that can affect the findings. Since practicality is an aspect heavily dependent on personal opinion and preferences, the amount of experience in the use of a measure influences how it is perceived. The disparities in clinician preference for choosing between the base of the first metatarsal marker and the navicular marker as the apex marker can be explained by differences in clinician experience. Here, more experienced clinicians disagreed with their less experienced colleagues, whose preference of the first metatarsal marker may be explained by the fact that they had only started using the navicular marker after the introductory training session. Additionally, as mentioned before, there is a lower rate of placement error for the navicular marker than the base of first metatarsal marker [302]. This was evidenced by Measures 2, 2p, 4 and 4p, which used the base of first metatarsal marker, holding the greatest mean differences across repeated measurement attempts, indicating possibly greater placement error (Table 18). As for the differing preferences between the sustentaculum tali marker and the heel marker, this may have been influenced by the complexity of placement. For instance, heel marker placement requires many technical steps including manually separating the fatty pad and calcaneum, and drawing a precise line to dissect the calcaneum, that may be perceived to be complex. As for the sustentaculum tali marker, this can be relatively straightforward to place, by positioning it at a fixed distance guided by the position of the heel marker.

The high acceptance rate amongst the clinical scientists reflects the relatively minor changes made to routine data processing protocols.

6.7 Limitations

Since only eight MLA measure definitions were assessed, there is the possibility that another MLA measure beyond those used in this study would yield better results. However, to minimise this limitation, the latest recommendations from the literature were assimilated, including the addition of a navicular marker to the original OFM. This posed the second and third limitations of an increased risk of placement error and increased marker placement time. However, from this study's intra-rater repeatability assessment, the differences in repeat measurements were similar between the measures which utilised the navicular marker and those which did not (Table 18). Therefore, the potential limitation of increased risk of placement error was not apparent in this study. Furthermore, there is a fourth limitation with regards to the use of clinically assessed AHI to assess the accuracy of the MLA measures. It may be argued that the use of radiographic measurements would be better suited for this role, due to being able to accurately visualise the MLA. However, the clinical AHI assessment method used in this study has previously been validated against radiographic measures in different populations [297] and provided the benefit of not unnecessarily exposing participants to radiation. Additionally, there is a potential fifth limitation, where there could be skin movement artefacts when capturing the dynamic MLA form, especially at initial foot contact. This limitation applies to all forms of dynamic assessment and cannot be completely eliminated and would have equally affected all MLA measures. With regards to the MCDA, all criteria were given equal weighting on the final score. However, it is possible that some criteria may have relatively greater importance in determining how best to characterise the MLA. Lastly, although FFF was included in this study to aid in evaluating versatility, other foot pathologies that may be seen in the clinical setting were not included.

6.8 Conclusion

Overall, the MCDA results suggest the optimal measure for characterising the MLA across both static and dynamic settings should use real markers on the heel, navicular, head of the first metatarsal and base of the fifth metatarsal. This study did not find the use of projected markers to improve measurement accuracy, but suggested they may improve repeatability. Further studies to assess the use of the measures on different pathologies are advised. One such pathology that bears importance in this matter is cerebral palsy, which will now be explored.

7 Clinical case study: application of the optimal MLA measure in different foot pathologies seen in cerebral palsy

This chapter presents the evaluation of the clinical applicability of Measure 3, which was deemed to be the optimal MLA measure within a population of NF and FFF without significant foot and ankle pathology. To further validate measure 3, by means of specifically evaluating it using MCDA criterion f1, it was used to explore foot kinematics during gait from cases of four participants with cerebral palsy (CP).

7.1 Introduction

From the previous chapter, the use of Measure 3 was tested on two populations: 1) general population aged 8-25 years (study 1) and 2) flexible flat feet population aged 8-16 years (study 2). The participants included in these two populations had no recent injuries, previous surgery or excessive trauma to the foot. In comparison, the participants with CP evaluated in this chapter represented a common population seen at the OGL, who often present with foot deformities.

Cerebral palsy refers to a group of permanent movement disorders which stem from brain damage that occurs during foetal development or early infancy. These disorders, which have an incidence of 2.11 per 1000 live births [310], affect muscle tone, movement, and coordination. Cerebral palsy may also result in disturbances of sensation, perception, cognition, communication and behaviour, as well as epilepsy. There are four main forms of cerebral palsy: spastic (muscle tightness), dyskinetic (involuntary muscle movements), ataxic (impaired balance and coordination), and mixed [311]. Cerebral palsy can affect different parts of the body, such as the whole body (quadriplegia), one side of the body (hemiplegia), primarily the lower limbs (diplegia), or primarily one limb (monoplegia) [312,313]. Across its forms, CP can result in many lower limb issues, commonly through the following

two mechanisms pertaining to muscle tone and coordination: 1) muscle spasticity and increased tone can lead to imbalances across the muscle groups [313,314], and 2) impairment within the cerebral motor cortex can impact coordination [315]. Over time, the muscular dysfunction stemming from these mechanisms can manifest in the form of soft tissue contractures and bony deformities [316].

Specifically in paediatric patients with CP, foot and ankle deformity is common [137], with reported rates of up to 93% [317]. Foot deformities in CP are classified according to their effect on the ankle, hindfoot, midfoot and forefoot [318,319]. The most common foot deformities among patients with CP are equinus, planovalgus and equinovarus, but other combinations of deformities are also possible, including midfoot break, equinovalgus, calcaneovalgus and equinocavovarus in severe cases [318–320]. Each deformity affects the MLA in a different manner. For example, in a planovalgus foot, the midtarsal joints remain in an unlocked position during the stance phase of gait. This impairs plantarflexion of the first metatarsal, thereby inhibiting windlass mechanism activation to elevate the MLA, as required in the third rocker of gait [321,322]. As for equinovarus, overactivity of the gastrocnemius-soleus complex and dysfunction of the tibialis anterior commonly result in a persistently elevated MLA, due to windlass mechanism activation. This prevents deformation of the MLA as required during the first and second rockers of gait [321,322].

Due to the previously outlined variability of effects on the foot and ankle in CP, the gait pattern generated can differ on an individual basis. Clinical gait analysis (CGA) can be utilised to identify abnormal walking characteristics arising from defective MLA function [323]. Therefore, this chapter aimed to evaluate the newly developed MLA Measure 3, in assessing foot pathologies present in CP. Given that CP patients present with a range of foot and ankle deformities which also manifest in pathologies beyond this condition, such assessment holds the potential to inform a wide range of treatments.

7.2 Methodology

7.2.1 Clinical considerations

To explore the potential clinical utility of Measure 3, this study used retrospective data collected from patients who were referred to the OGL for routine CGA and on whom an additional navicular marker had been attached. The data was collected and used with the approval of the National Research Ethics Service (reference: 21/LO/0426).

7.2.2 Subject and participants

Four subjects diagnosed with CP were involved in this study. The subject details are summarised in Table 19. This is followed by photographs presenting the MLA structure in the sagittal plane, including the placement of markers. It should be noted that the head of the first metatarsal marker was removed for the walking trials and then reconstructed virtually using other forefoot markers during data processing, as per routine OGL protocols.

Participant	Age	Sex	Diagnosis	Weightbearing foot posture (subjective description)
A	9	M	CP – asymmetric diplegia	Right – midfoot planus Left – equinus
B	17	M	CP – asymmetric spastic diplegia	Right – forefoot adduction Left – equino-valgus
C	16	M	CP – spastic diplegia	Right – hallux varus Left – planovalgus
D	56	F	CP – spastic diplegia	Right – planus with hallux valgus Left – planovalgus with hammer toe

Table 19: Subject demographics and diagnoses

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7.2.3 Data collection and processing

The data collection and processing protocol presented in Chapter 5 was followed. It must also be acknowledged that the presented clinical data in this chapter was collected by OGL physiotherapist Julie Letherland. The data was processed by Jerneja Uhan and Julie Stebbins was the second reviewer.

7.2.4 Abnormal Gait identification

The current OFM foot kinematics calculated for each subject were compared against corresponding mean values of typically developing children or adults, who were age and gender matched. However, it must be noted that the OGL data gathered from typically developed children and adults did not utilise the navicular marker. Therefore, MLA Measure 3 angles were calculated for each subject and compared to mean angle values that were based on 30 participants with an age range of 8-25 years and a gender split of 17 females and 13 males (study 1 from this thesis). The reason for not matching the compared data for Measure 3 by age and gender is due to the results demonstrating the same characteristics of the MLA angle irrespective of these variables. Refer to Chapter 5 section 2 for more details on the cohort.

7.3 Results

7.3.1 Case A

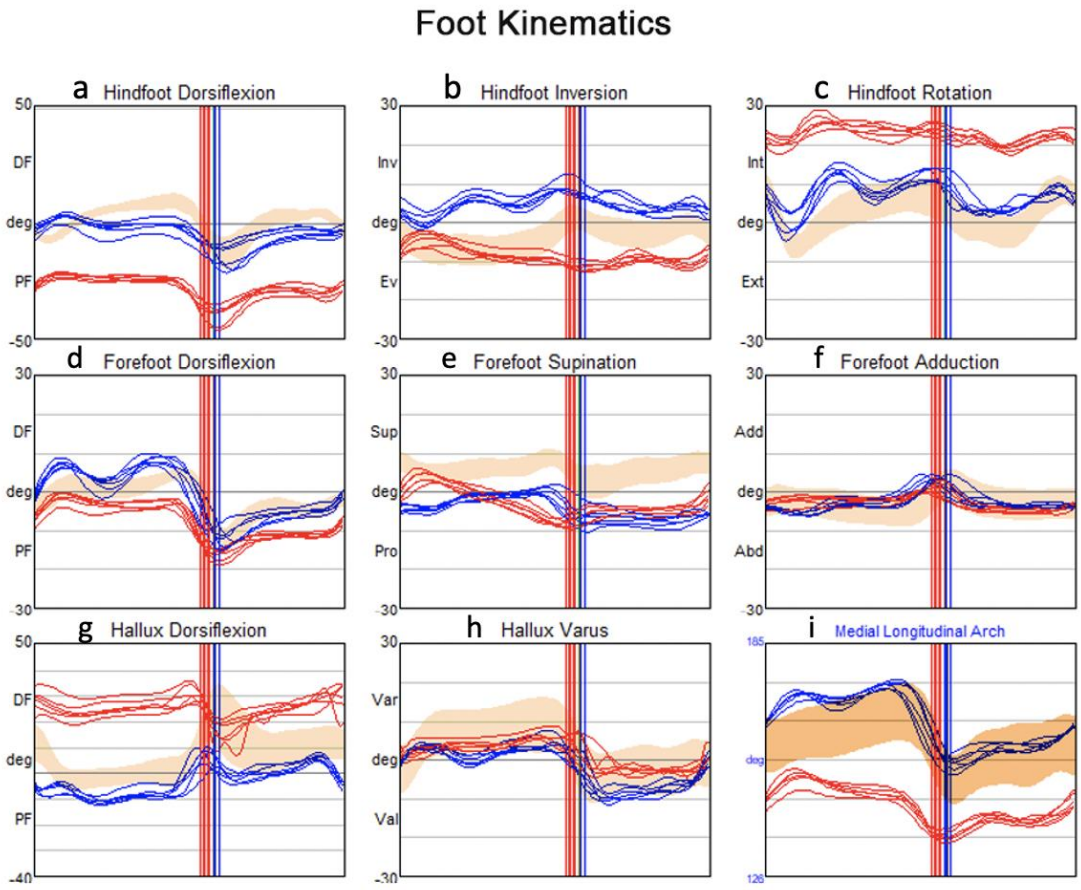


Figure 22: The foot kinematics obtained using the OFM for participant A. The orange band represents the corresponding mean values of 14 healthy children matched for age (8-9 years) and gender for all graphs except MLA graph i, for which the mean values of 30 healthy children and adults aged 8-25 years are depicted. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.



a) LF Standing



b) RF Standing



c) LF Walking



d) RF Walking

Figure 23: a-d present the MLA structures of the left (LF) and right feet (RF) of subject A, a 9-year-old male participant with asymmetric diplegic CP. The photos are from the same visit.

The first case study presents the kinematics of a 9-year-old male participant with asymmetric diplegic CP. From the graphs presenting foot kinematics (Figure 22), the left foot was in equinus. As for the right foot, the graphs closely followed the general population's curve. From graph (b) which assesses the hindfoot in the coronal plane, it can be observed that the left hindfoot was slightly everted, whereas the right hindfoot was inverted.

When looking at forefoot graphs (d-f), both feet presented with a pronated forefoot relative to the hindfoot (e). Although, it can be observed that the right foot, despite being pronated, followed the pattern of kinematics demonstrated in the general population's curve. As for the left foot, it was demonstrated to progressively increase in pronation throughout the stance phase. Based on video

assessment, this can be attributed to progressive rolling onto the medial side of the forefoot and pushing off through the hallux. The progressive increase in arch height (reduction in MLA angle) seen on the MLA graphs fits with this push off through the hallux.

Upon detailed observation of hallux dorsiflexion graph (j), it can be noted that the left hallux was overly dorsiflexed in contrast to the right foot. When combining the information on hallux dorsiflexion (g) and the MLA angle (i), it may be inferred that the higher arch of the left foot throughout the stance phase could be associated with over-activation of the windlass mechanism.

7.3.2 Case B

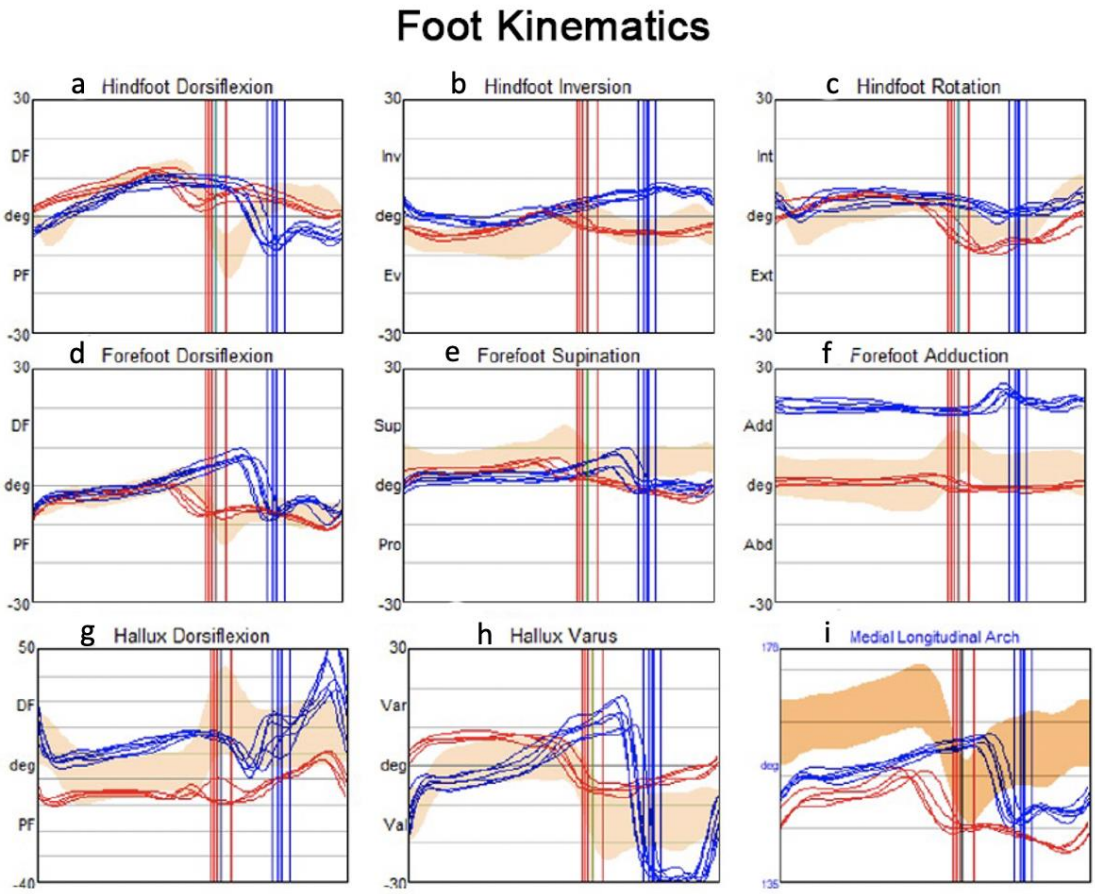


Figure 24: The foot kinematics obtained using the OFM for participant B. The orange band represents the corresponding mean values of 21 healthy adults matched for age (17 years and above) and gender (male) for all graphs except MLA graph (i), for which the mean values of 30 healthy children and adults aged 8-25 years are depicted. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.



e) LF Standing



f) RF Standing



g) LF Walking



h) RF Walking

Figure 25: e-h present the MLA structures of the left and right feet of subject B, a 17-year-old male participant with asymmetric diplegic CP. The photos are from the same visit

The second case study presents the kinematic analysis of a 17-year-old male participant with asymmetric diplegic CP. From the current graphs presenting foot kinematics (Figure 24), it appears that there was a reduction in ROM of the left foot overall. As for the right foot, it can be observed that there was a prolonged stance phase on this side.

From graphs (a-c) assessing the hindfoot, it can be observed that the right hindfoot persisted in inversion throughout the stance and, to a greater extent, the swing phase. As for the left hindfoot, it closely followed the general population's curve, with eversion in both stance and swing phases. However, the sagittal plane graph suggests that the left foot lands flat on the floor and is not showing the presence of the first rocker.

When looking at the forefoot graphs (d-f), the right foot presented as adducted in both stance and swing phases, while the left foot followed the general population's curve during the stance phase and presented with slight abduction during the swing phase. In addition, the left foot presented with pronation throughout the swing phase. The MLA graph (i) demonstrated the arch height to increase across the swing phase (reduction in MLA angle). Putting this information together, it can be inferred that the hindfoot remains in a neutral position in swing, while the forefoot relative to the hindfoot drops into pronation to result in a relatively increased arch height.

Upon detailed observation of the hallux dorsiflexion graph (g), it can be noted that both the right and left hallux are dorsiflexed in swing, relative to the stance phase. This is likely as a result of the extensor hallucis longus being recruited to aid ankle dorsiflexion and prevent foot drop during swing. This was associated with a decrease in MLA angle during the swing phase (l). In addition, it can also be observed from MLA angle graph (i), that the right foot stance phase was prolonged when compared to the left foot. However, the trend of relative changes in arch height through the GC was similar across both feet.

7.3.3 Case C

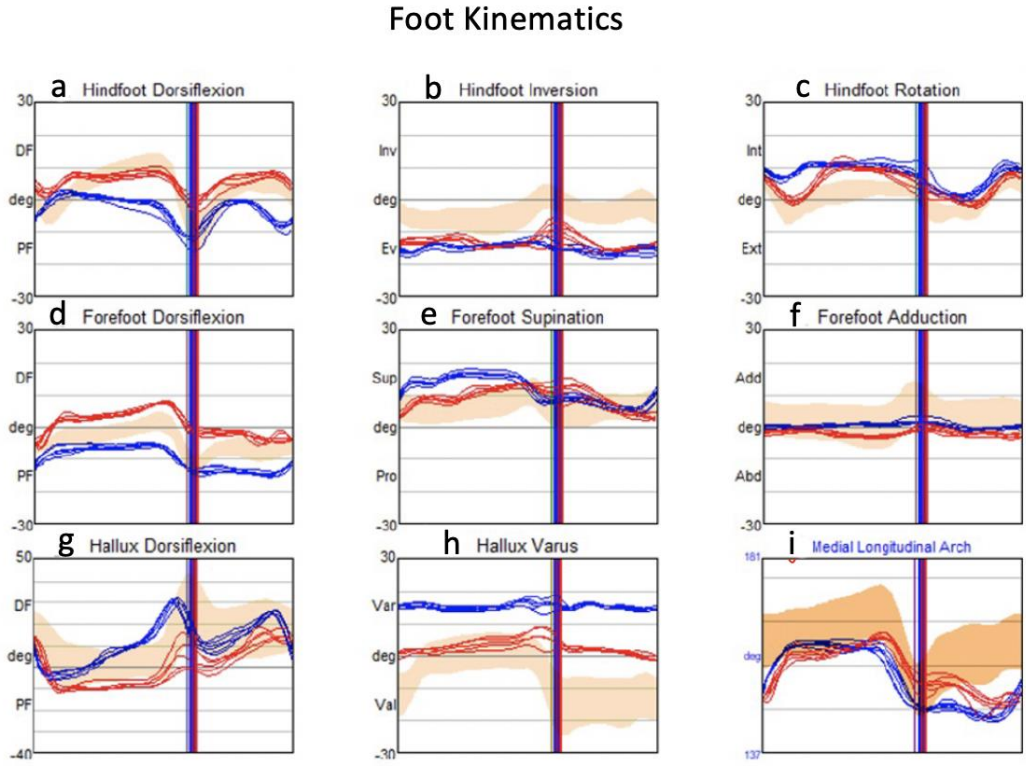


Figure 26: The foot kinematics obtained using the OFM for participant C. The orange band represents the corresponding mean values of 10 healthy children matched for age (13-16 years) and gender (male) for all graphs except MLA graph (l), for which the mean values of 30 healthy children and adults aged 8-25 years are depicted. The blue lines denote one full GC for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.



i) LF Standing



j) RF Standing



k) LF Walking



l) RF Walking

Figure 27: i-l present the MLA structures of the left and right feet of subject C, a 16-year-old male participant with CP. The photos are from the same visit.

The third case study presents the kinematic analysis of a 16-year-old male participant with CP. From the graphs presenting foot kinematics (Figure 26), it can be observed that through both stance and swing phases, the right foot was persistently plantarflexed. Both hindfeet were everted, and the right foot did not re-supinate at toe-off.

When looking at forefoot graphs (d-f), the right foot presented with persistent plantarflexion, especially in the swing phase, while the left foot presented with persistent dorsiflexion in both phases. Both left and right feet presented with slight supination throughout the stance phase and both left and right forefeet were pronated in the swing phase relative to the tibia.

Upon further observation of hallux dorsiflexion graph (j), both sides showed slightly increased dorsiflexion towards the end of the swing phase. This is likely a result of the extensor hallucis longus being recruited to aid ankle dorsiflexion and prevent foot drop during the swing phase. This was associated with an increase in MLA height during the swing phase in comparison to the stance phase.

In addition, it can also be observed from MLA angle graph (l), that in both feet, the MLA angle flattened greatly during the middle of the stance phase. When comparing the swing and stance phases, it can be noted that both feet presented with a higher arch in the swing phase. In light of the information obtained from observing hallux dorsiflexion (j) in relation to the MLA angle (l), it can be inferred that the relatively increased arch height of the right foot seen in the swing phase can potentially be attributed to relative hallux dorsiflexion that occurs at this point.

7.3.4 Case D

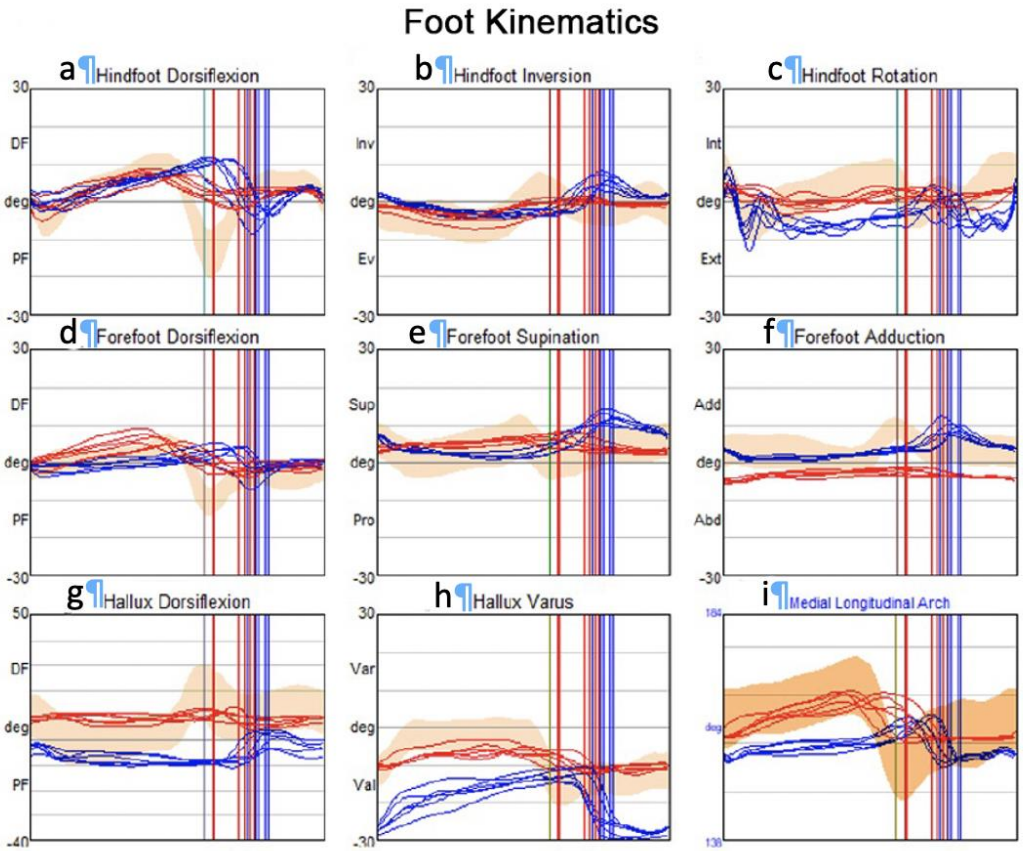


Figure 28: The foot kinematics obtained using the OFM for participant D. The orange band represents the corresponding mean values of 21 healthy adults matched for age and gender for all graphs except MLA graph (l), for which the mean values of 30 healthy children and adults aged 8-25 years are depicted. The blue lines denote one full GC for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.



m) LF Standing



n) RF Standing



o) LF Walking



p) RF Walking

Figure 29: m-p present the MLA structures of the left and right feet of subject D, a 56-year-old female participant with CP. The photos are from the same visit.

The fourth case study presents the kinematic analysis of a 56-year-old female participant with CP. From the current graphs presenting foot kinematics (Figure 28), it appears that there was a reduction in ROM, particularly on the left side. It can also be observed that there was a prolonged stance phase bilaterally, spanning from 70% to 80% of the GC.

From the sagittal plane hindfoot graph (a), it can be observed that there was a limited first rocker on the left, which combined with the video information indicates that there was a low heel-strike with limited ankle dorsiflexion. There was also an early third rocker on the left, relative to toe-off timing, indicating the heel was lifted off the ground early with insufficient push off. The range of motion in all three planes was limited on the left.

When looking at forefoot graphs (d-f), the left foot presented with slight forefoot abduction. In addition, there was slight supination and dorsiflexion presented in the right foot compared to the left foot around the time of toe-off. The left foot demonstrated limited forefoot ROM.

Upon further observation of hallux dorsiflexion graph (g), the right hallux presented as being plantarflexed throughout the stance phase, while undergoing relative dorsiflexion in the swing phase, in comparison to the general population curves. The left hallux showed limited movement throughout both phases and was held in slight dorsiflexion throughout the GC. As observed in the other case studies, this is likely a result of the extensor hallucis longus being recruited to aid ankle dorsiflexion and prevent foot drop during swing.

In addition, it can be observed from MLA angle graph (l), that the range in arch height through the GC was similar across both feet. However, when comparing hallux dorsiflexion (g) in relation to the MLA angle (i), it can be inferred that the timing of the increased arch height of the right foot seen in the swing phase can potentially be attributed to the movement towards hallux dorsiflexion that occurs at this point, as the timing and patterns matched closely. For the left foot, the patterns of hallux (g) and MLA movements (i) were not as strongly associated . Instead, the MLA followed a normal pattern, suggesting it was more influenced by other aspects of foot biomechanics.

7.4 Discussion

This chapter aimed to explore the potential clinical utility of MLA Measure 3, which was defined to be optimal in Chapter 6. For this, case studies on four CP participants were compiled to evaluate the complementary kinematic outputs produced by the OFM and the MLA measure. These outputs demonstrated evidence of the pathophysiological mechanisms through which altered foot structure in CP affects gait.

To date, there have been many clinical studies aimed at characterising pathological gait due to foot deformity, using MSFMs. However, none have directly assessed the dynamic movement of the MLA using 3D angles independently. As for this study, the participants represented typical patients referred for CGA. Although specific gait deviations, including that of the MLA, varied across the patients, there were some fundamental similarities. Specifically, there was reduced sagittal ROM and a prolonged stance phase due to compensatory effects. There was also typically a lack of heel (first) or toe (third) rockers noted.

The gait patterns associated with CP are multifactorial and can manifest due to several reasons. However, it was interesting to explore the potential relationship of hallux plantar/dorsiflexion and the MLA using the new MLA measure. Here, a potential close relationship was observed, where increased hallux dorsiflexion often coincided with an increased arch height in the same part of the GC. The new MLA measure has also demonstrated its ability to convey information on the rigidity of the arch, as well as denote whether the windlass mechanism is active. Not all theoretically expected aspects of MLA behaviour were exhibited. Specifically, when the hindfoot is in valgus, the MLA is expected to flatten [10,11]. This occurs due to the subtalar joint axis shifting away from the midline of the body, impairing the cuboid locking mechanism and leading to the midfoot being in an unlocked position. However, these changes were not exhibited in the collected data on individuals with CP, suggesting the potential involvement of other variables which would hold greater impact on the MLA form in

participants with this condition. In addition, it must be noted that these observations were corroborated by two-dimensional video gait analysis and CGA, thereby strengthening the findings from Chapter 6. Overall, Measure 3 demonstrated the ability to effectively characterise the MLA and successfully generate measurement outputs, that could be transformed into graphs in conjunction with other OFM outcomes, to provide interesting insights. Such application in context of a wide range of foot and ankle pathologies that are seen in the clinical setting underpins how this measure fulfilled MCDA criteria f1.

Another important goal was to evaluate the clinical practicality and feasibility of implementing this study's MLA measure in a clinical setting. Prior to conducting data collection with the MLA measure, a session on the ease of marker placement and landmark identification was held with the physiotherapy members of the OGL team (Chapter 6). Since the new MLA measure required only one additional marker to the OFM marker set, there was minimal interference to the standardised procedure, and anatomical landmarks for marker placement were easily identifiable. From this chapter, it can also be noted that the OFM and MLA Measure 3 can be used in conjunction with one another, as they can be simultaneously tracked by the motion capture system with all markers clearly visible.

7.5 Limitations

There are several limitations to this study. It must be noted that this was an exploratory study, which aimed to gain an insight on the utility of Measure 3 in context of pathology. Hence, no statistical tests were carried out due to the sample size being insufficient, as well as due to time constraints for carrying out a comprehensive clinical study. Therefore, the kinematic comparisons made between different planes and movements in the results section involved visual analysis only. The strength of this case study is that it facilitated assessment of a wide array of CP presentations, spanning a range of ages, genders, foot sizes, foot types and pathological variants. This underpins its clinical utility,

where it successfully generated meaningful data that could either correlate or critique theoretical understanding of the MLA, to potentially inform clinical management plans.

Regarding the use of the navicular marker in individuals with severe foot and ankle pathologies, it is essential to acknowledge the potential risk of the marker falling off or being disrupted during data collection. In particular, it may be prone to falling off when it is passed by the opposite foot in the swing phase of gait. In addition to the cases presented here, data was collected on a further 6 participants with such pathologies, and in none of the 10 cases did the navicular marker fall off or get hit. Nevertheless, further exploration is needed to find the best method to address the risk that the use of the navicular marker carries.

Future studies should include a larger sample of participants and more detailed analysis of kinetics, muscle-activity and plantar pressure. Furthermore, to fully realise the clinical potential of Measure 3, they should conduct evaluation in relation to symptoms, including before and after interventions.

7.6 Conclusion

Overall, this study serves as an essential first step to identify the versatile use and clinical application of a novel measure of the MLA. It evaluated participants with CP and compared their MLA patterns to those of typically developing individuals. Evidence of the pathophysiological mechanisms through which altered foot structure in CP affects the GC was observed using the complementary kinematic outputs of the OFM and MLA Measure 3.

8 Validation of remote measurement methods for anthropometric assessment of the foot and medial longitudinal arch

This chapter presents the development and validation of remote methods for clinical assessment of foot posture, namely the Arch Height Index (AHI) and the Arch Index (AI). The emphasis on utilising remote methods for data collection stems from the circumstances arising from the COVID-19 pandemic. With governmental regulations in place, in particular social distancing, the need for assessment methods that could be done without any physical contact was essential, in order to stay on track with the DPhil timeline. Such methods also hold broader implications, including those of increased accessibility and feasibility, which can provide long-term benefits in wider clinical settings.

8.1 Background

The MLA of the foot is a structure which provides essential insight on gait and function [324–326]. It can be assessed using several different methods, of which some are more commonly used than others. Of these, radiological assessment is typically recognised as the gold standard, due to its high level of accuracy [194]. However, it carries the disadvantages of being less accessible, expensive and posing the risk of exposure to ionising radiation[194]. Clinical assessment serves as an alternative without such drawbacks, with the literature reporting the AHI and AI among the most commonly used measures for quantifying MLA morphology. Therefore, from a practical perspective, with respect to feasibility during consultations and cost-effectiveness, they can be considered as attractive alternatives to radiological assessment for clinical characterisation of foot structure.

The AHI was first introduced by Williams and McClay [297]. It is a measure which quantifies the MLA, by dividing the arch height at 50%-foot length by the truncated foot length (Figure 31). It holds good intra-rater with an ICC of 0.94-0.98 [297] and inter-rater repeatability with an ICC of 0.81-0.85) [297],

and has been validated against equivalent radiographic measurements with an ICC of 0.84-0.85 [297]. This method is simple to conduct, requiring only callipers to perform the assessment. Despite its practicality, this method still requires manual collection of measurements, which poses the limitation of its accuracy being dependent on user experience [327]. Recently there has been a new trend of using a semi-automated system, which also holds high intra- and inter-rater repeatability [327]. It utilises a portable instrument comprised of a heel cup to facilitate foot placement, and a series of sliding callipers and rulers for acquiring measurements to calculate the AHI. This method holds the drawback of being more expensive and comparatively less accessible for wider clinical use than manually operated callipers. As for the AI, this was first introduced by Cavanagh and Rogers [201]. This method involves the creation of a footprint, which is then divided into three equal sections, excluding the toes. The area of the middle section is divided by the total area of the three sections excluding the toes, to provide the AI (Figure 36). In the past, the footprints were typically created using ink or water. More recently, there have been developments of various methods such as pressure plates [328], carbon paper [221] and carbonless paper [329]. The carbon paper method has been demonstrated to hold excellent intra-rater repeatability with an ICC of 0.99 [221]. The pressure plate method is commonly used in clinical settings and is recognised as a gold standard for AI assessment. Specifically in this study's setting, it poses the limitation of being less accessible, as it is a stationary, fixed object which requires in-person assessment of the participant to be conducted by an examiner who is familiar with operating it. Overall, it can be observed that both the AHI and AI are highly reliable assessment measures that have been extensively used in research and clinical settings.

Recently, there has been a shift towards the development and use of remote and telemedicine techniques, due to the benefits of accessibility and convenience. The benefits of remote techniques have been further highlighted in context of the COVID-19 pandemic. Therefore, this study aimed to propose and validate remote assessment techniques of foot arch height and shape, that could potentially be used in wider clinical and research settings. A standardised in-person AHI assessment

method was used as a comparator for a newly devised remote AHI assessment method. Intra-rater repeatability of each method was measured, and the correlation between the two methods was assessed to determine validity of the remote method. In addition, a standardised instrumented clinical footprint AI assessment method was used as a comparator to determine the validity of a newly devised remote footprint AI assessment method.

8.2 Aims

1. Determine the repeatability of a remote AHI assessment method.

2. Determine the validity of remote AHI and AI assessment methods.

8.3 Hypotheses

H1 The remote AHI assessment method holds excellent intra-rater repeatability (ICC ≥ 0.75 as per [330]).

H2 The remote AHI assessment method is a valid method, as determined by a high correlation with the in-person clinical assessment counterpart.

H3 The remote AI assessment method is a valid method, as determined by a high correlation with the instrumented, clinical assessment counterpart.

8.4 Methods

8.4.1 Ethical Considerations

Ethical approval required from the National Research Ethics Service (REC reference: 21/NE/0228, York - North East Committee) was obtained prior to the start of the study.

8.4.2 Subjects

For the AHI measurements, this study included 40 feet from a total of 10 males and 10 females who were recruited from the university population and surrounding community. The mean age of the cohort was 38 years, with a range of 21-75 years. Each participant visited the OGL on two separate days, that were not consecutive. For the AI measurements, 13 participants with a mean age of 30 years and a range of 25-36 years, were recruited. Each participant visited the OGL only once. Some of the participants were included in both cohorts. Participants of both recruited cohorts were free of any lower extremity abnormalities or injuries at the time of data collection.

8.4.3 In-person AHI measurement

For the in-person AHI measurement, callipers were used to take the constituent measurements for its calculation. A4 grid paper was used, on which a thin black line that represented the long axis of the foot was drawn. Participants were asked to place their foot on the paper, with its position being guided by a black line which passed through the long axis of the foot (the middle of their heel to the second toe). In addition, participants were asked to stand in a relaxed standing position, with their weight equally distributed on both feet (50% WB). A standardised procedure for collecting the required measurements to calculate the AHI was implemented. Horizontal callipers (Fihure 30) were used to measure foot length (FL) and truncated foot length (TFL), which is the distance from the heel to first metatarsal head, parallel to the black line. A vertical sliding calliper was then positioned at 50% of the FL, and subsequently used to measure the height of the dorsal arch (DH). The AHI was calculated as the ratio of the DH to the TFL[297]. This process was conducted on both feet across both visits.



Figure 30: The callipers used in this study

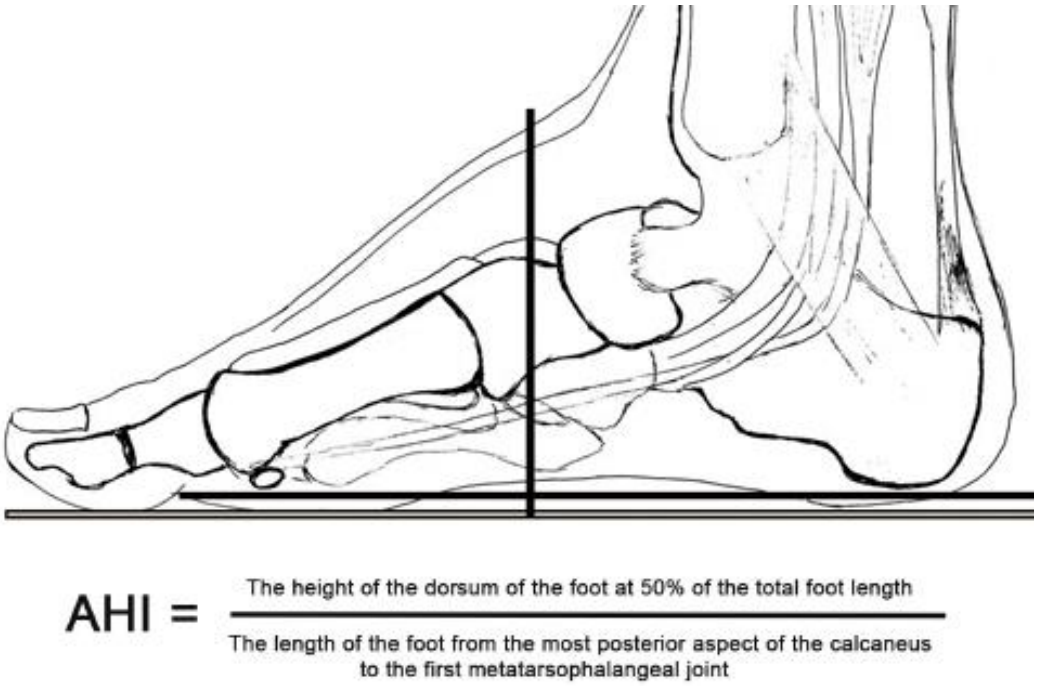


Figure 31: The AHI equation [331]

8.4.4 In-person AI measurement

To conduct in-person AI measurements, an EMED® pressure plate (novel® GmbH, Germany) (Figure 32) was used. Foot pressure readings were collected from the right foot, with the participant standing with their weight equally distributed on both feet (50% WB) and having their right foot on the pressure plate and left foot on the floor. To ensure participant safety during data collection, a chair was positioned in front of the participant to hold onto in the case of instability. For each participant, novel® geometry software (version 14.3.5) was used to calculate the AI from the pressure print.



Figure 32: A photograph of the Emed novel® pressure plate from the novel website

8.4.5 Remote AHI measurement

For remote measurement of AHI, participants were asked to photograph their feet using a smartphone camera and adhere to the following protocol on how to position their feet, to allow for consistency in camera distance and angulation (Figure 33). They were asked to step with one foot onto A4 white paper and use the other foot behind the main body in a toe off position for support (Figure 33 a, c). Such foot positioning aimed to place the bodyweight exactly above the ankle joint and prevent interference from the other foot, in order to obtain clear pictures. Another piece of A4 white paper was used as a tool to ensure consistency in distance between the foot and the camera (Figure 33 a). The camera was placed in the middle of the paper, then the paper was removed, and a side view photo

was taken (Figure 33 b). For further details on foot positioning and obtaining photographs, see Appendix B. Matlab was utilised for deriving the FL, TFL and DH measurements from the photographs, which were subsequently used to calculate the AHI as the ratio of the DH to the TFL [297]. This was achieved using a semi-automated algorithm, which conducted AHI calculation following manual marking of points 2, 3, 4 and 5 (Figure 34). In addition, a plantar foot line, which is represented by point 1 (Figure 34), was created. This line represented the main reference point for calculating the AHI, as points 2,3,4 and the autogenerated arch height at 50% FL line were all perpendicular to the plantar foot line. Once these points were marked, the algorithm automatically calculated the distance between the corresponding points. No enhancements or modifications were made to any of the digital images.

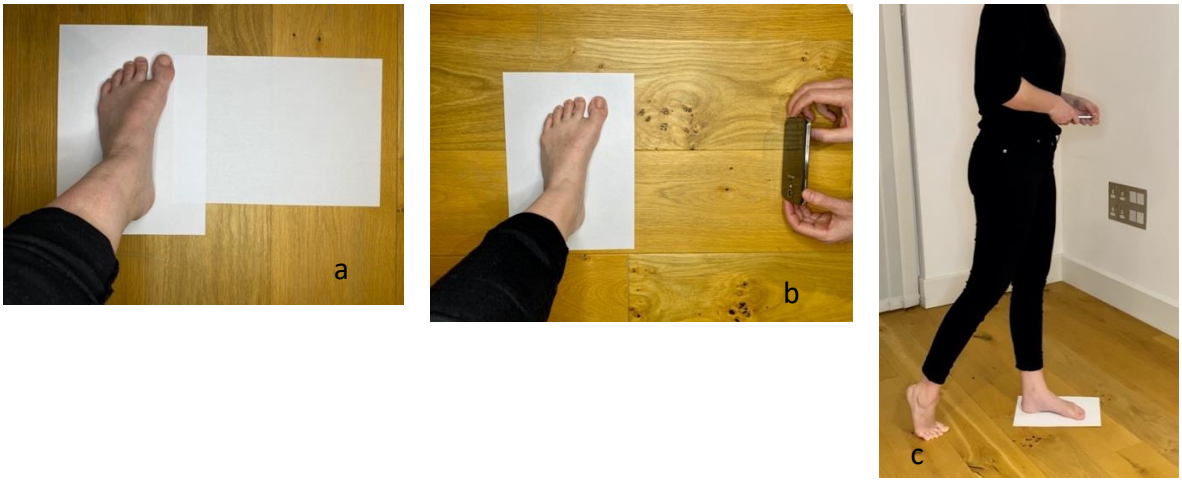


Figure 33: a) and b) present the process of positioning the A4 paper and camera for obtaining side photos and picture c) presents the positioning of the camera for capturing the top view for the remote method

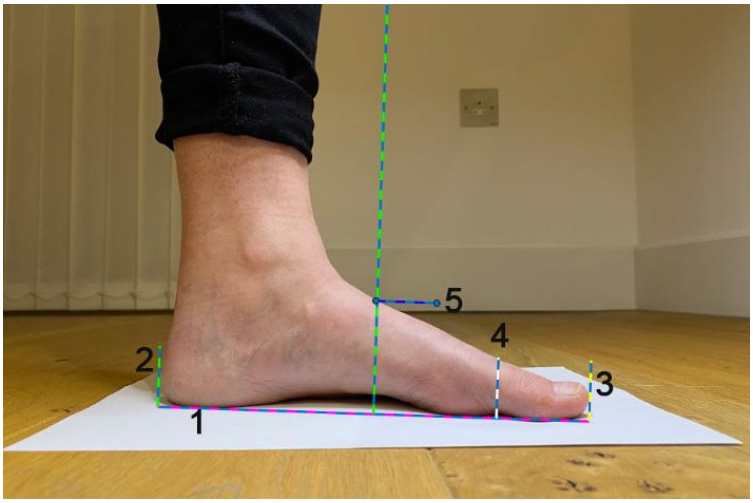


Figure 34: Presents the measurements required to calculate AHI in Matlab 1) plantar foot line; 2) posterior part of the heel; 3) distal part of the toe; 4) distal end of 1st metatarsal joint, 5) dorsum height. ***Between numbers 2 and 3*** *– Foot length: defined as the distance between the posterior part of the calcaneus and the distal part of the toe:* ***Between midpoint of 1 and number 5*** *– Dorsum height at 50% foot length:* ***Between numbers 2 and 4*** *– Truncated foot length: defined as foot length from the posterior part of calcaneus to the distal part of the 1st metatarsal joint*

8.4.6 Remote AI measurement

For remote measurement of the AI, Invisible Ink paper (Nekoosa, USA) was used. Participants were asked to wipe their right foot with Nekoosa wipes and position their right foot on the middle of the Invisible Ink paper and press their foot onto it. In this stance, they had to ensure their bodyweight was being exerted on the right foot and that their left foot was lifted off the ground (Figure 35) (Appendix C). The generated invisible ink paper footprints were scanned and imported into Matlab for extraction of necessary measures to obtain the AI (Figure 36).



Figure 35: The process of positioning for obtaining footprints using the remote method

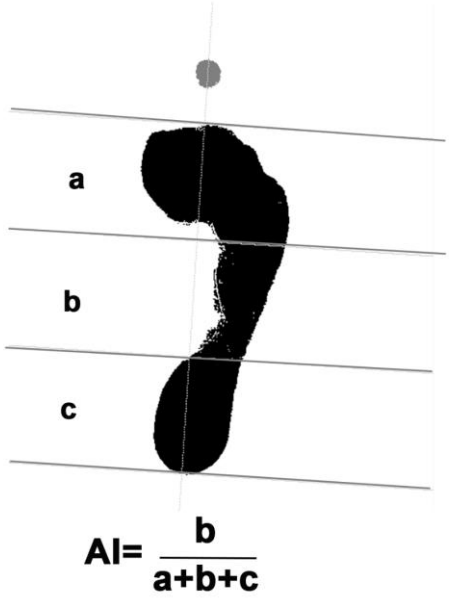


Figure 36: The equation for calculating the AI

8.5 Data analysis

Data from the remote methods were compared against in-person methods to assess their validity. In addition, both in-person and remote AHI assessment methods were evaluated for repeatability. Each foot of every participant was assessed as an independent sample, as the study methodology entailed making comparisons of data across different methods of measurements and repeated measurements.

8.5.1.1 Arch Height Index

Upon determining the data to be normally distributed using the Shapiro-Wilk test and QQ plots, the descriptive statistics (mean, SD) of the AHI together with the measurements taken to derive it (FL, TFL, DH) were calculated for the remote and in-person methods for each measurement day. For assessing intra-rater repeatability, two-way mixed effects, absolute agreement, single rater intra-class coefficients (A,1) (ICC) were calculated in each of the in-person and remote methods. Mean differences for between-day measurements in each of the methods were also calculated. To assess the validity of the remote methods, mean differences for these measurements between the in-person and remote methods were reported. In addition, Pearson correlation and linear regression analyses were conducted to determine the relationship between in-person and remote methods. Lastly, the agreement between the in-person and remote methods was assessed through the creation of a Bland-Altman plot [332].The accepted threshold would be for 95% of plotted points to fall within the limits of agreement, defined as +/- 1.96 SD of the mean difference [333].

8.5.1.2 Arch Index

Upon determining the data to be normally distributed using the Shapiro-Wilk test and QQ plots, the descriptive statistics (mean, SD) of the AI together with the measurements associated with it (forefoot width and rearfoot width) were calculated for the remote and in-person methods. Mean differences

for these measurements between the in-person and remote methods were reported. In addition, the Pearson correlation coefficient was calculated to determine the validity of the remote assessment method in relation to the in-person method. Lastly, the agreement between the in-person and remote methods was assessed through the creation of a Bland-Altman plot, for which an accepted level of agreement would entail 95% of plotted points falling within the limits of agreement. SPSS was used to conduct analysis, using a threshold of alpha = 0.05.

8.6 Results

8.6.1 Descriptive statistics of assessment methods of AHI

The mean values of AHI and the measurements required to derive it, for the in-person and remote assessment methods, for both day repeats of data collection, are presented in Table 20.

Measurement	In-person day 1 (SD)	In-person day 2 (SD)	Remote day 1 (SD)	Remote day 2 (SD)	Mean difference between methods (day 1) (SD)	Mean difference between methods (day 2) (SD)
AHI	0.307 (0.03)	0.307 (0.03)	0.321 (0.03)	0.322 (0.03)	-0.015 (0.02)	-0.015 (0.02)
Foot length (mm)	255.3 (14.63)	255.9 (13.86)	251.2 (12.10)	251.4 (12.13)	4.1 (7.28)	4.5 (7.57)
Truncated foot length (mm)	199.2 (11.85)	199.1 (11.84)	197.0 (9.47)	197.0 (9.41)	2.3 (2.56)	2.1 (2.44)
Dorsum height at 50%-foot length (mm)	60.9 (5.42)	61.0 (5.49)	61.3 (5.91)	61.4 (5.81)	-0.4 (3.56)	-0.4 (3.42)

Table 20: The mean and standard deviation (SD) values of FL, TFL, DH and AHI for both the in-person and remote methods

8.6.2 Repeatability assessment of AHI assessment methods

Intra-rater repeatability of each of the AHI assessment methods was evaluated by calculating the ICC between the measurements repeated across both days of data collection (table 21). Mean differences

in AHI, FL, TFL and DH across the repeat measurements for each assessment method were also calculated (table 22).

AHI assessment method	ICC	95% CI of ICC
In-person	0.998 (p<.05)	0.997-0.999
Remote	0.995 (p<.05)	0.990-0.997

Table 21: The intra-rater repeatability of each AHI assessment method

Measurement	Mean difference in-person method (SD)	Mean difference remote method (SD)
AHI	-0.0004 (0.002)	-0.001 (0.005)
Foot length (mm)	-0.6 (3.2)	-0.2 (0.2)
Truncated foot length (mm)	0.1 (0.6)	-0.1 (0.4)
Dorsum height at 50%-foot length (mm)	-0.1 (0.5)	-0.1 (0.9)

Table 22: The mean and SD of differences in FL, TFL, DH and AHI across each measurement attempt for each of the in-person and remote methods (day 1 – day 2)

The difference between all repeated measurement attempts were no greater than 1 mm. The smallest mean difference in between-day repeat measurements of the AHI was seen in the in-person assessment method.

8.6.3 Validity assessment of remote AHI assessment methods

The remote AHI method was strongly correlated with the in-person method (Pearson's r = 0.802, p<0.05).

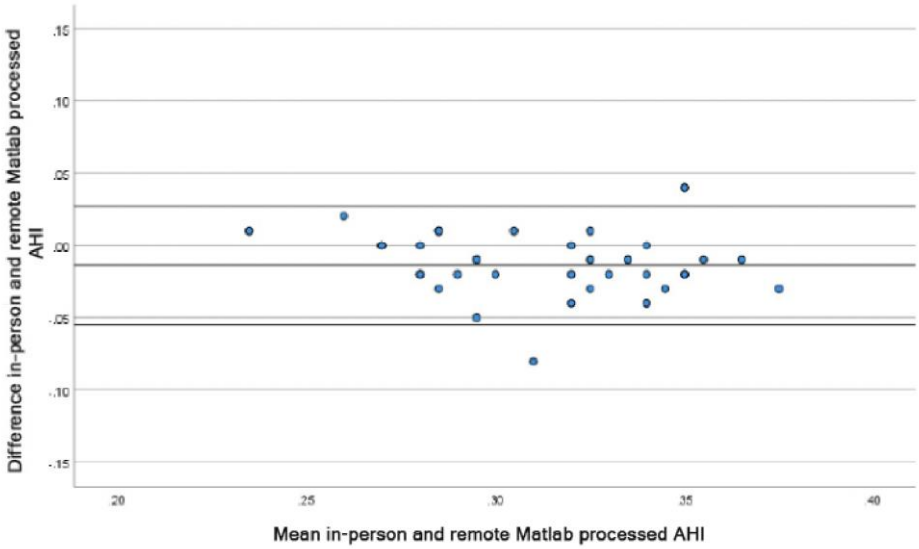


Figure 37: The Bland-Altman plot between in-person and remote AHI assessment methods

The Bland-Altman plot (Figure 37) demonstrated a strong level of agreement between the in-person and remote AHI measurements, due to most plotted points being within the limits of agreement. The mean bias was -0.014 and the upper and lower limits of agreement were 0.028 and -0.055 respectively.

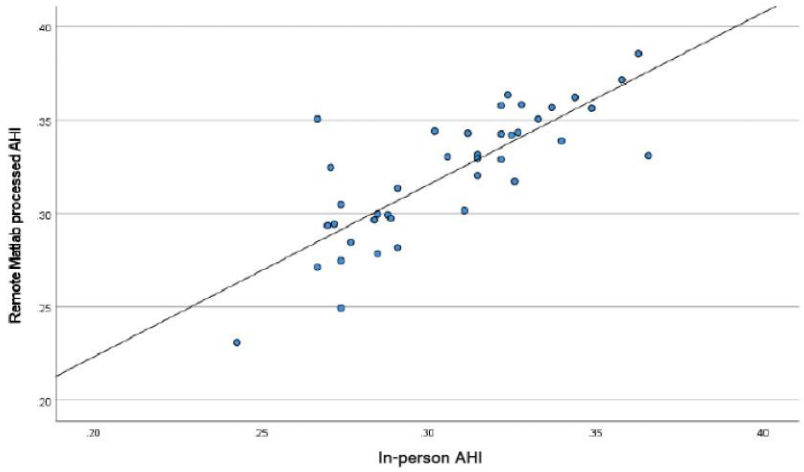


Figure 38: The linear regression analysis between in-person and remote AHI assessments

The linear regression graph (Figure 38) demonstrates the remote AHI values that can be predicted for a given in-person AHI. The R^2 value was 0.644 and the gradient was 0.921 ($p<.05$).

4.4 Descriptive statistics of AI assessment methods

Measurement	In-person (SD)	Remote (SD)	Pairwise mean difference between methods (SD)
AI	0.217 (0.1)	0.229 (0.1)	-0.012 (0.019)
Forefoot width (mm)	90.8 (9.9)	90.9 (9.6)	-0.2 (2.5)
Rearfoot width (mm)	49.8 (6.7)	49.5 (6.4)	0.3 (0.9)

Table 23: The mean and SD values of forefoot width, rearfoot width and AI for each of the in-person and remote methods

The mean AI calculations were similar between the two methods. There was less than 1 mm difference in AI between the in-person and remote assessment methods.

8.6.4 Validity assessment of the remote AI assessment method

Measurement	Correlation between in-person and remote methods
AI	0.977 ($p<.001$)
Forefoot width (mm)	0.968 ($p<.001$)
Rearfoot width (mm)	0.991 ($p<.001$)

Table 24: The Pearson correlation coefficients between in-person and remote AI assessment methods

Strong, significant Pearson correlation coefficients between the in-person and remote AI assessment methods were obtained across all measurements of AI, forefoot width and rearfoot width.

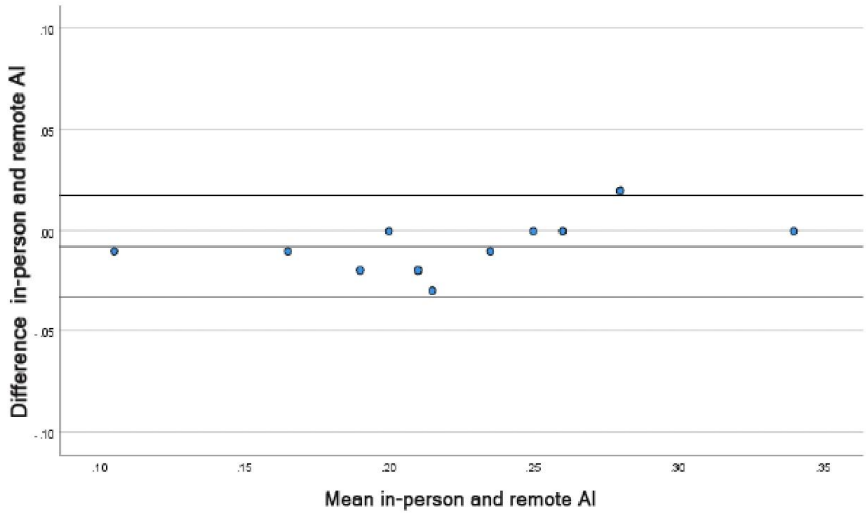


Figure 39: The Bland-Altman plot between in-person and remote AI assessment methods

The Bland-Altman plot (Figure 39) demonstrated a strong level of agreement between the in-person and remote AI measurements, due to most plotted points being within the limits of agreement. There are 11 visible points out of the total of 13, as two sets of points overlapped. The mean bias was -0.008 and the upper and lower limits of agreement were 0.018 and -0.033 respectively.

8.7 Discussion

The purpose of this study was to assess the validity of remote methods for measuring AHI and AI, and to compare the repeatability of remote measurements against their in-person counterparts. The results indicated both the remote AHI and AI measurement methods to have high validity, based on their strong correlations exceeding 0.9 ($p<.05$) with corresponding in-person assessment methods. All ICCs for intra-rater repeatability for the remote and in-person AHI measurements were significant and greater than 0.9, indicating strong repeatability of all the methods.

8.7.1 Arch Height Index

The results from this study demonstrated that both the in-person and remote methods can be used for reliable AHI measurement, underpinned by the strong, significant ($p < .05$) ICCs for intra-rater repeatability (Table 21). Such findings are supported by Williams and McClay [297], who used callipers to conduct manual measurements in a similar manner to the in-person method of this study and reported similarly high intra-rater repeatability ICCs ranging from 0.939-0.975 across 10% and 90% weight bearing stances [297]. Despite the manual calliper AHI assessment method yielding high intra-rater repeatability results, many researchers are turning to use the semi-automated systems, which offer an automated approach of measuring AHI [327]. This method has demonstrated strong intra-rater repeatability upon being used in the standing stance, with an ICC of 0.92 reported with its use in the adult population [327]. However, as conveyed previously, this method holds the drawback of being expensive and comparatively less accessible for wider clinical use than using callipers manually.

With regards to assessing the repeatability of remote AHI measurements, only one study has previously been reported in the literature. This study by Pohl and Fahr [327], used a standardised approach, where bodyweight distribution was controlled by positioning the photographed foot on two blocks-one supporting the forefoot and the other supporting the rearfoot [327]. The other foot was placed on a weighing scale, which was used to monitor bodyweight distribution. Further standardisation was achieved by marking the first metatarsal head to enable the identification of this landmark in the photos. The camera was positioned at a fixed distance [327]. Despite using comparatively more complex equipment, the intra-rater repeatability, albeit strong (ICC = 0.94) [327], was nonetheless similar to that obtained from the remote assessment method used in this study (Table 21). Therefore, it can be observed that reliable measurements can be taken using only simple equipment and instructions. This study's remote method used two sheets of A4 paper, which are easily accessible items, to standardise the camera distance for capturing the photographs. For standardising bodyweight distribution, this has not been demonstrated to affect AHI measurements

[297]. Moreover, the marking of landmarks to minimise error when extracting measurements from the photographs can be deemed less important, given the rise in technology over the years, where smartphones capture high resolution images on which foot landmarks can be accurately identified. Unlike Pohl and Fahr [327], this study conducted data processing on computer rather than printing off physical copies of photographs, thereby holding the advantage of saving time and resources [327]. However, there were some issues posed in processing these virtual images. When using Photoshop, lines had to be constructed by hand and involved visually counting pixels, for example, to mark the 50%-foot length point, from which DH would be assessed. Therefore, Matlab was utilised to resolve this issue through the creation of a semi-automated algorithm, which removed the need to visually count pixels in such a manner. This improved the intra-rater repeatability of the AHI measurements, as demonstrated by the smaller between-day differences.

This study also illustrated the validity of the remote AHI assessment method, through its strong correlation with the in-person method (Figure 38). Furthermore, the linear regression analysis yielded an R^2 of 0.644, indicating a moderate, linear relationship between the in-person and remote AHI assessment methods. In addition, the gradient of 0.921 was close to 1, suggesting that this relatively linear relationship occurs uniformly, where for every 1 unit increase in the in-person AHI measurement, there would be an almost 1 unit increase yielded by the remote counterpart. This was expected, since both methods were used to acquire the same measurements for the same formula to derive the AHI (Figure 31).

Notably, this study used the in-person AHI method as a gold standard for validating the remote AHI measurements. The rationale for this choice of gold standard is supported by the findings of Williams and McClay [297], who reported the AHI measurements taken using callipers to hold the strongest association with radiographic MLA assessment across both 10% (ICC = 0.844) and 90% (ICC = 0.851) weight bearing stances [297]. Furthermore, in-person AHI measurements, in addition to photographic

AHI measurements from a method similar to the remote method used in this study, have demonstrated high correlations against radiographic measurements [297,334].

From the Bland-Altman plot (Figure 37), it can be observed that the remote method tended to generate slightly higher AHI measurements in comparison to the in-person method. This can possibly be explained by the effects of measuring a 3D structure using a 2D virtual image on the screen, where the marked points from which FL is extracted might not have reflected the true length. This would serve as a factor responsible for variability in the remote AHI measurements. Moreover, given the Bland-Altman plot findings, it could be suggested to consider the application of an offset value when taking remote AHI measurements. This can be derived by collating data from future studies upon assessment of a broad population sample, to increase comparability with the in-person AHI method.

8.7.2 Arch Index

The results of this study support the potential for the remote method of AI assessment to be used as a valid alternative to the conventionally used instrumented, in-person method. This is underpinned by the strong, significant ($p< 0.05$) correlation in AI measurements between the two methods (Table 24). Moreover, it is supported by a good level of agreement between both methods, outlined by the Bland-Altman plot (Figure 39) which showed a mean bias of only -0.008 which was close to 0, indicating minimal overestimation of AI measurements by the remote method compared to the in-person method.

These findings are supported by Urry and Wearing [335], who reported a similarly strong, significant correlation of 0.938 ($p<0.05$) between their instrumented pressure plate AI measurement method and remote equivalent ink footprint method [335]; however, their study concluded the measures not to be suitable for interchangeable use, due to relative overestimation of the heel area (2.2%), and underestimation of the midfoot (10.2%) and lesser toe (17.7 %) areas in the pressure plate method

relative to the ink footprint method [335]. Such discrepancies are essential to consider, as these components require precise measurements for the generated AI calculation, to represent the foot structure accurately. Notably, their study's methodology involved the placement of ink paper on the pressure platform to enable simultaneous collection of measurements across both methods. Whilst this may hold the benefit of reducing error from variations in foot stance and positioning that could occur upon taking measurements on separate attempts, the ink paper may have affected the sensitivity of the pressure plate to the foot and affected the generated footprint [335]. This is an important factor, particularly in the case of the midfoot, which was the region which held considerable measurement discrepancy across the two methods. The midfoot is already a site which generates low pressure, as the bodyweight load has the tendency to go to the heel and forefoot rather than the midfoot, due to physiological mechanisms involving the tissue surrounding the MLA, which help to support it and prevent its collapse from compressive force exerted upon it [54,336]. Therefore, it is likely to have been most affected by reduced sensitivity of the pressure plate. In this study, the in-person and remote AI assessments were conducted separately to prevent the pressure plate measurements being affected, while ensuring foot placement across both methods was consistent, with the use of a standardised protocol. Furthermore, the inkless paper used in this study's remote AI measurement method is a highly sensitive method that is used by police forces in the United States of America for obtaining criminal fingerprints, based on their manufacturing webpage [329]. It utilises a wipe, which causes a chemical reaction with the footprint paper, that is more sensitive than typically used ink which is subject to drying out and thereby affecting the quality of the footprint. The impact of this is underpinned by strong, significant correlations between this study's remote and in-person measurements of AI alongside forefoot width and rearfoot width, which are needed to define the long axis from which the footprint is divided to enable AI calculation (Figure 36).

Lastly, another essential aspect to address from this study is the standardisation of AI processing from the footprints. To obtain AI values, software is required to interpret the footprint generated by each

method and gather the constituent measurements for its formula. Variability in software algorithms may cause differences in output. The study by Urry and Wearing [335] used two different types of software for AI calculation in each of the methods that they were comparing [335]. For their in-person measurements, the novel® software was used, which is the same as that used in this study's in-person AI assessment. As for their remote measurement processing, the software used was one that is freely available but does not report the process of obtaining AI. This could have increased the propensity for differences in the AI values generated, because of variability in the formulation of measurements from the footprints. In this study, the algorithm used to calculate AI from the remote measurements was based on the novel® geometry software algorithm used for the in-person measurements taken with the pressure plate. This was achieved by specifically extracting the instructions from the geometry program on AI calculation by the novel® system and generating a code in Matlab to emulate them, when applied to the remote measurements.

8.8 Limitations

There were some limitations present in this study. For AHI measures, only intra-rater repeatability was assessed. However, there are previous studies that have reported strong inter-rater repeatability for in-person methods of AHI measurement with callipers [210,297]. In addition, for in-person and instrumented, and remote assessment of AHI and AI, the participants were limited to healthy individuals with no notable foot deformities or surgeries. Therefore, there is the possibility of error being higher in the presence of foot pathology.

Furthermore, with regards to the in-person and remote methods for AI measurement, the sample size used was small, albeit being representative of the general population with a wide age range and balance of genders. Therefore, further assessment of repeatability and validity across multiple settings with a larger sample size, incorporating a varied spectrum of foot types, needs to be conducted to definitively confirm its feasibility for wider clinical use.

Future research and work is needed to determine the feasibility of using the in-person and instrumented, and remote AHI and AI assessment methods in patients with clinical foot pathologies. Additionally, a greater sample size would allow for increased external validity of the findings, in order to justify the interchangeable use of the remote AHI and AI assessment methods with their in-person and instrumented counterparts in the wider clinical setting.

8.9 Conclusion

This study demonstrated that both the in-person and remote AHI assessment methods are highly reliable. In addition, it suggested that remote AHI and AI assessment methods have the potential to be used as a substitute for in-person and instrumented assessments, underpinned by the results demonstrating their strong validity. Given the lifting of COVID-19 social distancing restrictions partway through this project, together with willingness of participants to attend clinical assessment, remote assessment methods were ultimately not utilised in the longitudinal study on FFF, which will be discussed in the next chapter. However, this work could provide the foundation for further studies allowing greater participation through use of these remote methods.

9 A longitudinal study with 7-8 years follow-up on a flexible flat feet cohort

A viable method for remote data collection of foot posture has been established, as described in the previous chapter. While it was deemed suitable for use in this prospective study, following the lifting of the COVID-19 restrictions, clinical data collection became a feasible option. Therefore, data collection in person was performed in the OGL.

9.1 Introduction

There is no clear evidence on the long-term implications of persistent FFF, with no longitudinal study on this condition having been conducted to address this. Currently, only cross-sectional studies, predominantly on children and to a lesser extent on adults have given insight into the effects of FFF on kinematics, symptoms and quality of life (QofL) [1,2-7,30–38].

Prior to addressing FFF, it is necessary to understand the natural process of development that occurs in typically developing feet, in order to put changes in FFF into context [2,73,81,111,113–115,341]. At birth, a large proportion of the foot is cartilage and soft tissue. Following this, there is gradual ossification of the various foot bones. Ossification of the midfoot bones, such as the navicular, happens relatively later than the other foot bones (including the phalanges, talus and calcaneus) [12,77–84]. It can even occur as late as 4-5 years of age. This explains why the foot arch is not formed at birth and gradually appears over time. Studies utilising a variety of static foot posture measures have demonstrated the change from a flat foot to a normal arch by the age of 6 to 8 years [1,6,10–20].

After this point of development, the arch has been demonstrated to increase in height until the age of around 13 years [2,11,343,344]. Many studies have evaluated arch height up until 18 years of age

and shown limited evidence of any changes that occur beyond this age. The precise point at which foot arch development is complete remains difficult to determine, due to differences across studies in the gender and body composition of participants, and choice of techniques to measure arch height [7]. In contrast to arch height, changes in foot length have been reported to occur rapidly, with around 2 millimetres of growth per month, until the age of 3 years [12]. While growth beyond this age is relatively slower, the foot has been demonstrated to significantly grow from 6-14 years in boys and 6-13 years in girls, followed by a plateau [342,344,345].

The properties of the soft tissues within the feet also change and develop over time. Young children have fewer cross-links between the collagen fibres within their tendons and ligaments, which increases elasticity and flexibility, thereby facilitating greater joint ROM [12,87]. This has been evidenced using kinematic analysis, with a study on children ranging from 5-15 years, demonstrating significantly higher ankle dorsiflexion range in younger children compared to older children [346]. The ratio of foot size to bodyweight also changes over time. Young children have larger feet compared to their bodyweight than adults, resulting in lower peak plantar pressures when walking [184]. With increasing age in adulthood, the foot becomes wider and flatter [347]. In addition, the thickness of the plantar fatty pad in the foot is reduced, resulting in higher peak pressures in the region of the metatarsal heads and heel when walking [184].

While there is reasonable understanding and underlying evidence for how feet typically develop from childhood to adulthood, there is far less evidence on the progression of FFF through these time points. It is thought that if FFF is present in childhood, there is maintenance of a child-like foot structure (i.e. persistence of a low arch) beyond the completion of foot development and into adulthood [143,348]. However, there are currently no longitudinal studies that support this theory.

Thus far, only cross-sectional studies have been reported in the literature. These studies have reported reduced walking speed in children with FFF compared to NF [5,306,349,350]. In addition, variations in lower limb kinematics in children with FFF including reduced ankle dorsiflexion [349,351] and increased hindfoot eversion [122,252,351] forefoot supination [122,252,350,352] and abduction [122,252,352] have been reported in comparison to NF. The kinematic differences observed in FFF have also been evaluated in relation to symptoms, with a notable finding of increased forefoot abduction throughout the stance phase in symptomatic FFF compared to both asymptomatic FFF and NF [136]. Furthermore, the kinematic finding of increased forefoot supination observed in FFF was inversely correlated with a physical quality of life (QofL) domain [5]. In addition, minimum hindfoot eversion was positively correlated with the physical QofL domain, although most other hindfoot eversion measurements were not. Irrespective of the impact of kinematic associations, children with FFF were noted to have poorer QofL outcomes alongside significantly increased odds of knee, hip and back pain [5,7,139]. With these findings, it is evident that children with FFF exhibit differences in foot and ankle kinematics, which can impact gait, function, and QofL.

Comparatively, there is limited evidence on the impact of FFF in adults. When using the strict criteria of including studies explicitly assessing persistent FFF that has been present since childhood and excluding cases of other flat feet and adult acquired FFF, the only available evidence includes studies focusing on the use of orthoses [158,166,353,354]. However, these studies on FFF and orthoses have either not used control groups or have reported results in a manner that cannot allow for identification of kinematic or symptom differences between adults with FFF and NF.

An understanding of the long-term effects of FFF, in terms of structural changes and impact on symptoms and QofL, is crucial for informing treatment decisions. By acquiring evidence on this, informed decisions on whether and when to treat FFF can be made. Given the current lack of longitudinal evidence on this matter, this study aimed to address this gap by investigating differences

in foot posture and walking pattern in FFF between childhood and adulthood, alongside evaluating the association between childhood foot posture and adulthood QofL.

9.2 Objectives

Objective 2: Use the outcome of objective 1 (see section 6.8 page 94) to investigate changes in static foot posture from childhood into adulthood in those with flexible flat feet compared to those with neutral foot postures.

H0 There will be no significant change in static foot posture in adulthood compared to childhood, regardless of initial foot type.

Objective 3: Use the outcome of objective 1 (see section 6.8 page 94) to investigate change in dynamic foot motion during walking from childhood into adulthood in those with flexible flat feet compared to those with neutral foot postures.

H0 There will be no significant change in dynamic foot motion during walking in adulthood compared to childhood, regardless of initial foot type.

Objective 4: To investigate the relationship between foot posture and walking patterns in childhood and quality of life in adulthood.

H0 Foot posture and walking patterns in childhood are not associated with quality of life in adulthood.

9.3 Ethical Considerations

This study used a combination of “baseline data” from a previous study on subjects with neutral feet (NF) and flexible flat feet (FFF), and “follow-up data”, newly acquired from following up a portion of the baseline data subjects. The baseline data was collected as part of the doctoral studies of Mr Alpesh Kothari, who gained the approval of the National Research Ethics Service (REC reference: 12/SC/0334, Oxford — South Centre B Committee). Separate approval was gained for the collection of follow-up data from the National Research Ethics Service (REC reference: 21/NE/0228, York- North-East Committee).

9.4 Participants and their recruitment

9.4.1 Baseline participants

Baseline data collection was undertaken by Mr Alpesh Kothari between August 2012 and April 2014. The study participants included 95 children (190 feet) with a mean age of 11 years (age range of 8-15 years). Its recruitment was mainly conducted through advertisement in clinical practice. For more detailed information on this study's recruitment process and inclusion criteria, please refer to Figure 40, that was extracted from the doctoral thesis of Mr Alpesh Kothari [252].

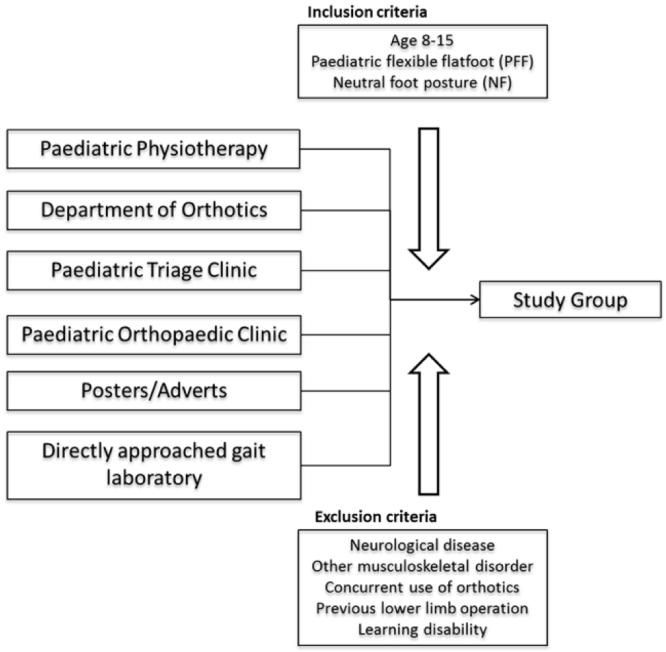


Figure 40: The selection criteria and route of entry of children into the baseline study of flexible flat feet

9.4.2 Follow-up participants

For the follow-up data, the recruitment process entailed triaging participants from the baseline study, using the email addresses and telephone numbers of their parents to determine if they were eligible, as per the inclusion and exclusion criteria (Figure 41).

The inclusion criteria for the follow-up of the baseline study were the following:

1. If the participant is aged below 16 years, both the participant and their legal guardian are willing and able to give assent/informed consent for taking part in the study.
2. If the participant is aged 16 years or above, the participant is willing and able to give informed consent for taking part in the study.
3. The participant must have taken part in the baseline data collection study named "Defining surgical indications for children with flexible flatfeet".
4. No previous/current surgeries or significant injuries to legs or feet (upon clinical assessment by a trained podiatrist).
5. Presence of the navicular marker in the baseline study marker data set

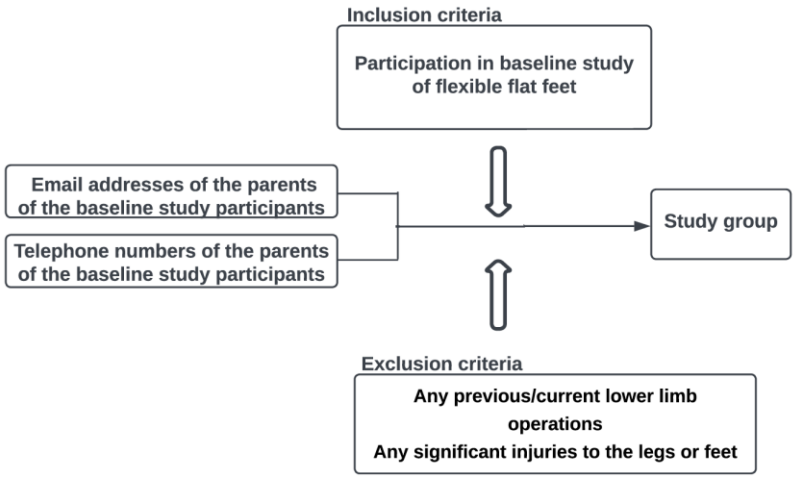


Figure 41: The selection criteria and route of entry of children into the follow-up study of FFF

Twenty participants from the baseline study returned for the follow-up study, with 10 having FFF and 10 NF. The demographic characteristics of the baseline cohort, divided into those who returned at follow-up, and those who did not are presented in Table 25. It can be seen that there were no significant differences between the participants who returned for follow-up and those who did not, indicating there was no recruitment bias introduced by only having a subset of the baseline cohort return at follow-up. Furthermore, these 20 participants represented everyone who wished to return for follow-up assessment, indicating that no-one was excluded based on the inclusion/exclusion criteria.

Characteristic	**Baseline cohort**	**Baseline cohort not followed-up**	**Baseline cohort followed-up**
Number of participants	95	75	20
Age at baseline in years (SD)	11.9 (2.2)	11.9 (2.2)	12.2 (2.0)
Gender	F45 M50	F35 M40	F 10 M10
Height at baseline in cm (SD)	153.0 (13.7)	153.3 (14.2)	152.2 (12.0)
Weight at baseline in kg (SD)	44.0 (14.4)	44.8 (14.7)	42.6 (13.5)
BMI (SD)	18.6 (3.4)	18.6 (3.4)	18.0 (3.4)
AHI at baseline (SD)	0.31 (0.03)	0.31 (0.03)	0.31 (0.03)
Arch type frequency (proportion)	FFF 48 (50.5%) NF 47 (49.5%)	FFF 38 (50.7%) NF 37 (49.3%)	FFF 10 (50.0%) NF 10 (50.0%)

Table 25: The baseline anthropometric characteristics of all participants, participants not included in the follow-up study and participants followed up

9.5 Equipment

To capture both baseline and follow-up motion data, 10 mm retro-reflective markers and sixteen infra-red Vicon MX-T40 cameras (Vicon Motion Systems, Oxford, UK) were used for tracking. To identify gait events and measure the ground reaction force, two AMTI OR6-6-1000 and one OR6S6 force-plates were used. For further details, refer to Chapter 5.

9.6 Gait Analysis Data Collection

Gait analysis was undertaken in the OGL at the Nuffield Orthopaedic Centre in Oxford at both baseline and follow-up. The protocol that was used for system calibration and subject preparation is presented in Chapter 5.

9.7 Data processing

The kinematic data processing for the baseline and follow-up data is presented in Chapter 5. It must be noted that the MLA angles for the baseline data were retrospectively calculated. This was possible due to the baseline data set having included the navicular marker. The reason for including the navicular marker in the baseline study was to assess the navicular motion in gait.

For static foot posture assessment, the mean measurement value from the whole static standing trial data was calculated for each variable. For walking pattern assessment, the mean, minimum, maximum and range across the GC were calculated from the whole GC and measurements at toe-off and heel contact for each variable were also extracted.

9.8 Foot type

Foot posture was formally classified in the baseline study, on the basis of specific radiological, anthropometric, footprint and gait analysis parameters [140]. Children were categorised into two groups, as either having FFF or NF. The foot posture measurement indices for each group were consistent with previously published literature [133,134,201,325,355]. In addition to fulfilling these objective criteria, a prerequisite for qualifying as FFF was the observation of a lowered MLA when standing and the recreation of the MLA when standing on tiptoes. To ensure the exclusion of developmental flat feet in the baseline study, a lower age limit of eight years was set for recruitment [139].

9.9 Quality of Life

Quality of life is a multi-dimensional concept that incorporates an individual's perception of well-being in the context of the environment and culture in which they live [356]. It is underpinned by an individual's physical health and psychological state [356–358]. Given its broad definition, it can be adapted to the situation of interest. This may entail focusing the information gathered towards a specific condition in a particular region, such as osteoarthritis of the foot and ankle, or tailoring it towards a particular demographic, such as children or adults [359–364]. To ensure such information is accurate and applicable to the population of interest, it is essential to use a validated assessment tool. Through this, objectives including evaluating the effectiveness of healthcare interventions, monitoring the progression of disease, informing healthcare resource allocation and policy, alongside improving patient-centred care can be achieved [356,363–367]. In the context of this study on FFF, QofL data was collected to help form an evidence-based treatment paradigm.

9.9.1 Oxford Ankle Foot Questionnaire

To assess QofL at baseline, a specific measure targeted towards the assessed cohort of children of 8-16 years was utilised. This was the Oxford Ankle Foot Questionnaire for children (OxAFQ-C) [364]. The OxAFQ-C consists of 15 questions, from which discrete scores for the domains of physical, school and play and emotional are calculated. It takes into account the impact of foot and ankle issues experienced from both the child and parent's perspectives.

During baseline data collection, both the child participant and their guardian were asked to complete the questionnaire in an appointment [252]. This involved answering closed questions using a five-point Likert scale which provided a score. Subsequently, scores for each domain were calculated as a sum of the scores from corresponding answers divided by the maximum possible total score. The total scores for each domain were converted to a percentage [364].

The repeatability of the OxAFQ-C has been demonstrated by ICCs for intra-rater repeatability ranging from 0.76-0.95 in each domain when assessing children [368]. It has also displayed convergent and discriminant validity from comparison with the established Kidscreen HRQOL [368,369].

To enable direct comparability, the OxAFQ-C was also used in the follow-up study, even though the participants were no longer children. However, it was necessary to omit the school and play domain from the OxAFQ-C for reasons of sensibleness and inapplicability, and only evaluate the physical and emotional domains. It must be acknowledged that this tool has not been validated in adults and that there is no previous literature that has prospectively assessed QofL across both childhood and adulthood [364,368,369]. Therefore, its findings were interpreted with caution and supplemented by the Foot Health Status Questionnaire (FHSQ) QofL tool, that has been validated in adults [362].

9.9.2 Foot Health Status Questionnaire

The FHSQ was developed for use in adults, following a review of existing foot health questionnaires [362]. For this study, it was adapted as an online version, which only the participants themselves completed. It comprised eight domains: foot pain, foot function, general foot health, physical activity, social capacity, general health, shoes, and vigour [362]. These were scored based on responses to a five-point scale [362]. Domain scores were automatically calculated using the FHSQ software, to generate a percentage.

The FHSQ has demonstrated adequate intra-rater repeatability for each of its domains, when assessed through Cronbach's alpha, with a minimum acceptable cut-off of 0.7 [370]. Specifically, Cronbach's alpha values ranged from 0.85 to 0.88 across the footwear, foot function, general foot health and foot pain domains upon assessment of podiatric patients [362]. In addition, ICCs for intra-rater repeatability ranging from 0.74-0.92 for these aforementioned domains have been reported when assessing patients in routine care, with repeat assessments taken a week apart [362].

The FHSQ has been validated in terms of Its construct validity, by assessing whether its domains demonstrated no significant difference in relation to the actual data characteristics [362]. This entailed the conduction of confirmatory factor analysis, in which the model comprising the foot function, general foot health and foot pain domains achieved an acceptable level of goodness of fit that was assessed using the root mean square error of approximation, goodness of fit index and comparative fit index [362]. Notably, the comparative fit index was 0.96, indicative of high validity, due to being above a 0.95 threshold [371].

The FHSQ has demonstrated the ability to clinically evaluate foot health and function, by detecting changes reflective of the extent of foot pathology [372–375]. This has been exemplified in a population of older adults, where those with minor foot pathologies such as hyperkeratosis and nail pathology had a higher mean FHSQ foot function score of 88.8 compared to those with morphological disorders including hammertoes, with a mean score of 77.9 [372]. In addition, it demonstrated the lowest mean score of 53.9 in those with acute diseases such as plantar fasciitis [372]. Moreover, the FHSQ has shown the sensitivity for determining changes reflective of clinical improvement. This was demonstrated in 175 patients with plantar fasciitis, in which thresholds for score improvements of 14 points in foot pain, 7 points in foot function and 9 points in general foot health were found to be able to convey improvements in foot health [376].

The FHSQ is scored out of 100, with 0 indicating the worst QofL and 100 the best QofL. A score cut-off for distinguishing between good and poor QofL can be determined based on the literature [362]. Specifically, a score of 75/100 was set by Dominguez to represent high QofL, with increments of 25 to differentiate the other three categories of very low, low and medium QofL [373]. This cut-off of 75 has been empirically demonstrated to be viable, with the mean QofL scores of 1647 adults with known foot problems including keratosis, hallux valgus and flat feet ranging from 50.75 to 74.61 in the foot pain, footwear, general foot health, overall health and vigour domains [363]. Therefore, with known

foot pathologies scoring below 75 in these domains, it would be justified to deem those above this threshold to have good QofL.

9.10 Statistics

Given the sample at follow-up was limited to those who had already taken part in the baseline study, a new sample size calculation was not applicable. Rather, measures were taken to maximise the recruitment of baseline study participants. In addition, a statistician (Robin Prescott, Emeritus Professor Of Health Technology Assessment at Centre for Public Health Sciences, University of Edinburgh) was consulted to advise on choices of statistical analyses.

The data was assessed for normality using the Shapiro-Wilk test. In terms of missing data, no imputation methods were used. Where there was missing data for a particular test, the participant was excluded for that test. Statistical Package for the Social Sciences (SPSS) version 29 was used to run the statistical tests.

To fulfil the objectives of investigating differences in foot posture (objective 1) and walking patterns (objective 2) between childhood and adulthood, various static and dynamic measurements were taken from the followed-up participants. The measurements for each static and dynamic variable taken at follow-up are presented in the form of mean values and standard deviations. The follow-up data for each variable was directly compared against corresponding baseline data through several statistical tests. Scatter plots were formed to enable visual inspection of trends, including their direction and linearity. Paired t-test analysis was conducted to check for significant differences between baseline and follow-up measurements for each variable. If a significant difference was detected on the paired t-test or if a definitive visual trend was observed on the scatter plot, further analyses were conducted. These included multiple regression to determine the equation of the line in the variable measurement between baseline and follow-up, for the whole cohort and for FFF and NF participant groups independently. In addition, 2x2 Analysis of Variance (ANOVA) was conducted for each variable to assess its relationship with foot type and time point of measurement via interaction

effects analysis. Post-hoc testing was not conducted, as this was an exploratory study. While it is acknowledged that this would rebalance the compounding risk and adjust the p-values to reflect this risk of type I error, a fixed significance level of $p<.05$ was used to determine variables that should be investigated in the future rather than provide definitive results. For the static and dynamic variables in which notable and significant findings were observed, Bland–Altman plots were constructed to visually inspect the distribution of differences between baseline and follow-up measurements.

All variables had Pearson correlation analysis conducted to assess for associations between baseline and follow-up measurements. If a significant association was detected, interaction effects in regression analysis between foot type and timepoint of data collection was also evaluated.

To address the objective of investigating the association between foot posture in childhood and QofL in adulthood (objective 3), various QofL data was collected from the followed-up participants. Aspects of the childhood OxAFQ-C questionnaire that were deemed applicable for adults were extracted, and the follow-up participants answered these questions. In this study, this included the physical and emotional QofL domains. Direct comparisons between baseline and follow-up QofL scores in these domains were made by visual inspection of the distribution of scores amongst the participants at both time points. This included commenting on trends pertaining to demographic characteristics and foot type.

The FHSQ, which has been validated for use in adults, was utilised to collect QofL information at follow-up and compared with baseline static and dynamic measurements for characterising the foot. Independent t-test analyses were used to determine if there were significant differences in scores for each FHSQ domain between those scoring 75 or below (poor scores) and those scoring above 75 (good scores) for each variable. This statistical assessment was only conducted if there were 4 or more participants in each of the good and poor score category definitions, to avoid bias. This was

accompanied by visual assessment of trends in data between variable measurements and QofL scores.

The results obtained upon conducting these analyses will now be presented.

10 Evaluation of static foot posture across childhood and adulthood

This chapter outlines the results obtained upon analysis of static foot posture in childhood and adulthood. Static foot posture can be characterised through several variables, which quantify its form in weightbearing and non-weightbearing. The AHI, standing and sitting MLA angles, and arch rigidity provide a direct perspective of MLA height, while hindfoot eversion which is influenced by the MLA, gives an indirect perspective of this structure.

10.1.1 Results

Upon conducting the Shapiro-Wilk test for normality, it was confirmed that all the data for each variable were normally distributed. The descriptive statistics (Table 26) of the static foot posture variables revealed changes between baseline and follow-up for both FFF and NF individuals. Specifically, the AHI variable showed a decrease in arch height over time for both foot types. On the other hand, the standing and sitting MLA angle variables suggested an increase in arch height over time for FFF, as indicated by a decrease in MLA angle measurements. For the NF group, the standing MLA angle indicated a decrease in arch height over time, while the sitting MLA angle showed an increase in this regard.

To gain further insight into the measurements taken at the two time points, visual analysis was conducted initially, using scatter plots (Figure 42) between baseline and follow-up measurements of the variables. This analysis demonstrated positive, linear associations for the AHI and standing and sitting MLA angle variables. Supplementing the visual analysis, paired t-tests were performed (Table 27), revealing significant differences in only the AHI and sitting MLA angle measurements between the two time points. The variables which demonstrated a positive linear relationship visible in the scatter plots or exhibited differences between baseline and follow-up measurements in the paired t-tests, underwent further evaluation for investigating change between time points and foot types. This

included the conduction of ANOVA and slope analyses to compare the changes over time between FFF and NF groups (Table 27). These analyses revealed differences between the two foot types in the AHI and standing and sitting MLA angle variables. In addition, the AHI and standing and sitting MLA angle variables, which demonstrated significant correlations between baseline and follow-up measurements, underwent interaction effects regression analysis. The specific nature of the observed results will be further elaborated in the discussion section.

Static foot posture variable	**FFF baseline**	**FFF follow-up**	**NF baseline**	**NF follow-up**
AHI	0.28 (0.03)	0.24 (0.04)	0.33 (0.02)	0.27 (0.04)
Standing MLA angle (°)	173 (5)	170 (10)	160 (7)	161 (5)
Sitting MLA angle (°)	167 (6)	162 (7)	155 (8)	153 (9)
Hindfoot eversion (°)	-3 (5)	-2 (5)	-3 (6)	-1 (4)
Arch rigidity (°)	6 (4)	8 (5)	5 (5)	9 (9)

Table 26 presents the mean and standard deviation (SD) values at baseline and follow-up for the static foot posture variables in the FFF and NF groups

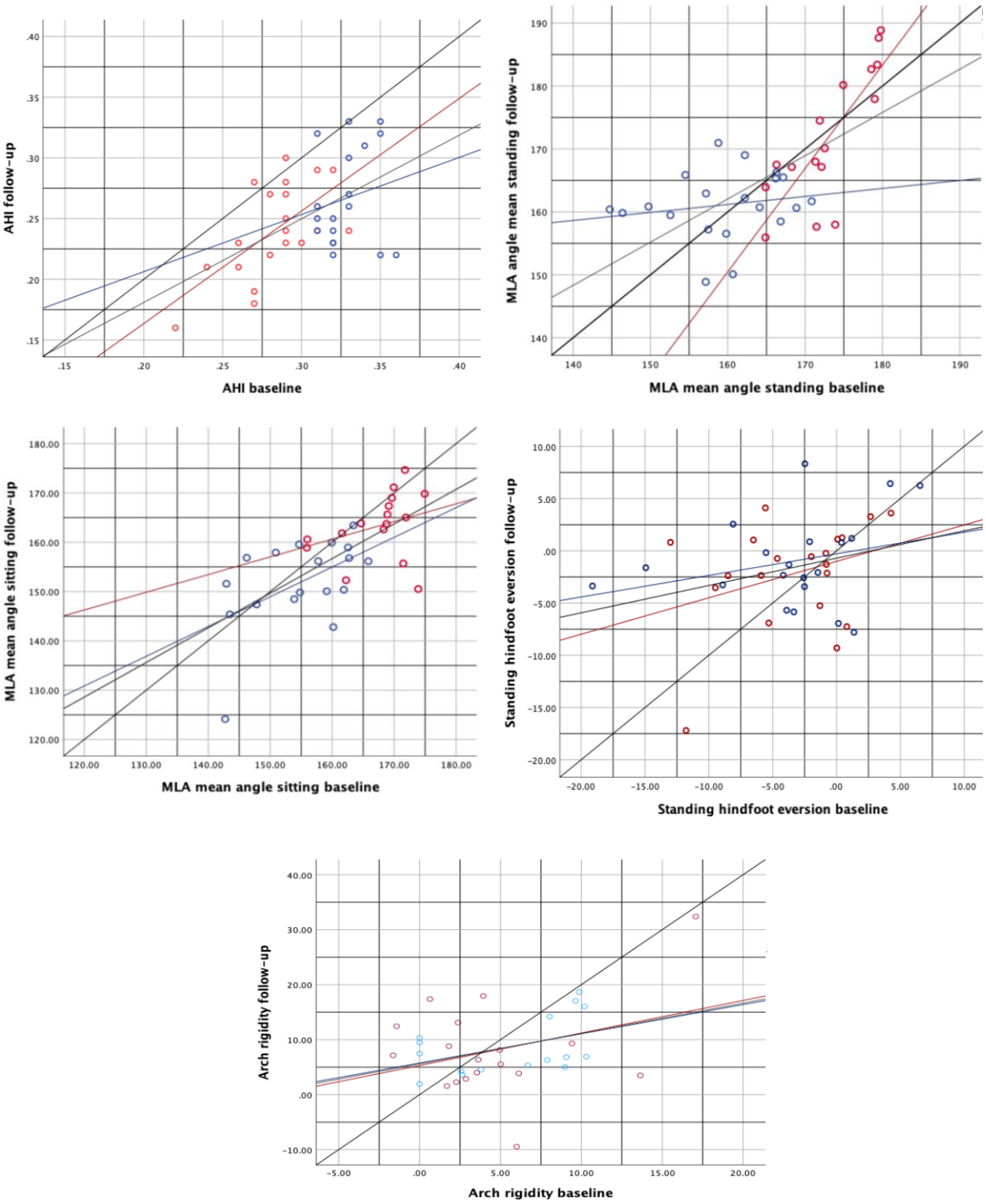


Figure 42: The scatter plots showing the relationship between baseline and follow-up variable measurements for static foot posture assessment. The FFF data are represented by red circles and the NF data by blue circles. The red and blue lines represent the individual group slopes of FFF and NF respectively, and the dark green line represents the overall group slope. Additionally, the 45° line is coloured in black.

Measurement variables of foot posture	**Scatter plot (visual assessment)**	**Equation of the best fit line group for baseline to follow-up (p value)**	**Pearson correlation baseline and follow-up (p value)**	**Equation of the best fit line for baseline to follow-up FFF**	**Equation of the best fit line for baseline to follow-up NF**	**Interaction effect regression gradient (p value)**	**Paired t-test (p value)**	**2x2 ANOVA time point (p value)**	**2x2 ANOVA foot type (p value)**	**2X2 ANOVA interaction effects (p value)**
AHI	Positive linear	0 + 0.69x **(p<.001)**	0.528 **(p=.001)**	0 + 0.93x	0 + 0.47x	(p=.459)	**(p<.001)**	**(p<.001)**	**(p<.001)**	(p=.171)
MLA standing	Positive linear	52 + 0.69x **(p<.001)**	0.658 **(p<.001)**	112 + 1.64x	141 + 0.13x	**(p<.001)**	(p=.820)	(p=.698)	**(p<.001)**	(p=.223)
MLA chair	Positive linear	44 + 0.70x **(p<.001)**	0.668 **(p<.001)**	103 + 0.36x	59 + 0.60x	(p=.545)	**(p=.011)**	**(p=.024)**	**(p<.001)**	(p=.401)
Hindfoot eversion standing	No association		0.294 (p=.066)				(p=.061)			
Arch rigidity	No association		0.177 (p=.332)				(p=.329)			

Table 27: The variables commonly used in the literature for the assessment of static foot posture. Significant p values are presented in bold.

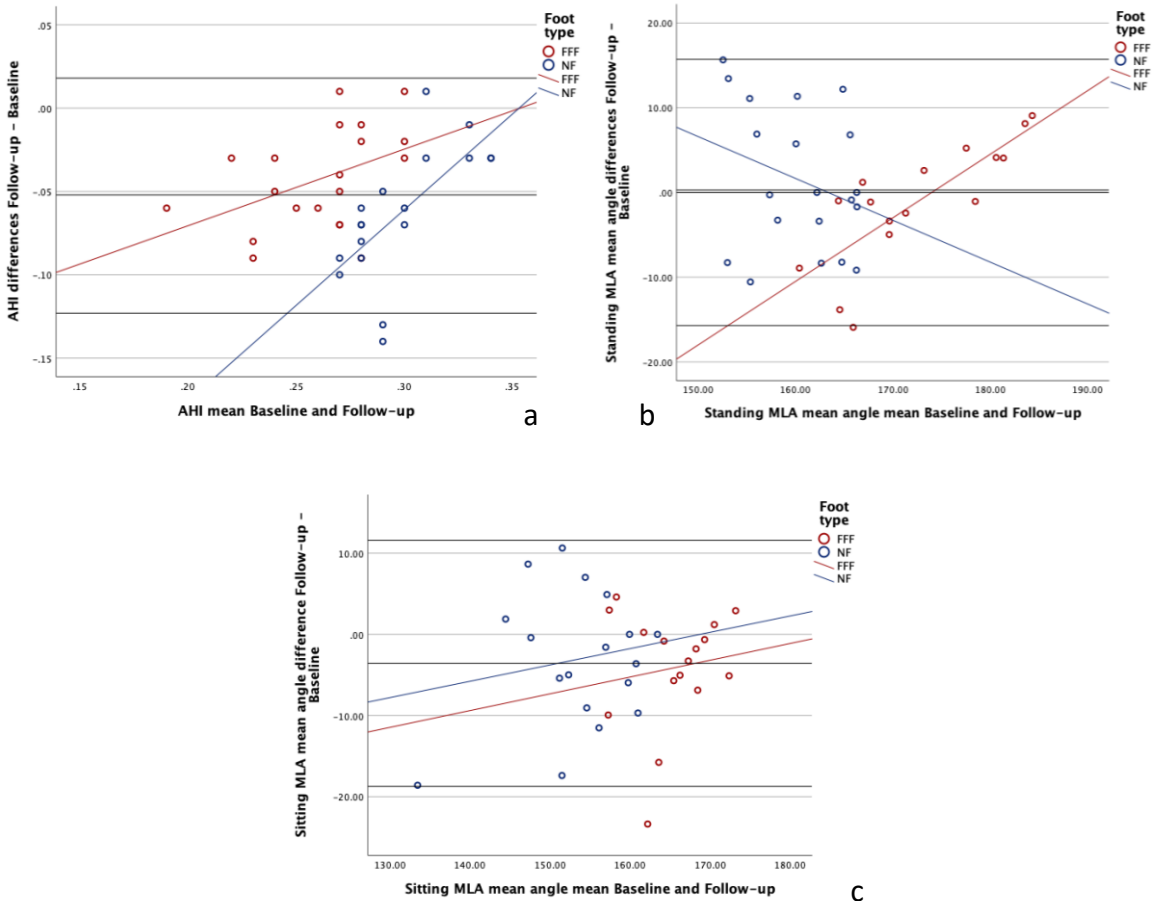


Figure 43 a-c : The Bland-Altman plots for the a) AHI b) standing MLA angle and c) sitting MLA angle, showing the distribution of mean measurements between baseline and follow-up against the difference in measurements by subtracting baseline from follow-up. The red colour represents the distribution of FFF data, while the blue colour represents the distribution of NF data. The black horizontal lines represent the limits of agreement.

10.2 Discussion

The aim of this study was to assess the changes in foot posture that occur following the completion of arch development in childhood into adulthood, alongside identifying any differences in such changes between FFF and NF cohorts. From this study's results, the AHI variable indicated that the foot arch will get flatter over time, which was supported by the standing MLA angle variable in FFF only. The MLA was comparatively flatter in FFF in comparison to NF in the AHI and standing and sitting angle variables at both time points of assessment.

The various methods to assess static foot posture have been discussed in chapter 4. The static assessment variables used in this study are widely acknowledged and commonly utilised in both academic research and clinical practice and have been demonstrated to be valid and reliable indicators of foot posture in the general population [5,122,212,221,291,377–380]. The MLA angle, which utilises surface markers and motion capture to characterise the MLA form, was newly developed in this study. This study utilised non-weightbearing positions in addition to weightbearing positions, to provide an insight on the structural alignment of the foot without the influence of external forces or movement [10,11].

10.2.1 AHI

From the static foot posture variables, the AHI is one that is most commonly used in studies for arch height assessment in FFF [109,139,151,194,381,382]. In this study, the AHI indicated significant differences in MLA height between baseline and follow-up as per the paired t-test, while also demonstrating a significant correlation between the measurements taken at each time point (Table 27). The mean values for both FFF and NF were comparatively lower at follow-up, suggesting a relatively flatter arch in comparison to baseline. This finding was also suggested by the Bland-Altman plot (Figure 43a), on which the mean difference line was at approximately -0.05. In addition, the limits of agreement for the mean change in AHI ranged from -0.12 to 0.02. Given the majority

of mean differences falling within this range were below 0, there is a high likelihood that within the general population, a decrease in AHI from childhood to adulthood would also be observed. Furthermore, the slopes on the Bland-Altman plot suggest that the lower the mean AHI across baseline and follow-up in both FFF and NF, the greater the reduction in AHI at follow-up. This indicates that flatter feet would have a higher likelihood of experiencing a greater extent of flattening over time in comparison to higher arched feet.

When comparing between the two foot types, the lack of significance in both interaction effects of the regression and ANOVA analyses suggests that the change in AHI between baseline and follow-up did not differ between FFF and NF (Table 27). Rather, there were differences in AHI present at both time points, indicated by the foot type ANOVA results. The mean NF AHI was higher than the mean FFF AHI in each of the baseline and follow-up measurements, indicative of a flatter arch in FFF in both childhood and adulthood (Table 26).

It must be noted that the AHI measurement technique at follow-up had a slight discrepancy to that at baseline. While the same calculation process was utilised at both time points, the follow-up study utilised graph paper unlike the baseline study. The graph paper had a long line representing the longitudinal axis of the foot, which facilitated foot length measurement with the callipers to derive the AHI and avoided reliance on visual judgment for demarcating the locations of the toes and heel of the foot. In addition, the graph paper had 1 mm spaced lines running perpendicularly and a line marking the long axis of the foot to aid mapping of these landmarks. Such differences in methodology may be explanatory of the statistically significant difference in mean AHI noted at follow-up in comparison to baseline. Alternatively, they might have not had an effect and the differences noted would have been due to true flattening of the arch over time.

10.2.2 MLA standing angle

The standing MLA angle scatterplot demonstrated no overall change in arch height between baseline and follow-up, with most data points being scattered around the 45° line. This is supported by the paired t-test, which indicated no significant difference in standing MLA angle between the two time points of assessment (Table 27). The lack of overall change can also be observed from the minimal difference in mean standing MLA angle between baseline and follow-up for both FFF and NF participants (Table 26). This was also illustrated in the Bland-Altman plot, where the mean difference line was close to 0°. In addition, there was a relatively even distribution of data points above and below the zero-difference line, with most follow-up measurements ranging from being 10° below to 10° above their corresponding baseline measurement (Figure 43b). This makes it difficult to determine any particular direction of change and indicates that there may be no true difference in standing MLA angle given the limits of agreement included a change of 0°.

When comparing standing MLA angle by foot type, the interaction effect of the regression analysis yielded a significant result, indicating that the change in standing MLA angle over time was different between FFF and NF. This was visible from the individual slopes, with a gradient of 1.64 in FFF and 0.13 in NF and y intercepts which were not very dissimilar (Table 27). Therefore, there was evidence to suggest that there was a significant difference in how the standing MLA angle changed over time between FFF and NF groups. This is corroborated by observing the foot type ANOVA results, where it can be noted that there was a significant difference in standing MLA angle between FFF and NF foot types (Table 27). Since the gradient in FFF was markedly larger, it suggests the baseline measurement value had a much greater influence on the follow-up measurement in contrast to NF. Given that the gradient is above 1 in FFF, it suggests this condition will deteriorate over time by means of the follow-up standing MLA angle being much larger and the MLA being flatter than at baseline. Therefore, the prognosis in FFF is that it would be expected to flatten over time. Comparatively in NF, given the very small gradient in the standing MLA slope that is close to 0, this

suggests the baseline measurements would have minimal impact on those at follow-up. Therefore, for this foot type, it is difficult to predict MLA in adulthood. Furthermore, the slope on the Bland-Altman plot suggests that the higher the mean standing MLA angle across baseline and follow-up in FFF, the greater the increase in standing MLA angle at follow-up. Given the inverse relation between this variable and MLA angle, this indicates that flatter FFF would have higher likelihood of experiencing a greater extent of flattening over time in comparison to higher arched FFF.

10.2.3 Sitting MLA angle

In contrast to the standing MLA angle, the sitting MLA angle enables characterisation of the arch form in FFF when the foot is unloaded. Due to removal of the effects of the bodyweight, the arch can maintain its integrity [2,73,111]. Both variables provide vital information when compared against one another, on how the foot behaves and adapts under different loading conditions. The sitting MLA angle measurements taken at baseline and follow-up were demonstrated to be associated based on the correlation analysis (Table 27). In addition, a significant difference between measurements across the two time points was noted from the paired t-test. This was visually evident in the scatter plots, with most measurements falling below the 45° line, and mean values for both FFF and NF indicating a comparatively lower sitting MLA angle at follow-up (Figure 42). Since the sitting MLA angle is inversely proportional to arch height, this would convey an increase in arch height over time for the participants. This was also observed in the Bland-Altman plot, where the mean difference line was approximately -4° (Figure 43c). In addition, most measurements fell within the limits of agreement, with a relatively greater proportion of measurements below the zero-difference line in the 0-20° range. However, since the limits of agreement included 0°, there is the possibility that there is no true difference in sitting MLA angle between childhood and adulthood. With regards to comparisons between FFF and NF, there were no significant results from the interaction effect of the regression and ANOVA analyses, suggesting that foot type did not significantly affect the change in unloaded MLA between baseline and follow-

up (Table 27). The foot type ANOVA results indicated that there were significant differences in sitting MLA angle between FFF and NF present at both time points. This is supported by the presence of higher mean measurements in FFF at both baseline and follow-up in comparison to NF (Table 26). Therefore, it is indicated that there is a comparatively flatter arch in FFF across both childhood and adulthood, even in the unloaded condition. This challenges the conceptual definition of FFF, where the MLA in this condition is restored upon removal of bodyweight force exertion, manifesting without a collapsed arch [1, 2]. Therefore, in the sitting stance, the arch in FFF would be expected to be similar to NF. Although, it may be hypothesised that the soft tissues in FFF group may have had increased laxity due to repeated excess stretching over time in comparison to the NF group. This may have impaired their ability to provide rigid support for the arch, resulting in a flatter arch in the FFF group, despite being in a non-weightbearing position. To investigate whether the difference in sitting MLA height between FFF and NF noted in this study exists in the wider population and the reasons for it if so, further studies are needed.

10.2.4 Hindfoot eversion and arch rigidity

In the literature, hindfoot eversion [5,122,377–379] and foot arch rigidity [380,383] have been often used for assessment of foot posture. The hindfoot eversion variable provides information on the alignment and position of the rear aspect of the foot in the coronal plane, specifically the STJ [5,11,122,377–379]. In fact, its wide use in both research and clinical settings is due to its close association with excessive pronation in the STJ, which is a feature that is closely linked with FFF. As for determining arch rigidity, this entails measuring the difference in arch height between standing (weight-bearing) and sitting (non-weight-bearing) positions [380,383]. This study showed no association between baseline and follow-up measurements of these variables, neither in terms of correlation nor significant differences across the time points. This may be explained by the possibility that the specific FFF participants in this study did not have the expected variation of excessive hindfoot eversion, especially as this feature is an association of the condition, rather than

a defining characteristic. Therefore, these variables in context of this study were not followed up further.

10.2.5 Overall discussion

From the presented static foot posture variables, several conclusions can be drawn. The weightbearing posture variables of AHI and standing MLA angle did not convey a uniform trend for changes in arch height across all feet, with the former suggesting flattening and the latter no change overall. This could be due to the differences in measurement techniques, particularly as the AHI is a two-dimensional measure and the MLA angle is a three-dimensional measure. Whether the detected two-dimensional changes of the arch translate and align to those captured in three dimensions is currently unknown and requires further research for evaluation. However, both variables suggested that foot type affects how the arch changes over time, with both suggesting an increase in flatness over time in FFF, with the amount of change related to the degree of flatness in the baseline measurement. The NF group did not demonstrate such systematic change over time. Whether the finding from the AHI measurement was due to a true change over time, or differences in measurement techniques, cannot be confirmed. However, assuming it was due to the former reason, there are several explanations that can be hypothesised to explain why these findings of arch flattening occurred. It may be that the arch flattens as a consequence of muscle and ligamentous changes in the arch structure over time. Such changes may lead to a reduction in elasticity and integrity of the arch, causing its collapse [384]. Although, these have been typically observed in studies on elderly populations, meaning such explanation may not be applicable in this study's younger demographic. As for the studies that have utilised younger participants for this purpose [342,344], they have either assessed children until the early teenager years or undertaken assessment of the effects of pregnancy on arch height [385–388]. However, the study evaluating arch height in pregnancy used cut-off values to categorise foot posture and thus only provided frequencies of each foot type rather than the distribution of arch height in the studied population

[385–388]. The findings from the pregnancy studies may also not be applicable to the general population, due to the influence of hormonal changes exclusive to pregnancy that would increase tissue elasticity [385–388]. Therefore, there has not been a previous study assessing the fine changes that may occur in the foot in a comparable manner to this study's population. The closest comparators were studies by Waseda et al. [342,344] and Morita et al. [342,344], which utilised the AHI and demonstrated the trend of generally increased AHI between the ages of 6 and 18 years [342,344]. In particular, there was a markedly steeper increase in AHI between 11 and 18 years compared to 8 and 10 years. It must be acknowledged that in the 11–18-year range, the increase in foot length would be coming to completion, while the arch height would have already done so by approximately 8 years [342,344]. Given the lack of data surrounding the late teen years and into the twenties, it is difficult to ascertain whether such a trend of increasing AHI would continue. In addition, the studies providing this data were all cross-sectional and so cannot convey MLA height change through time on an individual basis. From the clinical perspective, it is observed that the feet in older age tend to present as flatter and wider in morphology [389]. However, the precise transitioning point from having an increased arch height as noted through foot development in the teenage years to getting flatter through adulthood is unknown. This is particularly important, given the participants demonstrating the trend of arch flattening over time were of older age than those followed up in the Japanese study, in which the opposite trend of increased arch height over time in childhood was noted [342,344]. Another possible influence for the flattening of the arch over time observed from the AHI measurements pertains to bodyweight. It may be hypothesised that the progressive rise in bodyweight with growth would lead to an increased force on the arch, and consequently cause increased flattening, despite the counteractive effects of increasing tissue stiffness with age to support the arch [87,382].

Another key finding in this study was of the disparities in the overall trends between the weightbearing variables of AHI and standing MLA angle, which demonstrated arch flattening over

time in FFF, and the non-weightbearing variable of sitting MLA angle in which the slope indicated a rise in arch height over time. This may theoretically be due to the possibility that in FFF, there is increasing weakness of the intrinsic foot muscles over time due to less physical activity, which may cause the foot arch to be flatter when under the load of the bodyweight, but not when this force is not being exerted [129,390].

10.3 Limitations

The present study has several limitations that need to be considered. Firstly, it was the first prospective study to examine the characteristics and outcomes of FFF and NF from immediately after the completion of foot development into young adulthood. As a result, there is a lack of previous studies to compare results to, or to establish methods of prospective foot posture assessment. Therefore, this study was more exploratory in nature, with limited guidance on expected outcomes and comparisons. This is particularly the case for the AHI measurements, for which there were slight differences in measurement techniques between baseline and follow-up. Consequently, the observed differences between these two time points could not conclusively be deemed to occur as a result of true changes in arch height. Secondly, a notable limitation of this study was the small sample size. Due to the specific eligibility criteria for participant inclusion, the number of individuals included in the study was limited, although recalling 20 participants from the original 95 was still a success in the context of many participants having moved home or being in education or work commitments which would have limited their ability to participate in the follow-up study. Consequently, the findings may not be generalisable to a larger population or accurately represent the full range of variations within individuals with FFF, although the impact of this smaller sample size was reduced, due to it being representative of the original cohort (Table 25). This is evidenced by similarities in baseline characteristics between those who were excluded and included at follow-up. Therefore, while this study provides valuable insights into FFF and its immediate post-development characteristics, it is crucial to interpret the findings with caution.

Further research with larger and more diverse samples is necessary to establish a more comprehensive understanding of this condition and its implications.

10.4 Conclusion

From the assessments of static foot posture, the first null hypothesis can be rejected on the basis that significant differences between baseline and follow-up AHI and sitting MLA angle measurements were observed. There was evidence from the standing MLA angle to suggest the change in arch height between baseline and follow-up was different between FFF and NF, with a flatter arch in childhood tending to get flatter over time, and a neutral foot being unpredictable as to its arch shape in adulthood. In addition, the AHI and sitting and standing MLA angles all showed the arch height in FFF to be comparatively lower than in NF at both time points of assessment. To provide further evidence from the dynamic perspective, walking kinematic measurements were explored. These are reported and discussed in the next chapter.

11 Evaluation of walking patterns across childhood and adulthood

This chapter outlines the results obtained upon analysis of walking patterns in childhood and adulthood. Walking patterns can be characterised by several variables, which are measured through CGA. Some directly characterise the MLA during gait, in this case the walking MLA angle. Others characterise kinematic movements of foot segments including the hallux, forefoot and hindfoot, which influence the MLA during gait.

11.1 Results

Upon conducting the Shapiro-Wilk test for normality, it was confirmed that all the data for each variable were normally distributed. The descriptive statistics (Table 28) of some walking pattern variables demonstrated trends of change between baseline and follow-up for FFF and NF individuals. Notably, the FFF group showed an increase in all walking MLA angle variable measurements, between the two time points. For individual participants, differences in kinematic waveforms between baseline and follow-up can be observed in the Appendix D3.

To gain further insight into the measurements taken at the two time points, visual analysis was conducted initially, using scatter plots (Figure 45) between baseline and follow-up measurements of the variables. This analysis demonstrated positive, linear associations for most walking MLA variables. Supplementing the visual analysis, paired t-tests were performed (Table 29), revealing significant differences in most walking MLA angle and walking hindfoot eversion variable measurements between the two time points. The variables which demonstrated a positive linear relationship visible in the scatter plots or exhibited differences between baseline and follow-up measurements in the paired t-tests, underwent further evaluation for investigating change between time points and foot types. This included the conduction of ANOVA and slope analyses to compare the changes over time between FFF and NF groups (Table 29). These analyses revealed

differences between the two foot types in several walking MLA angle variables. In addition, the variables which demonstrated significant correlations between baseline and follow-up measurements, which were predominately most of the walking MLA angle and walking hindfoot eversion variables, underwent interaction effects regression analysis. The specific nature of the observed results will be further elaborated upon in the discussion section.

Dynamic variable	FFF baseline	FFF follow-up	NF baseline	NF follow-up
Walking MLA Mean	171 (6)	165 (7)	156 (8)	156 (4)
Walking MLA Min	163 (7)	153 (9)	146 (9)	145 (4)
Walking MLA Max	180 (6)	173 (9)	166 (8)	164 (5)
Walking MLA Heel Contact	169 (6)	165 (7)	154 (10)	155 (4)
Walking MLA Toe-off	166 (6)	158 (6)	149 (9)	147 (5)
Walking Hindfoot Eversion Mean	-1 (5)	0.5 (5)	-2 (5)	-0.3 (4)
Walking Hindfoot Eversion Min	-6 (5)	-4 (5)	-7(5)	-5 (4)
Walking Hindfoot Eversion Max	5 (6)	8 (6)	4 (5)	7 (5)
Walking Hindfoot Eversion Heel Contact	0.6 (6)	2 (5)	-0.9 (6)	0.8 (4)
Walking Hindfoot Eversion Toe-off	4 (6)	6 (6)	3 (5)	5 (5)
Walking Forefoot Dorsiflexion Toe-off	-5 (4)	-6 (4)	-6 (5)	-10 (5)
Walking Forefoot Supination Range	8 (3)	8 (2)	7 (2)	7 (2)
Walking Hallux Dorsiflexion Min	-8 (8)	-6 (8)	-11 (7)	-4 (10)
Walking Hallux Dorsiflexion Range	30 (12)	24 (7)	34 (10)	24 (7)
Walking Hallux Dorsiflexion Heel Contact	9 (11)	3 (9)	13 (12)	12 (9)

Table 28: The mean values at baseline and follow-up for the walking patterns variables in FFF and NF with notable findings. A list of all the mean values is presented in Appendix Da.

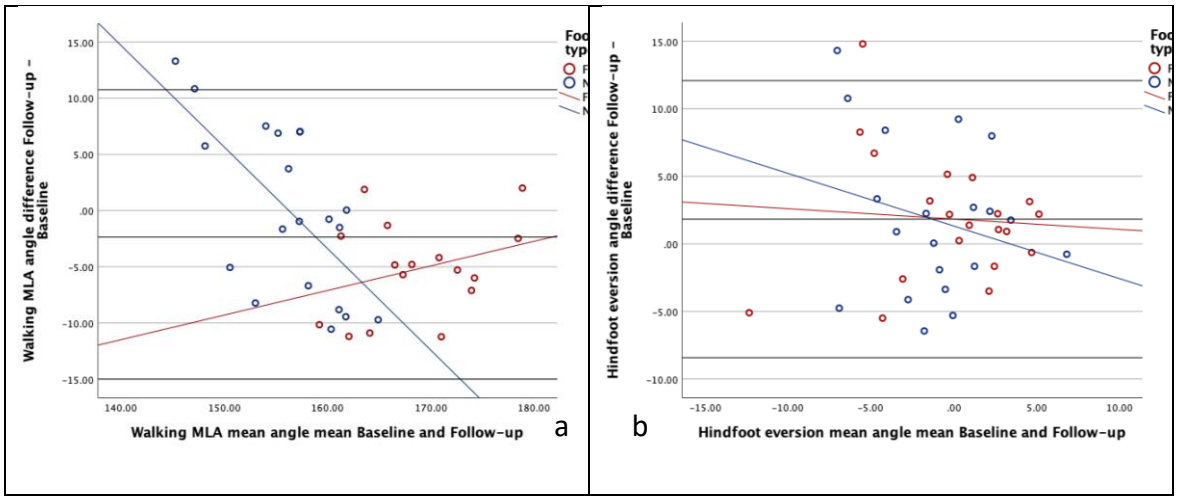
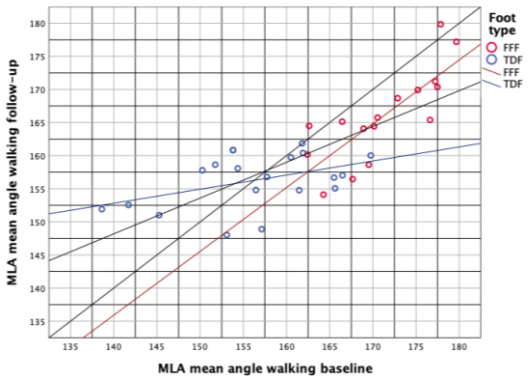
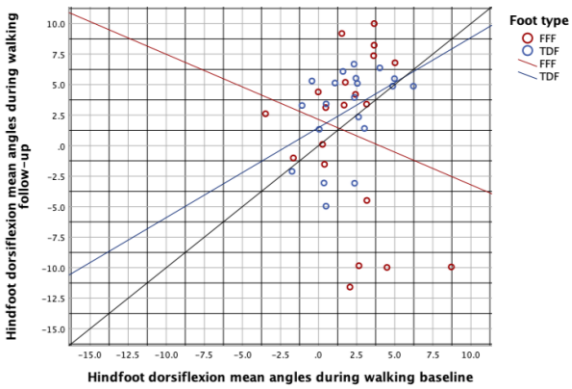
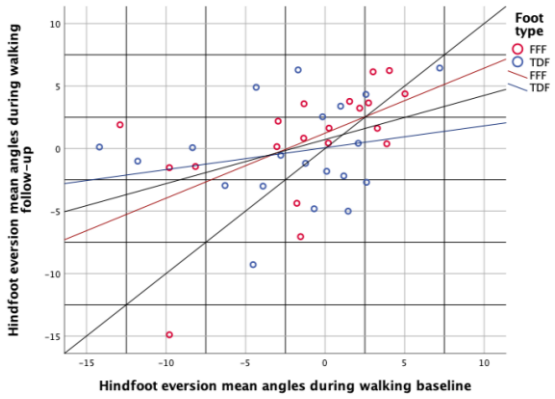
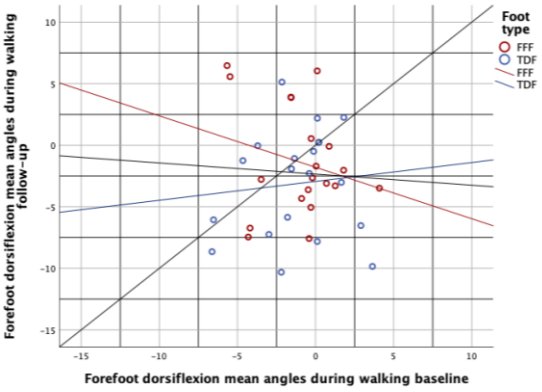


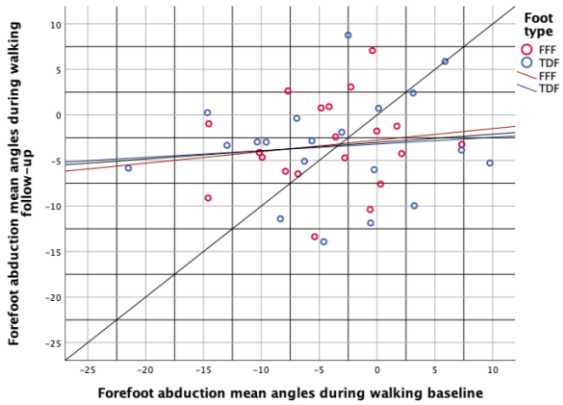
Figure 44 a-b: The Bland-Altman plot for a) walking MLA angle and b) hindfoot eversion mean angle measurements, showing the distribution of mean measurements between baseline and follow-up against the difference in measurements by subtracting baseline from follow-up. The red colour represents the distribution of FFF data, while the blue colour represents the distribution of NF data. The black horizontal lines represent the limits of agreement.

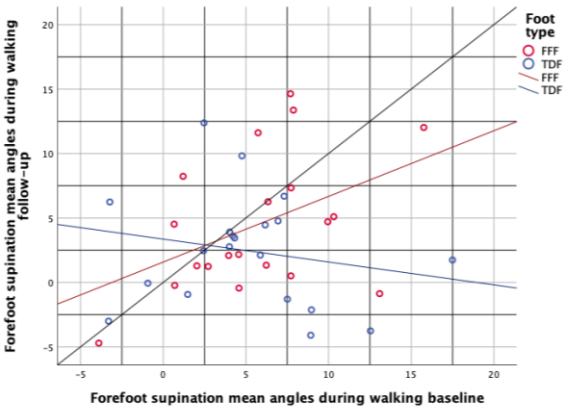

MLA mean angle walking follow-up
MLA mean angle walking baseline
Foot type
FFF
TDF
FFF
TDF


Hindfoot dorsiflexion mean angles during walking follow-up
Hindfoot dorsiflexion mean angles during walking baseline
Foot type
FFF
TDF
FFF
TDF


Hindfoot eversion mean angles during walking follow-up
Hindfoot eversion mean angles during walking baseline
Foot type
FFF
TDF
FFF
TDF


Forefoot dorsiflexion mean angles during walking follow-up
Forefoot dorsiflexion mean angles during walking baseline
Foot type
FFF
TDF
FFF
TDF


Forefoot abduction mean angles during walking follow-up
Forefoot abduction mean angles during walking baseline
Foot type
FFF
TDF
FFF
TDF


Forefoot supination mean angles during walking follow-up
Forefoot supination mean angles during walking baseline
Foot type
FFF
TDF
FFF
TDF

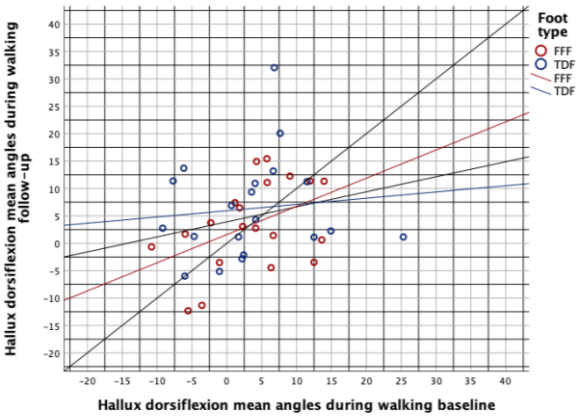


Figure 45: Demonstrates scatter plots which visually represent the relationship between baseline and follow-up variable measurements for walking pattern assessment. The FFF data is represented by red circles and the NF data by blue circles. The red and blue lines represent the individual group slopes of FFF and NF respectively, and the dark green line represents the overall group slope. Additionally, the 45° line is coloured in black.

Measurement variables of gait pattern	**Scatter plot (visual assessment)**	**Equation of the best fit line group for baseline to follow-up (p value)**	**Pearson correlation baseline and follow-up (p value)**	**Equation of the best fit line for baseline to follow-up FFF**	**Equation of the best fit line for baseline to follow-up NF**	**Interaction effect regression gradient (p value)**	**Paired t-test (p value)**	**2x2 ANOVA time point (p value)**	**2x2 ANOVA foot type (p value)**	**2X2 ANOVA interaction effects (p value)**
Walking MLA Mean	Positive, linear	73 + 0.54x **(p=<.001)**	0.765 **(p=.000)**	1 + 0.96x	123 + 0.21x	**(p=.001)**	**(p=.042)**	**(p=.035)**	**(p=<.001)**	**(p=.038)**
Walking MLA Min	Positive, linear	86 + 0.41x **(p=<.001)**	0.568 **(p=.000)**	90 + 0.39x	107 + 0.26x	(p=.693)	**(p=.006)**	**(p=.003)**	**(p=<.001)**	**(p=.015)**
Walking MLA Max	Positive, linear	57 + 0.65x **(p=<.001)**	0.787 **(p=.000)**	37 + 1.18x	108 + 0.34x	**(p=.001)**	**(p=.003)**	**(p=.015)**	**(p=<.001)**	(p=.136)
Walking MLA Heel Contact	Positive, linear	77 + 0.52x **(p=<.001)**	0.708 **(p=.000)**	44 + 0.73x	137 + 0.12x	**(p=.016)**	(p=.524)	(p=.275)	**(p=<.001)**	(p=.136)
Walking MLA Toe-off	Positive, linear	68 + 0.54x **(p=<.001)**	0.770 **(p=.000)**	99 + 0.37x	108 + 0.26x	(p=.632)	**(p=.002)**	**(p=.002)**	**(p=<.001)**	(p=.083)
Walking Hindfoot Eversion Mean	No	1 + 0.35x **(p=.009)**	0.406 **(p=.009)**	1 + 0.52x	0 + 0.18x	(p=.190)	**(P=.033)**	(p=.904)	(p=.375)	(p=.251)
Walking Hindfoot Eversion Min	No	3 + 0.30x **(p=.041)**	0.324 **(p=.041)**	2 + 0.46x	4 + 0.13x	(p=.254)	**(p=.028)**	(p=.362)	(p=.450)	(p=.495)
Walking Hindfoot Eversion Max	No	6 + 0.31x **(p=.041)**	0.324 **(p=.041)**	6 + 0.46x	6 + 0.13x	(p=.276)	**(p=.006)**	(p=.879)	(p=.207)	(p=.467)
Walking Hindfoot	No		0.393 **(p=.012)**			(p=.425)	(p=.125)			

Eversion Heel Contact										
Walking Hindfoot Eversion Toe-off	No	4 + 0.38x **(p=.010)**	0.405 **(p=.010)**	4 + 0.49x	4 + 0.22x	(p=.339)	**(P=.018)**	(p=.298)	(p=.104)	(p=.748)
Walking Forefoot Dorsiflexion Toe-off	No	7 + 0.23x (p=.179)	0.217 (p=.179)	6 — 0.05x	8 + 0.30x		**(p=.019)**	**(p=.027)**	**(p=.006)**	(p=.260)
Walking Forefoot Supination Range	No		0.479 (**p=.002**)			(p=.367)	(p=.199)			
Walking Hallux Dorsiflexion Min	No	4 + 0.15x (p=.425)	0.130 (p=.425)	2 + 0.53x	7 — 0.28x		(**P=.020**)	(**P=.028**)	(p=.792)	(p=.253)
Walking Hallux Dorsiflexion Range	No	29 + 0.12x (p=.616)	0.082 (p=.616)	14 + 0.66x	44 + 0.41x		(**p=<.001**)	(**p<.001**)	(p=.286)	(p=.287)
Walking Hallux Dorsiflexion Heel Contact	No		0.378 (**p=.016**)			(p=0.633)	(p=.087)			

Table 29: The variables, commonly used in the literature for the assessment of walking patterns, which had notable findings. Significant p values are presented in bold. A list of all the walking variables is presented in Appendix Db.

11.2 Discussion

The aim of this study was to assess changes in walking patterns that occur following the completion of arch development from childhood into adulthood, alongside identifying differences in such changes between FFF and NF. From this study's results, the trends of a decrease in walking MLA angle and increase in walking hindfoot eversion angle from baseline to follow-up collectively across both foot types were suggested, based on significant differences in the majority of variables for these kinematic measurements. Only the walking MLA angle variable revealed conclusive differences between FFF and NF. It suggested the arch height in FFF would remain relatively unchanged from childhood into adulthood but change unpredictably in NF. In addition, it demonstrated the arch in FFF to be comparatively flatter than NF at both childhood and adulthood timepoints. Overall, the other explored variables yielded some trends, which will also be discussed in this chapter.

11.2.1 Walking MLA angle

The walking MLA angle was retrospectively calculated from the previously collected baseline study data, to enable comparison to the prospectively collected measurements in this study. This was a particularly important variable for assessment between childhood and adulthood, given its potential for wide use in clinical and research settings to characterise the functional MLA form and inform management plans.

The walking MLA mean, minimum, maximum and toe-off angle variables demonstrated significant differences between baseline and follow-up measurements, while also eliciting significant correlations between measurements across the two time points (Table 29). The nature of change was observed by reviewing the mean differences for each of FFF and NF groups in these four variables, which indicated a mean decrease in these variables' measurements over time by 0-10° (Table 28). Given the inverse relation between MLA angle and arch height, this would indicate an increase in arch height over time. The clinical meaning of this magnitude of change is uncertain, given there are no previous study

findings to use as comparators. In addition, when reviewing the Bland-Altman plot for the walking MLA mean angle, there was an even distribution of measurements above and below the zero-difference line, with most measurements being no more than 10° and falling within the limits of agreement (Figure 44A). Given this distribution of data points, it can be concluded that there is no clear evidence of a trend of reduction in walking MLA mean measurements over time, despite the significance of the paired t-test result and the mean difference line being below 0°. In addition, it must be noted that the limits of agreement included 0°, thereby indicating the possibility that there may be no true difference between childhood and adulthood walking MLA mean angles.

When evaluating change in arch height over time, notable differences between FFF and NF were observed. The FFF slopes for walking MLA mean and max values indicated a relatively uniform change in arch height over time, with gradients close to 1 and a comparatively lower y intercept than in NF, where the follow-up measurement would be expected to be close to the baseline measurement (Table 29). This would indicate that within the FFF cohort, those with higher walking MLA angles at baseline would remain with relatively high angles at follow-up and so forth. In contrast, the NF slopes for the walking MLA mean and max variables had much smaller gradients that were relatively closer to 0 with larger y intercepts. This would indicate that irrespective of having a low, average or high MLA measurement at baseline, the follow-up measurements amongst the group would be similar to each other. Therefore, low NF walking MLA angles would get higher over time, average angles would stay similar and higher angles would get lower. This suggests that the arch in FFF would remain relatively unchanged in its form between childhood and adulthood, while the arch in NF would change unpredictably across subjects. Such differences in change over time are reflected by the significant interaction effect of the regression analysis results for walking MLA mean and max, alongside significant interaction effect of the ANOVA results for walking MLA mean (Table 29). Furthermore, the slope on the Bland-Altman plot suggested that the higher the mean walking MLA angle across baseline and follow-up in the FFF group, the lower the decrease in walking MLA angle at follow-up. Given the

inverse relation between this variable and MLA height, this indicates that flatter arched participants with FFF would have greater likelihood of experiencing a lesser extent of increase in MLA height over time in comparison to higher arched participants with FFF.

Another key finding is the differences in walking MLA angle between FFF and NF from childhood to adulthood, based on the foot type ANOVA results (Table 29). This analysis demonstrated significant differences between FFF and NF across the two time points in the walking MLA mean, min, max, toe-off and heel contact variables. In addition, it can be observed that the mean measurements of all walking MLA angle variables, except range, were higher in FFF than NF at both baseline and follow-up. Therefore, the walking MLA angle in FFF remained comparatively flatter than NF in childhood and adulthood.

Across the walking MLA angle variables that have been discussed, the statistical tests suggest that the walking MLA mean (across the GC) is the most sensitive measure for characterising changes in walking pattern over time (Table 29). This is supported by this variable being able to detect significant changes in arch height over time as per the paired t-test, absolute differences between FFF and NF arch height as per the foot type ANOVA test, and differences in change in arch height between FFF and NF through both interaction effects of the ANOVA and regression analyses. While the MLA has been used for the assessment of FFF, the majority of the literature has assessed it from a static perspective [2,73,111,337,349]. The reason for being less commonly used in dynamic assessment is typically due to the lack of MSFMs that have incorporated the MLA measure in their output [232,240,292]. Although, Caravaggi [248,249] incorporated a two-dimensional MLA measure to evaluate members of the general population with no foot deformity. However, the outcome of this study cannot be compared to the available literature, as it utilised a three-dimensional MLA measure for the purpose for detecting dynamic changes in specific foot postures over time.

11.2.2 Walking hindfoot eversion

The walking hindfoot eversion mean, min, max and toe-off angle variables demonstrated significant differences between baseline and follow-up measurements, with significant correlations between measurements across the two time points (Table 29). All four variables were suggestive of a significantly higher walking hindfoot eversion angle at follow-up, as noted by the paired t-test results and mean measurements which increased by 1.7-3° from baseline to follow-up across all subjects (FFF and NF). However, this mean difference is very small, and it is difficult to ascertain the clinical utility of such a result, with no previous data to compare it with (Table 28). It must be noted from visual inspection of the scatter plots for the variables, that there was large variability in change over time amongst the participants. In particular, the Bland-Altman plot of walking hindfoot eversion mean demonstrated many participants to have an increase in this variable at follow-up by 5-10°, while a prominent number of others decreased by up to 5° (Figure 44B). Therefore, while the mean difference is indicative of an increase in hindfoot eversion mean angle of around 2° from baseline to follow-up, there is the possibility of there being no true difference across these time points, as a difference of 0° is within the limits of agreement. When comparing FFF to NF, there were no significant results in the interaction effects of the ANOVA or regression analyses (Table 29). This indicated that change in hindfoot eversion did not differ by foot type. Such a conclusion is supported by the minimal differences in individual slopes for FFF and NF across the assessed hindfoot eversion variables. In addition, the foot type ANOVA results were also non-significant, indicating no difference in hindfoot eversion between FFF and NF across both time points. This was corroborated by the similarity between mean FFF and NF measurements at both baseline and follow-up. Therefore, the hindfoot eversion variable findings demonstrated a small overall increase from childhood to adulthood, of questionable clinical significance, but no differences between FFF and NF.

While this data cannot be directly compared to the literature, as such measurements have not been prospectively assessed in a single cohort, insights can be drawn from cross-sectional studies. Studies

on children with ages ranging between 5-18 years have demonstrated greater hindfoot eversion in the stance phase of the GC in FFF compared to NF [5,136]. Although other studies have demonstrated opposing findings, with greater maximum eversion measurements in NF compared to FFF [352]. As for adults, the extent of research has been limited, with a study measuring maximum hindfoot eversion in 52–80 year-old participants, noting a relatively lower mean measurement of 3.96° in their NF group, in comparison to 4.71° and 12.83° in their moderate and severe flat foot groups [391]. While there is a collective consensus on the presence of physiological hindfoot eversion in childhood and adulthood during walking, this study is the first to evaluate changes that occur with this motion over time. From a physiological perspective, due to overpronation of the foot and laxity of the ligaments in FFF, a comparatively greater extent of hindfoot eversion would be expected. The overall absence of this finding in this study may be attributed to the spread of data within the small sample assessed. Although, given the inconclusive findings from the literature, it may be due to the fact that increased hindfoot eversion may not always be consistently present in the FFF population. Therefore, further research is required.

11.2.3 Walking forefoot dorsiflexion

For walking forefoot dorsiflexion, only the toe-off variable demonstrated a significant difference between baseline and follow-up measurements. There was a mean decrease of 1-4° in both the FFF and NF groups (Table 28) at follow-up compared to baseline. However, given such minimal difference, together with the lack of a significant correlation between measurements taken across the two time points, it is difficult to determine the clinical utility of this result. When comparing by foot type, the interaction effect of the ANOVA result was not significant, indicating no differences in change in walking forefoot dorsiflexion over time between FFF and NF (Table 29). Although, from the foot type ANOVA result, it can be inferred that there were significant differences between FFF and NF in walking forefoot dorsiflexion at toe-off between baseline and follow-up. This must be interpreted with caution, given the differences in mean measurements in this regard were so small.

11.2.4 Walking hallux dorsiflexion

For walking hallux dorsiflexion, significant differences between baseline and follow-up were only noted in the min and range variables. These indicated an increase in hallux dorsiflexion min by 2-7° and a decrease in hallux dorsiflexion range by 6-10° for FFF and NF (Table 28). The clinical utility of such recorded changes is uncertain, especially given there were no significant correlations between baseline and follow-up measurements for these two variables (Table 29). Although, the finding of a potentially reduced hallux dorsiflexion range of motion with age may be hypothetically explained by reductions in soft tissue elasticity which occur over time [392,393].

When assessing these two variables by foot type, the interaction effect of the ANOVA analysis did not yield significant results. Therefore, the change in walking hallux dorsiflexion over time was not considered to differ between FFF and NF. In addition, the foot type ANOVA analysis suggested no significant difference between FFF and NF in childhood and adulthood (Table 29).

11.2.5 Overall discussion

When interpreting the findings of this prospective study, it is essential to acknowledge the baseline differences between FFF and NF that exist, irrespective of potential changes over time, as evaluated by this study. From the baseline study, the participants with FFF demonstrated increased hindfoot plantarflexion during the loading response and increased maximum hindfoot eversion. In addition, increased forefoot dorsiflexion range of motion, increased maximum and minimum forefoot supination and reduced forefoot adduction at foot off were noted. While many of these variables did not manifest with observable differences in the prospective study analysis, the aforementioned findings provide an interesting discussion point. The walking forefoot dorsiflexion toe-off angle was significantly different between FFF and NF in both childhood and adulthood, as per the foot type ANOVA results (Table 29). In contrast, the walking hindfoot eversion variables did not demonstrate

such significant differences in this regard. This raises the question as to why certain kinematic differences between the two foot types were only present in childhood, while others were present in both childhood and adulthood. It may be possible that individuals with FFF adopt different compensatory strategies to optimise gait as they age, which affects some kinematic variables more than others.

Overall, the kinematic findings which were largely obtained from the walking MLA angle variables, convey that FFF will not improve into adulthood. This was evidenced by the arch in FFF being observed as being comparatively flatter than NF in both childhood and adulthood and undergoing minimal change over time as per the walking MLA angle mean FFF slope analysis. These findings are further strengthened by the fact that this study accounted for the walking speed of the participants at each time point of assessment. The walking speed of the cohort in this study was similar at 1.16 m/s (SD 0.16) to their walking speed at baseline, which was 1.26 m/s (SD 0.36). Such similarity was corroborated by the paired t-test, which noted no significant difference (p=0.130) in walking speed between baseline and follow-up. In addition, the walking speed of FFF and NF participants was similar at both baseline, at 1.38 m/s (SD 0.23) and 1.24 m/s (SD 0.15), and follow-up, at 1.14 m/s (SD 0.14) and 1.13 m/s (SD 0.13) respectively. Furthermore, no significant differences in walking speed between the participants of these two foot types were found at baseline (p= 0.106) and follow-up (p=0.747). Given these similarities, the differences in kinematic variable measurements between baseline and follow-up would be unlikely to be influenced by the walking speed. Therefore, the differences can be deemed to likely occur due to changes in the foot itself rather than due to walking speed.

11.3 Limitations

This study has several limitations. Firstly, it is important to acknowledge that this study took an exploratory approach by evaluating a wide range of variables that have not been longitudinally studied in context of FFF, to gain a more comprehensive understanding of the differences between FFF and NF. While this exploratory approach broadened the knowledge of FFF, the lack of previous research examining these specific variables within context of this condition necessitates caution when interpreting the findings. Therefore, further research and replication of these findings are needed to establish their validity and robustness. Secondly, not all participants from the baseline study were followed up, as only those who could be contacted and gave their consent were included. This selective follow-up process resulted in a further reduction in sample size from the established baseline study, which was initially designed to be adequately powered for its specific objectives. The reduced sample size may have introduced a potential bias and affected the generalisability of the findings noted at follow-up. Although, the demographic characteristics at baseline for those followed up were very similar to those that were not, as evidenced in table 25 in Chapter 9. Nevertheless, despite such similarity in the samples, there was a minor discrepancy in methodology for deriving the walking MLA angle between baseline and follow-up. The baseline data collection protocol utilised real first metatarsal head markers for static measurements and used these markers to formulate virtual first metatarsal head markers based on the position of the real marker, to capture the walking MLA measurements. In contrast, the follow-up study used real first metatarsal head markers for deriving both static and walking MLA measurements. A final limitation pertained to the inability to determine if the observed changes in kinematic variables over time had clinically meaningful implications. Given the sample did not specifically target individuals with foot symptoms, but rather followed-up those from the baseline study, it could not investigate the association between kinematic changes and symptoms. Consequently, this prevented comparability with the findings of Kerr at al. [136], who had grouped their sample by foot type and symptoms together. An insight on symptoms in such manner

would be useful for establishing meaning of the results, where the differences in measurements shown in this study could be assessed to determine if they are associated with differences in measures that are known to reflect clinical implications.

11.4 Conclusion

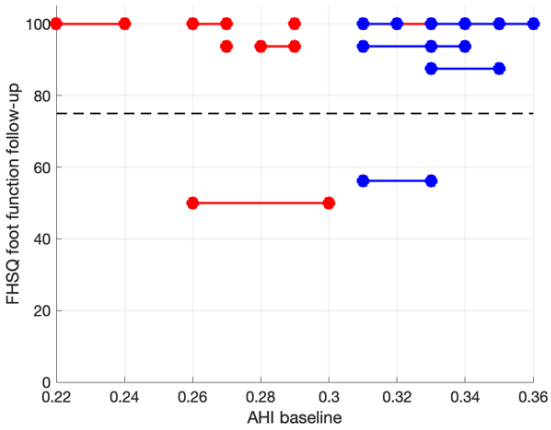
From the assessments of walking pattern, the second null hypothesis can be rejected due to the presence of significant differences between baseline and follow-up in the walking MLA angle and hindfoot eversion angle variables. When assessing by foot type, the walking MLA angle variable suggested the MLA in FFF remains relatively unchanged over time. While having this insight on walking pattern changes over time is beneficial for informing treatment decisions, there are aspects beyond foot arch structure that must be considered. This pertains to QofL, which can provide an insight on the broader implications of FFF, which will be explored in the next chapter.

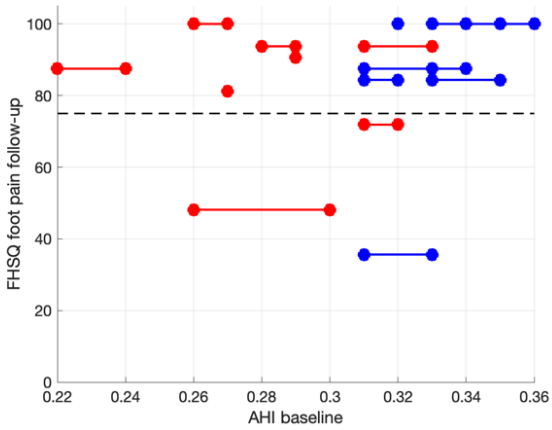
12 Evaluation of quality of life outcomes

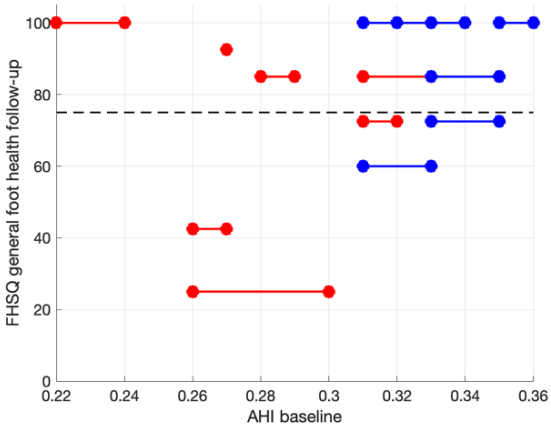
This chapter outlines the results obtained upon analysis of quality of life (QofL) scores in childhood and adulthood. In addition, it assesses the trends in adult QofL scores in relation to static foot posture and walking pattern in childhood. Due to the small sample size, there was an emphasis on visually inspecting the distribution of data to determine trends.

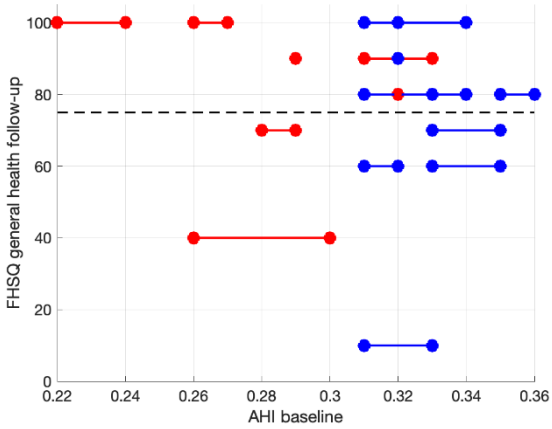
12.1 Results

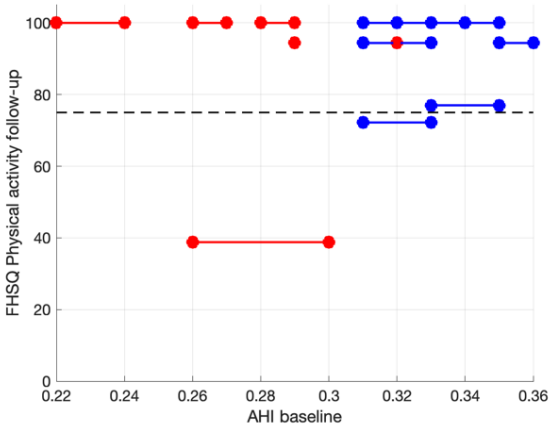
Upon conducting the Shapiro-Wilk test for normality, it was confirmed that all the data for each variable were normally distributed. The OxAFQ-C scores for both physical and emotional domains demonstrated the trend of worse QofL at follow-up in comparison to baseline for FFF individuals (Figure 47). The FHSQ scores, which were only taken at follow-up, demonstrated the trend of participants with low scores in a given foot QofL domain tending to have low scores in other QofL domains (Figure 46). When evaluating the associations between kinematic variables and FHSQ scores, poorer QofL was observed in those with higher forefoot supination range and lower minimum forefoot supination (greater forefoot pronation), and better QofL in those with greater hindfoot dorsiflexion range and toe-off measurements (Table 30). This was supported by the independent t-test analysis, in which significant differences between good and poor FHSQ scores in certain QofL domains were recorded for these variables (Table 31). The observed findings will be further elaborated upon in the discussion section.

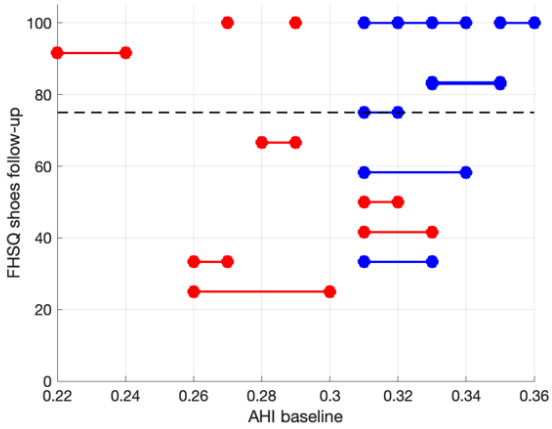

FHSQ foot function follow-up
AHI baseline


FHSQ foot pain follow-up
AHI baseline


FHSQ general foot health follow-up
AHI baseline


FHSQ general health follow-up
AHI baseline


FHSQ Physical activity follow-up
AHI baseline


FHSQ shoes follow-up
AHI baseline

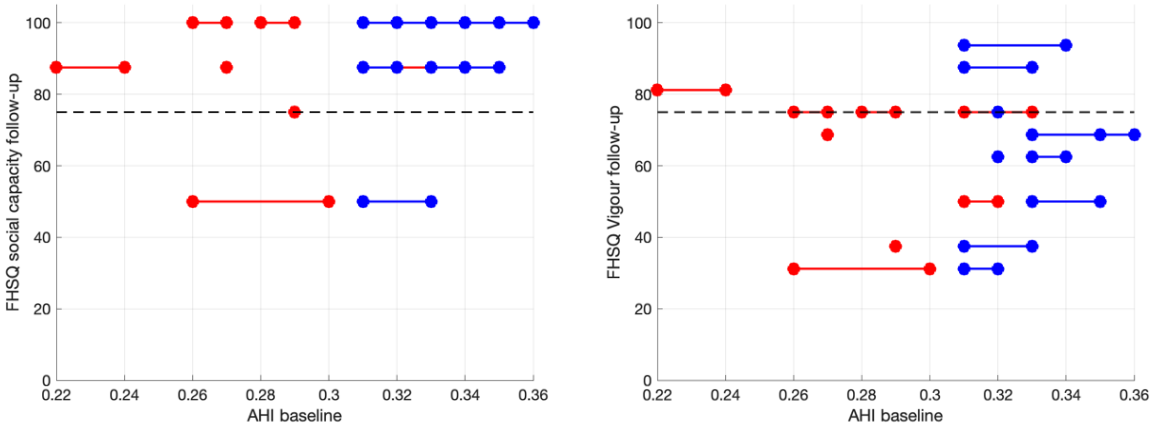


Figure 46: presents the distribution of scores for each participant across all domains of the FHSQ, in relation to their AHI at baseline. The participants with FFF are presented with red dots and those with NF are presented with blue dots. A score of 100 indicates the best QofL, while a score of 0 demonstrates the poorest QofL. There are lines connecting the left and right feet dots of each participant; in cases of overlap in measurements between both feet, a single dot is presented. A cut-off score of 75 was used to differentiate good and poor quality of life, based on the literature.

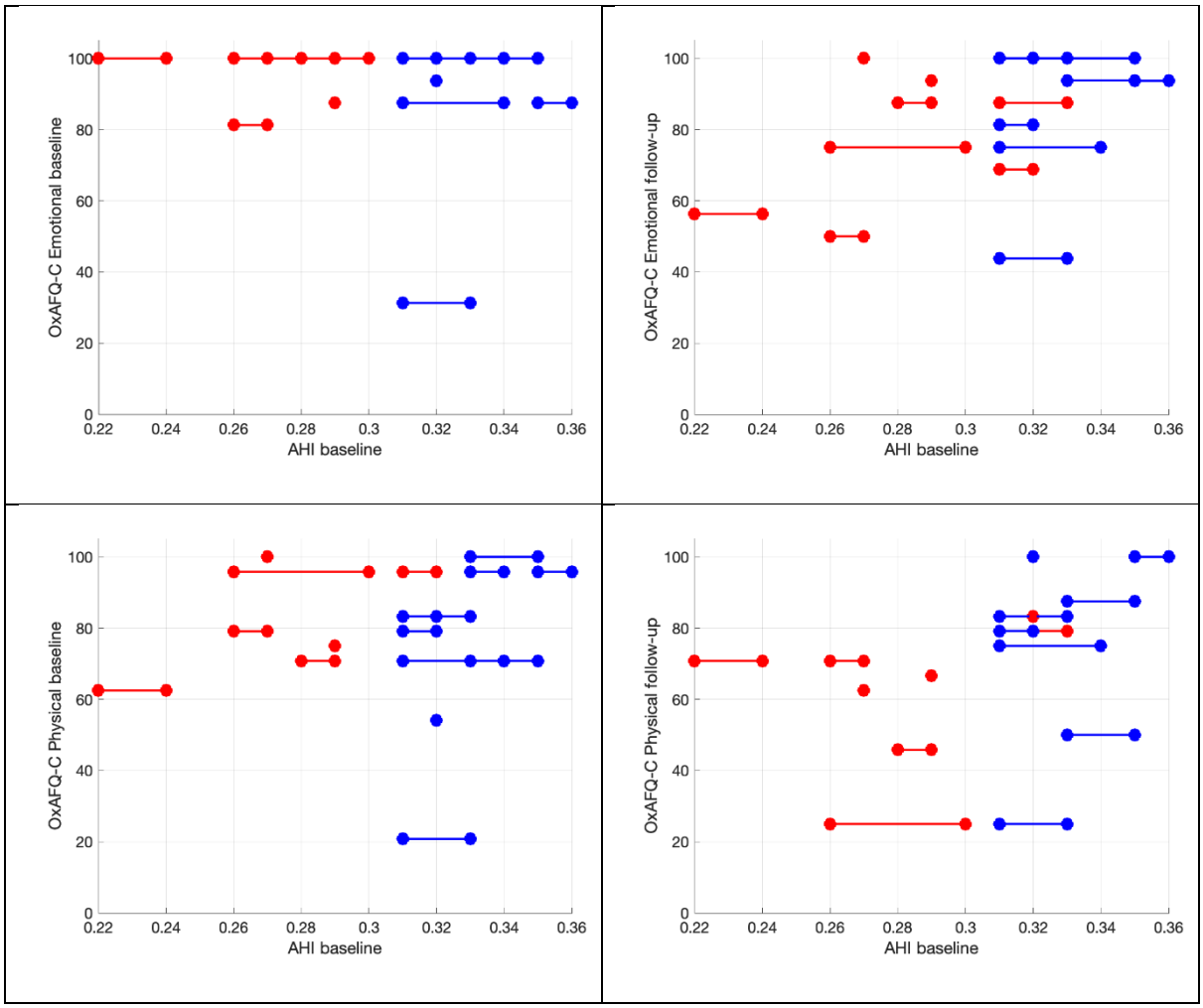


Figure 47: presents the distribution of scores for each participant across two domains from the children's OxAFQ-C questionnaire: physical and emotional, in relation to their AHI at baseline. The participants with FFF are presented with red dots and those with NF are presented with blue dots. The left side presents the distribution of scores in each domain at baseline for children aged 8-16 years, while the right side shows the corresponding domain score distribution at follow-up in the ages of 16-25 years. A score of 100 indicates the best QofL, while a score of 0 demonstrates the poorest QofL. There are lines connecting the left and right feet dots of each participant; in cases of overlap in measurement between both feet, a single dot is presented.

The Oxford Ankle Foot Questionnaire for Children

FFF physical baseline	FFF physical follow-up	FFF emotional baseline	FFF emotional follow-up	NF physical baseline	NF physical follow-up	NF emotional baseline	NF emotional follow-up
70.8	79.2	100	87.5	70.8	75.0	87.5	75.0
79.1	70.8	81.3	50.0	100	87.5	100	100
95.8	25.0	100	75.0	95.8	100	87.5	93.7
75.0	66.7	87.5	93.8	54.1	100	100	100
62.5	70.8	100	56.3	79.1	79.2	100	81.3
100	62.5	100	100	70.8	50.0	100	93.8
95.8	83.3	100	68.8	20.8	25.0	31.3	43.8
70.8	79.2	100	87.5	83.3	100.0	93.7	100
79.1	70.8	81.3	50.0	83.3	83.3	100	100
95.8	25.0	100	75.0	70.8	75.0	87.5	75.0
75.0	66.7	87.5	93.8	100	87.5	100	100
62.5	70.8	100	56.3	95.8	100	87.5	93.7
100	62.5	100	100	54.1	100	100	100
95.8	83.3	100	68.8	79.1	79.2	100	81.3
				70.8	50.0	100	93.8
				20.8	25.0	31.3	43.8
				83.3	100.0	93.7	100
				83.3	83.3	100	100

Table 30: presents a comparison of QofL scores obtained using the OxAFQ-C, between the FFF and NF groups at baseline and follow-up. The baseline and follow-up data per domain are matched- representative of the same participant.

Measurement variables of foot posture	FHSQ shoes (p value)	FHSQ general foot health (p value)	FHSQ General health (p value)	FHSQ Vigorous (p value)
Walking Hindfoot dorsiflexion max	**.032**	.202	.310	.608
Walking Hindfoot dorsiflexion range	.688	.856	.689	**.028**
Walking Hindfoot dorsiflexion toe-off	.192	.158	**.014**	.597
Walking Forefoot dorsiflexion range	.934	.352	**.013**	.136
Walking Forefoot dorsiflexion heel contact	.146	**.029**	.695	.673
Walking Forefoot supination min	.437	**.015**	.779	.056
Walking Forefoot supination range	.192	**<.001**	.708	.395
Walking Hallux dorsiflexion min	.797	.698	**.003**	.070

Table 31: presents the variables which demonstrated any significant differences in scores between those scoring 75 and below (poor) and those scoring above 75 (good), using independent t-tests. This analysis was only conducted if there were four or more participants in each of the good and poor sides of the results, to omit the risk of result bias. Significant p values are presented in bold. A full list of all the variables is presented in appendix C.

12.2 Discussion

The aim of this section of the study was to explore the participants' QofL outcomes by observing trends in scores, particularly when comparing between FFF and NF. It also evaluated the association between static and dynamic foot kinematic variables in childhood and QofL in adulthood. The results of this study suggested poorer future QofL outcomes into adulthood for FFF and found forefoot supination and hindfoot dorsiflexion in childhood to be associated with QofL in adulthood.

So far, several studies have conducted research on FFF and its association with QofL in a cross-sectional manner [2,5,7,8,73,81,111,113–115,133,143,144,153,251,252,337–340,348,375,394–397]. They have primarily focused on examining symptomatic and asymptomatic individuals with FFF, encompassing both children and adults. However, clinicians acknowledge the diverse manifestations of symptomatic FFF, which poses challenges of distinguishing it from asymptomatic cases, particularly when a binary grouping approach has been employed [133,398,399], which results in oversimplification and loss of data, by failing to account for the broad and continuous spectrum of symptoms of varying severities in this population [7,400].

To address this limitation, a handful of research studies have compared FFF with NF controls, aiming to gain insights into the variety of FFF presentations and distinctions [5,7,136]. However, to date, no studies have explored the relationship between childhood FFF and QofL into adulthood, nor have they captured the dynamic progression of FFF over time.

There have been various questionnaires that have been utilised to evaluate QofL in FFF [359–364,401]. These include general QofL questionnaires, as well as questionnaires developed specifically for foot and ankle conditions [362,364,402–405]. However, all the studies using them have adopted a cross-sectional design, focusing on assessing FFF and its impact on QofL at a specific moment in time. Comparing the outcomes of two cross-sectional studies for assessment of changes over time can be

challenging and may not produce accurate or meaningful results due to disparities in populations, study design, questionnaire selection and region, alongside temporal variability of life events that can impact changes in QofL. Consequently, these studies cannot be directly linked. Cross-sectional studies are clearly easier to implement compared to longitudinal studies, due to a number of factors, including the absence of a single questionnaire specifically designed and validated to assess QofL in both children and adults, with a focus on feet. However, to maximise comparability, this study employed the same OxAFQ-C questionnaire for both baseline and follow-up assessments [364]. The OxAFQ-C questionnaire has been designed and validated on children aged 8-16 years. It consists of three domains, but only the physical and emotional domains were deemed suitable for use in both children and adults [364].

12.2.1 OxAFQ-C baseline and follow-up

There were 16 participants in this study with OxAFQ-C measurements at both baseline and follow-up, of which seven had FFF and nine had NF (Figure 47). The remaining four participants on which measurements were to be taken, had missing data from one or both of the time points. Three FFF participants experienced a decline in both physical and emotional QofL from childhood to adulthood, while only one NF participant did so. All FFF participants experienced decline in at least one of the two QofL domains over time. Five NF participants either maintained or improved both QofL domains over time, of which three had an improvement in both domains. Therefore, the OxAFQ-C identified generally poorer future outcomes for children with FFF and similar or better future outcomes for children with NF. From the emotional OxAFQ-C domain, eight experienced a decline in QofL over time, of which five had FFF. Notably, there was one NF participant with a low emotional OxAFQ-C score at baseline of 31.3, who nonetheless experienced a relative improvement to 43.8 at follow-up. Potentially, this could have been due to poor physical health which could directly affect emotion, given their scores in the physical domain were very low at 20.8 at baseline and 25.0 at follo—up (Table 30). For the OxAFQ-C physical scores, seven experienced a decline in QofL over time, of which five had FFF.

A notable finding was of the largest decline in QofL that was experienced by two participants with FFF. Their scores respectively went from 100 and 95.8 to 62.5 and 25.0. Furthermore, the participant with the steep QofL score decline from 95.8 to 25.0 did have a very high BMI of 48.0 at follow-up from 23.7 at baseline. Notably, their emotional QofL also experienced a decline being 75 at follow-up from 100 at baseline. Although, the disparity in decline between these two domains may have been due to the high BMI negatively impacting physical health to a greater degree.

These observations in the nature of QofL change over time provide an insight into the disparities in prognosis amongst the two foot types, suggesting poorer future outcomes in both emotional and physical aspects in FFF. Beyond the exploratory findings from this prospective analysis, there are considerations that must be made, pertaining to the use of these two OxAFQ-C questionnaire domains in adults. Due to lifestyle differences including emotional maturation and potentially reduced physical activity due to work and general life responsibilities, the information pertaining to these elements of QofL may not have been accurately represented at follow-up and therefore must be interpreted with caution. To address this limitation, the adult Foot Health Status Questionnaire (FHSQ) was additionally collected at follow-up [362]. While this may not have enabled direct comparison to the childhood questionnaire scores, measures were taken to select a QofL assessment that was focussed on foot and ankle concerns and that the structure of questions was similar to those from the baseline questionnaire, to maximise compatibility [362]. The FHSQ has questions in eight domains, spanning a variety of QofL measures: social capacity, general health, general foot health, foot function, foot pain, shoes, vigour and physical activity [362]. The trends in scores across the participants will now be discussed.

12.2.2 FHSQ physical activity and foot function

For the FHSQ physical domain and foot function domains, each had only two participants that scored poorly. This finding starkly contrasts with the OxAFQ-C physical scores at follow-up, in which a much larger portion of participants demonstrated poor QofL outcomes. Notably, both participants with poor physical QofL were the only ones to have scored poorly across all 8 FHSQ QofL domains. Therefore, there may be an implication that physical health and wellbeing ties in with other aspects covered by the remaining domains, including foot health and social QofL. In addition, there was an even mix of poor physical QofL outcomes by foot type, with one of these two poorly scoring participants having FFF and the other NF.

12.2.3 FHSQ foot pain and social capacity

The social capacity and foot pain QofL domains indicated three participants with a poor score. All three scoring poorly in foot pain also did so in general foot health. Notably, the two participants with the joint lowest scores of 50 in social capacity were both female and also had poor scores in the foot pain, foot function and general foot health domains. Interestingly, although no trend by foot type was apparent in foot pain and social capacity, the majority had good scores in these domains.

12.2.4 FHSQ general health and general foot health

The general health and general foot health domains presented with bigger discrepancies, with six and five participants scoring 75 or below respectively. Interestingly, there were poorer outcomes in general health in NF, with four with this foot type scoring poorly. In addition, all six who scored poorly in general health also did so in vigour. In terms of BMI and gender, no trend was noted, with a variety of high and low BMI participants of each gender scoring poorly in this domain. As for the five individuals with poor general foot health scores, there was great overlap in other foot domains, with three also scoring poorly in foot pain and of these two scoring poorly in foot function. This suggests the possibility of overlapping features in these foot QofL domains, which is plausible as foot pain has

been known to impact function. Although in terms of foot type, there were similar outcomes in general foot health, with three out of the five having FFF and the other two NF. Notably, three out of the five scoring poorly in general foot health had increased flexibility scores, and also scored poorly in the shoes domain. This may suggest the susceptibility of increased flexibility to negatively affect foot health.

12.2.5 FHSQ shoes and vigour

The domains that demonstrated the greatest frequency of poor QofL outcomes were shoes and vigour, with eight and 14 respectively scoring poorly. There was great overlap, with seven participants scoring poorly in shoes also doing so in vigour. Both domains showed no discernible trend pertaining to BMI or weight. While an even mix of both foot types scored poorly in vigour, a slightly greater frequency of poor scores in the shoes domain was seen in males, with five out of the eight scoring poorly being of this gender.

Overall, from the independent FHSQ domain scores, it is evident that there were various trends in QofL outcomes at follow-up, in particular the propensity for participants scoring low in a foot QofL domain, to score low in another QofL domain. As for the notion of poorer future outcomes in FFF, this was only established from the OxAFQ-C measure results, with the FHSQ not demonstrating any prominent disparity in QofL between these foot types across its domains. There were also no overall trends based on gender, BMI or flexibility noted in the FFF participants experiencing poor QofL outcomes in either of the measures, which provides some suggestion that it is this foot type alone that is the key driver of these results. However, it must be acknowledged that outcomes in QofL at the stages of childhood and adulthood may not be directly comparable, and so caution must be taken when drawing conclusions on changes in QofL over time.

In line with the existing cross-sectional literature, in which it is evident that children with FFF have poorer QofL [5,7,8,136], this exploratory longitudinal study provided an insight into the changes in QofL over time that tend to affect FFF more negatively than NF. Building upon these findings, it is crucial to identify the clinical and anatomical factors that contribute to symptom development in FFF in children and understand how these factors change over time with the transition into adulthood. This can further the understanding of the patho-mechanics of FFF and may be able to help guide the creation of management strategy guidelines for this condition, by identifying which features of FFF in childhood are likely to be problematic in adulthood, if left untreated. The assessment of these factors commonly involves both static and dynamic evaluation of the foot. In this study, the AHI, standing MLA angle, seated MLA angle and standing hindfoot eversion angle were used for the purpose of evaluating static structural characteristics of the feet against QofL scores.

12.2.6 FHSQ and static foot posture

The baseline AHI was assessed in relation to the OxAFQ-C obtained at follow-up, where no significant correlation between either of the physical and emotional domains was obtained. However, on visual observation of the data points, it is apparent that most participants had high OxAFQ-C scores. Therefore, with generally high QofL outcomes across the range of low to high AHI measurements, it is not really possible to ascertain a correlation. In the follow-up study, the t-test analysis showed no significant differences in scores of the analysed FHSQ domains between those with poor scores and those with good scores across all static variables. Although, there was an interesting observation in the standing MLA angle variable, where the two FFF participants with the lowest angles, such that they were similar to some of the NF participants, both had good general health FHSQ scores of 90 each. This may suggest that FFF with a physical characteristic of a lower standing MLA angle, equivalent of a higher arched foot, may have better outcomes in QofL. Although, a trend of poorer outcomes for the FFF participants with higher standing MLA angles was not apparent. Therefore,

further research is necessary to conclusively determine the association between static foot measures including the MLA standing angle and QofL outcomes. It is important to note that solely evaluating static foot posture may not provide a comprehensive understanding of the impact of FFF on QofL over time. Therefore, it is necessary to evaluate the QofL in individuals with FFF during functional, weightbearing activities such as walking, to obtain a broader insight of the long-term effects this foot type has in this regard.

12.2.7 FHSQ and walking pattern

Kinematic variables, which measure changes in foot movement during dynamic activities, have been extensively employed to identify specific motions that may have a negative impact on QofL [5,136,139,165,352]. Early identification of these variables can enhance children's QofL and facilitate the development of effective management plans, ensuring a smooth transition into adulthood with an improved QofL.

Kothari et al. [5] investigated the relationship between kinematics and QofL in FFF. From the baseline data analysis, Kothari et al. [5] reported significant inverse correlations in most phases of the GC, between forefoot supination and OxAQF-C physical domain QofL outcomes. As for the follow-up study, the t-test analysis yielded significant differences in scores between those with good and poor QofL scores for minimum and range of forefoot supination in the FHSQ general foot health measure. From the data distribution pertaining to these analyses, slight trends were seen, of a higher forefoot supination range in those scoring poorly in the general foot health domain, and a lower or even negative minimum forefoot supination in those scoring poorly in general foot health. This apparent association between forefoot supination and QofL seen across these results may be theoretically explained by the influence of forefoot supination on the alignment of the foot, which could possibly affect foot strike patterns and the efficiency of propulsion which follows forefoot supination in the GC [331].

12.2.8 FHSQ hindfoot eversion

Hindfoot eversion is an additional variable that has been evaluated in the baseline study by Kothari et al. [5] against OxAQF-C physical QofL, from which only one significant correlation was obtained, with most of the analysis suggesting no association. This was a positive correlation between minimum hindfoot eversion and OxAQF-C physical QofL. In a similar manner, this follow-up study found no evidence of association between this variable and QofL, with no significant differences noted between good and poor scores and no visible trends in each of the analysed FHSQ QofL domains for hindfoot eversion. With such findings, it cannot be concluded that hindfoot eversion holds implications on QofL in either childhood or adulthood.

The follow-up data revealed three additional variables, previously unreported in the literature, to be associated with disparities in QofL outcomes. These variables were hindfoot dorsiflexion, forefoot dorsiflexion and hallux dorsiflexion.

12.2.9 FHSQ hindfoot dorsiflexion

For the variable of hindfoot dorsiflexion, significant differences between good and poor QofL scores were noted for maximum hindfoot dorsiflexion in FHSQ shoes, hindfoot dorsiflexion range in FHSQ vigour, and hindfoot dorsiflexion at toe-off in FHSQ general health.

There were some trends pertaining to these measurements and QofL outcomes, on visual inspection. In both hindfoot dorsiflexion range and toe-off variables, greater measurement values demonstrated relatively higher scores in the vigour and general health domains respectively. In contrast, the highest QofL scores in the shoes domain were observed amongst the highest and lowest hindfoot dorsiflexion maximum measurements at baseline. These results suggest that greater hindfoot dorsiflexion motion may potentially be related to better QofL outcomes. This may be explained by physiological principles pertaining to hindfoot dorsiflexion, which occurs maximally in the late stance phase. If there is

inadequate hindfoot dorsiflexion, there is increased likelihood of tibial arrest, where the tibia does not progress forward over the foot. This could result in disruption of weight transfer of the foot leading to impaired quality of gait.

12.2.10 FHSQ forefoot dorsiflexion variables

For the forefoot dorsiflexion variables, significant differences between good and poor QofL scores were noted for forefoot dorsiflexion range in FHSQ general health and forefoot dorsiflexion at heel contact in FHSQ general foot health. However, there were no visible trends pertaining to these QofL outcomes for forefoot dorsiflexion range and heel contact, with a mix of good and poor scores across the higher and lower measurements. The reason for the lack of definitive association between forefoot dorsiflexion and QofL in this study is unclear, especially given this movement's role in gait. Primarily, forefoot dorsiflexion aids gait by enabling toe-off, which allows for propulsion and forward movement. It could be hypothesised that excessive forefoot dorsiflexion could be associated with an unstable foot, due to impairment of the midfoot locking mechanism, as a result of misalignment of the midfoot bones' axes. With such instability of the foot during gait, the participant would be more likely to experience poor QofL.

12.2.11 FHSQ hallux dorsiflexion

For the hallux dorsiflexion variables, a significant difference between good and poor QofL scores was noted for minimum hallux dorsiflexion in FHSQ general health. For this variable, the participants with greater hallux dorsiflexion minimum measurements that were above 0 degrees tended to have relatively poorer FHSQ general health scores, based on visually observing the distribution of data. This pattern may again relate to toe-off, with the quality of propulsion potentially being affected by this kinematic variable during gait.

Overall, it is apparent that the greatest associations with QofL were observed in the forefoot supination and hindfoot dorsiflexion variables, which each showed significant differences between good and poor QofL scores for multiple variable measurements. In addition, they demonstrated visible trends pertaining to QofL scores for higher and lower measurement values.

12.2.12 Overall discussion

Before concluding this discussion, it is essential to acknowledge several points that were noted upon exploration of the data and observation of patterns. From the graphs presented in Figure 46 and 47, it can be noticed that the presence of ceiling effects was observed in the data across all the graphs. This refers to the presence of a moderate frequency of participants scoring the maximum QofL score of 100, making it difficult to ascertain if there was variability of QofL amongst those with this score. These effects can create challenges in interpretation, as they limit the range and variation of scores, making it more difficult to draw meaningful conclusions [406].

From preliminary questioning during data collection visits, prior to QofL assessment, it was recorded that six participants had informally stated the presence of foot pain to the researcher. However, only three of them scored poorly in the FHSQ foot pain domain. The fact that some individuals reported foot pain but did not score poorly in the FHSQ foot pain domain raises an interesting point. It suggests that while an individual may subjectively feel pain, it may not necessarily have a clinically significant impact on their overall QofL. In addition, the influence of parental concern must also be considered. At follow-up, some of these six participants were accompanied by their parents when answering the foot pain question. Given at baseline, the parents were noted to overemphasise negative symptoms and outcomes in the proxy OXAFQ-C questionnaire [7], their presence may have skewed the responses to the researcher regarding the presence of foot pain at follow-up. This highlights the importance of using validated clinical assessment tools, as they can objectively measure and quantify the impact of foot pain on an individual's QofL. Without such tools, it becomes challenging to differentiate between

individuals who experience pain that affects their QofL and those with pain who are still able to maintain a relatively high QofL.

In addition, there were four participants who were currently wearing orthoses and four who had previously worn them. Furthermore, five participants had previously been involved in an exercise program, of which three also had previous physiotherapy visits. Despite these interventions, no trends were noted in the scores across the domains, with a combination of high and low scores amongst the participants that had each intervention. Although, it is likely that the small sample size might have limited the ability to detect trends. With a larger sample, it is possible that patterns would have emerged, allowing for more robust conclusions. It must also be noted that the interventions themselves may have varied among the participants. Factors such as the length, intensity and frequency of the exercise programs, as well as the type and duration of orthotics usage, may have differed between individuals. These variations in the implementation of interventions can contribute to heterogeneity of observed outcomes. To address these limitations and provide more conclusive evidence, a randomised controlled trial would be ideal for evaluating and comparing the impact of a given intervention on QofL.

Upon assessing the kinematic variables in relation to QofL outcomes, it is essential to address the fact that the MLA angle variables were newly created and introduced for the first time in this study. They were able to be retrospectively extracted from the baseline data set, as it had utilised the navicular marker. With further use of the MLA angle variable on larger sample sizes, in relation to QofL assessment, it is possible that trends may be seen. This would also enable comparison and clinically meaningful interpretation of the results, which cannot be done in this study.

12.3 Limitations

The present study has several limitations that need to be considered. The first pertains to the selection of participants in the baseline study, which was limited to children with FFF from an orthotic or orthopaedic clinic. This may arguably only represent a subset of individuals with this condition. Since the severity of FFF can vary and given not all individuals with this condition seek medical attention, the presentations of this condition in the healthcare setting may not reflect that which is seen in the entire population affected by it. Additionally, this study was the first to prospectively examine QofL in FFF, meaning there is a lack of previous evidence to provide established standards for prospective QofL research. Therefore, this study was more exploratory in nature, with limited guidance on expected outcomes and comparisons. Another limitation pertains to the retrospective collection of data, despite this study having a prospective design. This led to the possibility of recall bias, where the participants may have been limited in answering the QofL questions on the past. Despite providing an objective measure of QofL, questionnaires are subjected to limitations of sensitivity for the specific condition or symptoms being measured, although this limitation was mitigated through careful selection of the utilised QofL questionnaires that have extensively been tested for sensitivity in various studies [362,372–375]. Due to resource constraints and specific eligibility criteria for participant inclusion, the number of individuals included in this study was limited and resulted in a small sample size. Consequently, the findings may not be generalisable to a larger population or accurately represent the full spectrum of variations within individuals with FFF. Therefore, while this exploratory study provides valuable insights into FFF and its associated QofL over time, it is crucial to interpret the findings with caution. Further research with larger and more diverse samples is necessary to establish a more comprehensive understanding of this condition and its implications. Finally, the development of a single QofL questionnaire specifically designed to assess QofL in childhood and adulthood, with a focus on conditions related to feet such as FFF is crucial. This would provide accurate representation and assessment of QofL over time in these individuals.

12.4 Conclusion

From the assessments of QofL, the third null hypothesis can be rejected on the basis that trends in QofL that tie in with the measurements of several static and dynamic kinematic variables were observed. This is underpinned by the presence of significant differences between good and poor QofL scores, alongside visible trends between measurement values and QofL scores across multiple measurements in the forefoot supination and hindfoot dorsiflexion variables. However, at this stage, the explanation of the associations between these variables and QofL can only be hypothesised based on their potential impact on the effectiveness and stability of gait.

It was also noted that the QofL domains may be interlinked, with participants scoring poorly in certain domains also doing so in others. There is evidence from the OxAFQ-C assessments to support the notion that FFF individuals face poorer future outcomes in comparison to those with NF. To build upon these findings, further research on a larger sample size is required to investigate the kinematic variable measurements linked with differences in QofL. The current findings cannot convey clinically meaningful information at this stage because there is no established evidence to denote a threshold of a kinematic variable's measurement that would impact QofL. It would be beneficial to know a lower or higher threshold of a kinematic variable measurement at which implications on QofL would be observed.

13 Conclusions

This thesis aimed to provide longitudinal evidence on the prognosis of FFF from childhood to early adulthood, with the intention to help inform management plans. By knowing how the MLA in FFF changes with time, justification for whether to intervene or not in childhood can be made. To conduct such assessment, accurate and reliable depiction of the MLA is required. Therefore, an optimal measure of the MLA angle was selected, following rigorous qualitative and quantitative assessments pertaining to its use on members of the general population that were aged 8 to 25 years. These encompassed criteria pertaining to the measure's sensitivity to capture expected changes in MLA shape between loaded and unloaded conditions, alignment with currently accepted MLA assessment methods, as well as acceptable repeatability, versatility, and practicality of use. By aggregating the outcomes of these criteria, a measure which utilised real markers on the heel, navicular, head of the first metatarsal and base of the fifth metatarsal was deemed optimal for MLA assessment during dynamic activities.

To observe its applicability in the context of foot pathology, the MLA measure was trialled on four participants with CP, a condition which manifests with a wide variety of foot pathologies and gait patterns. This demonstrated that the measure was able to detect differences to non-pathological feet, and showed an interesting pattern related to the movements of the hallux, with an increased arch angle being detected in cases of increased hallux dorsiflexion in most cases.

Having established an optimal MLA measure that was valid and reliable, evaluation of the MLA could be conducted in conjunction with other measures which have been previously utilised in clinical and research settings. Collectively, these measures were used to characterise the MLA in childhood and adulthood, to detect changes over time and outline differences between FFF and NF. This entailed comparing measurements taken from the baseline study, in which the participants were aged 8 to 16 years, to those taken from this study as the follow-up study. In this study, there were 20 participants

aged 16 to 25 years, who had taken part in the baseline study. Static foot posture measures were utilised for this purpose, followed by dynamic walking pattern measures. The static assessment variables of foot posture included the AHI, standing MLA angle, sitting MLA angle, standing hindfoot eversion and arch rigidity index. Amongst the weightbearing variables, AHI found the MLA to be significantly flatter at follow-up compared to baseline while the MLA standing angle found no significant differences between these two time points. In contrast, the non-weightbearing variable of the sitting MLA angle found the MLA to be significantly higher at follow-up compared to baseline. The AHI and both standing and sitting MLA angle variables all noted the MLA in FFF to be lower than in NF, in both childhood and adulthood. Overall, it was concluded that if a child presents with a flat arch during static assessment, it is likely to remain flat into adulthood. In addition, the lower the arch in childhood, the greater the likelihood of increasing flatness in adulthood. In contrast, it is difficult to predict how the arch structure of children presenting with a neutral foot will develop over time, with some become flatter, and some becoming higher as an adult.

The dynamic assessment variables of walking pattern included walking MLA angles and hindfoot, forefoot and hallux kinematic angles across various phases of the GC. The walking MLA and hindfoot eversion angles provided evidence of change between baseline and follow-up. From the former variable, there was the trend of overall decrease over time, indicative of an increase in arch height. However, upon analysing by foot type, it was apparent that the MLA height in FFF persists over time and remains flatter in comparison to NF in both childhood and adulthood. Comparatively in NF, irrespective of having a low, average or high MLA measurement at baseline, the follow-up measurements amongst the group were relatively similar to each other. The hindfoot eversion variables demonstrated a small, but clinically questionable increase over time, between baseline and follow-up. No discrepancies between FFF and NF were observed in this variable.

For evaluating the implications of FFF on QofL, two assessment tools were utilised. OxAFQ-C assessments on physical and emotional QofL domains were taken at both baseline and follow-up, to enable direct comparison. From the 16 participants with such measurements at both time points, seven had FFF and nine had NF. Three FFF participants experienced a decline in both physical and emotional QofL from childhood to adulthood, while only one NF participant did so in this manner. All FFF participants experienced decline in at least one of the two QofL domains over time. Five NF participants either maintained or improved both QofL domains over time, of which three had an improvement in both domains. Therefore, the OXAFQ-C denoted generally poorer future outcomes for children with FFF and similar or better future outcomes for children with NF. The FHSQ was another QofL measure used for evaluation in follow-up only, where a cut-off score of 75 and below was used to distinguish poor from good QofL. From this tool, there were no trends indicative of differences in QofL between FFF and NF. There was the tendency for participants scoring low in one of the foot FHSQ domains to also score low in other domains.

Kinematic measurements at baseline were evaluated against FHSQ scores at follow-up, with the results indicating poorer QofL in those with higher forefoot supination range and lower minimum forefoot supination (increased pronation), and better QofL in those with greater hindfoot dorsiflexion range and toe-off measurements.

Putting these findings together, it is apparent that FFF in childhood does not tend to improve over time, into early adulthood. Based on static foot posture, those with FFF in childhood, if anything, are likely to have even flatter feet as an adult. Based on dynamic walking patterns, there is less evidence of deterioration, but there is continued flatfootedness. The QofL results from the OXAFQ-C indicated the tendency for poorer QofL outcomes over time in FFF. Therefore, this exploratory thesis has formed a base of evidence to aid in justifying and informing long-term management plans for FFF, underpinned by the potential negative associations with this condition in adulthood.

13.1 General Limitations

The main limitations pertaining to the various sections of this thesis will now be outlined. When developing the novel MLA measure, several evidence-based aspects were taken into consideration, following which eight configurations were developed. There may be the possibility of further configurations, which may be more optimal than the one derived in this study, that could be developed. The next potential limitation of the MLA measure study concerns the use of clinical AHI measurements instead of radiographic imaging, as comparators for further validating the new MLA measures. However, the AHI has been validated against radiographic imaging and has been shown to be a valid and representative tool that can be used when radiographic imaging is not available.

With regards to the longitudinal study of FFF, despite successfully recalling twenty participants from the baseline study, there was still the limitation of a small sample size. This was accompanied by potential recall bias from the participants, when relaying their previous symptoms and treatment history. In addition, there may have potentially been overreporting of symptoms, due to children often using their parents to guide them in answering questions. Overall, it must be acknowledged that this thesis predominantly utilised CGA, which holds the limitation of skin movement artefacts when capturing the dynamic MLA form, especially at initial foot contact. Although, this limitation applies to all forms of dynamic assessment, and it is well recognised in the field that it cannot be completely eliminated.

13.2 Future directions

To build upon the findings of this thesis, additional prospective longitudinal studies are required to evaluate the impact of treatment interventions on the progression of FFF into adulthood. This would entail the incorporation of randomised control trials, in which future outcomes in participants with FFF who are undertaking various treatments or are controls can be assessed, preferably in comparison to NF. These outcomes should ideally encompass static and dynamic measurements including the MLA angle, alongside validated QofL evaluations. Specifically, future studies should build upon the exploratory findings of this research, by assessing the threshold for a kinematic variable measurement at which there are clinically meaningful implications. Such assessments should be conducted on a larger sample size than that of this study, ideally encompassing a range of FFF presentations. Additionally, there is a need for the development of a QofL questionnaire with a specific focus on feet, that can be used in both children and adults. This will further facilitate the research for identifying clinically meaningful results in the population.

14 Appendix A : Data collection documentation

A1 Subject measurement sheet

PARTICIPATION RECORDING FORM

Participants study number			
Participants initials			
Age			
Gender	M	F	
Date of data collection			
Height		cm	
Weight		kg	
Inter ASIS distance		mm	

	RIGHT		LEFT	
LEG LENGTH		cm		cm
KNEE WIDTH		mm		mm
ANKLE WIDTH		mm		mm

ORTHOSIS RIGHT ☐ LEFT ☐ NO ☐

MLA visual assessment

	R		L	
Neutral	☐		☐	
High arch	☐		☐	
	+windlass		+windlass	
Flat foot	☐	☐	☐	☐

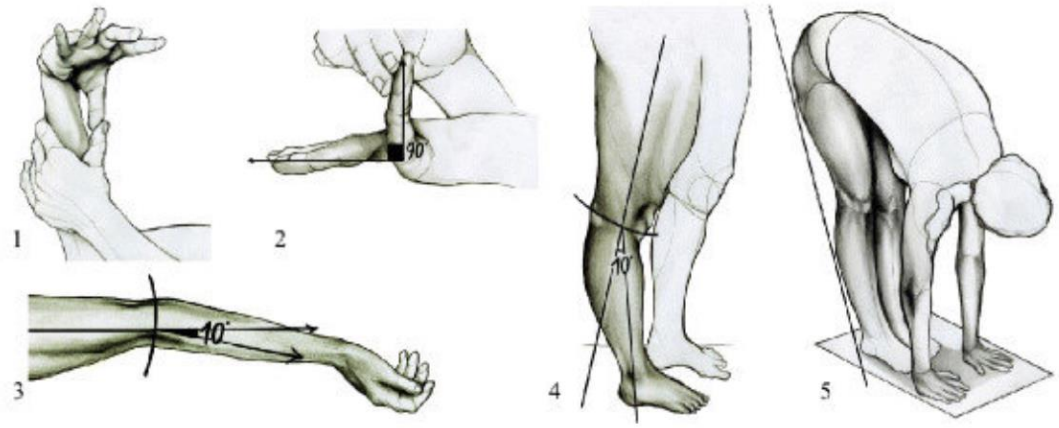
AHI standing

	R		L	
Foot length		mm		mm
Dorsum height at 50%		cm		cm
Truncated foot length		mm		mm

	R		L	
AHI sitting				
Foot length		mm		mm
Dorsum height at 50%		cm		cm
Truncated foot length		mm		mm

Specific joint laxity	YES		NO
1. Passive apposition of thumb to forearm	☐ Left	☐ Right	☐
2. Passive hyperextension of V-MCP > 90°	☐ Left	☐ Right	☐
3. Active hyperextension of elbow >10°	☐ Left	☐ Right	☐
4. Active hyperextension of knee >10°	☐ Left	☐ Right	☐
5. Ability to flex spine placing palms to floor without bending knees	☐		☐

*Each "YES" is 1 point. A score ≥ 4 out 9 is generally considered an indication of JH. (MCP: metacarpophalangeal).



15 Appendix B : Instructions on obtaining remote AHI measurements

FOOT PICTURES

You will need 2 pieces of A4 paper, a mobile phone with a camera, and a colleague/family member for this task.

You will be provided with guidance on how to take foot pictures in two views: top and side views.

Step 1. To be able to take accurate foot pictures, you will need to remove your shoes and socks and find an area with a hard-floored, entirely smooth surface that is big enough for you to comfortably fit in (e.g. wood floor, tiles etc). Please ensure you turn on all the lights in the room.

This task will require you lift one of the heels from the ground, If you do not feel confident with standing in this position, please use a chair without wheels or position yourself close to a wall, or something similar so you can get extra support.

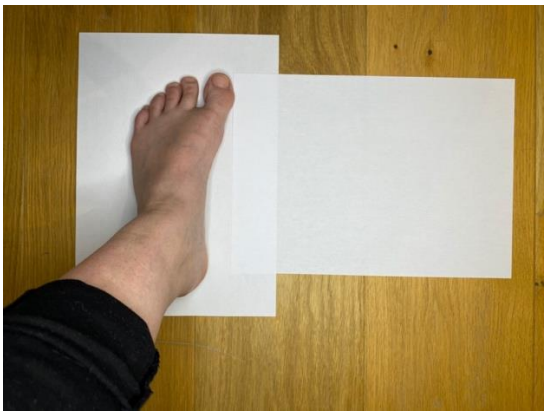
First, we will collect your **RIGHT** foot photos

Step 2. For capturing the side view, place one A4 paper lengthways on the floor directly in front of you. Stand with your feet shoulder width apart in relaxed standing position, ensuring the paper is still in front of you. Now take a step forward with your right foot so that it lands entirely within the A4 paper. The left foot stays at the same as at the initial position. Then, lift the heel of your left foot off the ground and hold this position. If you do not feel confident with standing in this position, please use a chair without wheels or position yourself close to a wall, or something similar so you can get extra support.



Step 3.
Your colleague should now get the second piece of A4 paper and orient it to be perpendicular (at a right angle) to the first piece of A4 paper. Keeping this perpendicular position, your colleague should slide the second piece of paper towards the inner side of

your foot until it makes initial contact with the inner side of your foot. Now, one short side of the second piece of paper should be touching part of the inner side of your foot as well as still be oriented perpendicular (at a right angle) to the first piece of A4 paper. The other short side of the second piece of A4 paper will mark the distance from where your colleague should take the picture. Your colleague should place the mobile phone here, in a way that its long side touches the ground when taking the picture. Ensure the mobile phone is straight when taking the picture, and that it does not lean forwards or backwards. Also, ensure the whole foot is clearly included in the middle of the picture. Now, your colleague should remove the second piece of A4 paper from the camera shot and take the picture.





Please be aware of camera location on your telephone when positioning your phone.

Step 4. For capturing the top view, stand with your feet shoulder width apart, with your right foot placed entirely within the first piece of A4 paper. Take the phone from your colleague and bring it to the level of your belly button. From this height, take a top view photo of your right foot, ensuring the entire foot and A4 paper is captured in the shot.





Now, you will be asked to repeat the same process for your **LEFT** foot photos.

For capturing the top view, stand with your feet shoulder width apart, with your left foot placed entirely within the first piece of A4 paper. Take the phone from your colleague and bring it to the level of your belly button. From this height, take a top view photo of your left foot, ensuring the entire foot and A4 paper is captured in the shot.





16 Appendix C : Instructions on obtaining remote AI measurements

FOOTPRINT

You will need the pack that you have received by post, containing two footprint sheets (one for your left foot and one for your right foot), a single foot wipe enclosed in one pack (this single wipe will be used to clean each foot) and a prepaid post return stamps.

Step 1. To be able to create accurate footprints, you will need to remove your shoes and socks and find an area with a hard-floored, entirely smooth surface that is big enough for you to comfortably fit a chair in. If your home only has carpet flooring, please place a book in A4 format, or something else that is hard and smooth on the floor, to act as your surface.

Step 2. Place a chair in the chosen area, ensuring you leave at least a metre of space in front of it. Carefully take out the footprint sheets and the pack containing the foot wipe and place them somewhere that would be nearby and reachable upon taking a seat. Now sit on the chair, ensuring you feel comfortable. If you do not feel confident with standing on one foot, please use a chair without wheels or position yourself close to wall, so you can get extra support.



Please ensure you complete the process and acquire both right and left footprints consecutively, ideally within 10 minutes, to avoid the foot wipe drying out. The foot wipe plays an important role, as if it dries out you won't be able to obtain your footprints. **Do not step on the floor with your wiped foot, as this will prevent obtaining full footprint.**

First, we will collect your **RIGHT** footprint.

Step 3. While staying seated, reach over and take one footprint sheet and place it **lengthways on the floor with the side with your participants number downwards (shinny side upwards),** directly in front of your right foot (meaning the short edge is just in front of your toes).



Now raise your right foot and place it on your left knee. Reach for the foot wipe and use it to clean the sole of your right foot thoroughly. Do not forget to pay extra attention towards the edges of the foot, between the toes and the end of the toes. Once you have thoroughly wiped your foot, place the wipe in a safe area, so it can be reused later. Make sure that you do not touch the floor with your right foot at this point, as this will not allow you to obtain a complete footprint.



Get up from the chair ensuring **only** your left foot is touching on the floor and then make your first step forward with your right foot, ensuring it lands perfectly within the footprint sheet. Then stay where you are and count to 15. Then step off the footprint sheet and pick it up and place it aside.





You may now freely step on the floor – there is no risk of damage or marks to your flooring. Be careful when picking up the footprint, try to grab for the very far so that your fingerprints will not interfere with the footprints. When putting them safely on side, please be careful that wipes does not get close to the collected footprints, as wipe is the ink, and it will destroy the footprint.

Now, you will be asked to repeat the same process for your **LEFT** footprint.

17 Appendix D : Walking pattern measurements and kinematic waveforms

D1 Mean baseline and follow-up measurements

Dynamic variable	FFF baseline	FFF follow-up	NF baseline	NF follow-up
Walking MLA Mean	171 (6)	165 (7)	156 (8)	156 (4)
Walking MLA Min	163 (7)	153 (9)	146 (9)	145 (4)
Walking MLA Max	180 (6)	173 (9)	166 (8)	164 (5)
Walking MLA Range	17 (5)	20 (12)	20 (2)	19 (3)
Walking MLA Heel Contact	169 (6)	165 (7)	154 (10)	155 (4)
Walking MLA Toe-off	166 (6)	158 (6)	149 (9)	147 (5)
Walking Hindfoot Dorsiflexion Mean	2 (3)	1 (7)	2 (3)	3 (4)
Walking Hindfoot Dorsiflexion Min	-11 (5)	-13 (9)	-13 (4)	-13 (7)
Walking Hindfoot Dorsiflexion Max	9 (4)	8 (8)	10 (4)	11 (4)
Walking Hindfoot Dorsiflexion Range	20 (4)	21 (5)	23 (4)	24 (4)
Walking Hindfoot Dorsiflexion Heel Contact	0.3 (4)	0.9 (7)	-0.5 (4)	1.3 (3)
Walking Hindfoot Dorsiflexion Toe-off	-5 (4)	-7 (7)	-7 (5)	-8 (6)
Walking Hindfoot Eversion Mean	-1 (5)	0.5 (5)	-2 (5)	-0.3 (4)
Walking Hindfoot Eversion Min	-6 (5)	-4 (5)	-7(5)	-5 (4)
Walking Hindfoot Eversion Max	5 (6)	8 (6)	4 (5)	7 (5)
Walking Hindfoot Eversion Range	11 (2)	13 (5)	11 (2)	11 (3)
Walking Hindfoot Eversion Heel Contact	0.6 (6)	2 (5)	-0.9 (6)	0.8 (4)
Walking Hindfoot Eversion Toe-off	4 (6)	6 (6)	3 (5)	5 (5)
Walking Forefoot Dorsiflexion Mean	-1 (3)	-1 (4)	-1 (3)	-3 (4)
Walking Forefoot Dorsiflexion Min	-10 (3)	-9 (4)	-11 (4)	-12 (5)
Walking Forefoot Dorsiflexion Max	6 (3)	7 (5)	6 (3)	5 (4)
Walking Forefoot Dorsiflexion Range	16 (4)	16 (3)	16 (3)	17 (3)
Walking Forefoot Dorsiflexion Heel Contact	-4 (5)	-2 (6)	-4 (3)	-5 (5)
Walking Forefoot Dorsiflexion Toe-off	-5 (4)	-6 (4)	-6 (5)	-10 (5)
Walking Forefoot Abduction Mean	-4 (6)	-3 (5)	-4 (8)	-3 (6)
Walking Forefoot Abduction Min	-7 (6)	-6 (5)	-8 (8)	-7 (5)
Walking Forefoot Abduction Max	0.0 (7)	2 (5)	2 (9)	3 (6)
Walking Forefoot Abduction Range	7 (3)	8 (4)	10 (4)	10 (2)

Walking Forefoot Abduction Heel Contact	-5 (6)	-4 (5)	-4 (8)	-4 (5)
Walking Forefoot Abduction Toe-off	-2 (7)	0.2 (5)	0.5 (8)	3 (6)
Walking Forefoot Supination Mean	6 (5)	5 (5)	5 (5)	2 (5)
Walking Forefoot Supination Min	2 (6)	1 (6)	2 (5)	-0.3 (5)
Walking Forefoot Supination Max	10 (5)	9 (5)	9 (5)	6 (5)
Walking Forefoot Supination Range	8 (3)	8 (2)	7 (2)	7 (2)
Walking Forefoot Supination Heel Contact	7 (6)	7 (5)	6 (6)	4 (5)
Walking Forefoot Supination Toe-off	5 (5)	5 (6)	5 (6)	2 (4)
Walking Hallux Dorsiflexion Mean	4 (7)	3 (8)	3 (9)	6 (10)
Walking Hallux Dorsiflexion Min	-8 (8)	-6 (8)	-11 (7)	-4 (10)
Walking Hallux Dorsiflexion Max	22 (9)	18 (12)	24 (12)	20 (10)
Walking Hallux Dorsiflexion Range	30 (12)	24 (7)	34 (10)	24 (7)
Walking Hallux Dorsiflexion Heel Contact	9 (11)	3 (9)	13 (12)	12 (9)
Walking Hallux Dorsiflexion Toe-off	14 (13)	12 (12)	18 (14)	17 (11)

D2 Walking pattern data analysis between baseline and follow-up measurements and by foot type

Measurement variables of gait pattern	Scatter plot (visual assessment)	Equation of the best fit line group for baseline to follow-up (p value)	Pearson correlation baseline and follow-up (p value)	Equation of the best fit line for baseline to follow-up FFF	Equation of the best fit line for baseline to follow-up NF	Interaction effect regression gradient (p value)	Paired t-test (p value)	2x2 ANOVA time point (p value)	2x2 ANOVA foot type (p value)	2X2 ANOVA interaction effects (p value)
Walking MLA Mean	Positive, linear	73 + 0.54x **(p=<.001)**	0.765 **(p=.000)**	1 + 0.96x	123 + 0.21x	**(p=.001)**	**(p=.042)**	**(p=.035)**	**(p=<.001)**	**(p=.038)**
Walking MLA Min	Positive, linear	86 + 0.41x **(p=<.001)**	0.568 **(p=.000)**	90 + 0.39x	107 + 0.26x	(p=.693)	**(p=.006)**	**(p=.003)**	**(p=<.001)**	**(p=.015)**
Walking MLA Max	Positive, linear	57 + 0.65x **(p=<.001)**	0.787 **(p=.000)**	37 + 1.18x	108 + 0.34x	**(p=.001)**	**(p=.003)**	**(p=.015)**	**(p=<.001)**	(p=.136)
Walking MLA Range	No association		0.146 (p=.395)				(p=.381)			
Walking MLA Heel Contact	Positive, linear	77 + 0.52x **(p=<.001)**	0.708 **(p=.000)**	44 + 0.73x	137 + 0.12x	**(p=.016)**	(p=.524)	(p=.275)	**(p=<.001)**	(p=.136)
Walking MLA Toe-off	Positive, linear	68 + 0.54x **(p=<.001)**	0.770 **(p=.000)**	99 + 0.37x	108 + 0.26x	(p=.632)	**(p=.002)**	**(p=.002)**	**(p=<.001)**	(p=.083)
Walking Hindfoot Dorsiflexion Mean	No association		-0.024 (p=.885)				(p=.905)			

Walking Hindfoot Dorsiflexion Min	No		0.054 (p=.740)				(p=.351)			
Walking Hindfoot Dorsiflexion Max	No		-0.036 (p=.826)				(p=.881)			
Walking Hindfoot Dorsiflexion Range	No		0.143 (p=.379)				(p=.189)			
Walking Hindfoot Dorsiflexion Heel Contact	No		0.052 (p=.748)				(p=.266)			
Walking Hindfoot Dorsiflexion Toe-off	No		0.100 (p=.539)				(p=.280)			
Walking Hindfoot Eversion Mean	No	1 + 0.35x **(p=.009)**	0.406 **(p=.009)**	1 + 0.52x	0 + 0.18x	(p=.190)	**(P=.033)**	(p=.904)	(p=.375)	(p=.251)
Walking Hindfoot Eversion Min	No	3 + 0.30x **(p=.041)**	0.324 **(p=.041)**	2 + 0.46x	4 + 0.13x	(p=.254)	**(p=.028)**	(p=.362)	(p=.450)	(p=.495)
Walking Hindfoot Eversion Max	No	6 + 0.31x **(p=.041)**	0.324 **(p=.041)**	6 + 0.46x	6 + 0.13x	(p=.276)	**(p=.006)**	(p=.879)	(p=.207)	(p=.467)

Walking Hindfoot Eversion Range	No		0.019 (p=.909)				(p=.253)			
Walking Hindfoot Eversion Heel Contact	No		0.393 **(p=.012)**			(p=.425)	(p=.125)			
Walking Hindfoot Eversion Toe-off	No	4 + 0.38x **(p=.010)**	0.405 **(p=.010)**	4 + 0.49x	4 + 0.22x	(p=.339)	**(P=.018)**	(p=.298)	(p=.104)	(p=.748)
Walking Forefoot Dorsiflexion Mean	No		-0.053 (p=.743)				(p=.172)			
Walking Forefoot Dorsiflexion Min	No		0.163 (p=.315)				(p=.813)			
Walking Forefoot Dorsiflexion Max	No		0.100 (p=.541)				(p=.960)			
Walking Forefoot Dorsiflexion Range	No		0.243 (p=.130)				(p=.703)			
Walking Forefoot Dorsiflexion Heel Contact	No		-0.079 (p=.630)				(p=.596)			

Walking Forefoot Dorsiflexion Toe-off	No	7 + 0.23x (p=.179)	0.217 (p=.179)	6 - 0.05x	8 + 0.30x		**(p=.019)**	**(p=.027)**	**(p=.006)**	(p=.260)
Walking Forefoot Abduction Mean	No		0.117 (p=.473)				(p=.606)			
Walking Forefoot Abduction Min	No		0.123 (p=.450)				(p=.468)			
Walking Forefoot Abduction Max	No		0.189 (p=.243)				(p=.335)			
Walking Forefoot Abduction Range	No		0.261 (p=.104)				(p=.492)			
Walking Forefoot Abduction Heel Contact	No		0.119 (p=.464)				(p=.565)			
Walking Forefoot Abduction Toe-off	No		0.163 (p=.315)				(p=.112)			
Walking Forefoot Supination Mean	No		0.152 (p=.350)				(p=.058)			

Walking Forefoot Supination Min	No		0.142 (p=.383)				(p=.174)			
Walking Forefoot Supination Max	No		0.124 (p=.445)				(p=.054)			
Walking Forefoot Supination Range	No		0.479 (**p=.002**)			(p=.367)	(p=.199)			
Walking Forefoot Supination Heel Contact	No		0.284 (p=.075)				(p=.163)			
Walking Forefoot Supination Toe-off	No		0.188 (p=.244)				(P=.088)			
Walking Hallux Dorsiflexion Mean	No		0.242 (p=.132)				(p=.390)			
Walking Hallux Dorsiflexion Min	No	4 + 0.15x (p=.425)	0.130 (p=.425)	2 + 0.53x	7 - 0.28x		(P=.020)	(P=.028)	(p=.792)	(p=.253)
Walking Hallux Dorsiflexion Max	No		0.216 (p=.181)				(p=.099)			
Walking Hallux Dorsiflexion Range	No	29 + 0.12x (p=.616)	0.082 (p=.616)	14 + 0.66x	44 + 0.41x		(p=<.001)	(p<.001)	(p=.286)	(p=.287)

Walking Hallux Dorsiflexion Heel Contact	No		0.378 (**p=.016**)			(p=0.633)	(p=.087)			
Walking Hallux Dorsiflexion Toe-off	No						(p=.602)			

D3- Kinematic waveforms

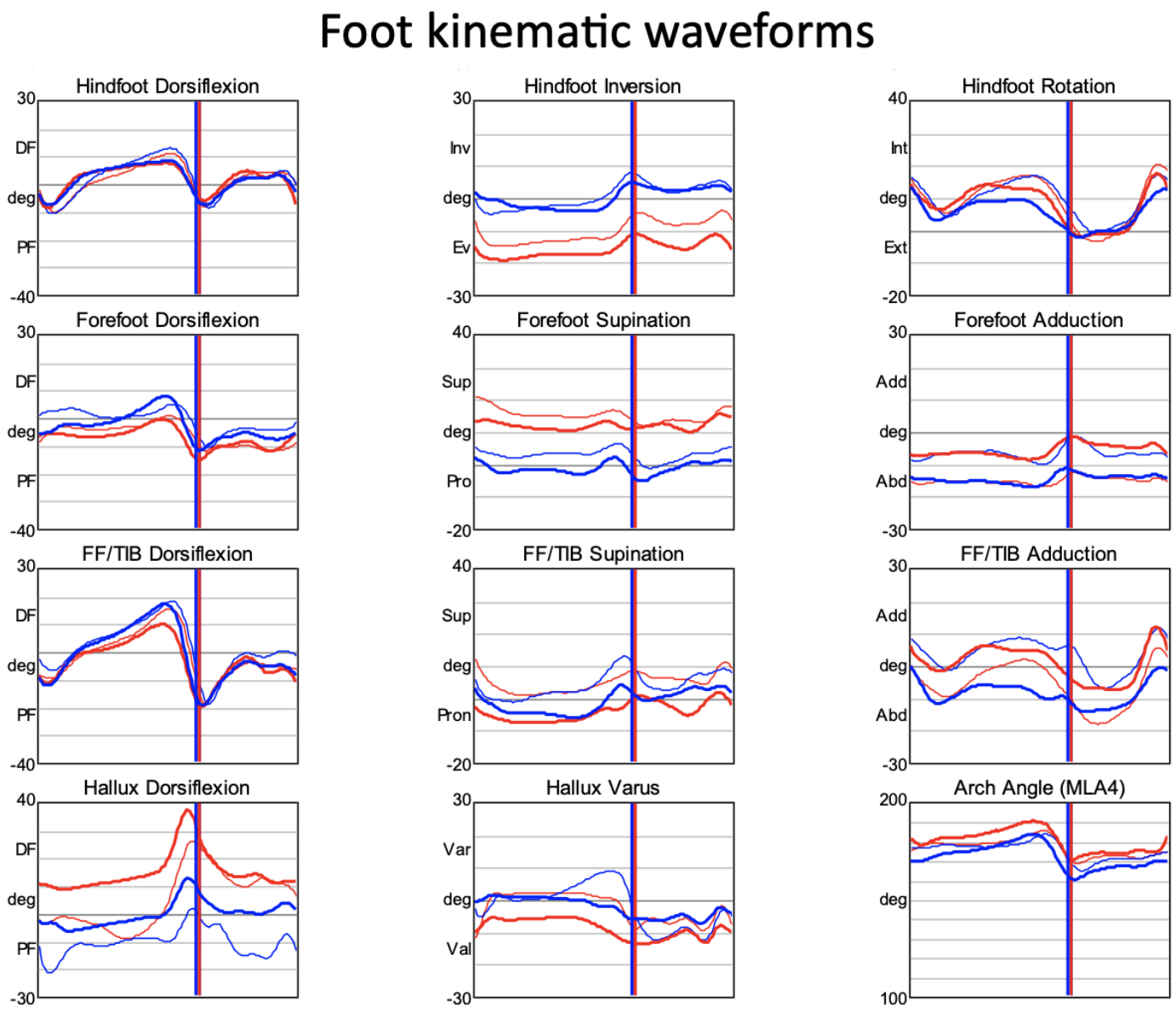


Figure 48: presents the change in foot kinematic waveforms between baseline and follow-up for participant 1, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

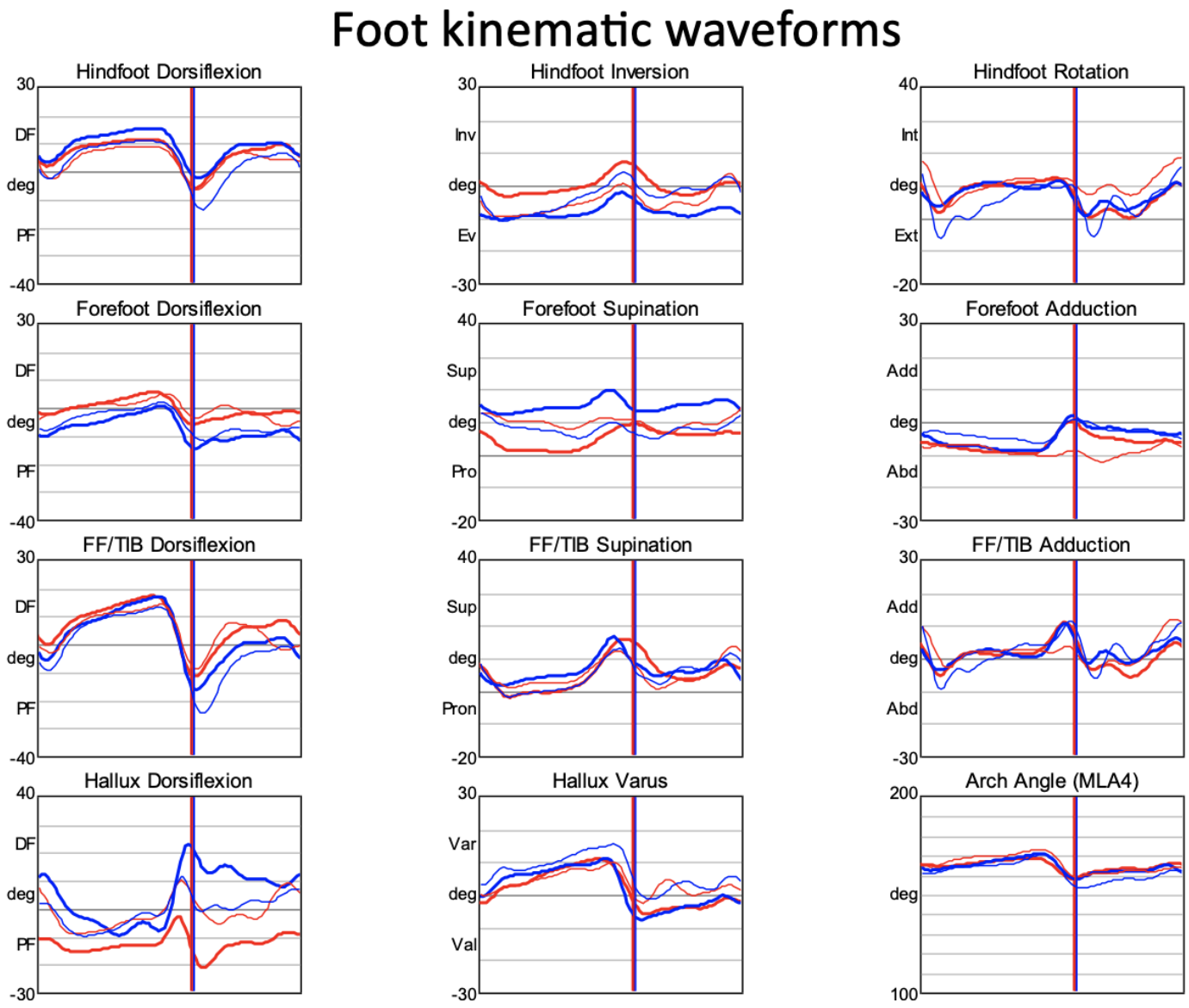


Figure 49: presents the change in foot kinematic waveforms between baseline and follow-up for participant 2, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

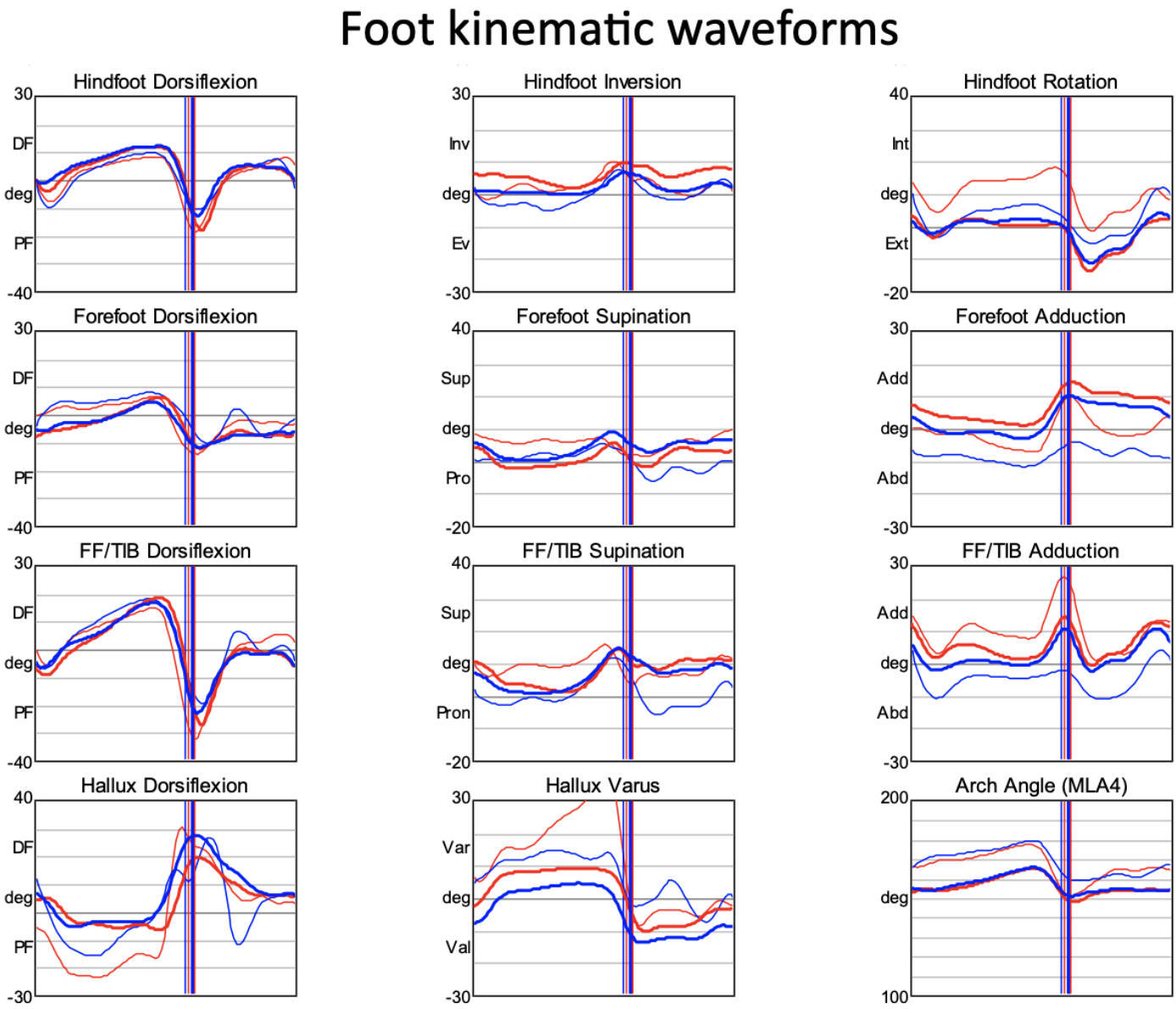


Figure 50: presents the change in foot kinematic waveforms between baseline and follow-up for participant 3, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

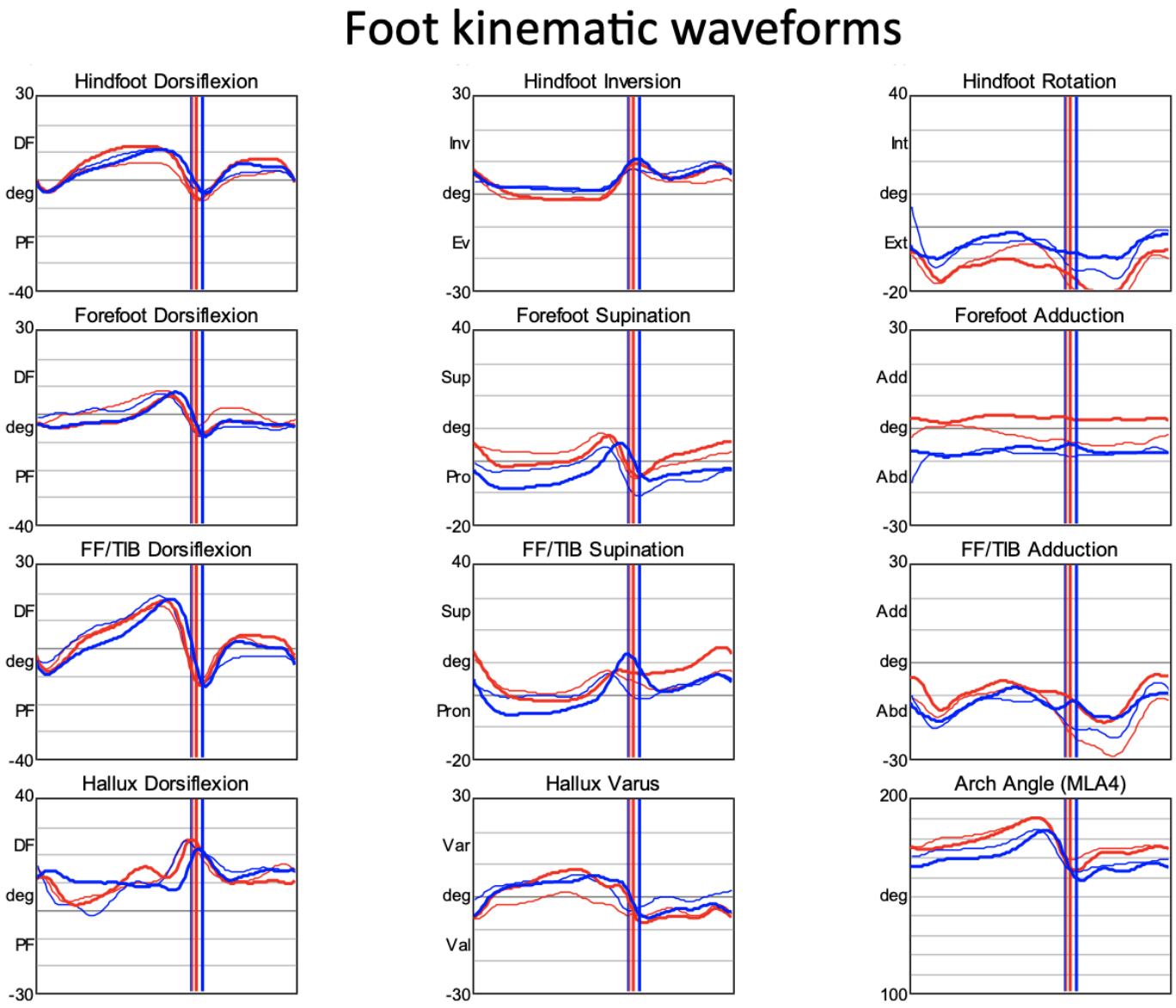


Figure 51: presents the change in foot kinematic waveforms between baseline and follow-up for participant 4, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

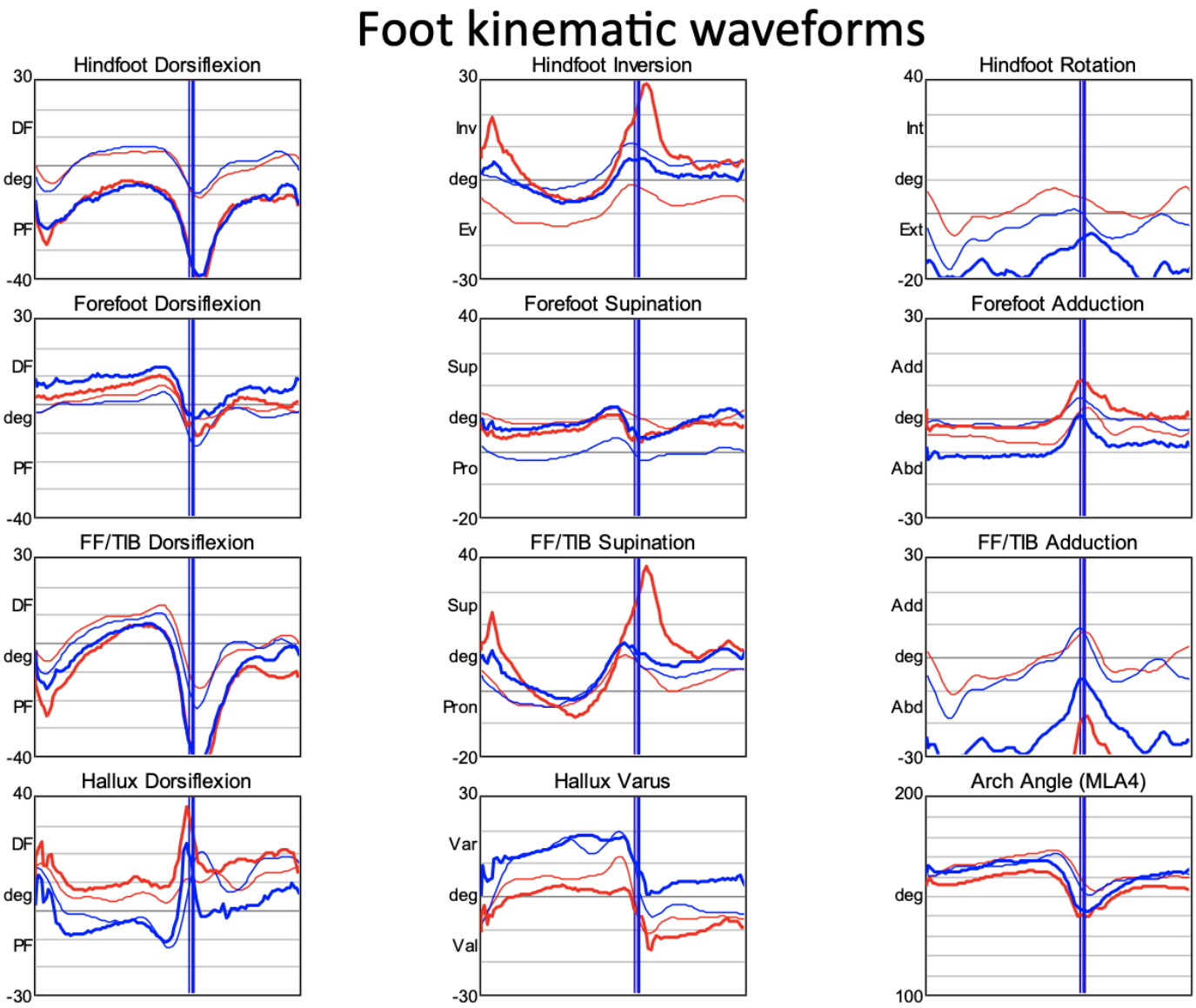


Figure 52: presents the change in foot kinematic waveforms between baseline and follow-up for participant 5, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

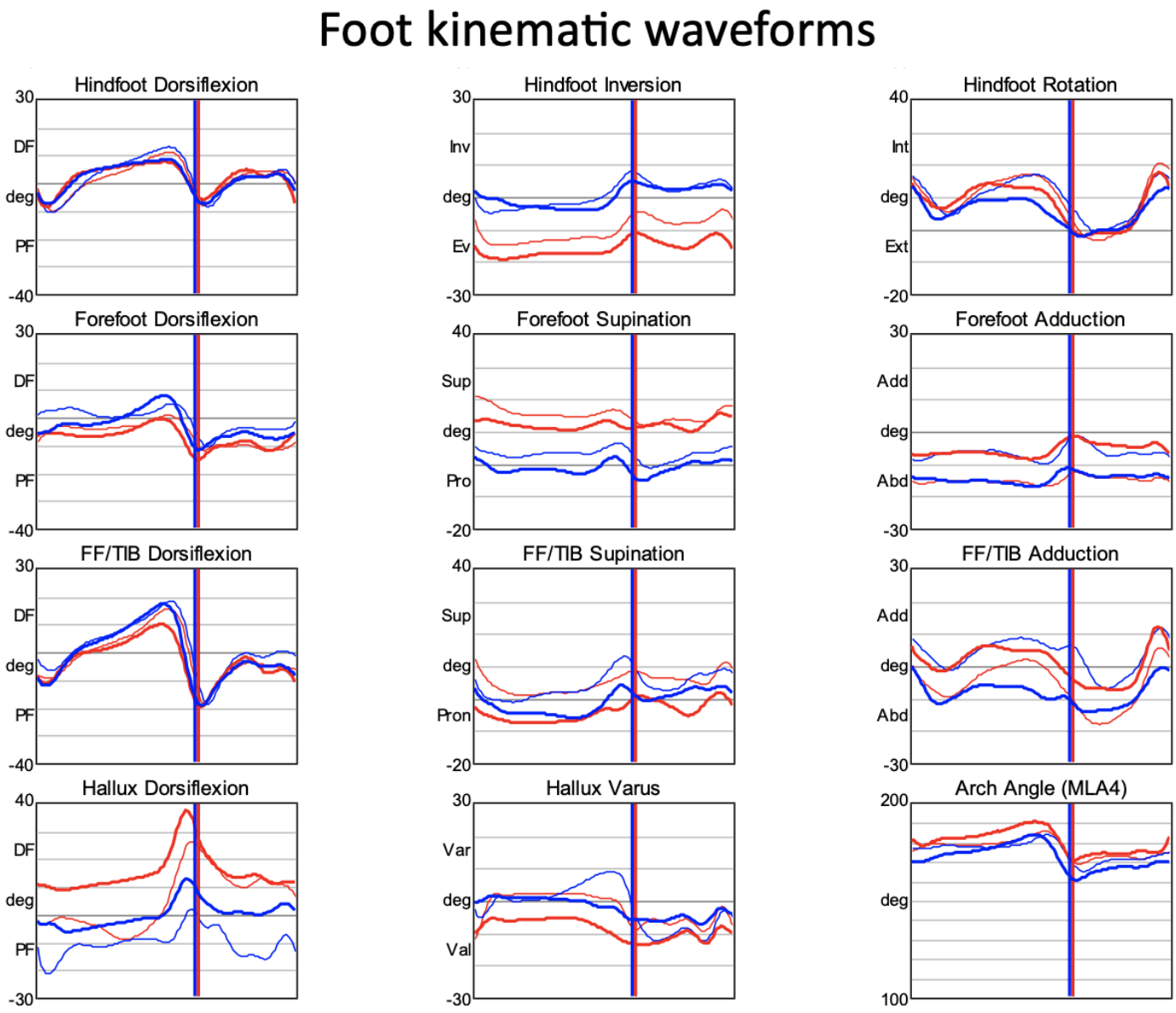


Figure 53: presents the change in foot kinematic waveforms between baseline and follow-up for participant 6, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

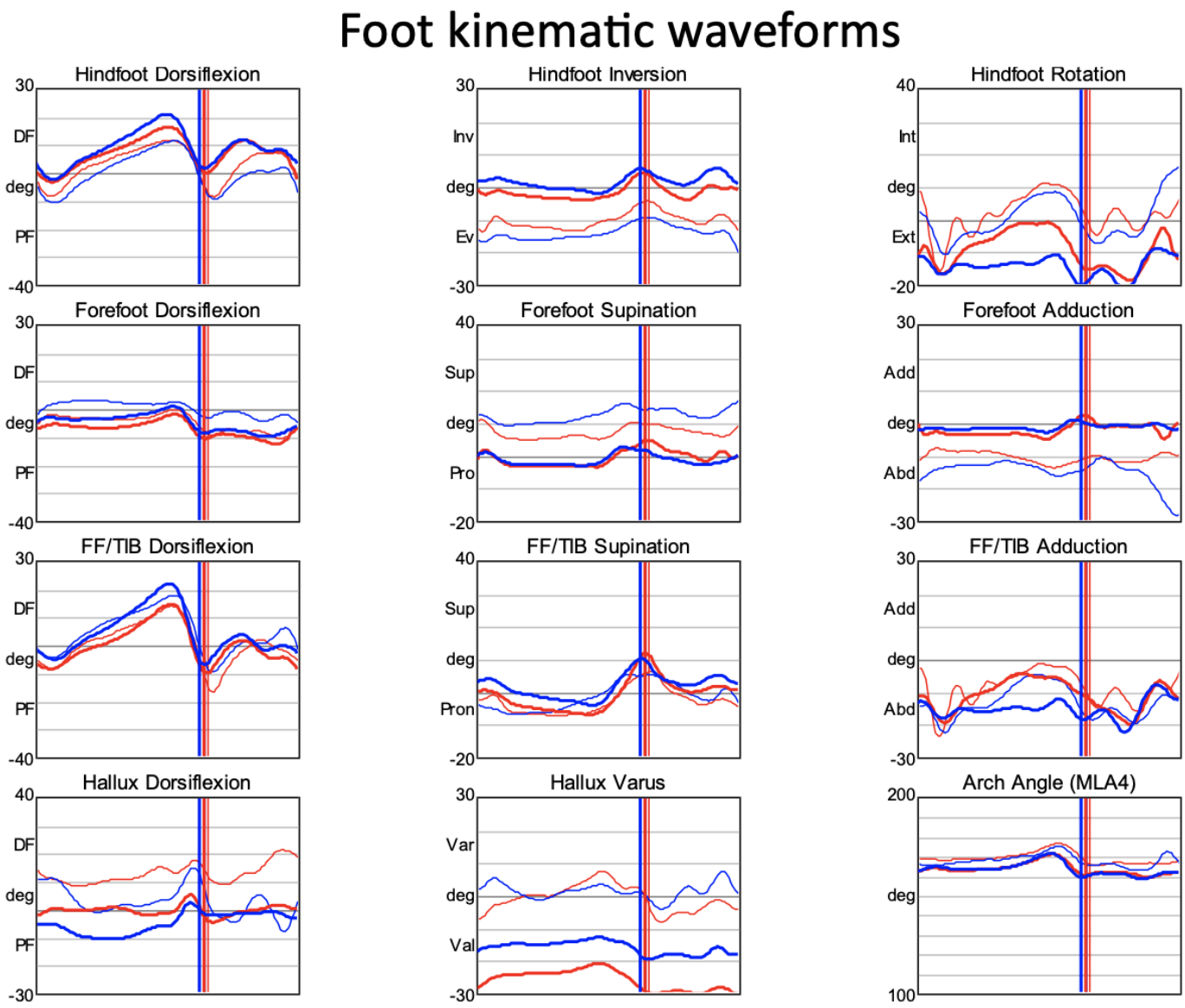


Figure 54: presents the change in foot kinematic waveforms between baseline and follow-up for participant 7, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

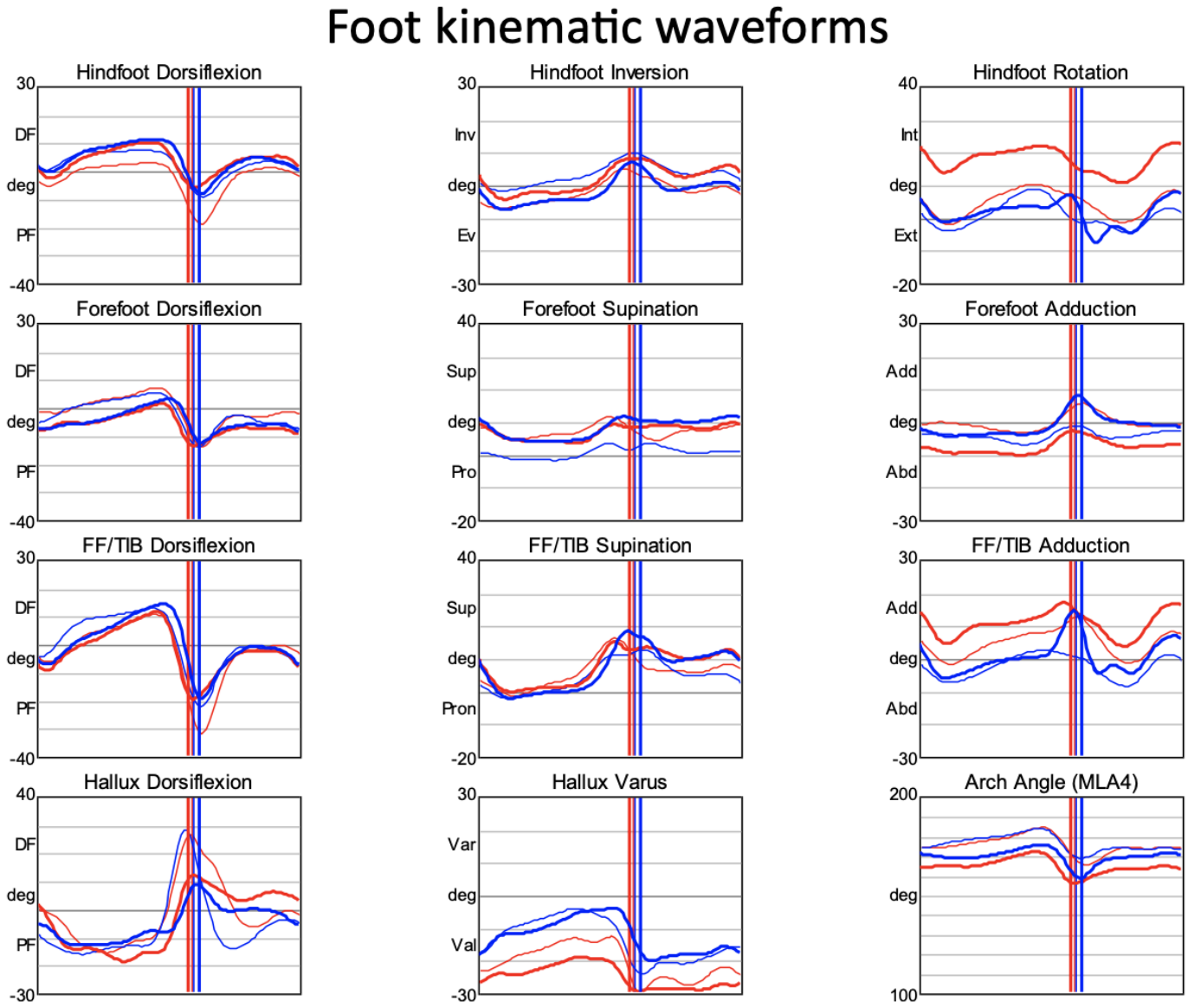


Figure 55 : presents the change in foot kinematic waveforms between baseline and follow-up for participant 8, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

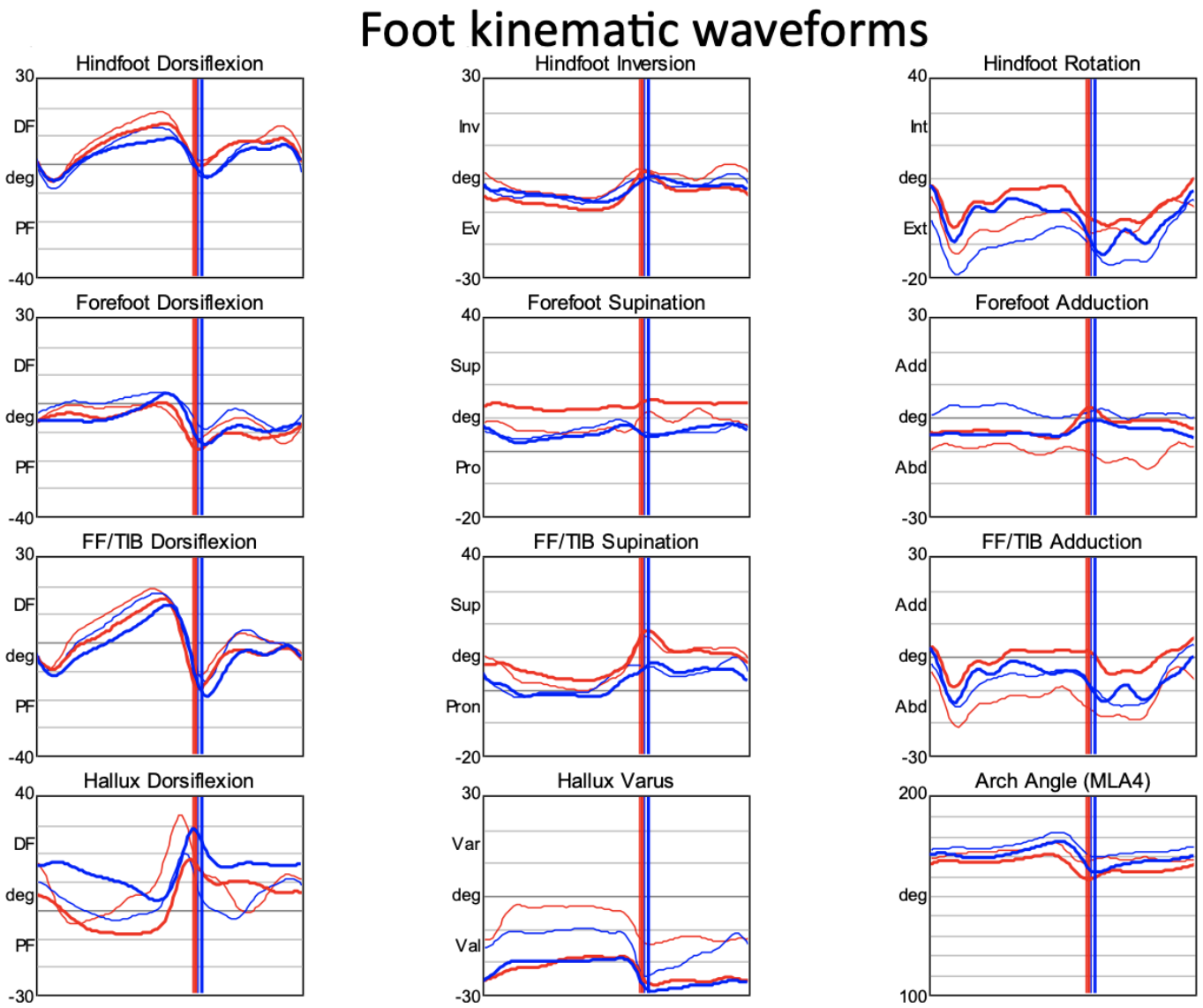


Figure 56: presents the change in foot kinematic waveforms between baseline and follow-up for participant 9, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

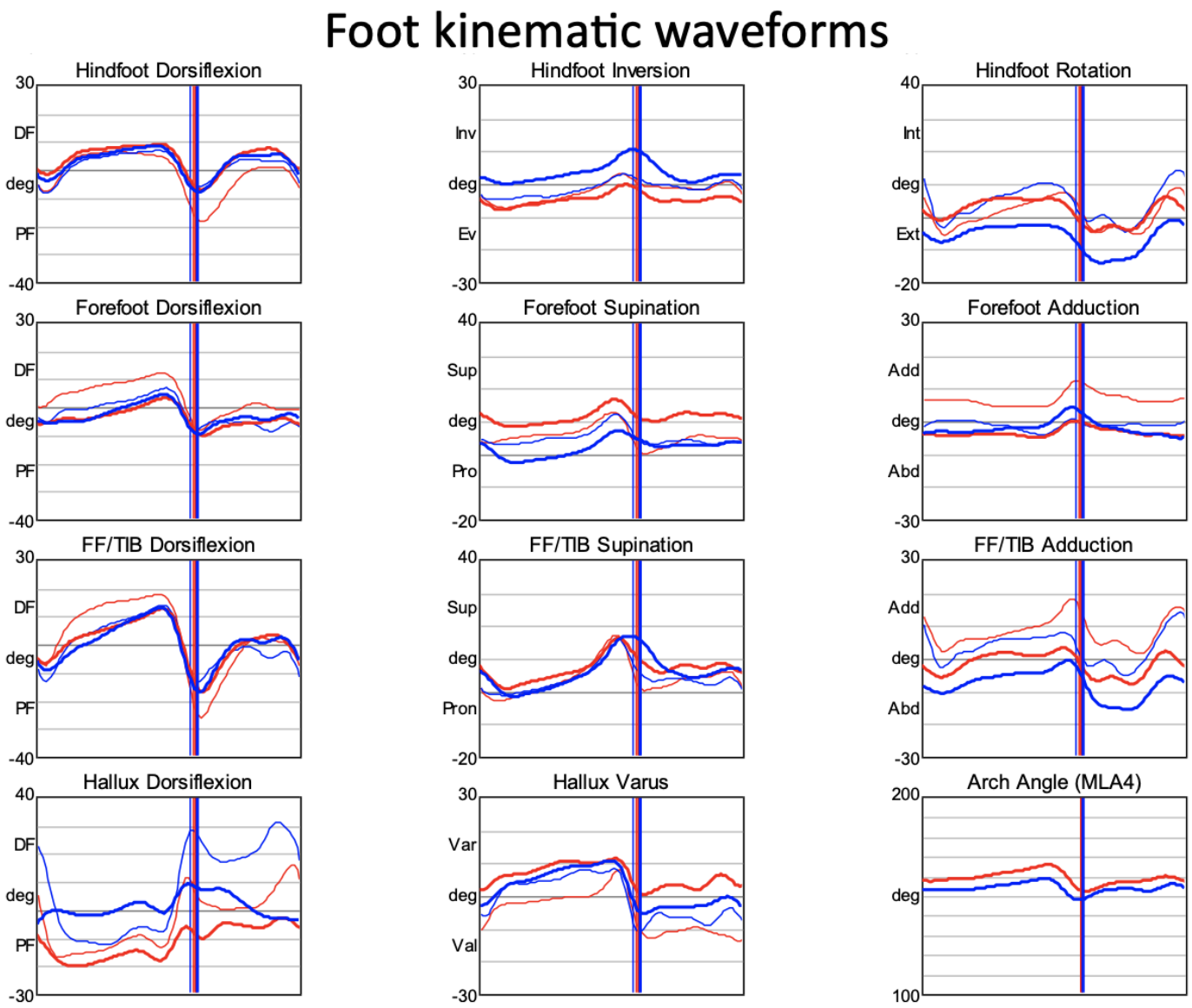


Figure 57: presents the change in foot kinematic waveforms between baseline and follow-up for participant 10, with flexible flat feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

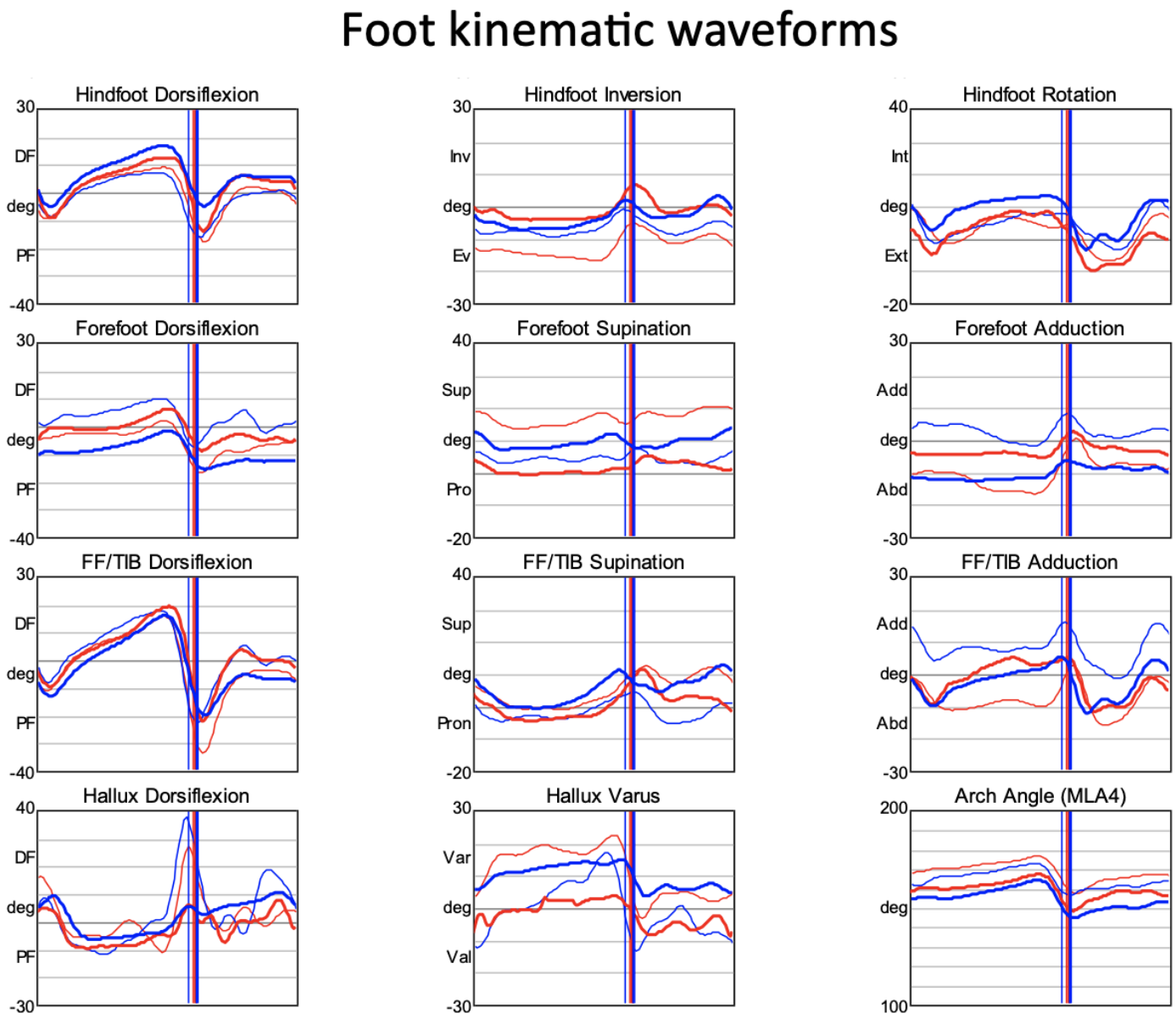


Figure 58: presents the change in foot kinematic waveforms between baseline and follow-up for participant 11, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

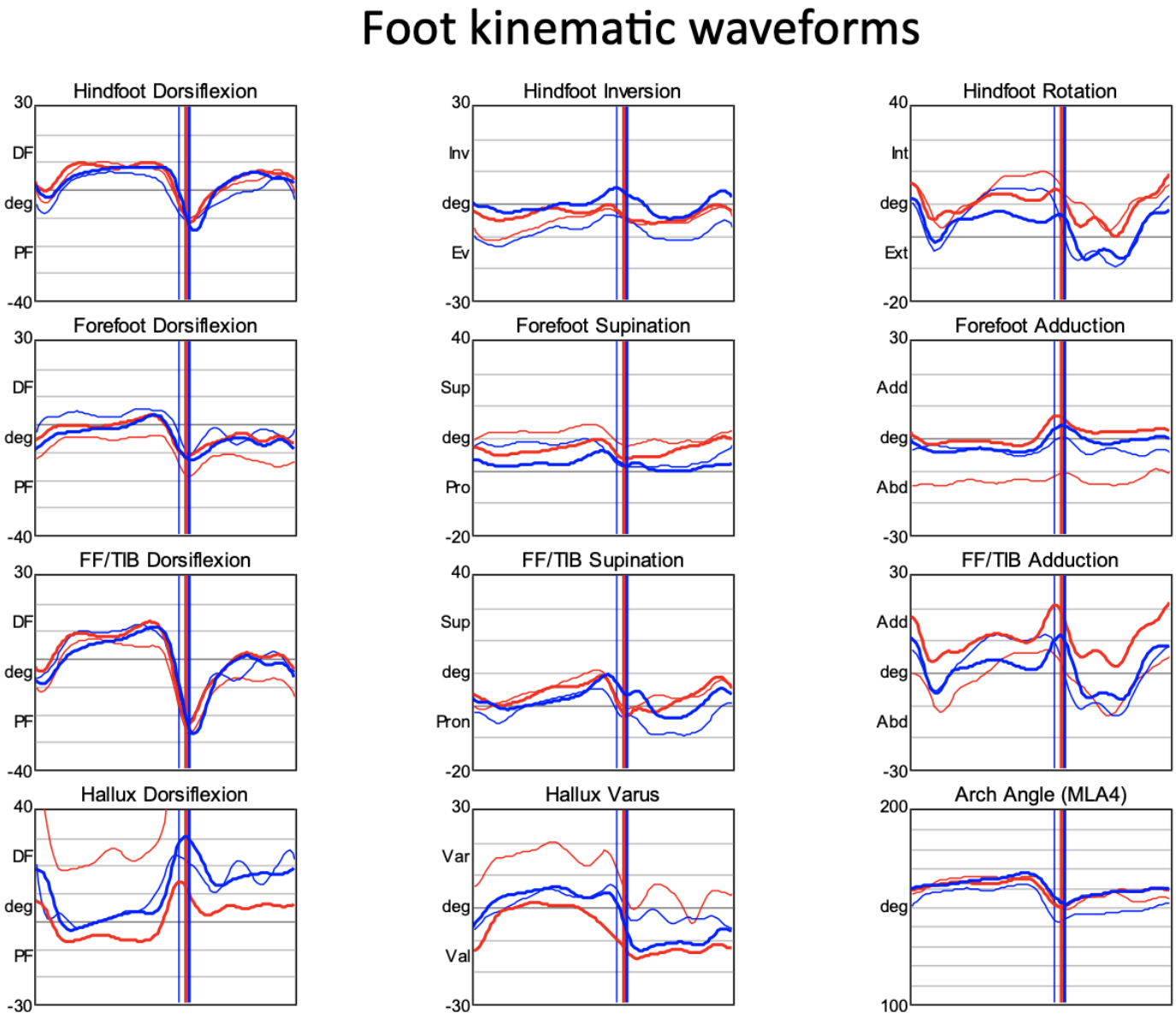


Figure 59: presents the change in foot kinematic waveforms between baseline and follow-up for participant 12, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

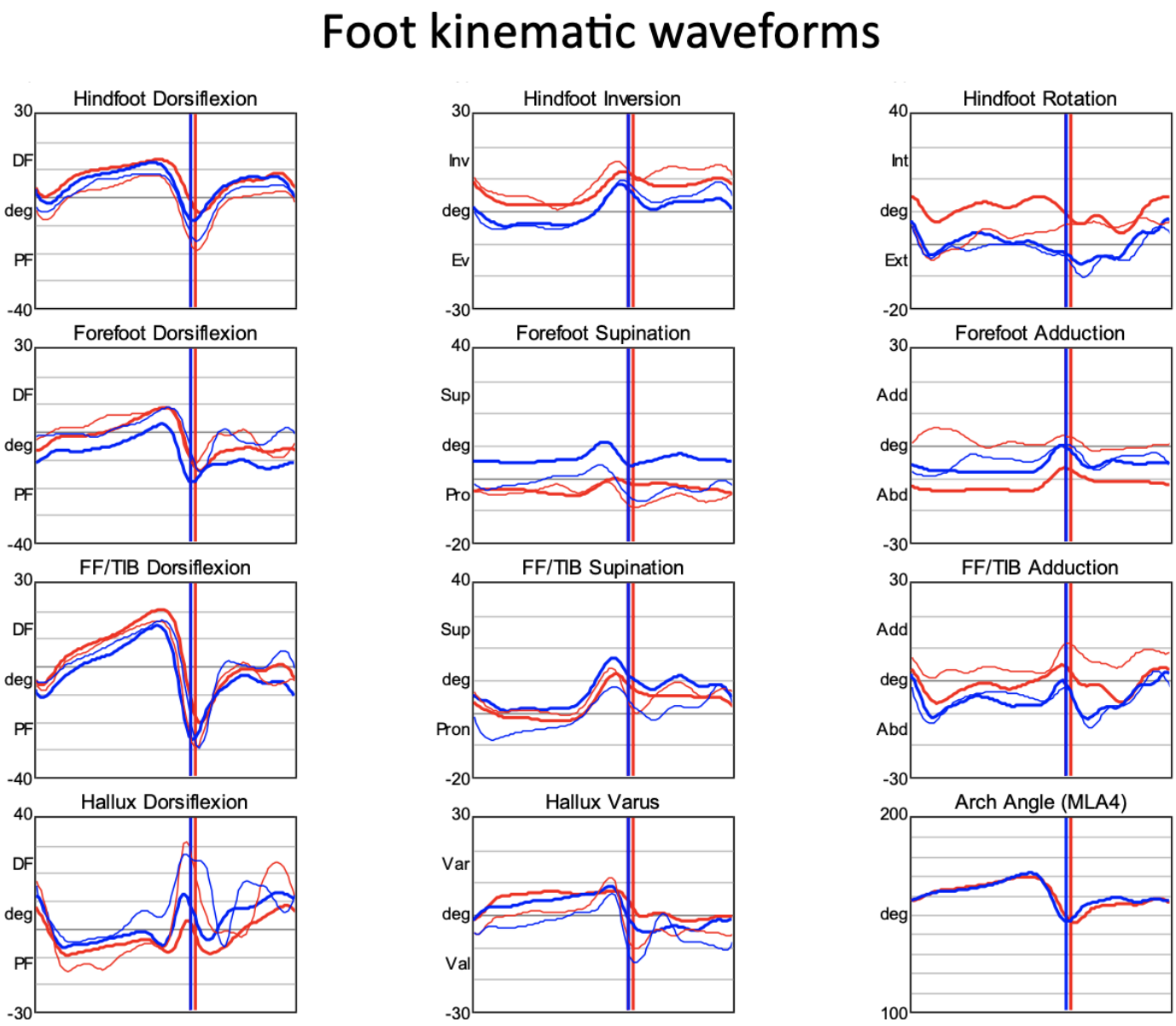


Figure 60: presents the change in foot kinematic waveforms between baseline and follow-up for participant 13, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

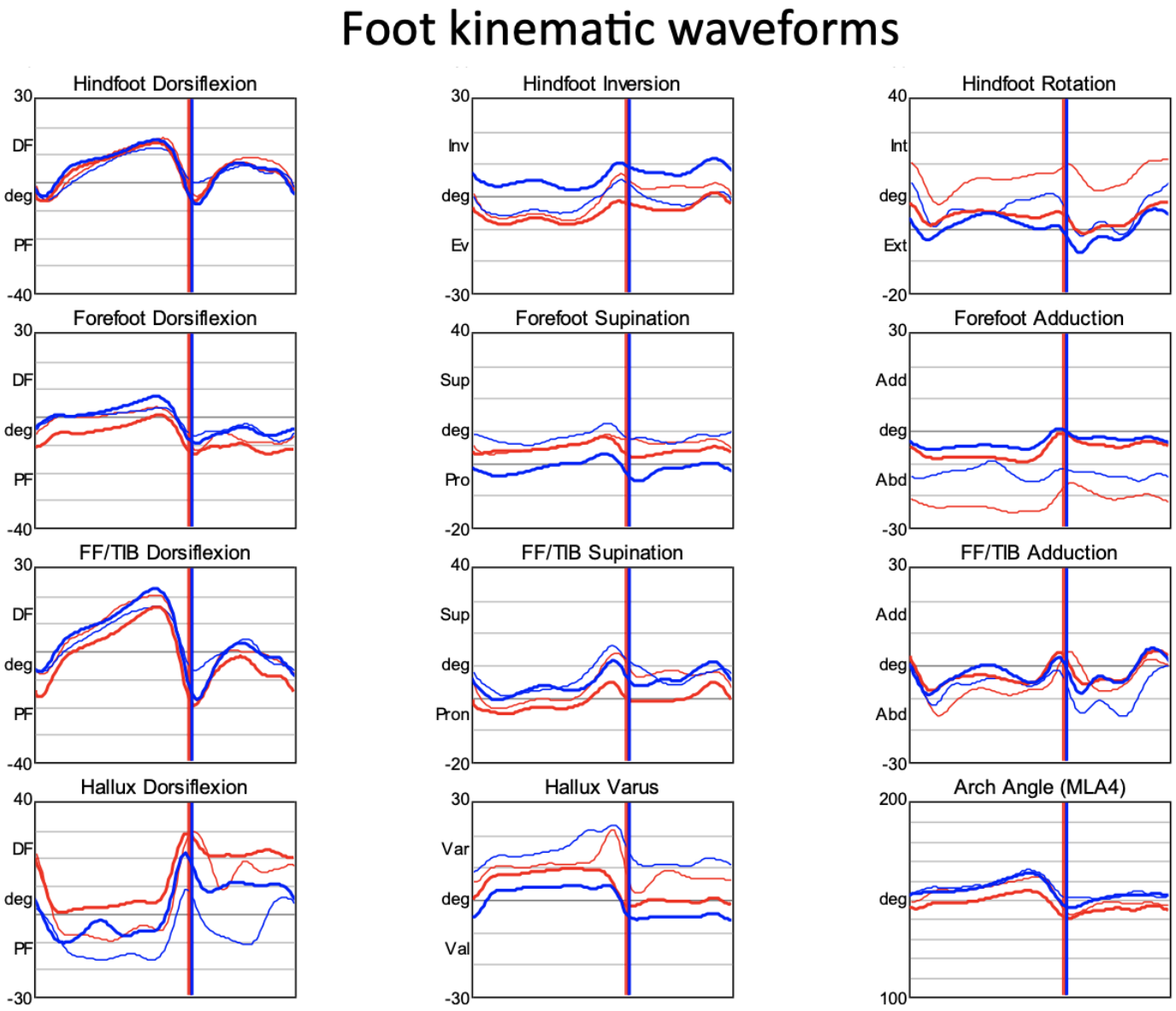


Figure 61: presents the change in foot kinematic waveforms between baseline and follow-up for participant 14, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

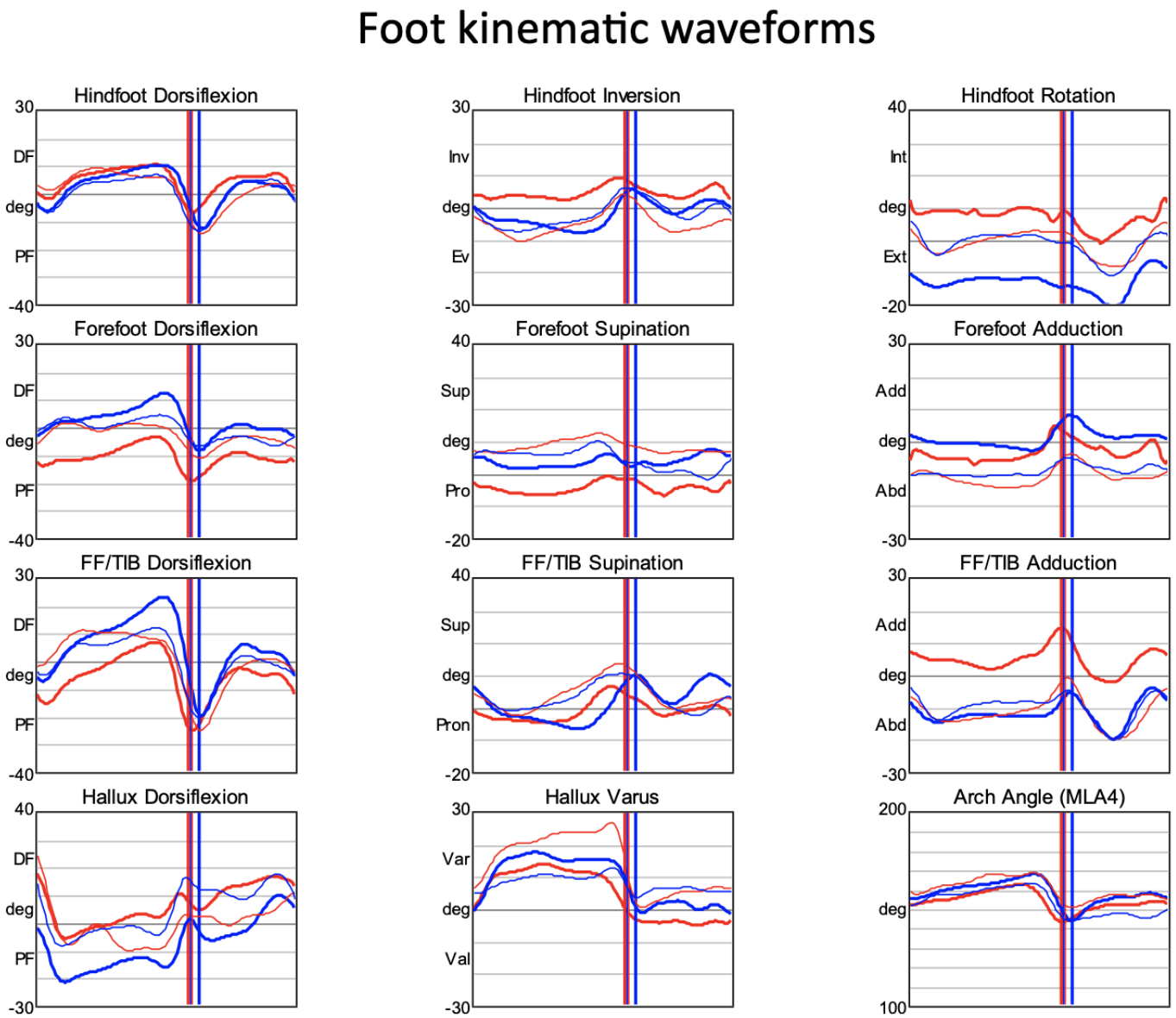


Figure 62: presents the change in foot kinematic waveforms between baseline and follow-up for participant 15, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

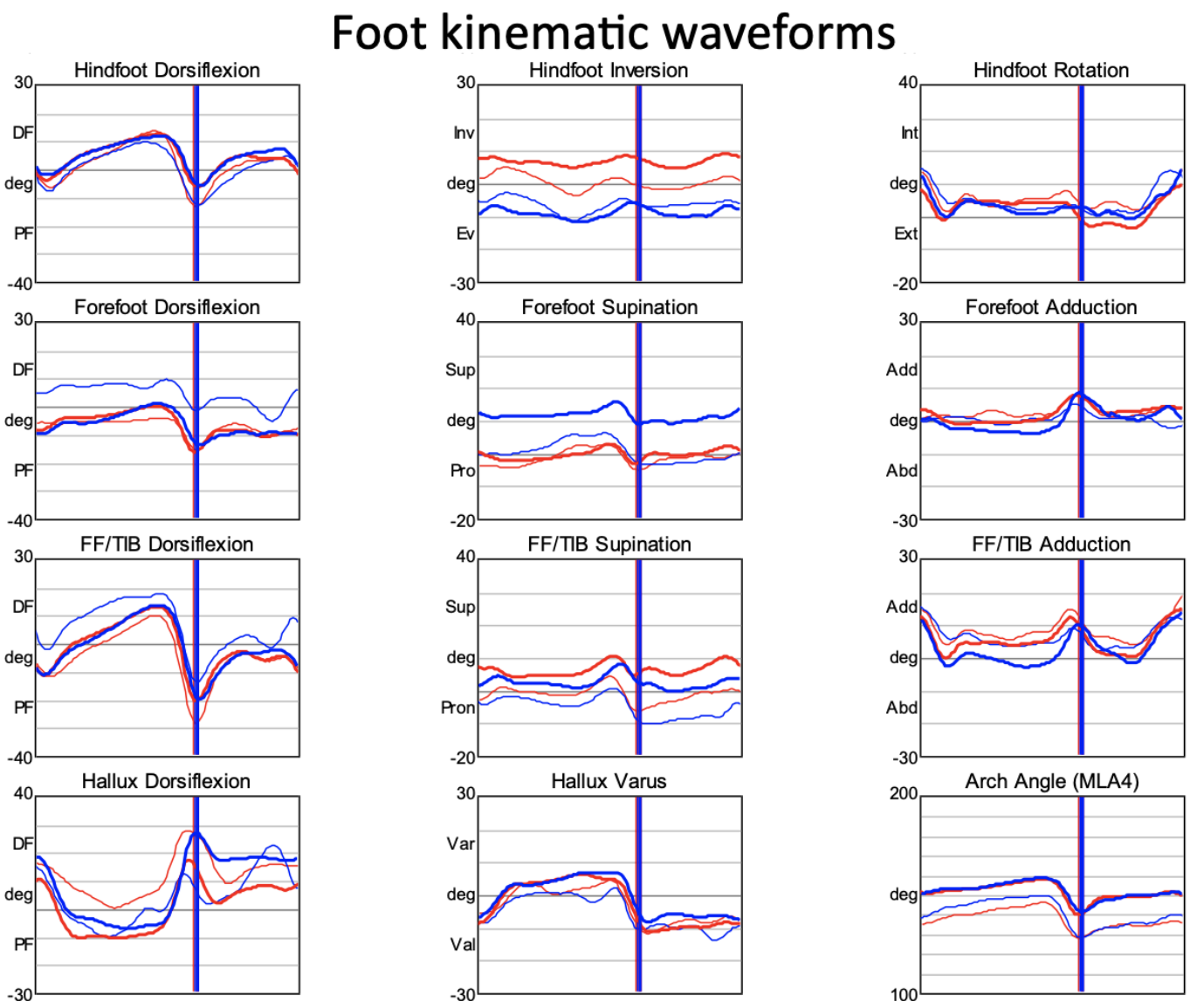


Figure 63: presents the change in foot kinematic waveforms between baseline and follow-up for participant 16, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

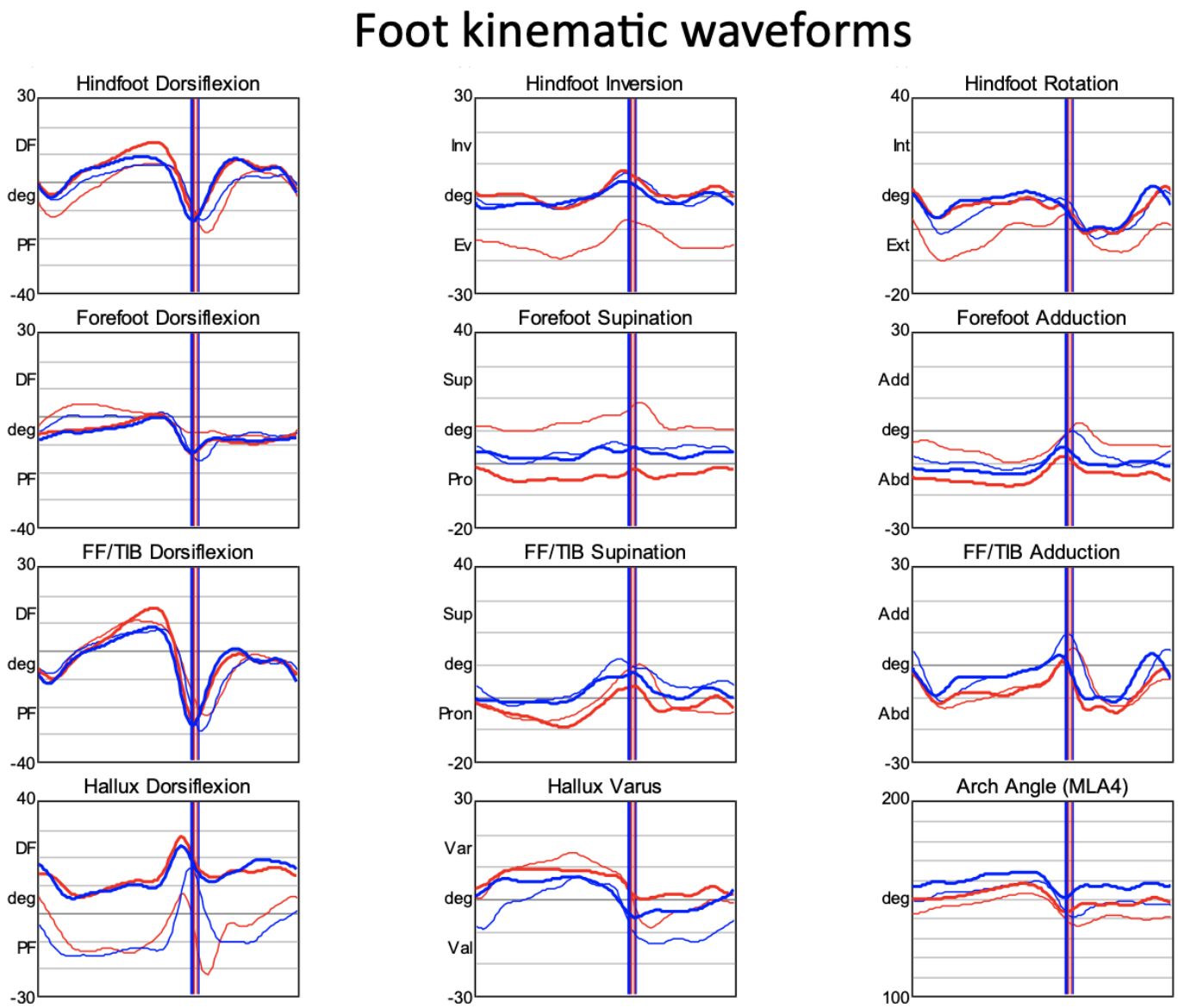


Figure 64: presents the change in foot kinematic waveforms between baseline and follow-up for participant 17, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

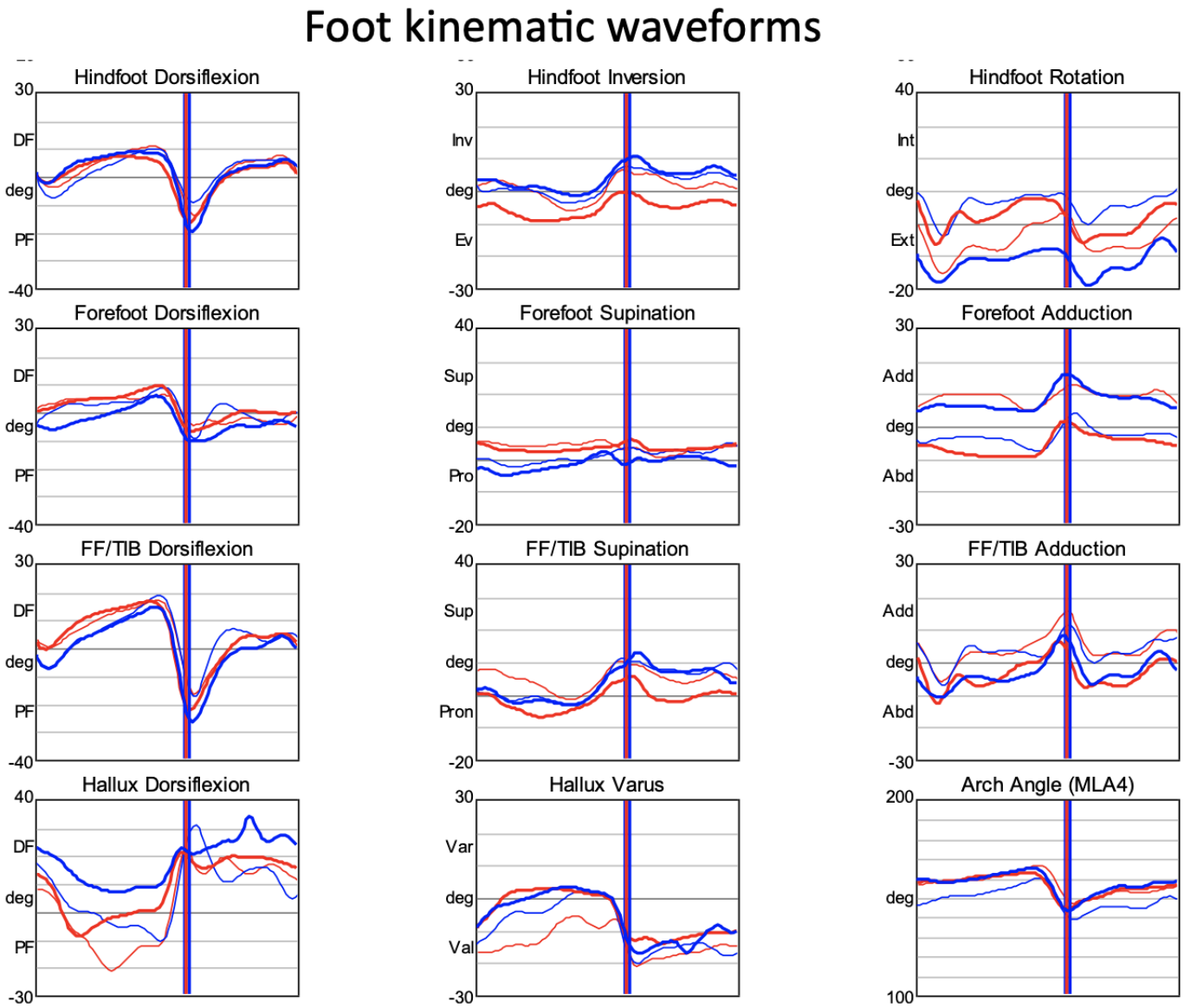


Figure 65: presents the change in foot kinematic waveforms between baseline and follow-up for participant 18, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

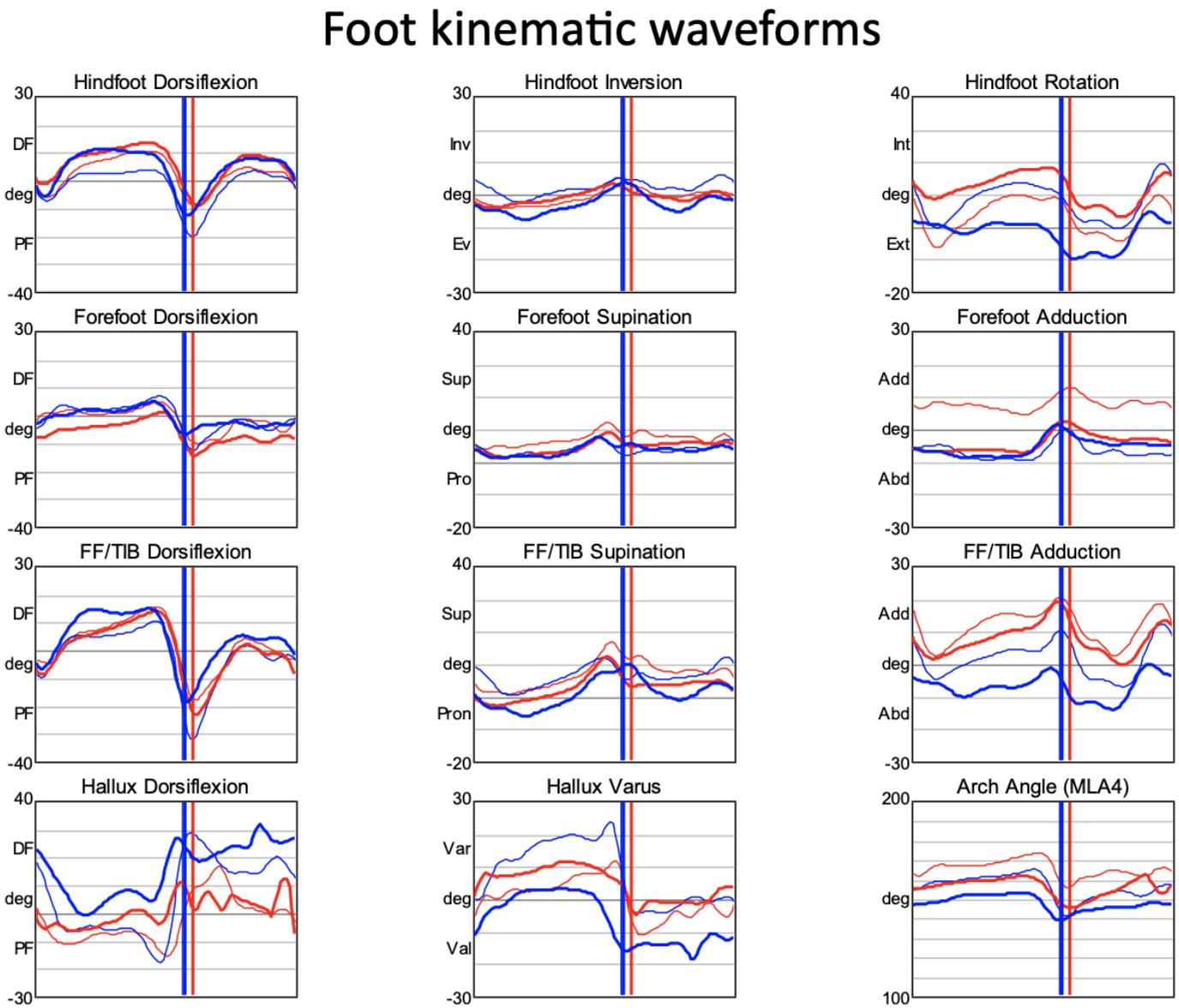


Figure 66: presents the change in foot kinematic waveforms between baseline and follow-up for participant 19, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

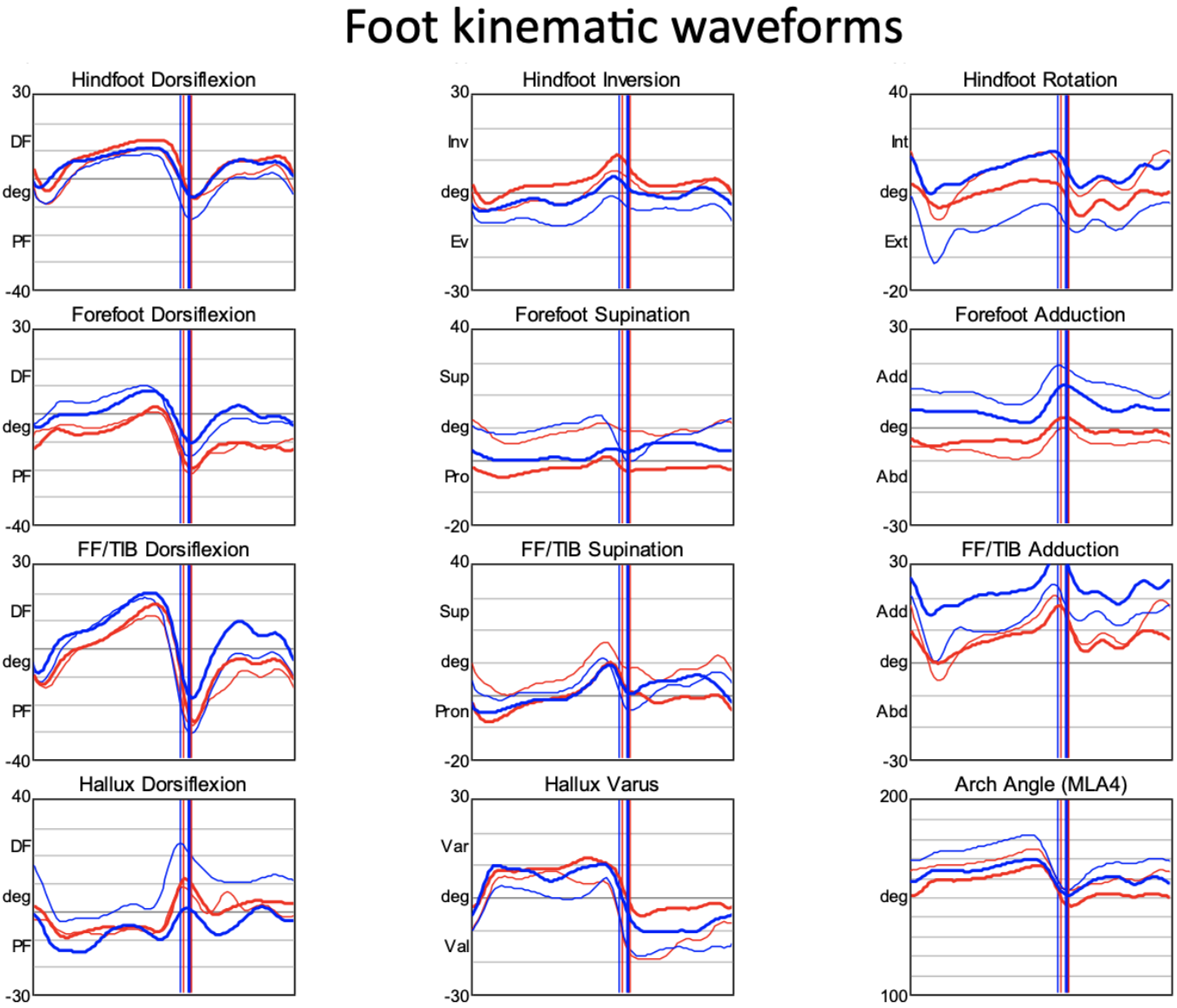


Figure 67: presents the change in foot kinematic waveforms between baseline and follow-up for participant 20, with neutral feet, using the OFM. The baseline data is represented by a thin line, while the follow-up data is depicted by a bold line. The blue lines denote one full gait cycle for the right foot, and the red lines the left foot. The vertical line divides the stance and swing phases.

18 Appendix C : Quality of life assessment

C1 Analysis results for significance in difference between good and poor quality of life scores

Measurement variables of foot posture	FHSQ shoes (p value)	FHSQ general foot health (p value)	FHSQ General health (p value)	FHSQ Vigorous (p value)
AHI	.345	.345	.369	.752
MLA standing	.298	.425	.119	.059
MLA chair	.097	.681	.291	.249
Hindfoot eversion mean static	.064	.220	.541	.074
Walking MLA mean	.213	.423	.162	.070
Walking MLA min	.117	.288	.214	.209
Walking MLA max	.278	.518	.116	.116
Walking MLA range	.520	.770	.395	.604
Walking MLA heel contact	.206	.328	.122	.063
Walking MLA toe-off	.308	.330	.102	.125
Walking HFTBA dorsiflexion mean	.083	.106	.197	.091
Walking HFTBA dorsiflexion min	.189	.238	.654	.074
Walking HFTBA dorsiflexion max	**.032**	.202	.310	.608
Walking HFTBA dorsiflexion range	.688	.856	.689	**.028**
Walking HFTBA dorsiflexion heel contact	.353	.716	.305	.089
Walking HFTBA dorsiflexion toe-off	.192	.158	**.014**	.597
Walking HFTBA eversion mean	.174	.434	.118	.241
Walking HFTBA eversion min	.265	.296	.167	.407
Walking HFTBA eversion max	.332	.569	.064	.177
Walking HFTBA eversion range	.883	.287	.125	.111
Walking HFTBA eversion heel contact	.182	.474	.170	.381
Walking HFTBA eversion toe-off	.380	.979	.118	.384
Walking FFHFA dorsiflexion mean	.346	.231	.737	.813
Walking FFHFA dorsiflexion min	.344	.823	.546	.195
Walking FFHFA dorsiflexion max	.390	.276	.102	.926
Walking FFHFA dorsiflexion range	.934	.352	**.013**	.136
Walking FFHFA dorsiflexion heel contact	.146	**.029**	.695	.673
Walking FFHFA dorsiflexion toe-off	.601	.898	.562	.588
Walking FFHFA abduction mean	.556	.214	.186	.969
Walking FFHFA abduction min	.415	.218	.246	.952
Walking FFHFA abduction max	.606	.231	.160	.740
Walking FFHFA abduction range	.695	.767	.394	.410
Walking FFHFA abduction heel contact	.788	.107	.229	.981
Walking FFHFA abduction toe-off	.432	.206	.257	.684
Walking FFHFA supination mean	.266	.086	.779	.062
Walking FFHFA supination min	.437	**.015**	.779	.056
Walking FFHFA supination max	.094	.394	.926	.075
Walking FFHFA supination range	.192	**<.001**	.708	.395

Walking FFHFA supination heel contact	.191	.140	.453	.051
Walking FFHFA supination toe-off	.262	.126	.667	.153
Walking HXFFA dorsiflexion mean	.296	.711	.080	.463
Walking HXFFA dorsiflexion min	.797	.698	**.003**	.070
Walking HXFFA dorsiflexion max	.848	.706	.784	.797
Walking HXFFA dorsiflexion range	.996	.516	.066	.302
Walking HXFFA dorsiflexion heel contact	.242	.354	.160	.155
Walking HXFFA dorsiflexion toe-off	.495	.494	.959	.480

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