

Paediatric Flexible Flatfoot:  
A New Stance -  
Beyond Static Assessment



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# Paediatric flexible flatfoot: a new stance – beyond static assessment

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Flatfoot is often asymptomatic but sometimes presents with symptoms, even in children. This thesis aimed to discover if there was a difference between children with and without symptoms, in the hope that this might aid treatment decisions.

Firstly, an audit was performed to discover the prevalence and type of symptoms, as well as current treatment protocols. Secondly, 107 volunteers from the general population and 20 patients were assessed in more detail. The participants were divided into groups and ANOVA tests were used to find the significant differences.

Pain and parental concern were frequently reported in the audit population. The majority of this population had moderate bilateral flexible flatfoot with an active Windlass mechanism and static heel valgus. Treatment was dependent on department.

The symptomatic group displayed reduced passive ankle dorsiflexion indicating tightness of the tendo-Achilles, as well as increased frequency of severe knee hyperextension and knee valgus upon clinical examination. During static stance, three differences were found between symptomatic and asymptomatic groups, two differences between flat feet and neutral feet.

During dynamic trials, the symptomatic group showed reduced stride length and percentage time spent in swing. The ground reaction profiles showed differences in early and late stance. Further investigation supported the idea that decreased late stance vertical ground reaction force peak was evidence of instability in the symptomatic group. Four kinematic parameters demonstrated significant differences at foot strike, five at midstance, and seven at foot off. In terms of kinetics, after controlling for relative stride length, four differences were found, but none between the asymptomatic and symptomatic flat feet. Plantar pressure was successfully used to estimate truncated foot length. The flat feet did not display increased peak midfoot pressure; it was actually lower in flat footed groups. Arch Index and Modified Arch Index were successfully used for instantaneous and continuous assessment of foot posture over stance.

The differences found between symptomatic and asymptomatic flat feet (particularly at foot off) shed some light upon the potential causes of symptoms.

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# Abbreviations

AF	Asymptomatic Flat feet (group in study)
AHI	Arch Height Index
AI	Arch Index
ALI	Arch Length Index
AM	Asymptomatic Mild flat feet (group in study)
AN	Asymptomatic Neutral feet (group in study)
ANCOVA	ANalysis of CO-Variance
ANOVA	ANalysis Of VAriance
ARI	Arch Rigidity Index
BMI	Body Mass Index
COM	Centre Of Mass
CSI	Chipaux-Smirak Index
DAH	Dorsal Arch Height
ESP	Early Stance Peak
FE	FEmur (segment in OFM)
FF	ForeFoot (segment in OFM)
FI	Footprint Index
FL	Foot Length
FPI	Foot Posture Index

## Tables

GP	General Practitioner
GRF	Ground Reaction Force
HF	HindFoot (segment in OFM)
HX	HalluX (segment in OFM)
ICC	Intraclass Correlation Coefficient
LSP	Late Stance Peak
MAI	Modified Arch Index
MRC	Medical Research Council of Great Britain (in context) scale for quantifying muscle strength
NH	Navicular Height
NNH	Normalized Navicular Height
NOC	Nuffield Orthopaedic Centre
OFM	Oxford Foot Model
OGL	Oxford Gait Laboratory
PIG	Plug-In Gait model (Vicon)
SF	Symptomatic Flat feet (group in study)
SI	Staheli Index
TB	TiBia (segment in OFM)
TFI	Truncated Footprint Index
TFL	Truncated Foot Length
VGRF	Vertical Ground Reaction Force
VT	Vertical Tibia
WB	WeightBearing

# 1. Introduction

The term “flexible flatfoot” refers to a foot which has a normal arch during non-weightbearing, but significant flattening of the arch during weightbearing [61]. Treatment of flat feet which are clearly symptomatic is not controversial, but there is uncertainty about whether to treat asymptomatic flat feet [36, 43]. The principal question of this thesis is as follows: what is the difference between symptomatic and asymptomatic flatfoot?

To determine what qualifies as “significant flattening” or “normal”, usually visually-based assessments are used. These assessments have cut-offs which are often contradictory or not prognostic. The question that must be asked is how is flatfoot defined (and how should it be)?

Weightbearing has traditionally been assessed during static stance (standing), but it must be considered whether and how static posture relates to performance during more demanding tasks such as walking (dynamic stance).

The nature of the symptoms is important for any study of this type. Correlation without a proposed mechanism cannot be considered as causative. So as part of this equation, the result should be properly defined, i.e. what are the short and long-term symptoms attributed to the idiopathic flatfoot.

Most treatments intend to correct a symptomatic flatfoot to more closely resemble a neutral foot. However most flatfoot is asymptomatic, so the question arises, are the treatments targeting the symptom-causing features at all?

## 1. Introduction

To clarify the definition of flatfoot, Section 2.1 reviews the literature to describe current flatfoot assessment methods. Since all babies are born with flat feet, this leads in to the question of normal foot development (Section 2.2) which in turn will help define our cohort for further study. The symptoms and complications which in the literature are associated with flatfoot are then outlined (Section 2.3). Finally basic considerations needed with respect to treatment are described (Section 2.4).

The question of treatment and symptoms was further investigated via clinical audit of current management protocols in flatfoot at a specialist orthopaedic hospital (Chapter 3). This Chapter begins by detailing the current gold standards within literature in terms of flatfoot treatment (Section 3.1). Principally the audit intended to uncover treatment pathways and recommendations (and how that varied across the hospital, Section 3.3.5). Additionally it furthered the understanding of symptom prevalence and the associated foot characteristics within the hospital population (Sections 3.3.3 and 3.3.4).

A large data set was amassed from 127 children, some asymptomatic with neutral feet, some asymptomatic but with flat feet, and a small group with symptomatic flat feet (Chapter 4). Within the symptomatic population, symptoms and signs were recorded and compared to the population of the audit (Sections 5.1 and 5.2) to gain insight regarding symptoms and provide context for the population sample. Within the asymptomatic population, more detailed arch assessments were taken including Arch Height Index and Foot Posture Index to further understanding of definitions of flatfoot and provide context for the population sample (Section 5.3).

Current assessment methods of foot posture tended to be either highly subjective or not comprehensive, this thesis will introduce comprehensive criteria. This also allowed the study to take an exploratory approach – this was a consciously made decision made from the point of view that something was missing from present assessments (since the difference between, and pathogenesis of, symptomatic and asymptomatic flat feet had not been established). This led to comparison of lower limb flexibility

## 1. Introduction

and skeletal alignment between asymptomatic neutral feet, asymptomatic flat feet, and symptomatic flat feet (Chapter 6), novelly utilizing marker-based technology to reduce error and subjectivity in skeletal alignment measures.

The author theorized that another key reason there has been so much difficulty in differentiating the pathologic flat foot is that previous assessment methods were not related to dynamic function. This project will improve on previous work on paediatric flexible flatfoot by developing and providing comprehensive assessment of function during dynamic stance. The methods employed during static stance are expanded to record and analyse spatio-temporal and ground reaction force data (Chapter 8), kinematic data (Chapter 9), kinetic data (Chapter 10), and plantar pressure (Chapter 11) for differences between asymptomatic neutral, asymptomatic flat, and symptomatic flat feet during walking.

The key hypothesis of this thesis is that there are differences between patients with symptomatic and asymptomatic flat foot and that these differences are responsible for the symptoms. Previous assessments have focused on selective static parameters and not compared symptomatic and asymptomatic populations which may explain the lack of understanding of symptoms and pathogenesis. The study investigates the differences between neutral, asymptomatic, and symptomatic flat feet in terms of comprehensive passive, static, and dynamic assessment. It is hoped that finding differences between symptomatic and asymptomatic flat feet will aid treatment decisions.

## 2. Background

This chapter describes what was known about flatfoot which motivated the existence and design of this work. Many others have studied flatfoot, but nobody has discovered the cause of symptoms in the idiopathic case. Therefore, the decision to treat in the asymptomatic case, and how to treat in the symptomatic case are under considerable uncertainty. Previous studies defining flatfoot are noted (Section 2.1). Current understanding of normal development of the foot is described (Section 2.2). Finally, the known long and short term implications of flatfoot and treatment options are considered (Sections 2.3-2.4).

Flatfoot is characterized by the complete or partial collapse of the medial longitudinal arch. Flatfoot encompasses a wide range of conditions. The most comprehensive guidelines regarding treatment were developed by the American College of Foot and Ankle Surgeons [61, 83]. The guidelines indicate that the symptomatic flatfoot should be treated, but not the asymptomatic. However, this may not be the best course of action; in the words of John F. Kennedy (as widely quoted, including [94]) ‘There are costs and risks to every programme of action, but they are far less than the long range risks and costs of comfortable inaction’. On a more pragmatic note, the risks of inaction may be more or less than the risk of action, but what is known is that prevention is better than cure and decisions are best made when well informed.

## 2. Background

Many have debated the potential non-issue of asymptomatic flexible flatfoot [18, 36, 43, 49]. It is currently problematic to justify treatment of asymptomatic flat feet, yet at the same time treatment for symptomatic flatfoot may be targeting symptomatically-irrelevant features associated with flatfoot to achieve “neutral” posture.

### 2.1. What is a flatfoot? – the definition of flatfoot

Flatfoot has traditionally been assessed by appearance, or by a method arising from that appearance. Any clinical measure used to assess flat foot may need to meet certain criteria to be practical:

- easy and fast to use,
- reliable,
- intra-rater consistent,
- inter-rater consistent;

and several criteria to be valid:

- has clinical relevance (e.g. influence treatment or lack thereof),
- objective,
- predictive of, or directly measures dynamic function,
- normal values clearly known.

The two main weaknesses of the methods described in this chapter are as follows. Firstly, static assessments have mostly proved ineffective at predicting dynamic behaviour [138]. Secondly, while clinicians have recognized idiopathic flatfoot in patients experiencing pain, they have not answered the question of why some of these feet display symptoms and some do not.

## 2. Background

### 2.1.1. Clinical assessments

Clinical assessments occur regularly, and are the most common assessments of flat-foot, requiring little or no equipment.

#### *Physiotherapists' qualitative assessments – clinical, FPI, and PFFP*

Assessment by clinician is the most important and commonly used tool to define foot type [30].

Within the Oxford Gait Laboratory (OGL), there is a standard clinical procedure to describe foot posture. The procedure divides the foot into 3 segments: hind-, mid-, and fore-foot. Varus or valgus of the hindfoot in standing is recorded looking at the foot from the posterior aspect. Planus or cavus of the arch in standing is recorded (cavus being excessive forefoot equinus, with angle between the horizontal weightbearing surface of the head and the shaft of the 1st metatarsal being above 40° degrees defining a true cavus deformity). Adduction or abduction of the forefoot in standing is recorded. Flexibility is assessed by the Windlass effect: when a collapsed arch can be recovered by the patient standing on tip toes.

The classic physiotherapists' test of foot posture is based on the Coleman block test, though it was actually designed to evaluate a cavus foot. It evaluates hindfoot flexibility and pronation of the forefoot. The patient's heel is placed on a wooden block one or two inches thick, bearing full weight while the first, second, and third metatarsals are allowed to plantarflex and pronate. If the heel position corrects while the patient is standing on the block, the hindfoot is considered flexible, with the initial deformity in the forefoot followed by the subsequent changes in the hindfoot.

The Foot Posture Index (FPI) [139] consists of six criteria: talar head palpation; supra-lateral and infra-lateral malleolar curvature; Helbing's sign (curvature of the Achilles

## 2. Background

Table 2.1.: Scoring criteria of the FPI. Adapted from Redmond et al. [139].

<b>Rearfoot score</b>	<b>-2</b>	<b>-1</b>	<b>0</b>	<b>1</b>	<b>2</b>
Talar Head Palpation	Palpable on lateral side, but not on medial side	Palpable on lateral side, slightly palpable on medial side	Equally palpable on lateral and medial side	Slightly palpable on lateral side, palpable on medial side	Not palpable on lateral side, but palpable on medial side
Curves above and below the malleoli	Curve below either straight or convex	Curve below concave, but flatter than the curve above	Curves roughly equal	Curve below more concave than curve above	Curve below markedly more concave than curve above
Calcaneal inversion / eversion	More than an estimated 5° inverted (varus)	Between vertical and an estimated 5° inverted (varus)	Vertical	Between vertical and an estimated 5° everted (valgus)	More than an estimated 5° everted (valgus)
<b>Forefoot score</b>	<b>-2</b>	<b>-1</b>	<b>0</b>	<b>1</b>	<b>2</b>
Prominence in region of talo-navicular	Markedly concave	Slightly but definitely concave	Flat	Bulging slightly	Bulging markedly
Medial arch height and congruence	High and acutely angled towards posterior end	Moderately high and slightly acute posteriorly	Normal and concentrically curved	Lowered with some flattening in central portion	Very low with severe flattening in central portion, ground contact
Forefoot ab/adduction	No lateral toes visible, medial toes clearly visible	Medial toes clearly more visible than lateral	Medial and lateral toes equally visible	Lateral toes clearly more visible than medial	No medial toes visible, lateral toes clearly visible

tendon); prominence in the region of the talo-navicular joint; congruence of the lateral border of the foot; abduction and adduction of the forefoot on the rearfoot. Each of these criteria are rated on a scale of  $-2$  to  $+2$  (Table 2.1). The sum of these values allows a verdict to be attained (equations 2.1):

$$\begin{array}{ll}
 -12 \leq \text{FPI} \leq -5 & \text{Highly Supinated,} \\
 -4 \leq \text{FPI} \leq -1 & \text{Supinated,} \\
 0 \leq \text{FPI} \leq 5 & \text{Normal,} \\
 6 \leq \text{FPI} \leq 9 & \text{Pronated,} \\
 10 \leq \text{FPI} \leq 12 & \text{Highly Pronated.}
 \end{array} \tag{2.1}$$

## 2. Background

The sum has a good to excellent intra-rater agreement, and a good inter-rater agreement (Table 2.2). Some training is required for the assessors, and approximately two minutes assessment time is needed per subject. The scale is not linear; however Keenan et al. [79] performed a Rasch analysis to convert the summed score into a linear scale.

The subjectivity of the FPI is ultimately its Achilles' heel, and this subjective nature is revealed by poor individual component reliability [44, 101], reducing the clinical relevance. The assessors may be good at giving similar numbers of points to flat feet on the basis of knowledge of foot types, but not under the same categories. However Mentiplay et al. [101] found that the utilization of the Microsoft Kinect or Vicon motion systems could improve the reliability considerably. The systems improved the estimates of malleolar curvature, prominence in the region of the talo-navicular joint, and medial arch congruence. The Vicon system improved the reliability of the forefoot abduction quantification. Neither system could improve the reliability of the talar head prominence nor calcaneal eversion estimates. Correlation between Vicon and Kinect was moderate to excellent in four measures, while poor with the clinician scores, supporting the validity of the instrument-based measures.

The FPI has been compared to footprint assessment methods [125]. While the results do not give an absolute comparison with an irrefutable arch assessment, differences between methods and particular age groups were analysed by Friedman ANOVA tests. The FPI was concluded to be the least sensitive at detecting changes in the medial longitudinal arch, and it actually proved unable to detect change in the arch after the age of three. Most likely this difficulty results from the subjective assessment of the evaluator, with few parameters available to identify conformational changes and classifications. The investigation concluded that the Chippaux-Smirak Index was more reliable and easier to apply.

The paediatric flatfoot proforma [45] is a recent development which appears to have

## 2. Background

Table 2.2.: Usability and validity of the Foot Posture Index. Papers selected were available, included Intraclass Correlation Coefficient (ICC) values if appropriate, and found by Scopus® [154] search including the measure and any of the following: repeatability, inter-rater, intra-rater, inter-tester, intra-tester, reliability, validity, correlation.

		Foot Posture Index		
Usability	Easy and fast to use	Yes, some training required for assessor, approximately 2 minutes time required to collect [139].		
	Reliable	Unknown		
	Intra-rater consistent	ICC:0.93-0.94	Evans et al. 2012 [46]	
		ICC:0.88	Cain et al. 2007 [20]	
	Inter-rater consistent	ICC:0.71-0.86	Evans et al. 2012 [46]	
		ICC:0.69	Cain et all. 2007 [20]	
Validity	Clinically relevant (and does it relate to symptoms)	No as individual components are unreliable [44]. Reliability of most individual components can be improved using Kinect or marker-based systems [101].		
	Objective	No, unless measured with Vicon / Kinect systems.		
	Predicts/measures dynamic function	Moderate or low	< 11.1% peak pressure	[151]
		Strong	13% NH drop, 45% NH	[121]
		Some	41% midstance ankle joint eversion	[140]
Normal values known	Yes			

greater item repeatability (inter-rater ICC>0.70). It is quick to use, with approximately 10 minutes needed per child. It is focused on the outcomes and treatment decisions so is clinically relevant. There is limited evidence regarding its use particularly with respect to its relationship with dynamic function, and more evidence regarding reliability and efficacy would be reassuring.

### *Dorsal Arch Height-based methods - DAH, DAH drop, AHI, ARI*

The Dorsal Arch Height (DAH) is the height of the dorsum of the foot at 50% of Foot Length (FL) (Fig. 2.1). The height can be measured in weightbearing (WB) or non-weightbearing. DAH drop is the difference between the weightbearing and non-weightbearing heights (equation 2.2):

$$DAH_{drop} = DAH_{non-WB} - DAH_{WB}. \quad (2.2)$$

## 2. Background

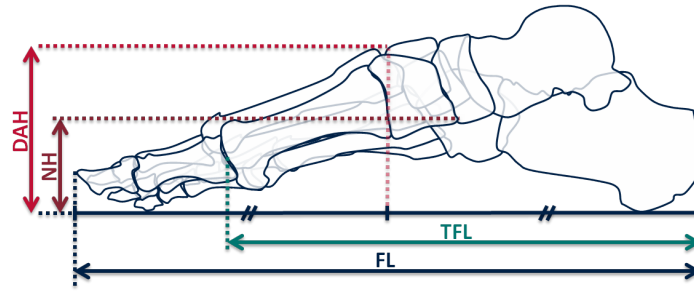


Figure 2.1.: Demonstration of dorsal arch and navicular related measurements (idealized to exclude the effects of soft tissue). Dorsal Arch Height (DAH) is the height of the foot at 50% Foot Length (FL). Navicular Height (NH) is the height of the navicular tuberosity. The Truncated Foot Length (TFL) is the length from heel to the first metatarso-phalangeal joint.

The Truncated Foot Length (TFL) (length of foot minus toes to make the measure more robust against toe variation and deformity) is the distance between first metatarso-phalangeal joint and the heel. In our study, we took the TFL to be described by the distance between the skin surface behind the calcaneal tuberosity and furthestmost weightbearing surface in the region of the metatarsal heads as this was found to be more reliable (further explanation in Section 5.3.1). Arch Height Index (AHI) [185] is the ratio of DAH to TFL (equation 2.3):

$$AHI = \frac{DAH}{TFL}. \quad (2.3)$$

The measure can be taken in weightbearing or non-weightbearing. The ratio of these two measures is known as the Arch Rigidity Index (ARI) (equation 2.4):

$$ARI = \frac{AHI_{WB}}{AHI_{non-WB}}. \quad (2.4)$$

A large number of studies have tested the reliability of the DAH, AHI, and DAH drop (Table 2.3). The AHI and DAH are generally very repeatable. The caliper-based measurements were the least reliable [33, 150], photographic techniques were an im-

## 2. Background

provement [33, 97, 132], and the best (in some cases almost perfect) repeatability was achieved using custom-made equipment [98, 99, 132, 171, 185]. Williams and McClay [185] found that division by the TFL (rather than FL) gave the best repeatability, this also allows the method to be resilient to hallux deformities (such as hallux valgus). The difference in weightbearing and non-weightbearing DAH is less repeatable. These measures can be applied in dynamic situations such as walking [23], it also correlates with some dynamic properties [23, 171]. Chuckpaiwong et al. found moderate correlations between DAH and AHI with clinical classification [30].

### *Navicular height-based measures – NH, NNH, NH drop, NH drift*

The Navicular Height (NH) is usually the height of the navicular tuberosity (Fig. 2.1), alternatively it may be to the floor (underside) of the navicular. The height can be measured in weightbearing, non-weightbearing, or in “Subtalar Joint Neutral” (also referred to as “Neutral Calcaneal Stance Position”).

The existence of subtalar joint neutral is disputed. The position was originally defined as the position in which the joint is ‘neither pronated nor supinated’ [145]. Root et al. [144, 145] saw this position as ideal. The joint is often placed in “neutral” by ensuring equal prominence of the talus on either side of the navicular [182] (perhaps surprising since the joint in question was not the talo-navicular but the talo-calcaneal). Many other definitions have (perhaps wrongly) been used, such as vertical calcaneus [65] (no reference to talus), or midpoints of joint range of motion [70] (unknown relation to talus). In addition to the problems of definition of the position, it is a notoriously unreliable position [42, 44, 103, 131]. The reliability has been found not to improve with experience [128].

The Normalized Navicular Height (NNH) is the NH divided by the aforementioned TFL (equation 2.5):

$$NNH = \frac{NH}{TFL}. \quad (2.5)$$

## 2. Background

Table 2.3.: Usability and validity of DAH-based assessment techniques. “Custom” indicates the use of custom-made equipment. “cc” indicates clinical classification. “pcc” is Pearson’s correlation coefficient. Papers selected by Scopus® [154] search including the measure in question and any of the following: repeatability, inter-rater, intra-rater, inter-rater, intra-rater, intra-tester, reliability, validity, correlation.

	DAH		AHI		DAH drop					
	Easy and fast to use	Depends on method	Inter-day, custom	Inter-day, photographic	Inter-day, custom	Inter-day, photographic				
Usability	Reliable	Inter-day, custom	ICC:0.98-0.99	[99]	Inter-day, custom	ICC:0.87-0.92	[132]			
		Photographic	ICC(3,1):0.94-0.97	[33]	Inter-day, photographic	ICC:0.88-0.94	[132]			
	Intra-rater consistent	Photographic	ICC(3,1):0.94-0.97	[33]	Photographic	ICC(3,1):0.90-0.93	[33]	Photographic	ICC(3,1):0.26-0.52	[33]
		Caliper	ICC(3,1):0.91-0.96	[33]	Caliper	ICC(3,1):0.69-0.84	[33]	Caliper	ICC(3,1):0.04-0.24	[33]
		Custom	ICC:0.97-0.99	[99]	Custom	ICC(2,1):0.98	[98]	Custom	ICC:0.91-0.92	[99]
		Photographic	ICC:0.82-0.96	[97]	Photographic	ICC:0.82-0.96	[97]	Photographic	ICC:0.88-0.92	[97]
		Caliper	ICC:0.91	[150]	Caliper	ICC:0.91	[150]	Caliper+Harris mat	ICC:0.91	[150]
		Custom	ICC(2,1):0.94-0.98	[185]	Custom	ICC(2,1):0.94-0.98	[185]	Custom	ICC:0.91-0.92	[99]
		Photographic	ICC(2,3):0.95-0.99	[33]	Photographic	ICC(2,3):0.95-0.96	[33]	Photographic	ICC(2,3):0.54	[33]
		Caliper	ICC(2,3):0.56-0.60	[33]	Caliper	ICC:0.99	[99]	Caliper	ICC(2,3):0.69	[33]
Custom	ICC:0.99	[99]	Custom	ICC(2,k):0.98	[171]	Custom	ICC:0.89	[99]		
Inter-rater consistent	Photographic	ICC:0.95	[97]	Photographic	ICC(2,k):0.96	[171]	Photographic	ICC:0.89	[99]	
	Custom	ICC(2,1):0.98	[98]	Custom	ICC(2,1):0.98	[98]	Custom	ICC:0.92	[97]	
	Custom	ICC:0.77-0.79	[185]	Custom	ICC:0.77-0.79	[185]	Custom	ICC:0.92	[97]	
	Caliper	ICC:0.76	[150]	Caliper	ICC:0.76	[150]	Caliper+Harris mat	ICC:0.77	[150]	
	Clinically relevant (and does it relate to symptoms)	Moderate correlation (pcc= -0.74) with cc [30].		Moderate correlation (pcc=0.70) with cc [30].		Unknown				
	Validity	Objective	Yes	Yes	Yes	Yes	Yes			
		Predicts/measures dynamic function	Can measure directly [23] marker ANOVA F= 152 [23] static:dynamic p<0.001		Predicts 30-60% of some pressure parameters [171]					
		Normal values known	Yes	Yes	Yes	Yes	Somewhat			

## 2. Background

Navicular Height drop [19, 112] is the difference between NH in neutral and resting calcaneal stance positions (equation 2.6):

$$NH_{drop} = NH_{neutral} - NH_{resting}. \quad (2.6)$$

Cobb et al. [33] found NH drop based on percentage of weightbearing to be reliable using photographic and caliper measures (intra-tester ICC(3,1)=0.39-0.55 and inter-tester ICC(2,3)=0.70-0.89), this may be an alternative in cases where the measures rely upon subtalar joint neutral.

Measures taken with a ruler led to poor inter-tester repeatability, those reported based on calipers and digital height gauges varied in success, other methods (photographic, custom equipment) were good to excellent in reliability, but radiographic measures were the most reliable (Table 2.4). Inter-rater navicular drop had markedly poorer reliability than was consistent with the equipment used, perhaps because of the poor reliability of subtalar joint neutral [157, 159]. Additionally, Evans et al. [47] found very poor validity leading to 9-19 mm difference between the true (as measured by sonogram) and ruler-based NH measurements, though the measures were of four year old children which may have added to the difficulty.

Chuckpaiwong et al. [30] found moderate correlations between navicular measures (NH, NNH) and clinical classifications. The NNH was better correlated with clinical classification of foot structure.

Bencke et al. [10] found only a moderate correlation between NH drop and dynamic foot posture. However the measures can be taken during dynamic situations by using a marker based system with generally high reliability [121, 137]. This allows genuine description of dynamic foot posture, but relies on the availability of specialist (stereophotogrammetric) equipment. If this equipment were readily available

## 2. Background

to the assessors, it seems that full standard kinematic analysis might be preferred and favoured. So the dynamic measure may be of less use than initially appears.

Navicular drift has been considered less commonly. It is the horizontal movement of the navicular tuberosity between non-weightbearing and weightbearing situations, or subtalar joint neutral and relaxed postures. Two studies have found acceptable to excellent intra-rater repeatability when measuring by custom methods and rulers respectively [13, 74].

### *Other geometric measures*

Several other geometry based measures have been developed and tested for reliability, but are less commonly used. Talar height and normalized talar height are based on the height of the medial protrusion of the talus [150]. Foot mobility is the square root of the sum of the NH drop and change in midfoot width [99]. Medial longitudinal arch angle and deviation are the angles of the talar navicular joint (the angle between the medial aspect of the head of the first metatarsal bone, the navicular tuberosity and the medial side of the calcaneus 40 mm from the most posterior point and 35 mm from the ground). The medial longitudinal arch angle and deviation have excellent repeatability when measured by markers [10], but the correlation with dynamic characteristics is limited [6].

### 2.1.2. Footprint assessment methods

Footprint assessments are readily available and inexpensive. This makes them a key tool in the assessment of flatfoot. Without such quantitative assessment, treatment is difficult to both justify and appraise. Therefore we aim to correlate the severity of the collapse to a measure that could be extracted from plantar prints or pressure.

The efficacy of this kind of assessment is questionable as a way to ascertain the age of arch development. The medial longitudinal arch is obscured in children owing to

## 2. Background

Table 2.4.: Usability and validity of navicular height-based assessment techniques – Navicular Height (NH), Normalized Navicular Height (NNH), and Navicular Height Drop (NH drop). “Custom” indicates the use of custom-made equipment. “cc” indicates clinical classification. “pcc” is Pearson’s correlation coefficient. Papers selected by Scopus® [154] search including the measure in question and any of the following: repeatability, inter-rater, intra-rater, inter-tester, intra-tester, reliability, validity, correlation.

	NH		NNH		NH drop		
	Easy and fast to use	Depends on method	Depends on method	Depends on method	Depends on method	Depends on method	
Usability	Reliable	Different time points, radiograph	ICC:0.99 [24]				
		Different radiographs	ICC:0.98 [24]				
	Intra-rater consistent	Photographic	ICC(3,1):0.82-0.83 [33]			Caliper	ICC(2,1):0.88 [10]
		Caliper	ICC(3,1):0.69-0.89 [33]			Ruler	ICC:0.95 [74]
		Height gauge	ICC(2,1):0.79-0.87 [157]	Photographic	ICC(3,1):0.78-0.84 [33]	Custom ruler	ICC:0.95-0.99 [13]
		Caliper	ICC(2,k):0.94-0.98	Caliper	ICC(3,1):0.62-0.89 [33]	Ruler	ICC(2,k):0.91-0.97 [159]
		Steel ruler	ICC:0.99 [110]	Custom	ICC(2,1):0.97-0.98 [185]	Caliper	ICC:0.72-0.83 [110]
		Custom	ICC:0.69-0.84 [47]	Caliper + Harris mat	ICC: 0.92 [150]	Height gauge	ICC(2,1):0.73-98 [157]
		Caliper	ICC(2,1):0.97-0.98 [185]				ICC(2,k):0.90-0.98
			ICC: 0.90 [150]				
	Photographic	ICC(2,3):0.93-0.99 [33]					
	Caliper	ICC(2,3):0.93 [33]					
Inter-rater consistent	Height gauge	ICC(2,1):0.77-0.92 [157]	Photographic	ICC(2,3):0.93 [33]	Ruler	ICC(2,1):0.56-0.76 [159]	
	Steel ruler	ICC(2,k):0.91-0.97 [47]	Caliper	ICC:(2,3):0.93 [33]	Height gauge	ICC(2,1):0.67-0.90 [157]	
	Custom	ICC:0.23 [185]	Custom	ICC:0.90-0.94 [185]			
	Caliper	ICC:0.61-0.92 [185]	Caliper + Harris mat	ICC: 0.75 [150]			
		ICC:0.74 [150]					
		Poor validity, ruler-sonogram 9-19mm [47].					
Clinically relevant	Moderate correlation (pcc=0.51) with cc [30].		Moderate correlation (pcc=0.71) with cc [30].			Unknown	
	Objective	Yes	Yes	Yes	Yes	Yes	
Predicts/measures dynamic function	Can measure directly [121, 137]		Can measure directly [121, 137]		Can measure directly [121, 137]		
	Marker, dynamic	ICC:0.65-0.83 [121]	Marker, dynamic	ICC:0.94-0.95 [121]	Marker, dynamic	ICC:0.94 [121]	
	Marker, dynamic	ICC: 0.95 [137]	Marker, dynamic	ICC: 0.95 [137]	Marker, dynamic	ICC:0.89-0.94 [137]	
Normal values known	Yes	Yes	Yes	Yes	ND correlated moderately with dynamic MLAD [10]	Yes	

## 2. Background

thick adipose padding at the plantar surface. This fatty tissue diminishes with age [92]. The adipose tissue affects the collected plantar prints. Since the presence of the adipose tissue depletes over the same developmental stage as the arch develops, the use of plantar prints to assess the arch (and not the depletion adipose tissue) is problematic. The hind- and fore-foot areas have been found to correlate with the fat free mass ( $r=0.75$ ,  $p<0.05$  and  $r=0.72$ ,  $p<0.05$  respectively); the mid-foot however correlates with fat mass ( $r=0.54$ ,  $p<0.05$ ) [181]. This is problematic as many of the popular footprint assessments (AI, CSI, SI) rely on the comparison between hind and/or fore with mid-foot. When this is combined with development, and the associated depletion of the fat pad, there could be a problem. This can however be compensated for either by use of average fat pad thickness for age or ultrasonic measurement of fat pad thickness.

Additionally, sometimes due to ankle valgus, additional problems can be caused. Traditional footprint assessment methods expect a wide footprint in the case of flatfoot (Fig. 2.2). However, if the ankle is in valgus, the lateral side of the foot can be pulled up from the ground. Furthermore, if the arch collapse is not severe enough to cause complete collapse to the floor, the flatfooted subject may appear to have the footprint typical of a high-arched foot. This makes the footprint assessment difficult, however it is one of the most readily available diagnostic techniques.

### *The problem with maximum pressure prints*

Footprint analyses are often based on accumulation of frames during a complete step or over a period of static stance. These are usually based on maxima or mean values at individual cells of the pressure measurement equipment over the period in question. The use of mean pressure is peculiar in this regard as most quantitative analysis of pressure focuses on exceeding thresholds, and so averaging over time would obscure this information.

The use of these representative prints leaves the final result susceptible to certain

## 2. Background



Figure 2.2.: Simulations demonstrating classic flat (left), neutral (centre), and cavus (right) footprints.

temporal features appearing as static. A roll on the heel with foot strike can create a elongated heel in the final representation. More variability and balance issues can appear as increased contact area and pressure values. Additionally, features involving motion of the foot against the floor such late stance heel twist can result in pressures being mis-allocated to the wrong section of the foot.

The temporal effects are inevitable in the case of ink based collection methods; however with modern methods of collection, individual frames and segments of stance can be analysed. Noting that there are many changes to foot structure over stance, in agreement with Leung et al. [84] it was felt more desirable for the present study to analyse instantaneous frames to best reflect the foot function.

*Midfoot width contact ratios (Staheli & Chippaux Smirak Indices) and the Alfa angle*

The angle describing the foot structure is commonly referred to as the Footprint angle, arch angle, or Alfa angle. It is formed from a line between the most medial point of the metatarsal head region and the apex of the MLA print concavity, and the internal tangent of the plantar print (Fig. 2.3). The classification according to Forriol and

## 2. Background

Pascual [48] is as follows (equations 2.7):

$$\begin{array}{ll} \alpha < 30^\circ & \text{low arch,} \\ 30^\circ \leq \alpha < 35^\circ & \text{dropped arch,} \\ 35^\circ \leq \alpha < 42^\circ & \text{intermediate arch,} \\ 42^\circ \leq \alpha < 47^\circ & \text{normal arch,} \\ 47^\circ \leq \alpha & \text{elevated arch,} \end{array} \quad (2.7)$$

According to Queen et al. [134] and Papuga and Burke [126], the Alfa angle has variable repeatability from fair to excellent (Table 2.5). This may be due to the difficulty in defining the anatomical points of interest (most medial points of fore- and hind-foot and most medial and distal part of the mid-foot).

Queen et al. [134], Shiang et al. [155], and Villarroya et al. [178] found weak to moderate correlations between the Alfa angle and navicular height-based parameters (NH, NNH [134]), in addition to other footprint indices (NH, AI, MAI, CSI, SI, TFI, FI, ALI [155]), and radiographic parameters (Calcaneal Inclination Angle, Talar First Metatarsal Angle [178]) respectively. Chuckpaiwong et al. [30] found a moderate correlation with clinical classifications, supporting the use of this measure in quantitative static assessment.

This angle is however impossible to define in the case of the absence of midfoot contact. The instantaneous plantar pressure maps used in this study often contain no apparent midfoot contact so this technique was excluded.

Two indices are based on the ratio of midfoot width to the width of the foot - the Staheli Index (SI) and Chippaux-Smirak Index (CSI).

The Staheli Index [163] is the ratio of the minimum midfoot to the maximum hindfoot width (Fig. 2.3, equation 2.8):

$$SI = \frac{\text{minimum midfoot width}}{\text{maximum hindfoot width}}. \quad (2.8)$$

## 2. Background

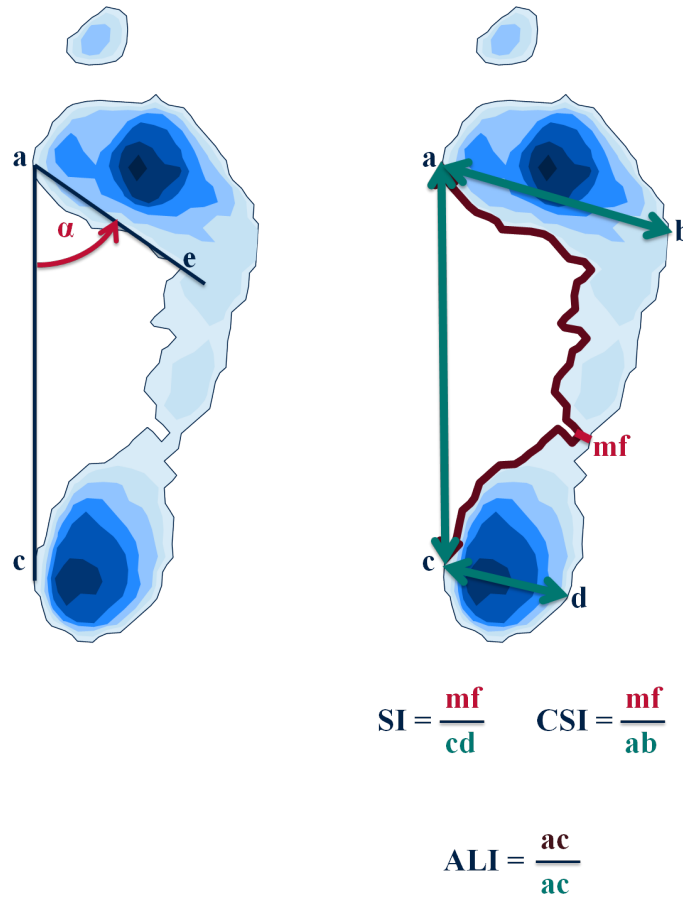


Figure 2.3.: Demonstration of Alfa angle ( $\alpha$ ), Staheli Index (SI), Chippaux-Smirak Index (CSI), and Arch Length Index (ALI). a is the most medial and b is the most lateral aspect of the forefoot, c is the most medial and d is the most lateral aspect of the hindfoot, e is the intersection of forefoot area and the medial aspect of the arch. The Alfa angle is the angle between e, a, and c. The SI is the ratio of the minimum width of the midfoot section to the maximum width of the hindfoot (length cd). The CSI is the ratio of the minimum width of the midfoot section to the maximum width of the forefoot (length ab). The ALI is the ratio of central perimeter of the foot between the medial aspects of the forefoot and hindfoot (a and c), to the direct distance between those points.

## 2. Background

Table 2.5.: Usability and validity of some pressure-based assessment techniques (CSI, SI, Alfa angle). “cc” indicates clinical classification. “pcc” is Pearson’s correlation coefficient. Inter-clinician reliability is based on comparison between different clinicians collecting the data, while the analysis remains consistent. Papers selected by Scopus® [154] search including the measure in question and any of the following: repeatability, inter-rater, intra-rater, inter-tester, intra-tester, reliability, validity, correlation.

	CSI		SI		Alfa angle	
	Yes	Yes	Yes	Yes	Yes	Yes
Usability	Reliable	ICC:0.881-0.970 [126]	Inter-clinician foot scanner	ICC:0.889-0.970 [126]	Inter-clinician foot scanner	ICC:0.689-0.895 [126]
	(day/clinician)	ICC(2,1):0.9139 [134]	Inter-day photobox	ICC(2,1):0.9142 [134]	Inter-day photobox	ICC(2,1):0.6377 [134]
	Intra-rater consistent	ICC:0.989-0.997 [126]	Foot scanner	ICC:0.991-0.998 [126]	Foot scanner	ICC:0.817-0.993 [126]
	Inter-rater consistent	ICC:0.971 [126]	Foot scanner	ICC:0.975 [126]	Foot scanner	ICC:0.605 [126]
Validity		ICC(2,k):0.9609 [134]	Photobox	ICC(2,k):0.9626 [134]	Photobox	ICC(2,k):0.8072 [134]
	Clinically relevant	Moderate correlation (pcc= -0.66) with cc [30].	Moderate correlation (pcc= -0.66) with cc [30].	Moderate correlation (pcc= -0.66) with cc [30].	Moderate correlation (pcc=0.739) with cc [30].	
	Objective	Yes	Yes	Yes	Yes	Yes
	Predicts/measures dynamic function	Unknown	Unknown	Unknown	Unknown	Unknown
Normal values known	Yes	Yes	Yes	Yes	Yes	Yes

## 2. Background

According to Staheli et al. [163] the normal feet are within two standard deviations from the mean (equations 2.9):

$$\begin{array}{ll} SI < 0.44 & \text{high arch,} \\ 0.44 \leq SI \leq 0.89 & \text{normal arch,} \\ 0.89 < SI & \text{flatfoot.} \end{array} \quad (2.9)$$

In practice, some have found these bounds to be too wide to define neutral feet [104].

The Chippaux-Smirak Index [48] is the ratio of the minimum midfoot width parallel to the maximum forefoot width (Fig. 2.3, equation 2.10):

$$CSI = \frac{\text{minimum midfoot width}}{\text{maximum forefoot width}}. \quad (2.10)$$

According to Forriol and Pascual [48], there are five categories based on this ratio (equations 2.11):

$$\begin{array}{ll} CSI = 0 & \text{elevated arch,} \\ 0 < CSI < 0.3 & \text{morphological normal arch,} \\ 0.3 \leq CSI < 0.4 & \text{intermediate foot,} \\ 0.4 \leq CSI < 0.45 & \text{lowered arch,} \\ 0.45 \leq CSI & \text{flatfoot.} \end{array} \quad (2.11)$$

According to Queen et al. [134] and Papuga and Burke [126], both CSI and SI have variable repeatability from good to excellent (Table 2.5). This is much better than the arch angle, probably because the points of interest are easier to identify.

The indices were found to have weak to moderate correlations with arch height measures NH and NNH [27, 134, 155]. Shiang et al. [155] found weak to moderate correlation with most other plantar pressure based methods (AI, MAI, TFI, FI, Alfa angle, and each other), though poor correlations with the ALI. Chen et al. [27] found mostly weak correlations between the indices and radiographic parameters (Calcaneal

## 2. Background

Inclination Angle, Talo Calcaneal Angle, Talar First Metatarsal Angle, Talar Inclination Angle), whereas Villarroya et al. [178] reported moderate correlation between the CSI and lateral radiographic angles (Calcaneal Inclination Angle, Talar First Metatarsal Angle). Chuckpaiwong et al. [30] found moderate correlations with clinical descriptions. Onodera et al. [125] came to the conclusion that the Chippaux-Smirak Index was the best footprint assessment. However, with instantaneous plantar pressure measured by electronic cell-based pressure platforms, the midfoot contact is often broken resulting in a common and not particularly informative ratio of zero.

*Cavanagh and Rogers' Arch Index and other area-based measures - AI, MAI, FI, TFI...*

Cavanagh and Rogers' Arch Index (AI, Fig. 2.4) is an index of the area of mid-foot in contact with the floor as a fraction of whole foot in contact with the floor [25] (equation 2.12):

$$AI = \frac{\text{area of midfoot contact}}{\text{area of foot contact (minus toes)}}. \quad (2.12)$$

The midfoot is defined as the central third of the truncated foot print (the foot print minus the toes). Cavanagh and Rogers defined the normal foot within these bounds (equations 2.13):

$$\begin{array}{ll} AI \leq 0.21 & \text{high arch,} \\ 0.21 < AI < 0.26 & \text{normal arch,} \\ 0.26 \leq AI & \text{flat arch.} \end{array} \quad (2.13)$$

The AI has been tested by many groups and has shown mostly excellent repeatability (Table 2.6). Many studies have shown moderate to high correlations with navicular height-based measures (NH, NNH) [29, 53, 95, 115, 134, 155]. Correlations with navicular motion measures (NDrop, NDrift) have been shown to be weak [13] to moderate [74]. Shiang et al. [155] found the correlation with other plantar pres-

## 2. Background

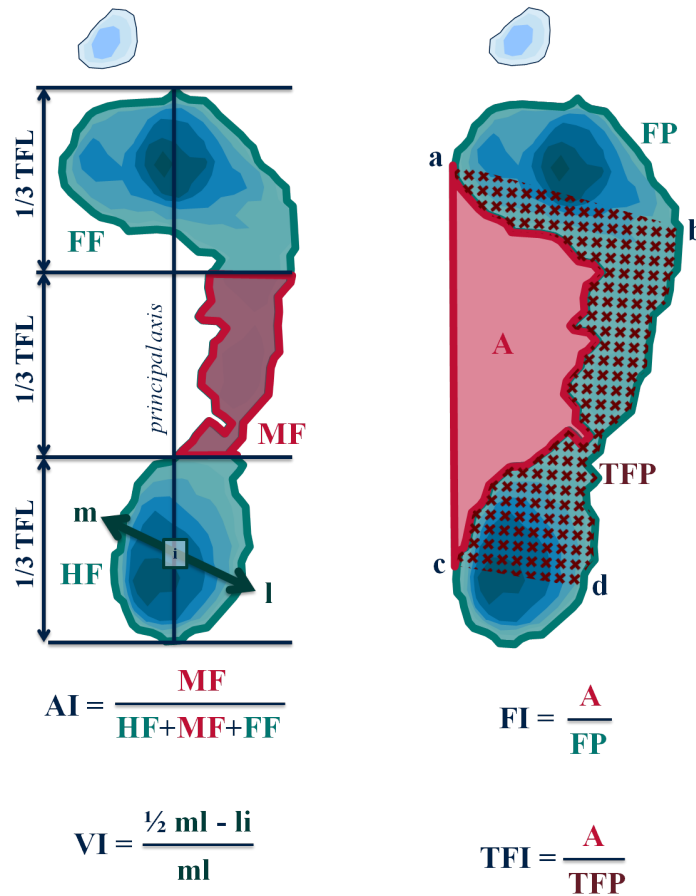


Figure 2.4.: Demonstration of Cavanagh and Rogers' Arch Index (AI), Valgus Index (VI), Footprint Index (FI), and Truncated Footprint Index (TFI). a is the most medial and b is the most lateral aspect of the forefoot, c is the most medial and d is the most lateral aspect of the hindfoot. m is the projection of the medial malleolus and l is the projection of the lateral malleolus onto the floor. The principal axis runs from the posterior aspect of the heel to the 2nd metatarsal head. The AI is the ratio of midfoot contact to foot (minus toes) contact (where the midfoot is defined as the central third of the footprint excluding the toes). The VI is the difference between 50% of the distance between the malleoli and the distance between the lateral malleoli and the intersection of the malleolar and principal axes, divided by the distance between the malleoli. In essence it describes the deviation of the principal axis from the centroid of the malleoli. The FI is the ratio of non-contact under the arch to the toe-less footprint area. The TFI is the ratio of non-contact under the arch to the truncated footprint area between the maximum hindfoot and (often parallel) forefoot width lines.

## 2. Background

Table 2.6.: Usability and validity of the Arch Index. MPP is Maximum Pressure Print. "pcc" is Pearson's correlation coefficient. Inter-clinician reliability is based on comparison between different clinicians collecting the data, while the analysis remains consistent. Papers selected by Scopus® [154] search including the measure in question and any of the following: repeatability, inter-rater, intra-rater, inter-tester, intra-tester, reliability, validity, correlation.

		AI	
Easy and fast to use		Yes	
Usability	Reliable (day/clinician)	Inter-day, platform MPP	ICC:0.99 Gurney et al., 2013 [59]
		Inter-day, static MPP	ICC:0.89-0.92 Tong and Kong, 2013 [172]
		Inter-day, dynamic MPP	ICC:0.86-0.92 Tong and Kong, 2013 [172]
		Inter-day, platform MPP	ICC:0.975 Akins et al., 2012 [1]
		Inter-clinician, foot scanner	ICC:0.90-0.97 Papuga and Burke, 2011 [126]
		Inter-day, Photobox	ICC(2,1):0.92 Queen et al., 2007 [134]
		Inter-day, ink print	ICC:0.94 Cavanagh and Rogers, 1987 [25]
Intra-rater consistent	Foot scanner	ICC:0.93-1.00 Papuga and Burke, 2011 [126]	
	Insole MPP	ICC:0.80 Jonely et al., 2011 [74]	
	Plantograph	ICC:(0.38)-(-0.41) Billis et al., 2007 [13]	
	Ink print	ICC:0.96 Cavanagh and Rogers, 1987 [25]	
Inter-rater consistent	Foot scanner	ICC:0.89 Papuga and Burke, 2011 [126]	
	Photobox	ICC(2,k):0.96 Queen et al., 2007 [134]	
Clinically relevant	Moderate correlation (pcc= -0.66) with clinical classification [30].		
Validity	Objective	Yes	
	Predicts/measures dynamic function	Not effective, not good correlation with dynamic measures [60]	
	Normal values known	Yes	

sure based measures to be moderate (FI, Alfa angle, SI, CSI) to strong (TFI, MAI), except the ALI which was weak. Moderate correlations have been found with some radiographic parameters: calcaneal first metatarsal angle [115], talo navicular coverage angle [115], talar first metatarsal angle [77], and talar inclination angle [77]. However, correlations with talar second metatarsal angle [115] and talo-calcaneal angle [77] was weak. The two sources disagreed with respect to the correlation with calcaneal inclination angle. This measure was shown to have a moderate correlation with clinician-graded foot posture [30]. The AI was found by Nikolaidou and Boudolos [122] to have the lowest rate of misclassification (15%) when compared with Martirosov's K Index, footprint angle and the CSI.

The Modified Arch Index (MAI) is similar to the Arch Index, except that the summa-

## 2. Background

tions are of the total pressure in the area rather than the area itself [29]. The MAI where investigated generally showed greater correlations with other measures than did the AI [29, 84, 155]. Using a mid-gait (dynamic, instantaneous) method Leung et al. [84] achieved excellent intra- and inter-rater repeatability. The MAI is more stable than the AI as it is less susceptible to influence from very light contact, which can have a disproportionate effect on the AI, and may explain its increased repeatability.

The Footprint Index (FI) and Truncated Footprint Index (TFI, also referred to as the “truncated arch index”) (Fig. 2.4) were found to have good inter-day and inter-rater repeatability [134]. The Footprint Index has been found to have moderate correlation with Navicular Height [134, 155], weak (SI), moderate (AI, MAI, CSI, Alfa angle), and strong (TFI) correlations with other plantar pressure indices [155].

*Less common footprint based indices - ALI, VI, Contact Indices, Martirosov's K Index.*

The Arch Length (or Longitudinal) Index (ALI) [63] is the ratio of the central perimeter of the foot between the medial aspects of the forefoot and hindfoot, to the direct distance between those points (Fig. 2.3). Though the intra-rater reliability was good, the inter-day reliability was found to be not good by Queen et al. [134]. Although moderate correlation with clinical descriptions was found by Chuckpaiwong et al. [30], and Queen et al. [134] found moderate correlation with Navicular Height (NH); Shiang et al. [155] found negligible correlation with NH and many plantar pressure based measures (AI, MAI, FI, TFI, CSI, SI, Alfa angle). Additionally this method does not work well if there is interrupted mid-foot contact or forefoot abduction, and so was excluded as an option for this study of dynamic foot posture in children.

The Valgus Index [160] quantifies the static valgus of the foot (Fig. 2.4). Billis et al. [13] found it to have acceptable reliability, to have moderate correlation with navicular drop, and small correlation with navicular drift.

The Contact Index I-VI [133], and Martirosov's K Index are relatively complicated

## 2. Background

indices requiring the identification of many landmarks. There is also little evidence regarding their repeatability.

### 2.1.3. Radiographic measures

Since radiography is considered by some to be the gold standard assessment for flat feet, there are many radiographic measures based on lateral and transverse radiographs (Figs. 2.5 and 2.6). The ethical concerns regarding exposure of children to radiation make it non-viable in healthy subjects. Additionally, it is generally limited to static assessment, and since the calculations are generally based on x-rays of a particular plane, it is a two-dimensional not three-dimensional record of foot position.

On the basis of lateral radiographs some measures demonstrate good repeatability. Cavanagh et al. [24] found the calcaneal inclination angle to be the most repeatable between trials and timepoints (ICC=0.95-0.98), followed by Chopard's joint angle (ICC=0.90), metatarsal inclination angle (ICC=0.75-0.83), naviculo-cuneiform angle (ICC=0.70-0.85), Lisfranc joint angle (ICC=0.71-0.75), and talar inclination angle (ICC=0.51-0.54). Saltzman et al. [150] found excellent intra- and inter-rater reliability (ICC=0.99) for calcaneal inclination, and calcaneo-first metatarsal angle (however this is based on single radiographs). Without the aid of radiographs, Williams et al. [185] achieved promising intra-rater repeatability of the first metatarsal inclination (ICC=0.910-0.995), but much worse inter-rater reliability (ICC=0.480-0.512) when measuring using a goniometer. Cavanagh found some correlation between radiographic measures (calcaneal inclination angle and metatarsal angle) and peak pressure under the heel and first metatarsal.

In the transverse plane Murley et al. [115] found good to excellent intra-rater and moderate to very good inter-rater reliability for the talar second metatarsal angle. The talo-navicular coverage angle has unknown reliability, but it has been found to

## 2. Background

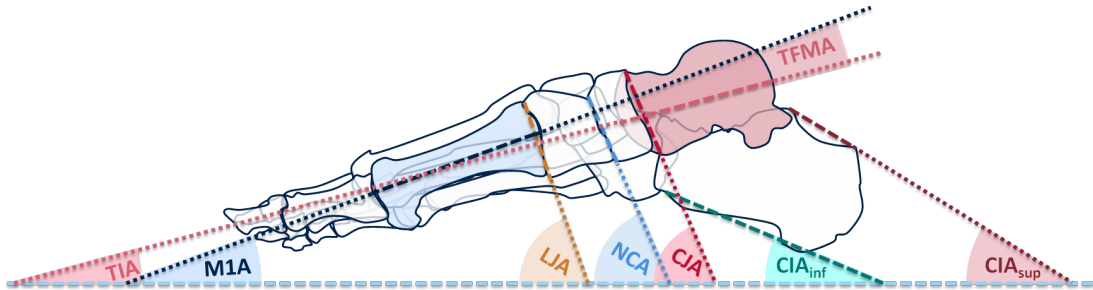


Figure 2.5.: Lateral radiographic parameters related to flatfoot. Talar Inclination Angle (TIA) is the angle of the diaphysis of the talus. First Metatarsal Inclination Angle (MIA) is the angle of the mid-line of the first metatarsal shaft to horizontal. Lisfranc Joint Angle (LJA) is the angle of the first metatarso-cuneiform joint to horizontal. The Naviculo-Cuneiform joint Angle (NCA) is the angle of the naviculo-cuneiform joint to horizontal. Chopard's Joint Angle (CJA) is the angle of the talo-navicular joint to horizontal. The Calcanal Inclination Angle (CIA) is the (inferior or superior) angle of the calcaneus to horizontal. The Talo First Metatarsal Angle (TFMA) or Meary's angle is the angle between the talar diaphysis and first metatarsal shaft.

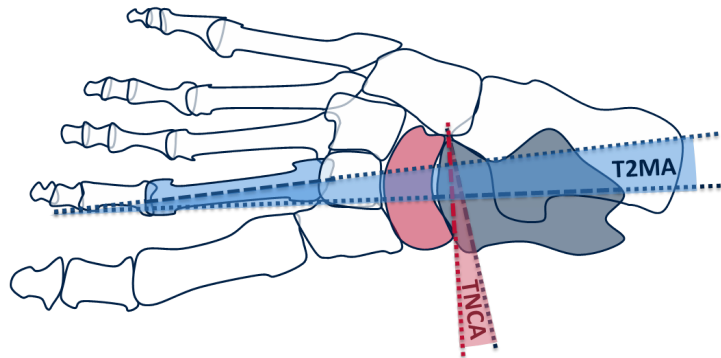


Figure 2.6.: Transverse radiographic parameters related to flatfoot. Talar Second Metatarsal Angle (T2MA) is the angle between the diaphysis of the talus and the mid-line of the first metatarsal shaft. The Talo-Navicular Coverage Angle (TNCA) is the angle between the articulated surface of the talus and navicular.

## 2. Background

relate to the onset of symptoms in flatfoot [109, 192]. This measure has demonstrated moderate correlation with NNH and AI [115].

Arch collapse can occur at the talo-navicular joint, the tarso-metatarsal joint, between the navicular and the cuneiform or some combination of those mentioned. The talar first metatarsal angle can encompass all these forms of arch collapse, and has been suggested as a reliable indicator of presence / absence of symptoms [129]. This measure has been shown to correlate with Normalized Navicular Height (moderate [148]), AI (moderate [77]), Alfa angle (moderate [178]), CSI (small [27] to moderate [178]), but not SI (very small [27]).

The talar first metatarsal angle may not have good repeatability though due to the difficulty of determining the diaphysis of the talus (not shown but implied [24]). The calcaneo-first metatarsal angle has excellent reliability though [150] and could be inferred to correlate with talar first metatarsal angle. The calcaneo-first metatarsal has good correlation (Pearson's correlation coefficients  $>0.70$ ) with geometric measures AHI [150], NNH [115, 150], and normalized talar height [150], as well as moderate correlation with pressure based measure the AI [115].

### 2.1.4. Verdict on good measures of flatfoot

Forty-one assessment methods have been noted - four clinical, four dorsal arch, four navicular tuberosity, seven other geometric, six popular and five unpopular plantar pressure based measurements, and eleven (usually) radiographic measures.

The relationships between the measures vary (summarized in Table 2.7). Stronger relationships were found between clinical classification and ALI than other plantar pressure assessments. Correlations between some measures have been documented fairly thoroughly, particularly AI, NH, NNH, CSI, SI, calcaneal inclination angle, Alfa angle, and clinical classification. Many measures appear to have no reported values for correlation with other measures: Coleman block tests, FPI, flat foot proforma,

## 2. Background

DAH drop, ARI, talar height, foot mobility, medial longitudinal arch, neutral calcaneal stance position, Martirosov's K index, contact indices I-VI, Lisfranc's joint angle, and naviculo-cuneiform joint angle. Most of these measure are not popular, however the dearth of correlations is perhaps surprising in the case of the FPI as it is such a widely used measure, we will report correlation of the FPI to the NNH and AHI in chapter 5.3.2. What is clear is that the correlation between most of these measures is not conclusive (particularly given the variety in definition and technical equipment used to find such measures).

The measurements were assessed for usability and validity (summarized in Table 2.8). Reliability and consistency were established in some measures (FPI sum, DAH, AHI, AI, SI, CSI, calcaneal first metatarsal angle, calcaneal inclination angle), however most measures had little or no data published about reliability. The clinical relevance of most measures was questionable as only two have been shown to correlate with symptoms (talar-first metatarsal angle (Meary's angle) and talo-navicular coverage angle). Most measures could be classified as objective, although in practice landmarks are often pinpointed by hand reducing objectivity. Some measures correlate with dynamic characteristics but only to a moderate degree. Many geometric measures have previously been applied to measure dynamic performance, but clinical and radiographic parameters have significant barriers to dynamic applicability (multifaceted and subjective nature, exposure to radiation and alignment issues). Some footprint based methods have been applied to semi-dynamic analysis (mid-gait snapshot or maximum pressure print) however there are issues with these methods (see part within Section 2.1.2 for dangers of maximum pressure print, for issues with analysing one frame within a temporally diverse set see Section 7.1). Appropriate reference values for many measures are disputed, and in any case often meaningless in terms of directing treatment owing to lack of established relationship to symptoms. While there are a myriad of arch assessment techniques, and some very comprehensive studies, the questions remain as to their usefulness owing to large gaps in knowledge.

Since clinical classifications were found to be the most trusted and common method



## 2. Background

Table 2.8.: Table of usability and validity of arch assessment techniques. The colours indicate the positive (green) and negative (orange) aspects of a measure. The numbers in brackets indicate the number of sources that have contributed to the judgement. This table has been constructed on the basis of more than 44 sources (44 to determine usability, relation to symptoms, and correlation with dynamic performance) [1, 6, 10, 13, 20, 23, 24, 25, 33, 42, 44, 45, 46, 59, 60, 74, 84, 97, 98, 99, 101, 103, 109, 110, 115, 121, 126, 128, 129, 131, 132, 134, 137, 140, 150, 151, 157, 159, 171, 172, 185, 189, 192, 193]. Reliability components are quoted with the same terminology as original sources. Clinical relevance “symptoms” indicates a correlation with symptoms. Objectivity ranges from not, through semi (objective but definition weak), to yes (potentially objective if process is automated). Dynamic correlations are moderate, “direct” indicates the measure has been previously directly applied to dynamic situation, “mid-gait” indicates the measure has been applied to a predefined snapshot during dynamic stance. Abbreviations described in previous table (Table 2.7)

Measure	Usability			Validity			
	Reliable	Intra-rater consistent	Inter-rater consistent	Clinically relevant	Objective	Dynamic correlation or applicability	Established reference values
Clinical classification	?	?	?	?	No	No	Implicit
Coleman block	?	?	?	?	Semi	No	Yes
FPI	?	Sum good-excellent (2) Components: no (1)	Sum good (2) Components: no (1)	?	Semi	No	Yes
FFP	?	?	Good (1)	Directs treatment	Semi	Some correlation (3)	?
DAH	Almost perfect (1)	Moderate-excellent (7)	Moderate-excellent (8)	?	Yes	Correlates (1), direct	Yes
DAH drop	?	Poor-excellent (4)	Moderate-excellent (4)	?	Yes	Direct	Somewhat
AHI	Excellent (1)	Moderate-excellent (4)	Moderate-excellent (6)	?	Yes	Correlates (1), direct	Yes
ARI	?	?	?	?	Yes	Direct	?
NH	Excellent (1)	Moderate-excellent (7)	Poor-excellent (6)	Poor validity (1)	Yes	Direct	Yes
NNH	?	Moderate-excellent (4)	Good-excellent (4)	?	Yes	Direct	Yes
NH drop	?	Good-excellent (6)	Moderate (2)	?	Yes	Moderate correlation (1), direct	Yes
NH drift	?	Acceptable-excellent (2)	?	?	Yes	Direct	?
TH	?	?	?	?	Yes	?	?
NTH	?	?	?	?	Yes	?	?
FM	?	?	?	?	Yes	?	?
MLA	Excellent (1)	?	?	?	Yes	Limited correlation (1)	?
MLAD	Excellent (1)	?	?	?	Yes	Limited correlation (1)	?
RCSP	?	?	?	?	Semi	?	?
NCSP	No (4)	No (1)	?	?	Semi	?	?
AI	Excellent (7)	Acceptable-excellent (4)	Excellent (2)	?	Yes	Not good correlation (1), midgait	Yes
MAI	?	Excellent (1)	Excellent (1)	?	Yes	Midgait	Yes
FI	Good (1)	?	Good (1)	?	Yes	?	?
TFI	Good (1)	?	Good (1)	?	Yes	?	?
SI	Good-excellent (2)	Excellent (1)	Good-excellent (2)	?	Yes	?	Yes
CSI	Good-excellent (2)	Excellent (1)	Good-excellent (2)	?	Yes	?	Yes
Valgus Index	Acceptable (1)	?	?	?	Yes	?	?
Contact indices I-VI	?	?	?	?	Semi	?	?
Maturosov's K index	?	?	?	?	Semi	?	?
Alfa angle	Not good-excellent (2)	Excellent (1)	Fair-good (2)	?	Yes	?	Yes
ALI	Not good (1)	Good (1)	?	?	Yes	?	Yes
TIA	Acceptable (1)	?	?	?	Yes	No	?
TFMA	Not good (1)	?	?	Symptoms (2)	Yes	No	?
T2MA	?	Good-excellent (1)	Moderate-very good (1)	?	Yes	No	?
CJA	Excellent (1)	?	?	?	Yes	No	?
TNCA	?	?	?	Symptoms (2)	Yes	No	?
TCA	?	?	?	?	Yes	No	?
NCA	Moderate (1)	?	?	?	Yes	No	?
LJA	Moderate (1)	?	?	?	Yes	No	?
C1MT	Excellent (1)	Excellent (1)	Excellent (1)	?	Yes	No	?
M1IA	Good (1)	Excellent (1)	Not good (1)	?	Yes	No	?
CIA	Excellent (1)	Excellent (1)	Excellent (1)	?	Yes	No	?

## 2. Background

[30], these will be the benchmark for the study. Since talar first metatarsal angle and talo-navicular coverage angle correspond with symptoms ([129, 193] and [109, 192] respectively), they would be the preferable quantitative methods, except for the implications of poor reliability, consistency, ethical concerns, and lack of dynamic applicability. The most similar measure with confirmed repeatability in the case of the talar first metatarsal angle was the calcaneo-first metatarsal angle. It would be ethically questionable to use these radiographic measures on children, particularly asymptomatic children, so the preference would be to use the measures that correlate with the calcaneo-first metatarsal angle which are repeatable, practicable, and can be applied to or predict dynamic function. Those measures are therefore geometric measures - the AHI and NNH, and footprint-based AI (with the option of MAI). In the case of the talo-navicular coverage angle, moderate correlation has been demonstrated with the NNH and the AI, the measure itself would potentially be well represented by a relaxed posture lateral navicular measurement but such a measure (and how to scale such a measure in children) has not been developed. Previous symptomatic studies indicate AI and NNH may correlate with symptoms, one implies AHI could be useful additionally, these are the measures that will be applied quantitatively in the main data collection where possible (Chapter 4), and would be recommended in similar future studies.

### 2.2. What is developmental flatfoot?

Flexible flatfoot occurs in 10-23% of the general adult population [7, 57, 12]. However, all children are born with flatfeet, and the arch develops with age. This type of age-related flatfoot is considered to be developmental and therefore not believed by most to be a cause for concern. There have been several studies in this area which will be summarized to allow exclusion of developmental cases which could otherwise confuse the analysis.

## 2. Background

The larger fat pad found in young children is there to protect the foot from overloading until the skeletal system has adapted to loading during stance and gait. By increasing loadable plantar surface area, an increased fat pad can reduce pressures to protect cartilage [152] and reduce shear forces [146]. This stage of foot ossification will continue until the age of five years, with the fat pad being absorbed into the foot [92]. The arch is thought to develop over the same time or slightly longer.

### *Studies on arch development*

The estimates of arch development age have varied significantly between a mere two years old and late adolescence. The earliest cited estimate of the age is two years [90]; however there is no corroboration for this assertion.

Pfeiffer et al. [130] investigated 835 children between the ages of three and six years old in a cross-sectional study. The diagnosis was based on valgus heel position (measured by laser surface scanner) and “poor” formation of the arch. They concluded that most children will develop a longitudinal arch by age four or five years, with boys and the obese having a significantly greater tendency to flatfoot beyond this age.

Onodera et al. [125] assessed 391 Brazilian children between the ages of three and ten years old. The statistically significant moment was deemed to occur within the ages of four and five years old on the basis of footprint assessments (AI, CSI, SI, and AA) and foot posture assessment.

Volpon [179] assessed 672 “healthy” white subjects between newborn and fifteen years old. Under the age of two years there was a high incidence of flatfoot. The arch rapidly developed between the the ages of two and six years.

Forriol and Pascual [48] used footprint assessment methods on 1676 children between three and seventeen years old. The cross-sectional study found a tendency

## 2. Background

for those in early childhood to present a low internal arch until the age of five or six years.

Two thousand three hundred children aged between four and thirteen years of age were analysed by Bhaskara Rao and Joseph [12]. The static footprints were assessed by the widest point of the midfoot. By considering diversion between habitually shod and unshod subjects at the age of six (the shod children having a higher prevalence of flatfoot) the researchers deduced that the critical point of arch formation must have been prior to the age of six years.

Stavlas et al. [166] analysed 5866 school aged children (six through seventeen years old). On the basis of dynamic footprints, statistically significant differences between age groups were found right through until the age of fifteen years old. They did not analyse children through the ages identified by the other studies, so it is difficult to directly compare the (seemingly contradictory) results.

### *Verdict on arch development*

The majority of studies put the age of arch development as sometime prior to the age of six. It is good to consider treatments early (particularly if conservative options are to work). Therefore, for elements of this study which seek to distinguish asymptomatic and symptomatic flatfoot, only children over the age of five will be included. This avoids the confusion caused by the fat pad, and appears to be a point at which arch development has occurred in most people.

### 2.3. What is symptomatic flatfoot?

The arch is a powerful shock absorber during standing, walking, jogging and sprinting. Restricted range of motion and consequent reduced dissipation, result in forces of weightbearing being transmitted up through the joints of the ankle, knee, and

## 2. Background

hip onward to the pelvis and spine [72]. Consequently flatfoot could be involved in arthritic conditions beyond the foot. Inman [69] showed that for a person with flatfoot, weightbearing forces are increased 20% during a slow walk and up to three or four times when sprinting.

Paediatric patients with flexible flatfoot are mostly asymptomatic, although according to textbooks sometimes they may have chronic low-grade discomfort on the medial longitudinal arch, talo-navicular areas or leg muscle pains. Where the foot is excessively pronated, the tibialis posterior is thought to sometimes be a cause for complaint, the pronation causing aphasical work of the muscle leading to overuse.

Few satisfactory studies could be found that quantify the prevalence of specific symptoms in flatfoot over large populations. The only study found on general symptom prevalence was produced by Benedetti et al. on the basis of 53 children with flexible flatfoot [11]. This study found most of the children with flat feet to report foot symptoms (65%) and functional limitation (68%), pain (54%) was usually in the plantar aspect of the foot and the medial hindfoot, fatigue-related discomfort was associated with 11%. Mal-alignments were also reported: heel valgus (83%), forefoot adduction (22%), absent varus correction upon toe rise (46%), internal knee rotation (44%). Symptoms were found to correlate with knee alignment. It is difficult to generalize this small study to the wider population as there may be much variation.

Adults with flexible flatfoot are also thought to be mostly without problems. They may have postural symptoms, weakness, and fatigue of the foot or leg. Symptoms of pain in the arch, heel or lateral side of the foot are exaggerated by weightbearing acts. Arthritic changes may also occur within the foot, (for example, sometimes the calcaneus can translate laterally into the fibula). Longstanding cases of flexible flatfoot can progress to rigid flatfoot as ligaments stretch beyond recovery [50, 146] though this may not be the norm [169].

Flatfoot has been correlated with increase [187], decrease [35], and no change [105] in the rate of injury in the asymptomatic population. This may be related to the type of

## 2. Background

injury, soft tissue injuries perhaps being associated with flatfoot. So the implications in terms of injury risk are unclear or limited [172].

### *Assorted features associated with flatfoot*

In neutral feet during standing, intrinsic muscles of the foot are inactive and play no role in support of the arch. Extrinsic muscles, soleus and gastrocnemius, act on the ankle to counterbalance moments in the talo-tibial joint (Joseph and Nightingale [75] as cited by Basmajian and de Luca [8]) via the calcaneal (Achilles) tendon, (Figure 2.7).

Patients with flatfoot may have abnormal muscular activity; and flatfeet are noted to have active peroneus longus, anterior tibialis, and posterior tibialis during standing (Gray [58] as cited by Basmajian and de Luca [8]). This may be an attempt to recover the arch or reduce pronation (Fig. 2.7). The calculations of Morton and Fuller [111] showed static strains to be well within the normal capacity of the ligaments, but more strenuous tasks to require dynamic muscular support (such as that experienced during the takeoff phase of walking). During locomotion, many muscles activate [8].

In addition to the lowered longitudinal arch, other clinical signs of flatfoot include [104]:

- Abduction of the forefoot on the hindfoot at the mid-tarsal joint,
- Plantarflexed and abducted talus,
- Increased angle of gait,
- Increased relaxed calcaneal stance position (excessive heel eversion),
- Decreased ankle foot dorsiflexion.,
- Helbing's sign - inward curvature of the Achilles tendon,
- Abnormal shoe wear.

## 2. Background

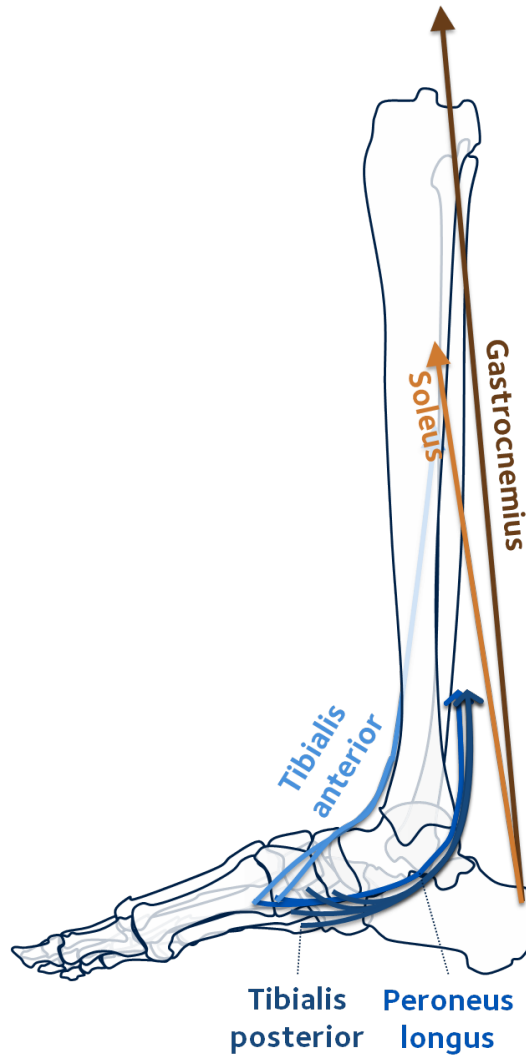


Figure 2.7.: Muscles active during quiet standing – medial view of origins and insertions. In neutral footed subjects the soleus and gastrocnemius may act to maintain balance. In flatfoot the peroneus longus, tibialis anterior and tibialis posterior may act to recover the arch.

## 2. Background

There may also be changes that can be detected by gait analysis [104]:

- Medial heel contact,
- Subtalar joint pronation at heel-strike,
- Reduced or negative re-supination,
- Abductory twist - rapid medial movement of the heel at the instant of heel-off,
- Early heel lift,
- Reduced propulsive gait,
- Increased genu valgum (knock knees) beyond physiologic norm.

Rose identifies joint laxity as the primary cause of flexible flatfoot [146]. According to Jay [72], the most important factor for arch integrity is the sustentaculum tali; the second strongest factor - the integrity posterior tibial tendon. Other important supporting factors include the deltoid ligaments, inferior calcaneo-navicular ligament, and plantar aponeurosis.

### 2.4. Treatment options

After the Second World War several studies were undertaken that suggested flatfeet should not be treated as they were not detrimental in the long term. However these studies were often performed on selected groups such as army recruits; and there have been many studies since which both confirm and refute this assertion. Consequently current procedure is largely that patients with flatfeet without symptoms are reassured and left untreated [21, 162, 169]; and there are relatively few studies in the area.

Paediatric asymptomatic flatfoot may develop into adult symptomatic flatfoot; the aforementioned abnormal kinetics may be the cause of problems later in life. Adult

## 2. Background

flexible flatfoot without posterior tibialis tendon dysfunction is generally a progression of the paediatric condition [83], often with associated contracted Achilles muscle [91]. Patients may have postural symptoms, weakness, fatigue, and pain in the foot. In the long term, patients may develop degenerative arthritis and ankylosis [107, 108], and the pathology may progress to a rigid condition.

The factors involved in the continuation of flatfoot are not fully understood, so selective treatment of those children who would go on to develop symptomatic adult flatfoot is difficult. The main questions are what makes the condition problematic, what loading and deterioration occurs, and how this effects the rest of the body.

The much debated issue is then whether to treat or not. There are essentially three options for a child with flatfoot: to do nothing and watch as, or if, the deformity diminishes on its own; to use a conservative treatment options such as physiotherapy or functional orthoses for control of the foot, allowing it to grow in the correct position (although the efficacy in cases of flexible flatfoot is debated); or surgical interventions. The surgical options are reconstructive procedures (soft tissue, osteotomies), arthrodesis, and arthroereisis [61].

The evidence from randomized controlled trials is currently too limited to draw definitive conclusions about the use of non-surgical interventions for paediatric pes planus. Future high quality trials are warranted in this field. Only limited interventions commonly used in practice have been studied and there is much debate over the treatment of symptomatic and asymptomatic pes planus. (Rome et al., Cochrane Database of Systematic Reviews, 2010 [143])

### 2.5. Summary

The literature has been reviewed. Current foot structure assessment methods were reviewed. AHI, NNH, AI, and MAI were selected as practical, ethical, and repeatable assessment techniques that may relate to the presence of symptoms, the clinical description would be used as a benchmark because of its universality and trust. The age of five was deemed to be sufficient to eliminate developmental flatfoot in future work. Research regarding symptoms and other findings related to flatfoot were noted. Current treatment options have been outlined. Now that this is done, the following chapter investigates the current practice at a specialist orthopaedic hospital where this research takes place: the prevalence, the symptoms, and the treatment of paediatric flatfoot.

### 3. Current management of flatfoot

This chapter describes the audit that was performed to better understand the population of flatfooted children and practice at the Nuffield Orthopaedic Centre. The audit was custom designed (Section 3.2). The author sought, firstly, to better understand the prevalence of idiopathic flatfoot, and the frequency of various symptoms among the population (Sections 3.3.2–3.3.4). Secondly, the origin of the patients and the treatment recommendations were examined for consistency in various departments (Section 3.3.5). The first aim will help explain to what extent the population of patients are representative in the main study (all subsequent chapters). The second aim will help understanding of current state of practice and should improve the impact of conclusions by adapting to what is known about the clinicians and patients.

The concept of a medical audit was introduced in the UK government 1989 white paper [38] as ‘the systematic critical analysis of the quality of medical care, including the procedures used for diagnosis and treatment, the use of resources and resulting outcome and quality of life for the patient’. In flatfoot there is considerable debate over whether to treat, never mind what treatment to use. This audit aimed to evaluate existing practice within departments in the Nuffield Orthopaedic Centre (NOC)

### 3. Current management of flatfoot

to determine to what extent it is consistent and conforms to established standards.

It was believed that there may be a wide variation in clinical practice of the management of flatfoot in the NOC. The audit was designed principally to examine how this practice compares with “gold standards” found in the literature.

There has been an ongoing debate as to how to treat patients with flatfoot. There was concern that there were differences in the care provided by different departments and clinicians within the NOC and the audit was created to test this.

#### 3.1. Clinical guidelines and gold standards

Generally in the case of asymptomatic flexible flatfoot, the recommendation is to reassure the family that it is not pathologic and is perfectly normal. However, in the case of idiopathic symptomatic flexible flat feet, the treatment is more contentious. A roundtable discussion between well-known experts revealed the variety of approaches to flexible flat feet among surgeons [80].

The most thorough, recent, written guidelines are provided by Harris et al. [61] and Lee et al. [83]. These clinical practice guidelines were developed by the Clinical Practice Guideline Pediatric Flatfoot Panel of the American College of Foot and Ankle Surgeons.

The initial stage of the guidelines is to differentiate the type of flatfoot (Fig. 3.1). The key variations are flexible, rigid, skewfoot, and other.

The flexible flatfoot is one which is neutral during non-weightbearing but has significant flattening during weightbearing. This is the principal focus of the present study.

Neurological and muscular abnormalities warrant very different treatment strategies which are dictated by the underlying pathology. The focus of this thesis is not on these

### 3. Current management of flatfoot

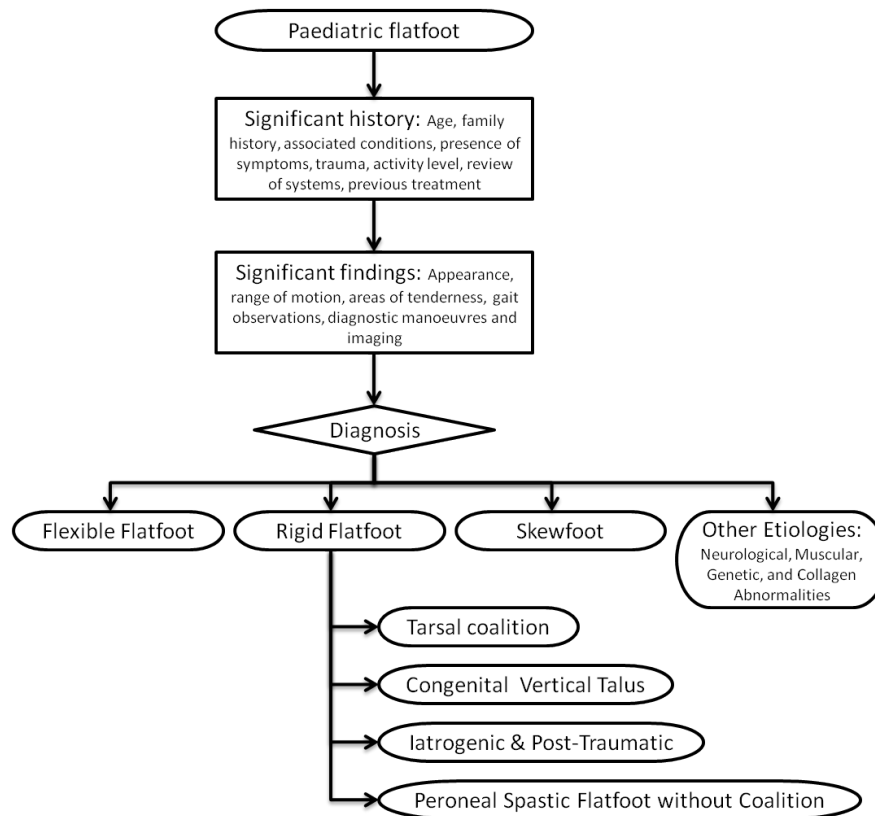


Figure 3.1.: Diagnosis of various categories of flatfoot according to Harris et al. [61]. Adapted from Harris et al.

conditions but on flat feet which are the subject of questions over how and whether to treat them at all. Therefore, these are excluded from all parts of the study.

The treatment strategy for all cases can be summarized by a process with two major decisions to be made (Fig. 3.2). The specifics of the history, findings, and treatment vary between the types of flatfoot relevant to the study (Table 3.1). However, there are plenty of similarities between the various recommendations. The initial decision to treat is based on the history and findings. In terms of the history, the common and most important consideration is the presence of symptoms (Table 3.1). Trauma and age are also of major consideration. The significant findings vary. The decision to treat in symptomatic and flexible cases is based on symptoms being present. In other rigid cases treatment appears to be mandated, even though symptoms may or may not exist.

The initial treatment options are broadly similar. It is not clear from Harris et al. [61]

### 3. Current management of flatfoot

Table 3.1.: Table summarizing treatment options, based on Harris et al. [61]. Colours highlight similarities between various diagnoses. NSAIDs - Non-Steroidal Anti-Inflammatory Drugs. ROM - Range Of Motion. Diagnosis comes from process described in Figure 3.1, treatment decision procedure outlined in Figure 3.2.

Diagnosis	Paediatric flexible flatfoot	Tarsal coalition	Peroneal/spastic flatfoot without coalition	latroequic & post-traumatic deformity	Skewfoot
Significant history	± Symptoms Low back, knee, heel pain Age Co-morbidities Family history	± Symptoms Age: pre/adolescent ± Weight gain Altered physical activity ± Trauma	± Symptoms Age: pre/adolescent Symptoms activity related ± Trauma - Tarsal coalition	± Symptoms ± Trauma / prior symptoms ± Prior treatment	± Symptoms History of foot deformity History of previous foot intervention
Significant findings	Systems review: Gait disturbances Prominent talar head Tight tendo-Achilles Co-morbid condition	Rearfoot pain Decreased rearfoot ROM ± Peroneal spasm + Tarsal coalition	Rearfoot pain Decreased rearfoot ROM Peroneal spasm Antalgic gait External rotation of foot Little propulsion in late stance	Variable pain ± Progressive deformity Pain with ambulation/ROM Antalgic gait	Forefoot adductovarus Rearfoot valgus Ankle equinus Presence of calluses or ulceration Radiographs
Decision (1). to treat if	Presence of symptoms	Presence of symptoms	Presence of symptoms	Presence of symptoms	Presence of symptoms
Initial treatment options	Activity modifications Orthoses Stretching (if equinus) NSAIDs (if severe) Manage co-morbidities Obesity Ligamentous laxity Hypotonia Proximal limb problems	Footwear modifications Arch supports Orthoses Activity modifications Footwear modifications Arch supports Immobilization (if severe) NSAIDs	Treat identifiable causes NSAIDs Activity modifications Footwear modifications Arch supports Orthoses Immobilization Nerve blocks & diagnostic injections	Footwear modifications Arch supports Orthoses Activity modifications NSAIDs Appropriate weight reduction Physical therapy	Manipulation & serial casting (infants) Stretching Activity modification Orthoses NSAIDs Manage co-morbidities
Decision (2). to operate if	Continued symptoms Osteotomy (various) Spacer in sinus tarsi Arthrodesis (subtalar/triple) Soft tissue procedures Heel chord lengthening Medial plication TAL/gastroc recession	Unsatisfactory clinical response Resection of coalition Arthrodesis Realignment osteotomy	Unsatisfactory clinical response Arthrodesis Realignment osteotomy	Unsatisfactory clinical response Soft tissue release Realignment osteotomy Realignment/resection arthrodesis Amputation	Continued symptoms Appropriate rearfoot correction Midfoot &/or forefoot osteotomies Posterior soft tissue lengthening

### 3. Current management of flatfoot

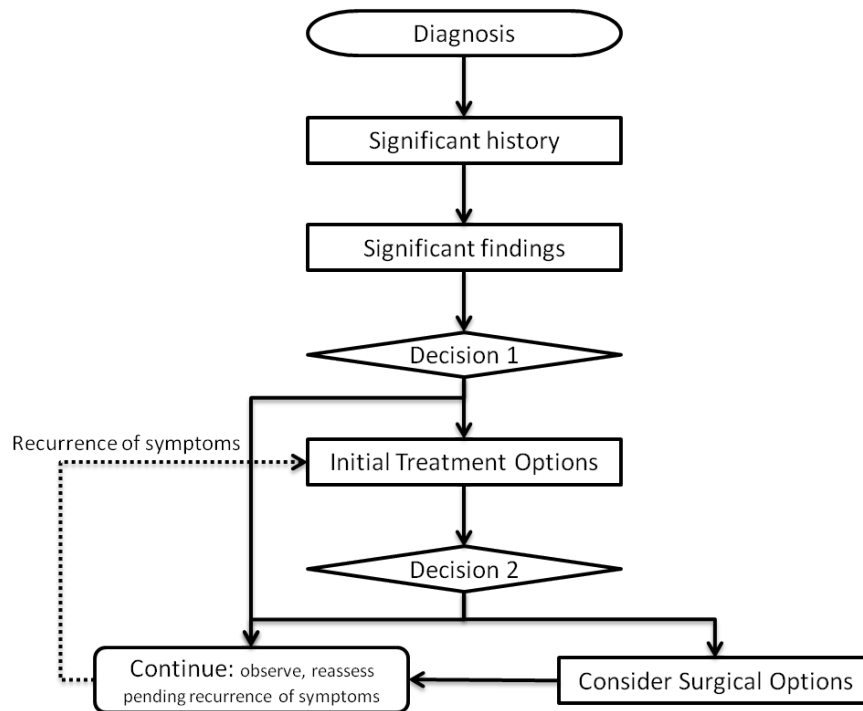


Figure 3.2.: Treatment decision making processes for paediatric flexible flatfoot according to Harris et al. [61]. Diagnosis comes from process denoted in Figure 3.1. Treatment options described in Table 3.1. Adapted from Harris et al.

if the order of the treatment options is related to their relevance but it has been preserved in the Table (Table 3.1).

All diagnoses appear to suggest activity modification which ‘may include stopping sports, discouraging running and jumping activities, and taking the child out of physical education class’ (Table 3.1). This seems to be quite an old fashioned solution, of the “lose weight and sit down more” school of thought. While in an extreme case it could prove useful in alleviating pain, as a conservative option it seems harsh and short sighted. A lack of physical activity could cause other long term concerns (including low bone density and other aspects of physical health [168]). Additionally, since a lack of physical exercise is linked to weight-gain this may be contradictory advice.

Non-steroidal anti-inflammatory drugs are also an option for all types of flatfoot.

Orthotics and the management of co-morbidities such as obesity can be advised in

### 3. Current management of flatfoot

all cases as well (Table 3.1). These are well-accepted and relatively easily enacted options. Off-the-shelf and custom made orthotics are available, and there are a multitude of options and schools of thought on orthotic design.

Additionally, footwear modifications and arch supports are listed in the rigid cases, though not in the cases of skewfoot and flexible flatfoot.

Other specific treatment options are mentioned in specific cases. For flexible flatfoot, if there is equinus, stretching may be prescribed.

Perhaps as a paper developed by the American College of Foot and Ankle Surgeons, this has overlooked or disregarded the potential importance of physiotherapy and prescribed exercise - particularly in the case of flexible flatfoot. Foot muscle strengthening exercises can at the very least theoretically improve the posture and symptoms. Examples of these muscles are the toe flexors, interosseous, lumbrical, and quadratus plantae muscles. Additionally, the supinators could be important in alleviating symptoms by supporting the re-supination (allowing a rigid structure to push off). Tibialis posterior tendon dysfunction is a common cause of flatfoot so the performance of this supinator is clearly important. Since it appears to have been excluded, perhaps physiotherapy and prescribed exercise could be considered as an option for all diagnoses.

On the basis of this consensus [61], clinical evidence [143], and some foot posture assessment measures (Navicular Height and resting calcaneal stance position) a paediatric flat foot proforma was developed and modified for children and repeatability [45]. While strictly speaking a proforma indicates something done for formality not function, in this case the proforma aims to aid the decision making process.

### 3.2. Audit design

The audit collected data for seven months (14/1/11-14/8/11). The audit was de-

### 3. Current management of flatfoot

signed to collect information about flatfoot in the population at the NOC; information about which department treats most of these patients, and the treatments that were recommended. From this the treatment pathways can be revealed, and these can be compared with the gold standards. Secondly, information about the prevalence of the condition, prevalence of the various symptoms (which have previously been described but never quantified), and the type of condition was obtained. This helps us to assess the relevance of any conclusions that are drawn from the thesis (i.e. to what population are any conclusions relevant).

The forms were designed with 15 questions on one page of A4 to be completed by the clinician (Fig. 3.3). This consisted of two sections, one of which was to be completed for all patients, and the second section only to be completed for those with idiopathic flatfoot. It was decided that it was better to require a form for each patient, and to ask the appropriate questions to determine whether they met criteria to warrant further investigation. This would allow the collection of information about flatfoot in the general NOC population, and the increasing participation in the audit by keeping it in the minds of clinicians that may not see many patients with idiopathic flatfoot. The form was further divided into seven parts for examination.

Firstly, the clinician, patient, and department were identified (Fig. 3.3 (a)). The clinician data identifies specialities and the individual that is making the decision. A database containing publicly available information on profession, qualifications, department, and interests of clinicians in the NOC was created. The patient information identifies the age, sex, and ID of the patient. This is necessary to prevent repeat visits from the same patient being classed as independent, and to differentiate infant specific conditions (congenital vertical talus) and treatment programmes (manipulation and serial casting for skewfoot). The department was included to better comprehend differences in population, and treatment consistency within departments.

Secondly, the inclusion criteria were tested (Fig. 3.3 (b)). The questions were designed to ensure those with neuromuscular and metabolic concerns were excluded,

### 3. Current management of flatfoot

Flatfoot Audit 2011

**[CLINIC NAME HERE]**

(a) **Date**    **Patient Label**

**Clinician (surname)**

(b) Are there lower limb or back concerns which flatfoot could theoretically be linked to?  Y /  N  
 Does the patient have flatfoot?  Y /  N  
 Can neuromuscular / metabolic reasons for flatfoot be excluded?  Y /  N  
*(if answered YES to ALL questions CONTINUE with form)*

(c) **Reason for visit** (tick all that apply)

<input type="checkbox"/>	Parental concern	
<input type="checkbox"/>	Patient concern	(specify)
<input type="checkbox"/>	Pain	LOCATION <input type="text"/>
<input type="checkbox"/>	Gait disturbance	MAIN ISSUES <input type="text"/>
<input type="checkbox"/>	Other	DESCRIBE <input type="text"/>

(d) **Examination**

	Right	Left
Flatfoot	Y / N	Y / N
Flexible	Y / N	Y / N
Severity	mild / moderate / severe	mild / moderate / severe
Heel valgus when standing	Y / N	Y / N
Pressure signs over arch	Y / N	Y / N
Arch responds to hallux extension	Y / N	Y / N
Maximum ankle dorsiflexion with subtalar joint neutral & knee extended (°)	<input type="text"/>	<input type="text"/>
Other orthopaedic deformities and background conditions	DESCRIBE <input type="text"/>	

(e) **Referral from:** (detail in a few words)

<input type="checkbox"/>	GP	<input type="checkbox"/>	Other NOC department	<input type="text"/>
<input type="checkbox"/>	Repeat visit	<input type="checkbox"/>	Other	<input type="text"/>

(f) **Treatment history relevant to flatfoot** (tick all that apply)

<input type="checkbox"/>	Physiotherapy	<input type="checkbox"/>	Surgery	<input type="text"/>
<input type="checkbox"/>	Gait analysis	<input type="checkbox"/>	Diagnostic imaging	<input type="text"/>
<input type="checkbox"/>	Shoe advice	<input type="checkbox"/>	Orthotic	<input type="text"/>
<input type="checkbox"/>	Weight loss	<input type="checkbox"/>	Prescribed exercise	<input type="text"/>
<input type="checkbox"/>	None	<input type="checkbox"/>	Pharmaceutical	<input type="text"/>
		<input type="checkbox"/>	Other	<input type="text"/>

(g) **Recommendation relevant to flatfoot** (tick all that apply)

<input type="checkbox"/>	Physiotherapy	<input type="checkbox"/>	Surgery	<input type="text"/>
<input type="checkbox"/>	Gait analysis	<input type="checkbox"/>	Diagnostic imaging	<input type="text"/>
<input type="checkbox"/>	Shoe advice	<input type="checkbox"/>	Orthotic	<input type="text"/>
<input type="checkbox"/>	Weight loss	<input type="checkbox"/>	Prescribed exercise	<input type="text"/>
<input type="checkbox"/>	None	<input type="checkbox"/>	Pharmaceutical	<input type="text"/>
		<input type="checkbox"/>	Other	<input type="text"/>
		<input type="checkbox"/>	Referral to other dept.	<input type="text"/>

(h) Thank you, Catriona Kerr, EPSRC Life Sciences Interface DTC DPhil candidate  
 Phone: 01865 227723, email: catriona.kerr@univ.ox.ac.uk  
 NDORMS (Botnar Research Laboratory), Nuffield Orthopaedic Centre NHS Trust, Oxford, UK

Figure 3.3.: Audit form. (a) identifies clinician, patient, and department. (b) evaluate applicability to complete study. (c) identify motivation behind the visit. (d) further information of the flatfoot. (e) how patient came to appointment. (f) description of treatment known to the clinician that was relevant to flatfoot. (g) description of recommendations. (h) contact information.

### 3. Current management of flatfoot

as well as those with concerns unrelated to the flatfoot. Three questions were asked:

1. Are there lower limb or back concerns which flatfoot could theoretically be linked to?
2. Does the patient have flatfoot?
3. Can neuromuscular / metabolic reasons for flatfoot be excluded?

Only if these conditions were met, should the form be completed in full. The questions fail in the case of clerical error, or clinician mis-judgement. Clerical error cannot be tackled, but mis-judgements can be mitigated. The first question was phrased to encourage inclusion unless the patient has clearly unrelated symptoms (e.g. an arm injury), hence the use of the word theoretically to reduce the effect of individual opinion. The third question was phrased to be conservative, to prevent the inclusion of patients with more complicated etiologies.

If the patient met the criteria, the motivation for the visit would be detailed (Fig. 3.3 (c)). Check-box questions were favoured to speed up the process and facilitate easy analysis. Concern, pain, and gait disturbance were described by clinicians as common complaints so were included as check-box options. Additional space was included to allow for other comments.

Eight questions about the foot posture were included (Fig. 3.3 (d)). These questions were designed not to change treatment protocol and were selected as issues that would be investigated by clinicians whether the audit was ongoing or not. Again check-box questions were favoured. The first part determines severity. Firstly, if the case is bilateral. Secondly, if it is flexible or not - that is whether in non-weightbearing the foot posture appears significantly closer to neutral. Thirdly they were asked to give a subjective rating on the severity. The next part asks more specific questions that could affect treatment: standing heel valgus, pressure signs under the arch, Windlass mechanism (for explanation, see Section 4.4.2), and ankle dorsiflexion with the knee extended (for convention, see Fig. 4.8 (f)). Additional space was provided for other issues that might affect treatment decision-making.

### 3. Current management of flatfoot

The remaining sections described the patient's progression through the system (Fig. 3.3 (e)-(g)). Three main origins of the patient were offered as General Practitioner (GP - a physician who provides primary care and general holistic advice), other departments of the NOC, and repeat visits. Prior treatment options were broadly similar to recommendation options: physiotherapy, gait analysis, shoe advice, weight loss, surgery, diagnostic imaging, orthotics, prescribed exercise, pharmaceuticals, and none. These covered the options recommended by Harris et al. (Table 3.1, [61]) except the activity modification which was thought to be unlikely advice from the NOC.

The forms were printed in purple as this colour was not being used for other common forms in the NOC. Additional materials were developed in line with this colour scheme (Fig. 3.4). Six departments were identified to which the patients could be referred (Paediatric Orthopaedics, Orthotics, The Oxford Gait Laboratory (OGL), OxSport, Physiotherapy, and Foot and Ankle). Each department was visited and the process was explained and materials were supplied.

In addition to plenty of forms, a folder was supplied to keep materials together (Fig. 3.4 (a) and (b)). Eye-catching boxes containing sweets were made to encourage participation and had some key instructions printed on them (Fig. 3.4 (c)). A help sheet was made for frequently asked questions, as well as a letter and document explaining motivation (Fig. 3.4 (d)-(f)).

The audit was approved by the Children's Operational Group at the NOC.

## 3.3. Results and discussion

### 3.3.1. Participation

Participation in the audit was mixed (Fig. 3.5 (a)). In total 191 forms were received.

3. Current management of flatfoot

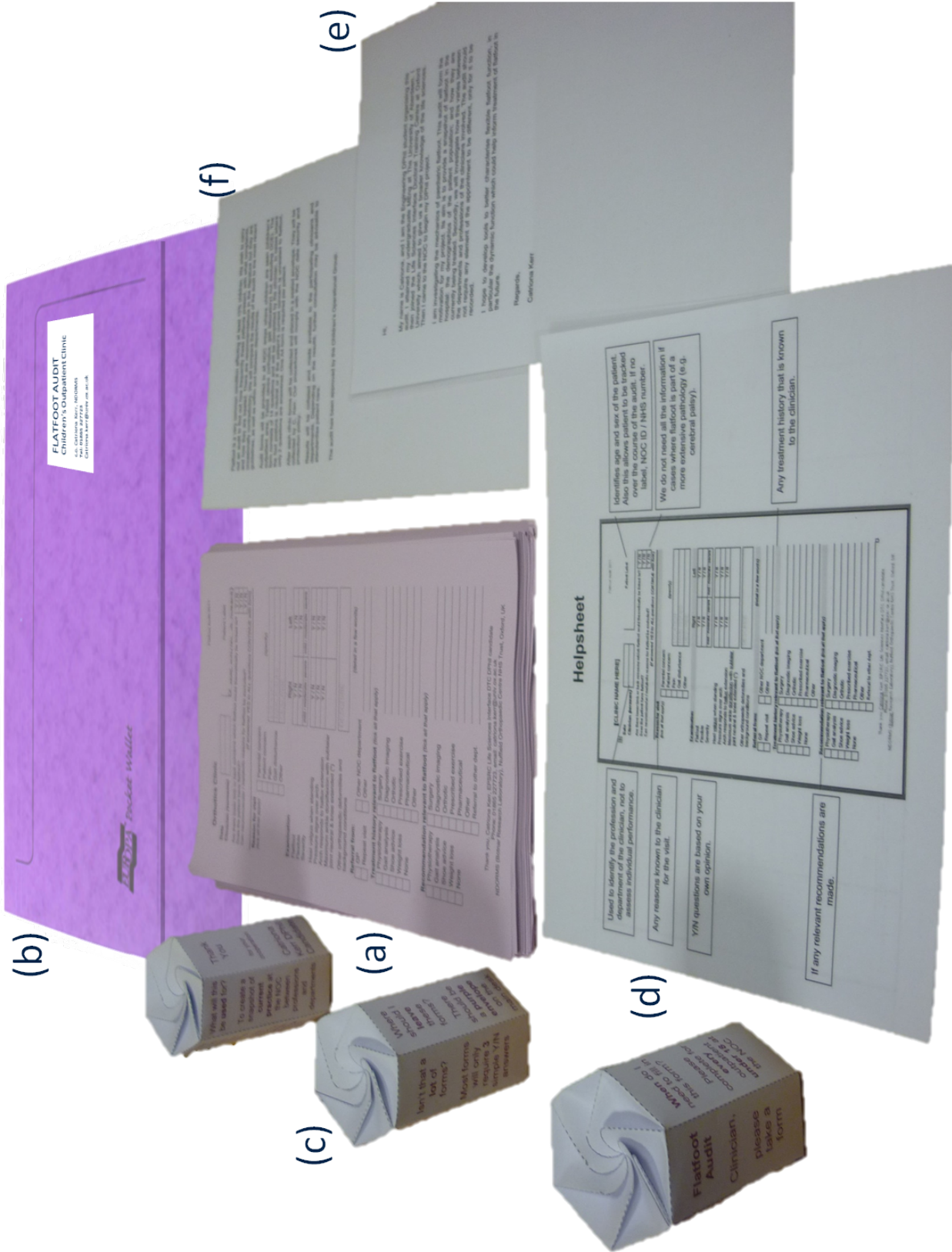


Figure 3.4.: Audit materials. (a) forms. (b) folder for collection of forms. (c) eye-catchers to encourage clinicians to complete forms. (d) help sheet to answer frequently answered questions. (e) letter for people that are interested in the audit. (f) document explaining motivation behind audit.

### 3. Current management of flatfoot

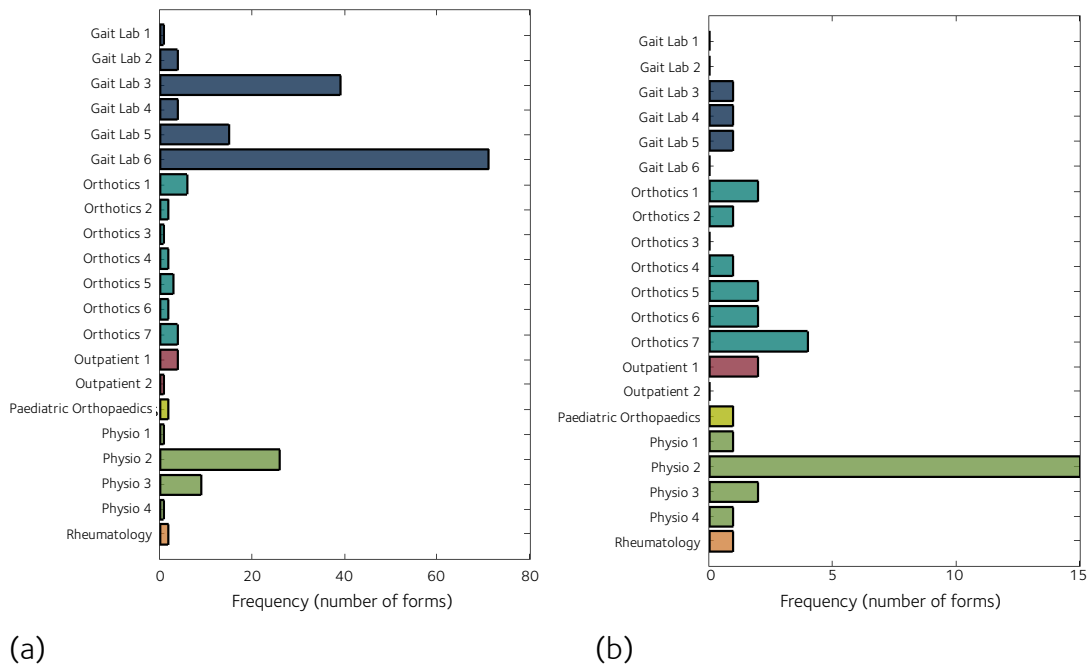


Figure 3.5.: Sources of (a) all forms (n=191) / (b) fully completed forms (n=38) that were received sorted by clinician speciality. Each bar refers to an individual clinician. 70%/53% of forms came from the Oxford Gait Laboratory, 14%/32% from the physiotherapy department, 11%/8% from the orthotics department, 1%/3% from both rheumatology and paediatric orthopaedic specialists, and 3%/5% from unidentified children's outpatient clinics.

The majority of forms were completed by a small number of clinicians. Two OGL clinicians provided 58% of the forms. The OGL was the only department which participated fully in the study by completing a form for every patient, most other departments did not complete forms for non-idiopathic flatfoot patients after the first day or so. Therefore only the prevalence of flatfoot and related concerns among patients of the OGL could be analysed.

Of the patients with forms, 38 met the inclusion criteria (Fig. 3.5 (b)). A large percentage of these (39%) were supplied by one physiotherapist who sees a large number of children with flatfoot.

Since only a small number of clinicians completed enough forms for any statistics or comparison, it was not possible to compare decision-making and populations between individual clinicians. Only two departments (physiotherapy and orthotics) completed enough forms fully to allow comparison. This may be because these depart-

### 3. Current management of flatfoot

ments are the ones which see the most cases related to idiopathic flatfoot.

#### 3.3.2. Oxford gait laboratory population

The OGL was the only department to participate fully in the study for its entire duration, completing 134 forms. These results correspond with part (b) of the form (Fig. 3.3). Of all patients, 51% had flatfoot (Fig. 3.6), this is much higher than in the general population by any other estimate (which put the prevalence between 10% and 23%, depending on population and definition). The majority of these patients had neuromuscular or metabolic complications (84% of cases of flatfoot), or had concerns unrelated to their foot posture. This left 2% of the whole group (three subjects) which met the inclusion criteria (Fig. 3.6).

#### 3.3.3. Reasons for appointments

A variety of motivations behind the appointments was recorded (Fig. 3.7). This corresponds with part (c) of the form (Fig. 3.3).

The majority of forms recorded parental concern. In a smaller number of cases were the patients themselves concerned (Fig. 3.7). This was expected among the paediatric population. Children often have trouble remembering the issues that are not present at the time of examination, and parents are often anxious over what may be small issues. In four cases (11%) the sole motivation for the visit was parental or patient concern.

Pain was also recorded for a majority of subjects (53%, Fig. 3.7). Foot, sole, arch, ankle, Achilles tendonitis, knee, and hip pain were specified in 7-16% of cases. Other descriptions of locations of pain were calf, shin, and leg. This is very close to the figure found (54%) in the most comprehensive study available on the symptoms prevalence

### 3. Current management of flatfoot

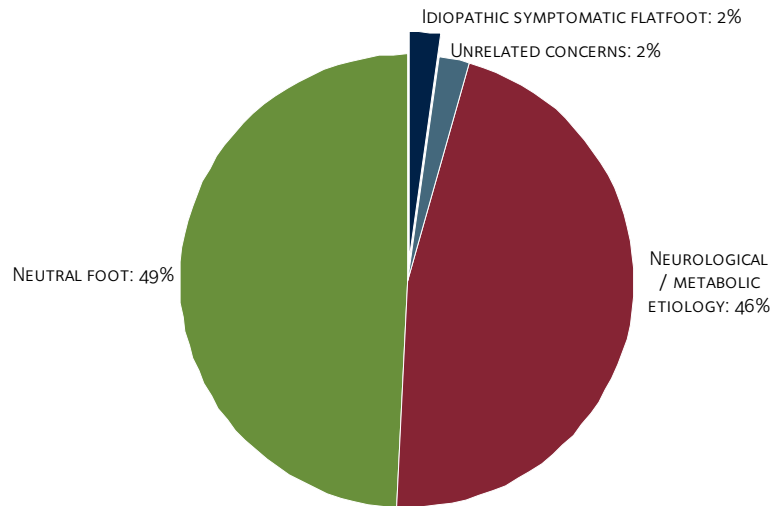


Figure 3.6.: Prevalence of flatfoot in the patients at the Oxford Gait Laboratory (OGL, n=134). The OGL was the only department to participate fully in the study, completing a form for every appointment. Of these 50% of patients were described as flat footed, of those a high percentage (84%) had neuromuscular or metabolic complications.

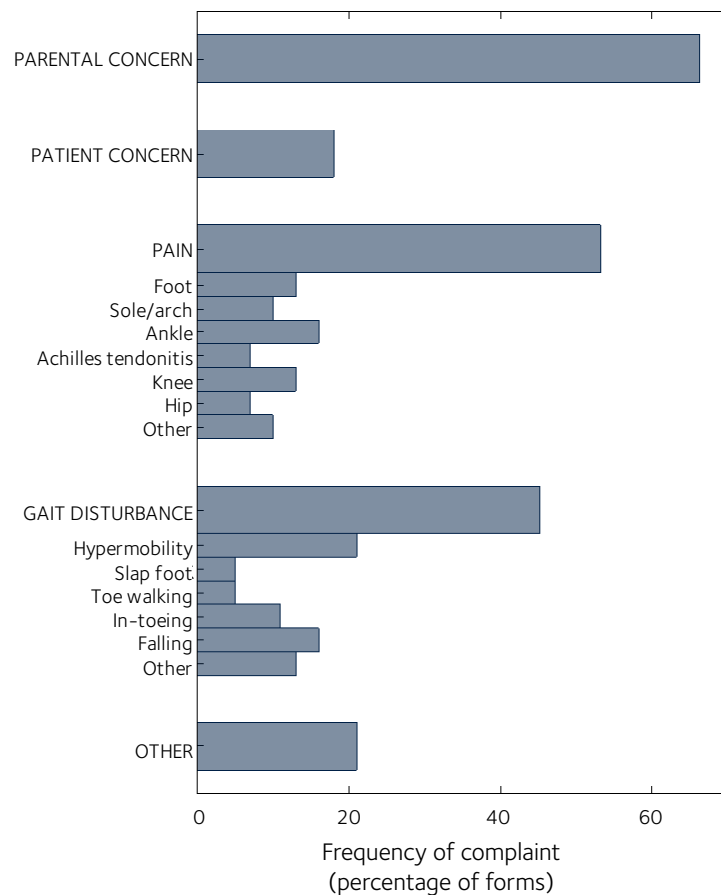


Figure 3.7.: Reasons for appointments, n=38.

### 3. Current management of flatfoot

in children with flatfoot [11], though this study had a lower rate of pain beyond the foot (14.9%).

Gait deviation was recorded in fewer patients (45%, Fig. 3.7). Hypermobility, balance concerns or frequent falling, and intoeing were recorded in 11–21%. Slap foot gait and toe walking were less common. Other notes included limping and fatigue. Fatigue was more commonly reported in the Benedetti et al. study (11.3%) [11].

Other motivations for appointments included foot deformity, lordosis, posterior tibialis tendon dysfunction, and dissatisfaction with current orthoses (Fig. 3.7). Learning difficulties were noted in a number of cases.

A comparison between the physiotherapy and orthotics departments revealed differences (Fig. 3.8). Parental concern was much more commonly noted in the physiotherapy department. Pain was always noted in the orthotics department, and was less common in the physiotherapy department (32%). Gait disturbance was commonly noted in the physiotherapy department (74%), yet rarely in the orthotics department (one case only). This may explain the difference between the Benedetti et al. study [11] and the present data-set in terms of functional limitations and gait disturbances, the Physiotherapy department rates are more similar in these respects whereas the orthotics department may either see different population or the clinicians may be less interested in these aspects.

#### 3.3.4. Description of foot posture

The vast majority of patients had moderate bilateral flexible flatfoot with active Windlass mechanism and static heel valgus (Fig. 3.9). This corresponds with part (d) of the form (Fig. 3.3). The rate of heel valgus was very similar to that previously reported (83%), though the Windlass mechanism was given positive confirmation in more NOC patients (83%) than the previous study (54%) [11].

The mean ankle dorsiflexion was  $11^{\circ}$  (Fig. 3.10). The mean within the physiotherapy

### 3. Current management of flatfoot

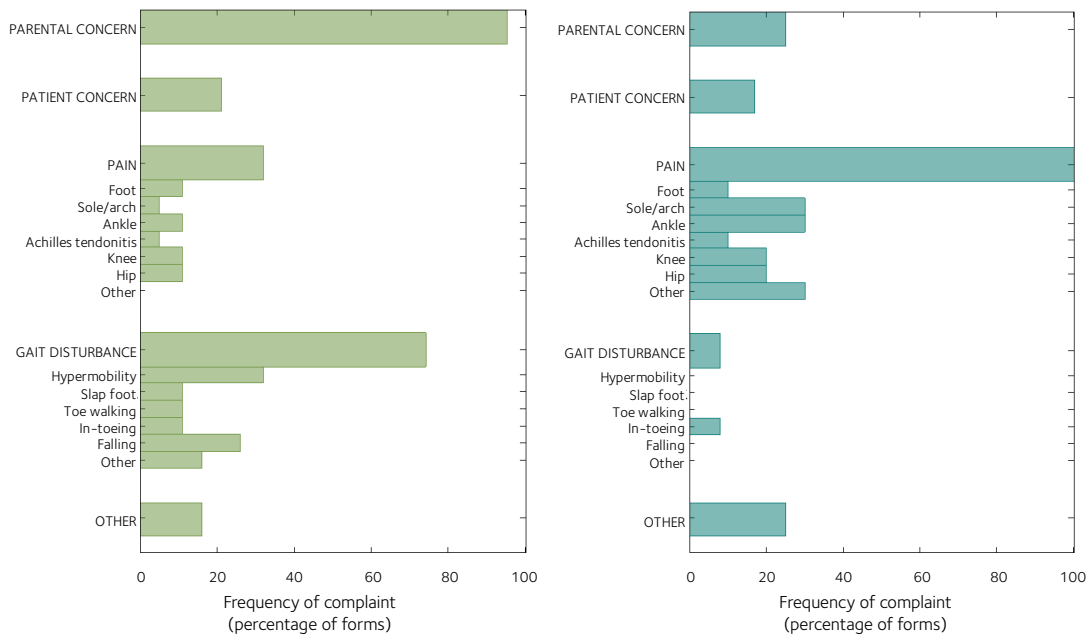


Figure 3.8.: Comparison of reasons for appointments in the physiotherapy (left, n=19) and orthotics (right, n=12) departments.

department was 11°, whereas the orthotics department recorded a lower average value of 6°. The previous study reported a mean value of 12.5° [11].

In other respects, the orthotics and physiotherapy department saw similar populations (Fig. 3.11). Both departments saw bilateral flexible flat feet usually with a static heel valgus. The main differences were the Windlass mechanism being absent in 26% of physiotherapy patients, and the classification of almost all orthotics patients as having moderately flat feet. Pressure signs under the arch were rare among all populations.

#### 3.3.5. Sources and recommendations

##### *Physiotherapy department*

The physiotherapy department receives the vast majority of these types of patients from GP referrals (Fig. 3.12). Generally these patients have received no previous treatment for their flatfoot. The standard result for patients appears to be a combi-

### 3. Current management of flatfoot

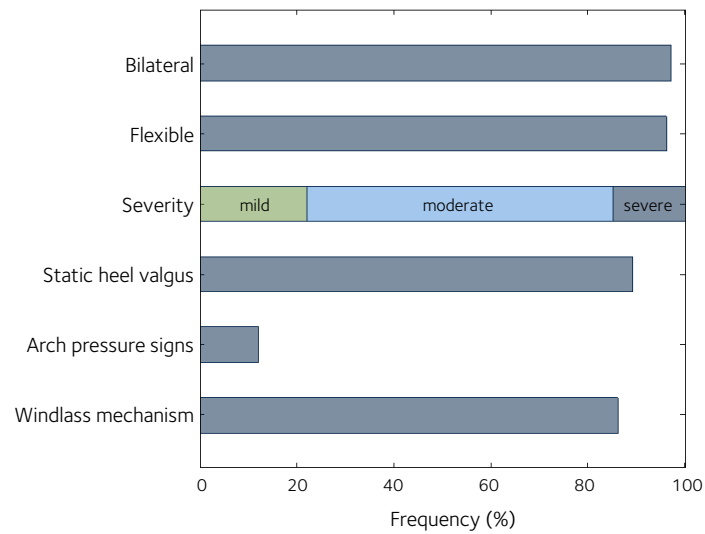


Figure 3.9.: Descriptions of foot posture (n=38). The majority of patients had moderate bilateral flexible flatfoot with active Windlass mechanism and static heel valgus.

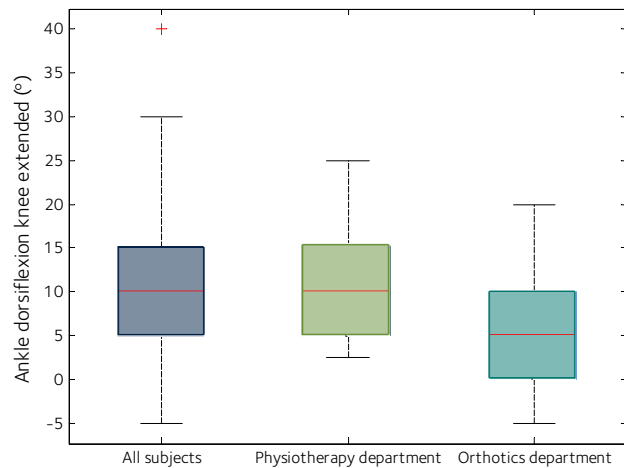


Figure 3.10.: Box plot of ankle dorsiflexion within the audit populations (n=38,19,12 respectively). The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

### 3. Current management of flatfoot

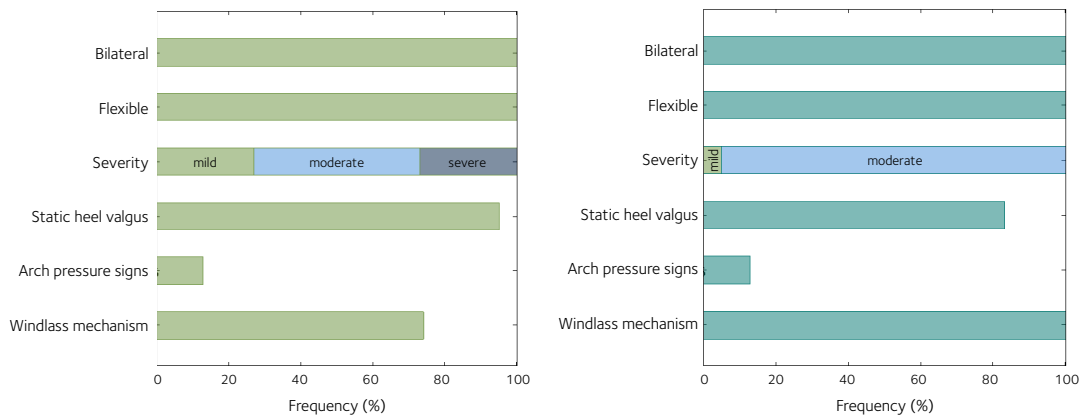


Figure 3.11.: Comparison of descriptions of foot posture for appointments in the physiotherapy (left, n=19) and orthotics (right, n=12) departments.

nation of orthotics, physiotherapy, and shoe advice. This does not seem to be related to severity of foot posture or symptoms.

There was a question raised over whether the orthotics recommendation indicated a referral to the orthotic department or a supply of orthotics. The department has access to their own off the shelf orthotics and, after consultation, it appears most likely that these have been supplied. In one case there was a referral, as off the shelf orthotics (previously prescribed) were 'not tolerated'.

Three patients received no recommendation. These cases were on the milder end of the spectrum, but two of them reported some gait disturbance. These subjects were very young, and it was perhaps expected that the condition would improve and could be monitored by the parent.

One patient received serial casting for the contracture of the tendo-Achilles; a condition and treatment which are thought to have a close association with flatfoot. The Achilles is thought to have to contract further in the case of flat foot (because of the inclination of the calcaneus) to achieve plantarflexion which can lead to the contracture. However, serial casting to stretch the tendo-Achilles, if the foot is not adequately supinated, may theoretically result in stretching the midfoot rather than the tendo-Achilles. Thus, this can be a vicious cycle and extra care in this treatment would be advisable, particularly considering the patient already has flatfoot.

### 3. Current management of flatfoot

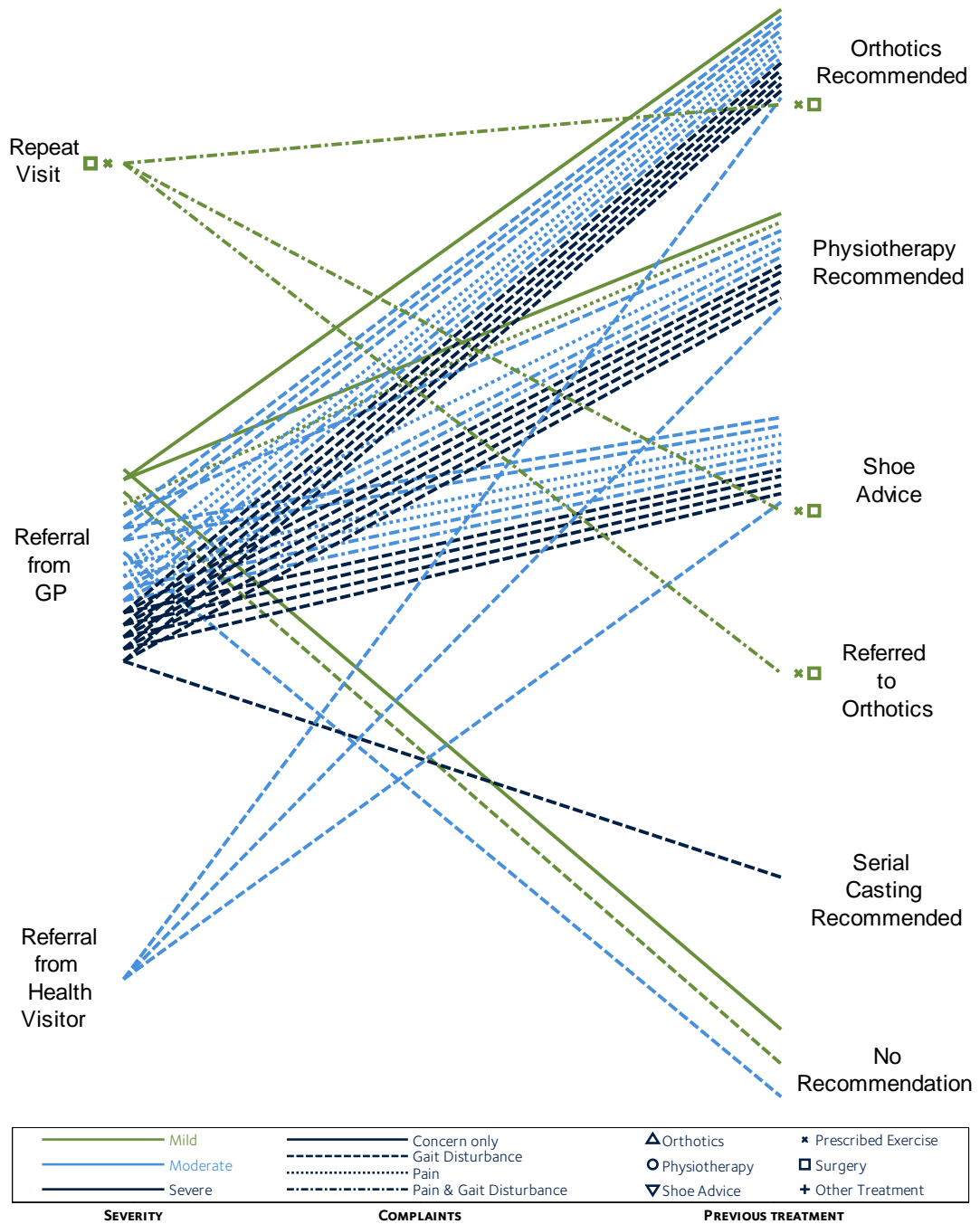


Figure 3.12.: Physiotherapy department - sources (left) and recommendations (right) for patients. Each point of origin on the left represents a patient, the lines which originate here describe the treatment that was recommended. The shade refers to the severity of the deformity. The style of the line indicates the complaints associated with the patient. The symbols represent treatment history relevant to flatfoot. In this figure the history of surgery and exercises refer to tendo-Achilles lengthening, and tendo-Achilles stretches respectively.

### 3. Current management of flatfoot

#### *Orthotics department*

Patients arriving at the orthotics department have generally received treatment previously (Fig. 3.13), most commonly in the form of orthotics. They are referred from a variety of sources. No patients arrived at this department without the symptom of pain. All patients were provided with custom-made orthotics. Seven patients received other forms of recommendations - physiotherapy, prescribed exercises, and shoe advice - but it is not clear from the forms why this is the case. It may be because of the patient or guardian asking for further advice.

#### *Other departments including the Oxford Gait Laboratory*

So few forms were completed for other departments as to make any analysis difficult (Fig. 3.14). Perhaps the most unusual subject was from the OGL; this patient had received a lot of previous treatments (physiotherapy, gait analysis, shoe advice, diagnostic imaging, and prescribed exercise), and was described as suffering from hypermobility, frequent falling, and decreased endurance, yet no recommendations were made. This may have been a clerical error as in fact no box had been ticked in that section, which may indicate that treatment was undecided at the time of form completion. (In the OGL the examination precedes the decision making process by some time.)

## 3.4. Summary and Conclusions

The gold standards of treatment provided in the literature are not prescriptive and often contradictory; in practice there is considerable art in treating a symptomatic patient with idiopathic flatfoot. Part of this may be caused by wide variation in structure and symptoms. Therefore proper description of these features was deemed important. It was expected that different departments may have different populations and

### 3. Current management of flatfoot

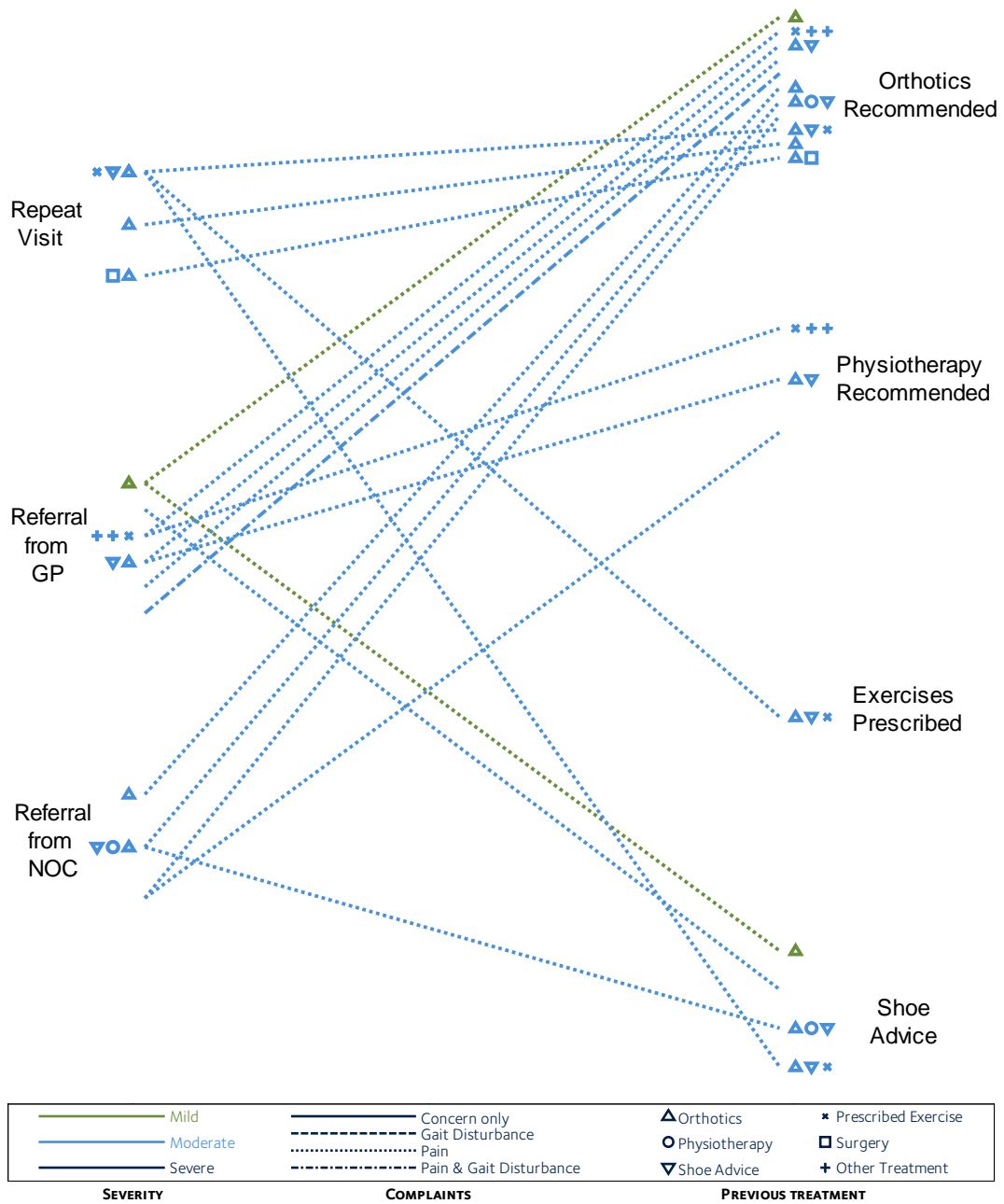


Figure 3.13.: Orthotics department – sources (left) and recommendations (right) for patients. Each point of origin on the left represents a patient, the lines which originate here describe the treatment that was recommended. The shade refers to the severity of the deformity. The style of the line indicates the complaints associated with the patient. The symbols represent treatment history relevant to flatfoot. In this figure, the other treatments refer to steroid injections.

### 3. Current management of flatfoot

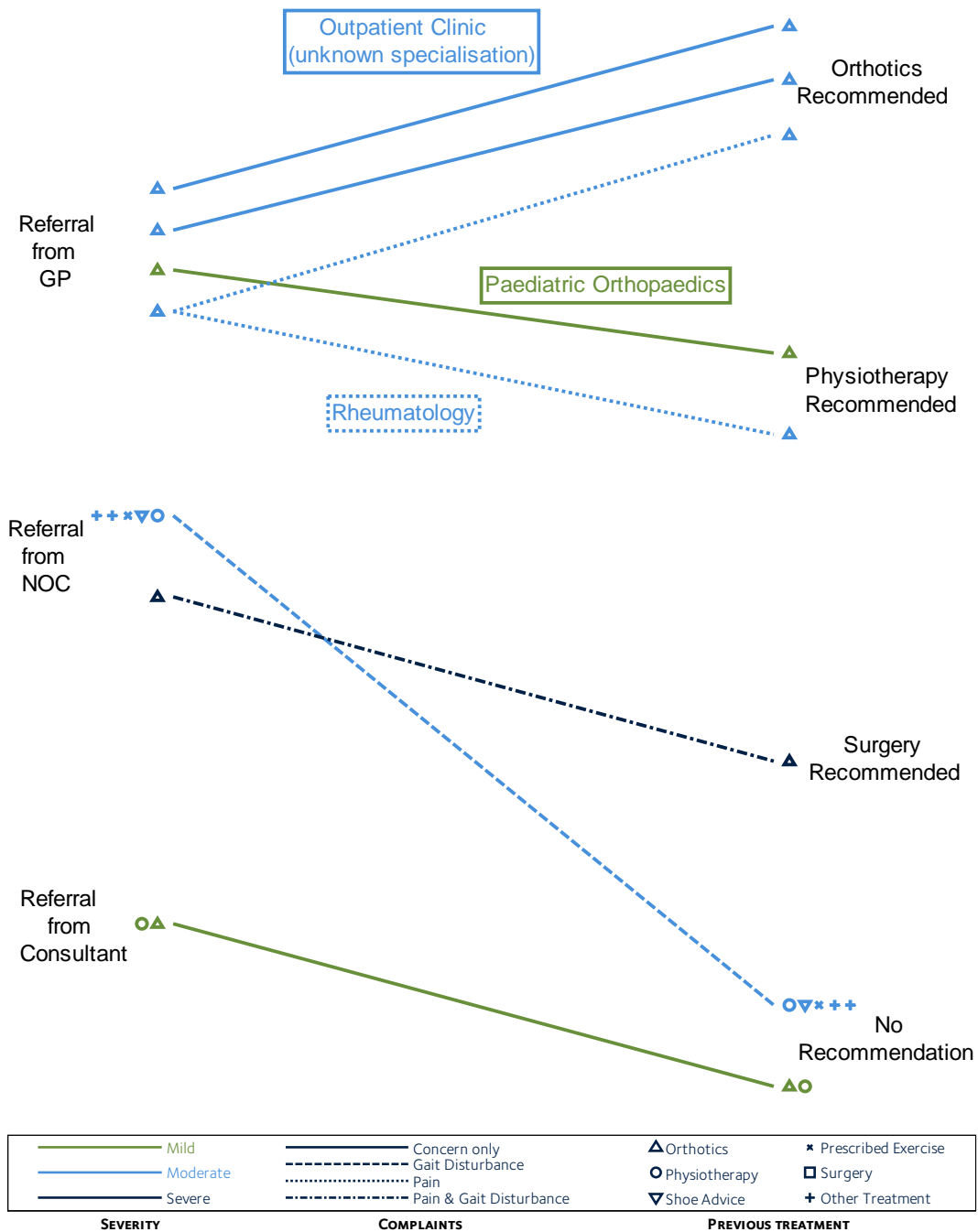


Figure 3.14.: Oxford Gait Laboratory (OGL) and other departments – sources (left) and recommendations (right) for patients. Two patients referred by GP are from the Children’s Outpatient Clinic, one was seen by a paediatric orthopaedic specialist, and one by a rheumatology specialist. The other patients were seen at the OGL. Each point of origin on the left represents a patient, the lines which originate here describe the treatment that was recommended. The shade refers to the severity of the deformity. The style of the line indicates the complaints associated with the patient. The symbols represent treatment history relevant to flatfoot.

### 3. Current management of flatfoot

treatment strategies. This is important to the patients as it affects their treatment, and vital to any conclusions of this thesis as it is important to know the population to which the conclusions are relevant to.

The audit was developed to quantify how patients are treated in the NOC. Forms and other materials were developed and supplied to six departments.

Participation was mixed; a large number of forms were completed by a small number of clinicians. The OGL completed forms for all patients (with and without flatfoot), and even though most of these patients had flatfoot, they often had metabolic and neurological disorders which excluded them from the complete study. Most departments did not complete forms for all patients. The physiotherapy and orthotics departments completed enough forms for patients to allow comparison.

Parental concern was a frequent motivation for visits, and in four cases concern was the sole motivation for the visit. Pain was a common complaint, often in the foot and ankle. Gait disturbances such as hypermobility, frequent falling, and in-toeing were often reported. Pain was present in all orthotics patients but only 32% of physiotherapy patients. Comparison with a previous study [11] demonstrated good agreement in terms of prevalence of pain but not other symptoms, when considered separately the physiotherapy department demonstrated close similarities with this study generally.

The majority of patients had moderate bilateral flexible flatfoot with an active Windlass mechanism and static heel valgus. The Windlass mechanism was intact in all orthotics patients but only 74% of physiotherapy patients. The orthotics department recorded lower maximum ankle dorsiflexion with the knee extended ( $6^\circ$ ), compared to the overall and physiotherapy populations ( $11^\circ$ ). This may be due to differences in the measurement technique. Again comparison with a previous study [11] demonstrated generally close alignment with the physiotherapy but not orthotics department. The discrepancy may indicate the orthotics department treats a different demographic, or that they are less interested in these aspects of assessment.

### 3. Current management of flatfoot

Treatment was highly dependent on department. The standard recommendations from the physiotherapy department were off-the-shelf orthotics, physiotherapy, and shoe advice. The recommendations of the orthotics department were custom made orthotics, and in some cases shoe advice and physiotherapy. The other departments did not return enough forms, either because of low numbers of patients with flatfoot or lack of participation, to generalize a standard treatment. The advice appeared to vary between these departments. In both the physiotherapy department and OGL some symptomatic patients received no recommendations, or were only to be monitored.

Considering the volume and expertise that the physiotherapy department appears to have, it may be worth considering whether all patients with the condition should be recommended here as a first stage. Then other departments could be consulted from this stage as appropriate.

The process of designing and carrying out the audit involved a steep learning curve. Participation was a major issue. Clinicians asked if it was possible for someone else to complete the forms; however, this was not practical given the number of concurrent clinics this would have involved. Some departments were not keen to commit to the process because of previous experiences. The clinics that completed more forms, were those that were involved with the development process, or that see a large number of idiopathic flat feet. It seems natural that those interested in the condition would be most enthusiastic about the audit. Alternatively, it may have been easier for these groups to remember to complete the forms.

Involving more clinicians in the audit design could have helped participation, turning the clinicians into stakeholders. However this may have affected the practice of those clinicians, by revealing more information about the study. It seems that the combination of collecting data about all patients attending outpatient clinics as well as specific populations (the one form per patient policy) may not have been practical in high volume practices. It was thought that this would raise the visibility of the

### 3. Current management of flatfoot

project; however it may have put people off. It may have been wiser to separate the process, to have a tally style process for the general population, and to have a separate detailed study for those with idiopathic flatfoot. In either case it is difficult to obtain data from those departments that only see these patients infrequently.

Now that essential information about the population with idiopathic flatfoot seen at the NOC has been described, the data will allow us to tell how representative our subjects are. The next part of the study considers more detailed and larger volumes of information.

## 4. Data collection methods

This chapter outlines the data collection that led to the major results of this thesis (all subsequent chapters). The motive behind the data collection in terms of the thesis is primarily to explore the difference between symptomatic and asymptomatic flexible flatfoot in children. Participants were included from patient and general populations (Section 4.2). A variety of data types was collected: Ground Reaction Force (GRF), kinematic, kinetic, plantar pressure, as well as clinical examinations. The equipment used in the project is described (Section 4.1). The methods and processes involved in collecting this data are made clear (Section 4.3 and 4.4). Specific post processing methods will be explained in the relevant subsequent chapters.

The key focus of the study is the hitherto neglected difference between asymptomatic and symptomatic flatfoot, in the hope that this will aid treatment decisions. The asymptomatic flat feet, which appear to resemble the symptomatic flat feet (yet have an unclear prognosis), are often referred to in clinical guidelines as physiologic (normal healthy functioning; not pathological) versus pathologic (abnormal functioning). Yet some asymptomatic feet will go on to develop symptoms in later life. The differences between symptomatic and asymptomatic flatfoot may reveal potential causes of symptoms allowing more informed treatment decision-making.

#### 4. Data collection methods

Previous studies have not focused on the difference between asymptomatic and symptomatic flatfoot, including only one of these groups in their analyses (except the recent publications of Kerr et al. [81] and Hösl et al. [66]). Specific differences in structure and function between these groups could be crucial to understanding why some of these feet display symptoms, and others do not.

The other oversight that may have been made by other studies is that they have often focused on static foot posture, without considering dynamic function. It has been observed that feet that appear flat during standing, are sometimes not flat whilst walking and vice versa. This could be important in determining why feet that appear similar during static stance, may not result in the same outcome for the individual. It is therefore important to characterize static and dynamic characteristics associated with the foot posture. Foot motion has been shown to be greater in walking than (slow) running [4, 89], so walking is perhaps the most relevant dynamic task.

A passive general examination is routinely given to patients in the Oxford Gait Laboratory (OGL). This examination could be compared between patient and asymptomatic populations easily to reveal fundamental differences between the populations. Some static foot posture assessment methods (selected in Section 2.1) were added to improve the description of foot posture available and facilitate comparison with other studies. The number of participants involved in the various elements of data collection are outlined in Table 4.1 alongside key purposes of recording and analysing the data.

In addition to this, during static and dynamic stance, other data was collected. Data was gathered by marker, force-plate, and pressure-plate equipment (Table 4.1). This allowed spatio-temporal, GRF, kinematic, kinetic, and plantar pressure information during static and dynamic stance to be analysed in the subsequent chapters of this thesis between the key groups: neutral, asymptomatic flat, and symptomatic flat feet (Chapters 5–11).

The aim of this project is to better characterize flatfoot, by considering a more com-

## 4. Data collection methods

Table 4.1.: Number of participants involved in each section of the data collection and the key purpose of collecting the data. Data is not universal owing to protocol variation, data quality, and compliance issues. The context is important to understand to what populations the results may apply and how the population fits in with others. N - Neutral group, A - Asymptomatic flat-footed group, S - Symptomatic flat-footed group. For a description of the data available per subgroup please refer to Table 6.2.

<b>Data type</b>	<b>Volunteers</b>	<b>Patients</b>	<b>Purpose</b>
<b>General examination</b>	107	20	Context of the participants Difference between N, A, & S
<b>Strength assessment</b>	0	20	Context of patients
<b>Symptom description</b>	0	20	Define the complications
<b>WB foot posture</b>	89	20	Subdivide groups
<b>Non-WB foot posture</b>	96	18	
<b>Foot Posture Index</b>	64	0	Context of the volunteers Proof of methods
<b>NNH</b>	51	0	
<b>Arch Height Index</b>	58	0	
<b>Force plates</b>	104	20	Objective comprehensive assessment
<b>Plug In Gait model</b>	104	20	Static and dynamic conditions
<b>Oxford Foot model</b>	86	17	Difference between N, A, & S
<b>Plantar pressure</b>	56	16	Proof of methods

plete picture of foot function, that is, to consider passive, static, and dynamic function. If a characteristic is found to be associated with flatfoot, what does it mean? Ultimately the goal must be to move towards understanding how these traits fit together and to identify the causes, contributions, co-morbidities, and consequences. This can be used to attempt to predict those cases that would likely go on to develop symptoms, and therefore benefit from treatment. These questions can only be answered by focusing on differences between symptomatic and asymptomatic flat foot, considering passive, static, and dynamic factors.

### 4.1. Technical equipment

Several pieces of technical equipment were used in this project. This section is an introduction to this equipment.

## 4. Data collection methods

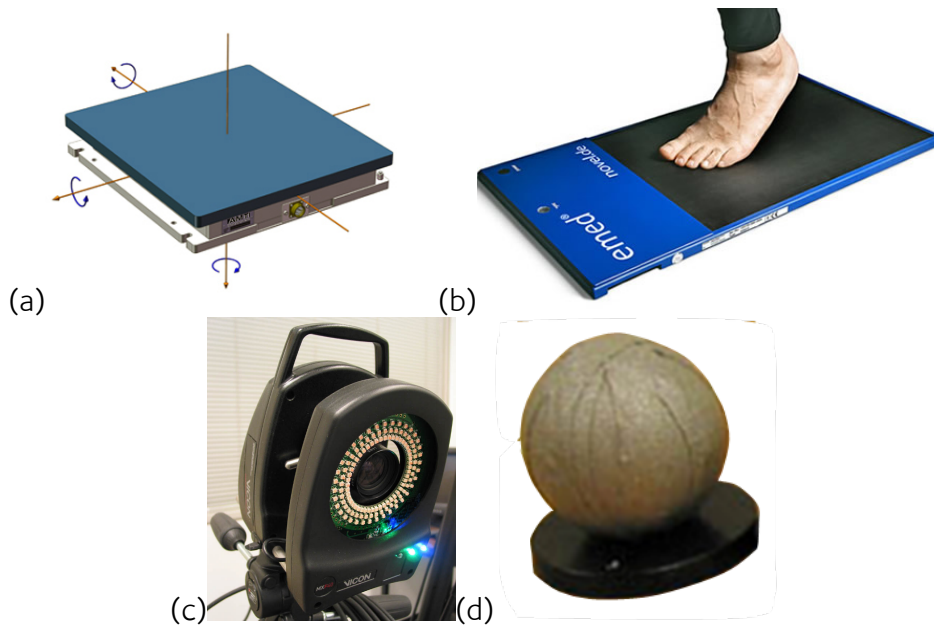


Figure 4.1.: Oxford Gait Laboratory (OGL, NOC, Oxford, UK) equipment. (a) AMTI force plate (Advanced Mechanical Technology, Inc., Watertown, MA, USA), three in lab: two OR6-7 (460 × 510 mm sensor area, 500-1000 lb capacity, 1000 Hz frequency), and one high frequency ORS6-6. (b) NOVEL pressure plate (Novel, Munich, Germany): one EMED-M (460 × 320 mm sensor area, 4 sensors/cm<sup>2</sup>, 10-1270 kPa range, 193 kN capacity, 50 Hz frequency). (c) VICON MX F40 infra-red camera (Vicon Motion Systems, Oxford, UK): one of 12 in the lab. (d) A retro-reflective marker from VICON. Laboratory set up is shown in Fig. 4.9. Pictures adapted from promotional material available at AMTI [3], Novel [124], and Vicon [177].

### 4.1.1. Force measurement

Force plates or force platforms measure Ground Reaction Force. AMTI force plates (Fig. 4.1) use strain gauge transducers, to measure the single equivalent force and a moment about a vertical axis on the surface at a particular spot (the centre of pressure). The data can be examined as an entity in itself. It can also be combined with other data such as kinematics to determine torque, power, and work at the joints

## 4. Data collection methods

using inverse dynamics.

### 4.1.2. Marker and kinematic measurement

From the 1870s, pioneering photographer, Eadweard Muybridge, ignited interest in the idea of gait analysis with his studies of human and animal (notably horse) locomotion (Fig. 4.2 (a)). During the late nineteenth century, two groups began to investigate gait from a more scientific perspective. Two German Scientists, Christian Wilhelm Braune and Otto Fischer took photos from two perspectives of a person connected to lights that flash at a constant rate (Fig. 4.2 (b)). Etienne-Jules Marey created a chronophotographic gun to take 12 consecutive frames a second (Fig. 4.2 (c)). These first generation, two-dimensional, models took years to progress. Thankfully things have progressed since this early model, and gait analysis can now be done in three dimensions relatively quickly (Fig. 4.3).

Since the 1970s, human (and other animal) movement has been studied via optoelectronic systems. Optoelectronic systems use video cameras (12 in the OGL, Fig. 4.1) to track image coordinates of “passive” or “active” markers. Passive systems have cameras which emit light and retro-reflective markers which reflect light back; they are sensitive to background and sunlight. Active systems have markers which emit light, are not sensitive to background light, and can even allow the cameras to identify separate markers, but are more limited in terms of numbers of markers and frequency of data collection. The OGL uses a passive Vicon system (Fig. 4.3).

An area is calibrated where data collection of a subject wearing a number of markers takes place. There is an array of cameras, and marker positions in 3D can be estimated using stereophotogrammetric methods [100]. The accuracy and precision are currently less than 5 mm depending on the system [28], this is sub-millimeter in the OGL Vicon system.

Detailed overviews of issues in motion capture and methods to deal with them have

#### 4. Data collection methods

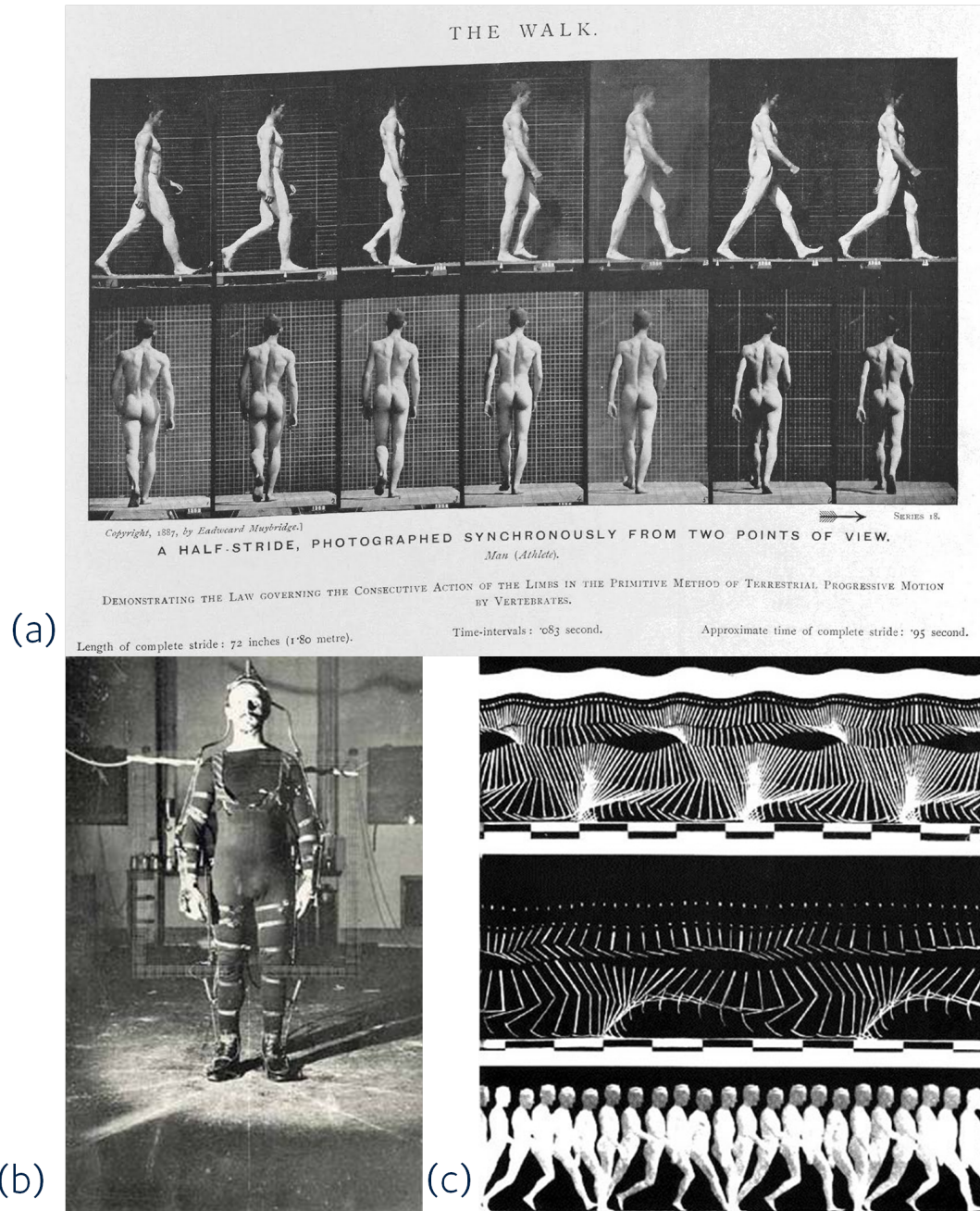


Figure 4.2.: Historical images of gait analysis. From top (a) Muybridge's photographs [117], (b) Braune and Fischer's light emitting marker system [15], (c) Marey's analysis of gait [93].

#### 4. Data collection methods

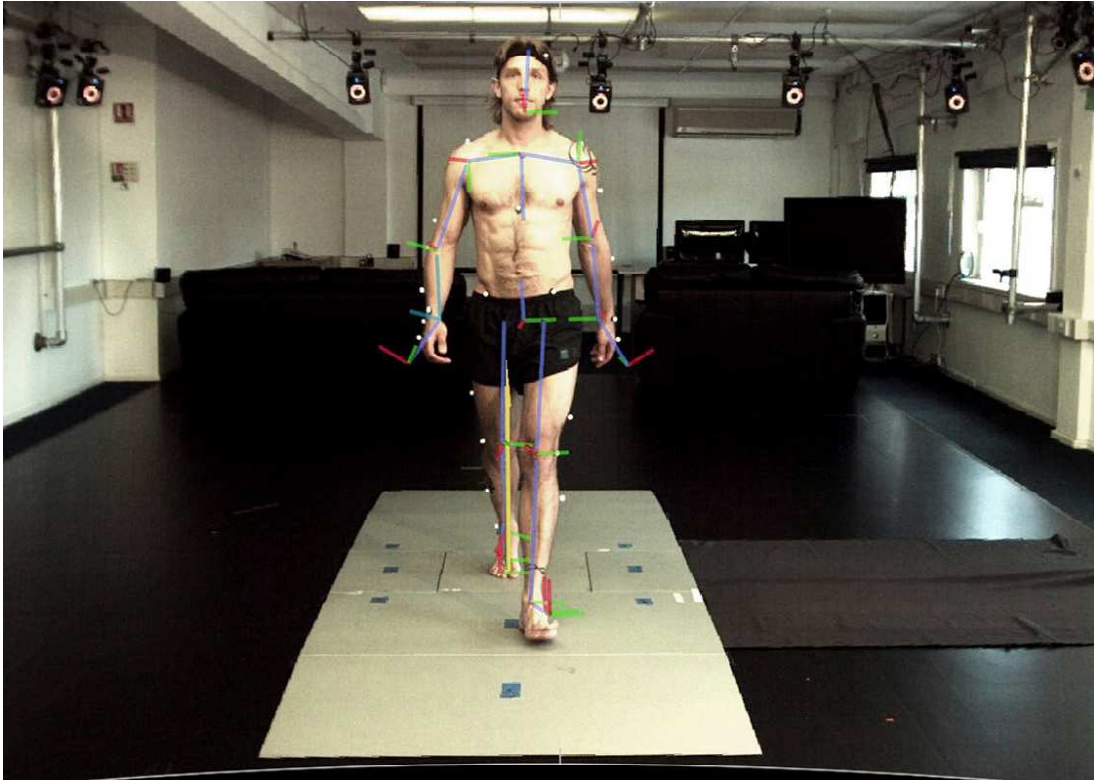


Figure 4.3.: Modern images of gait analysis: Vicon Nexus. Subject walking in laboratory with kinematic model superimposed. Vicon Nexus system. Images from vicon.com [175].

been published [28, 82]. The aim is to track the motion of the bones; however, there are three sources of inaccuracy in this assumption [22]:

1. Instrument errors, due to the motion capture system. These systematic and random errors result in apparent marker movement. This is minimized by having many cameras triangulate the position, and is small relative to the other sources of error.
2. Soft tissue artefact, due to real relative movement between marker and underlying bone, caused by soft tissue. This is worse in areas with larger amounts of soft tissue (e.g. thigh). Many studies have investigated this error; they are summarized by Leardini et al. [82] with displacements ranging between 1.8 mm (on metatarsal) to 55 mm (on thigh) .
3. Mis-location of markers will also result in erroneous calculation of bone posi-

#### 4. Data collection methods

tions. The miscalculation will have knock on effects on kinematics (joint angles) and kinetics (joint moments). The knock on effects are generally less than the original miscalculation [17, 76].

The high frequency content of instrument errors can be dealt with by using smoothing methods and thorough calibration. Soft tissue artefact, has a similar frequency content as the body movement and cannot be removed with smoothing methods. The error can be reduced by positioning markers in areas with limited soft tissue and through optimization techniques. Additionally, markers may be obscured from camera vision for part of the trial, in which case interpolating methods may be used. On the other hand multiple reflections will also cause confusion in the result; this can be limited by retro-reflective marker quality.

Another issue is that it is difficult to track the movement of some bones. In the case of the 27 bones of the foot, it is currently not possible to place a sufficient number of markers to track each bone in three dimensions nor access the surfaces of some of the bones, so the foot must be simplified into fewer “rigid” segments.

The “markerless” system (one without markers, instead using image analysis to identify the pertinent qualities) may be the future [180]; however, the accuracy of these systems has previously been inadequate for clinical application. Markerless systems are currently used mainly in the entertainment sector. Recently the systems have improved considerably, and there have been several papers touting the suitability of the Microsoft Kinect system [14, 32, 31]. As a low cost system, this may be particularly suitable for feedback and physiotherapy training.

##### 4.1.3. Plantar pressure measurement

This is the quantification of pressure between the sole (plantar surface) of the foot,

## 4. Data collection methods

and the supporting surface. The first peer-reviewed study of plantar pressure was in 1976 [56]. At the time of writing commercially available systems are only able to measure forces perpendicular to the surface. These systems are based on optical systems, pneumatic discrete sensors, resistive sensors, and capacitive sensors [51].

The optical system, a system which measures the refraction of light through glass and plastic is perhaps the optimal design as it has a near infinite resolution - only limited by the defects in the glass itself. This technology is not available commercially. The Novel platform used in this research (Fig. 4.1) uses elastomer-based capacitive sensors. Pressure reduces the thickness and increases the capacitance according to a linear law. These sensors show relatively high stability, low hysteresis, and high resistance to age-related deterioration compared with other systems. Ultimately a 2D image time series of pressures acting under the plantar surface of the foot is generated.

### 4.2. Data collected

It was required that at least three groups be included in the data set. These groups were: Asymptomatic Neutral (AN) feet, Asymptomatic Flat (AF) feet, and Symptomatic Flat (SF) feet (Fig. 4.4). An extra sub-group was included for Asymptomatic Mild (AM) flat feet, to account for the possibility that the symptomatic group may simply have had a more severe condition than the AF group. The asymptomatic participants were recruited from the general population, while the symptomatic participants needed a more targeted enrolment strategy and were selected retrospectively from the OGL database (Fig. 4.4).

A large data set was collected to form a normal database to be used in the OGL as a reference to which patient data could be compared. This data set was used to construct a picture of "normality" for children of various ages and genders (where appropriate). A patient could then be compared to this for their own age group and sex. In addition to the data that was collected for the normal database, data about

#### 4. Data collection methods

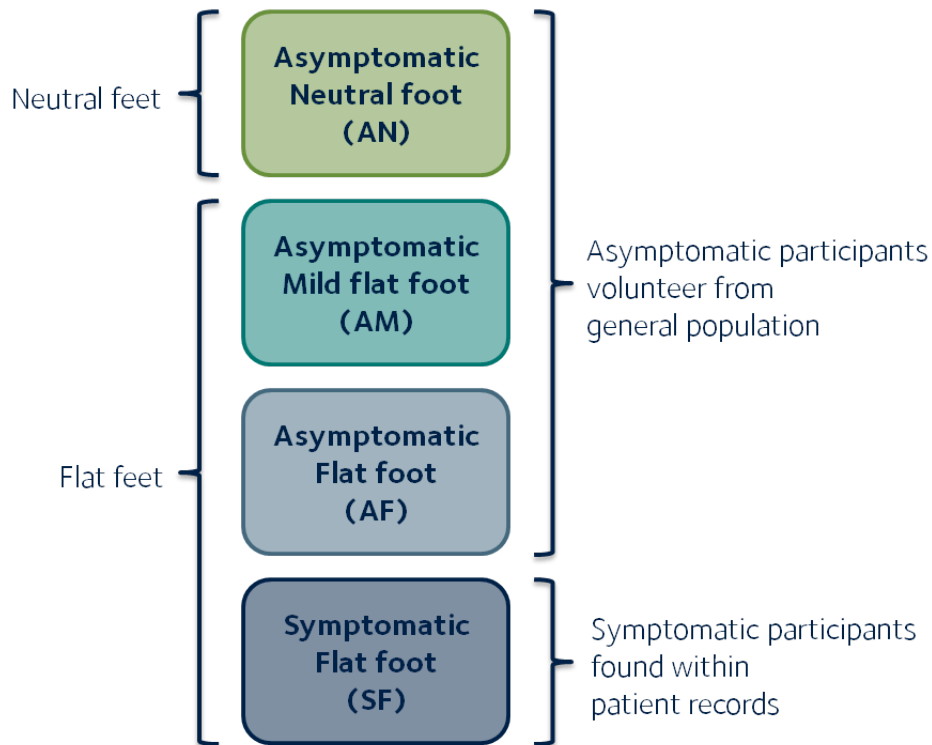


Figure 4.4.: Groups and data sourcing methods. Colours as used throughout the thesis.

foot structure was collected concurrently. The asymptomatic group were acquired as part of this data collection. It was expected that this group would include both flat and neutral feet, as flatfoot occurs in the general population [7, 57, 12]. Many of the volunteers did indeed have flatfoot, but any of these children with musculoskeletal complaints were excluded.

The subjects with symptomatic flatfoot were acquired by different means - their data was acquired retrospectively from patient records. Patients were selected if they had been referred to the OGL for idiopathic flatfoot, with symptoms attributed to flatfoot, if they had approved the use of their data for research purposes, and had no underlying diagnosis.

### 4.3. Asymptomatic participants

This data collection was approved by NRES Committee London – South East (09/

## 4. Data collection methods

H1102/88). In total, 107 healthy children, aged 1-17 years, were recruited for this study. These children were without orthopaedic and neuromuscular concerns, and were excluded if they had recently been injured. This data was collected by the OGL clinical team as part of a larger study attempting to characterize children within the general population, in an attempt to compile a “normal” reference database. This included an extensive clinical examination (Table 4.1). Some additions were made to the standard clinical examination to better characterize the structure of the foot. The instrumented data collection occurred either before or after the clinical examination.

### 4.3.1. Clinical examination

The passive examination comprised two sections. Firstly, the general examination of the participant which is standard procedure for any subject in the gait lab (Fig. 4.5 (a) and (b), Fig. 4.6 (a) and (b)). This allowed comparisons between the asymptomatic volunteers and the symptomatic patients. Secondly, there was a specific examination which added extra focus on the foot structure (Fig. 4.5 (c), Fig. 4.6 (c)). This allowed comparisons between this study and other studies of flatfoot, and the verification of the general examination classification of the foot structure.

#### *General examination*

In all 107 children, a general record of attributes (Fig. 4.5 (a)), flexibility and structure (Fig. 4.6 (a)) was taken (Table 4.1).

The date of birth and of the test were noted. The height was measured, to the nearest five millimetres, during standing against a wall ruler. The weight was measured during quiet standing on an AMTI force plate (Advanced Mechanical Technology, Inc., Watertown, MA, USA). Femoral anteversion (twisting rotation of the femur around its longitudinal axis), knee varus/valgus (Fig. 4.8(a)), and external tibial torsion (twisting

4. Data collection methods

**Data Collection Form  
For Normal Database**

(a) Name  Vicon Code   
 Date of Test  Date of Birth   
 Height  mm Weight  kg

Inter ASIS Distance  mm Sex  M  /  E

(b) 

	RIGHT	LEFT		RIGHT	LEFT
Leg Length	<input type="text"/>	<input type="text"/> mm	Shoulder Offset	<input type="text"/>	<input type="text"/>
Knee Width	<input type="text"/>	<input type="text"/> mm	Elbow Width	<input type="text"/>	<input type="text"/>
Ankle Width	<input type="text"/>	<input type="text"/> mm	Wrist Width	<input type="text"/>	<input type="text"/>
Knee Valgus/Varus	<input type="text"/>	<input type="text"/> deg	Hand Thickness	<input type="text"/>	<input type="text"/>

(c) 

Foot Length	<input type="text"/>	<input type="text"/>
Trunc. Foot Length	<input type="text"/>	<input type="text"/>

**EMG CHANNELS**

CHAN	MUSCLE GROUP	Test	CHAN	MUSCLE GROUP	Test
1	L Rectus	<input type="text"/>	2	R Rectus	<input type="text"/>
3	L Hamstrings	<input type="text"/>	4	R Hamstrings	<input type="text"/>
5	L Gastrocnemius	<input type="text"/>	6	R Gastrocnemius	<input type="text"/>
7	L Tibialis Anterior	<input type="text"/>	8	R Tibialis Anterior	<input type="text"/>

**COMMENTS:**

Data collected by:	<input type="text"/>
Data processed by:	<input type="text"/>
Clinical exam performed by:	<input type="text"/>
Markers and EMG applied by:	<input type="text"/>

Nexus software version	1.5.1
Polygon version	3.1 Build 207

Figure 4.5.: Page 1 of the asymptomatic data collection form. (a) Basic information about the participant. (b) Data required for kinematic and kinetic analysis. (c) Foot measurements required for Arch Height Index and Normalized Navicular Height calculations.

4. Data collection methods

**Data Collection Form  
For Normal Database**

<b>Clinical Exam</b>	<b>Right</b>	<b>Left</b>
Hip flexion		
Hip extension		
Hip abduction		
Hip internal rotation		
Hip external rotation		
Femoral anteversion		
Knee flexion		
Knee extension		
Knee valgus/varus		
Popliteal angle (uni)		
Popliteal angle (bi)		
Tibial torsion (external)		
Ankle dorsiflexion (KE)		
Ankle dorsiflexion (KF)		
Foot Description in		
- Weight-bearing		
- Non weight-bearing		

<b>Foot posture index</b>			<b>Right foot</b>	<b>Left foot</b>
			-2 to 2	-2 to 2
<b>Rearfoot</b>	Talar head palpation	Transverse		
	Curves above and below the lat. malleolus	Frontal/transverse		
	Inversion/eversion of the calcaneus	Frontal		
<b>Forefoot</b>	Prominence in the region of TNJ	Transverse		
	Congruence of the medial longitudinal arch	Sagittal		
	Abd/adduction on rearfoot	Transverse		
<b>Total score</b>				

<b>Nexus software version</b>	1.5.1
<b>Polygon version</b>	3.1 Build 207

Figure 4.6.: Page 2 of the asymptomatic data collection form. (a) Clinical examination of flexibility and structure. (b) Physiotherapists' descriptions of foot posture. (c) Foot Posture Index.

#### 4. Data collection methods

rotation of the tibia around its longitudinal axis) were measured by a physiotherapist to the nearest five degrees using a goniometer.

Flexibility (passive range of motion) was also measured by a physiotherapist using standardized methods. Twelve measurements were recorded: at the hip (Fig. 4.7), flexion and extension, abduction, internal and external rotation; at the knee (Fig. 4.8 (a)-(e)), flexion and extension, unilateral and bilateral popliteal angles; at the foot, ankle dorsiflexion with the knee extended and flexed (Fig. 4.8 (f)-(g)).

##### *Foot structure evaluation*

There were several methods of foot posture evaluation. Section 2.1 provides a more detailed description of the various foot posture assessment methods that were available, and why certain methods were chosen. Not every method was used for every child (Table 4.1) for a variety of reasons (e.g. error in examination or record keeping, foot size too small, or, when working with young children – compliance issues).

The most extensively applied method of foot posture assessments were the clinician's descriptions of foot posture. The physiotherapist analysed the position of the hindfoot, midfoot, and forefoot to provide a description of each foot, although these descriptions varied in the level of detail included. During non-weightbearing, 96 children had bilateral foot descriptions recorded; during weightbearing, 89 children had bilateral foot descriptions recorded.

FPI [139] was recorded bilaterally for 64 of the children. For the purpose of calculating Normalized Navicular Height (NNH) and Arch Height Index (AHI), in 58 of the children the Truncated Foot Length (TFL) was measured using calipers.

##### 4.3.2. Protocol surrounding the use of technical equipment

The Oxford Gait Laboratory was well equipped (Fig. 4.9) with three AMTI force plates

#### 4. Data collection methods

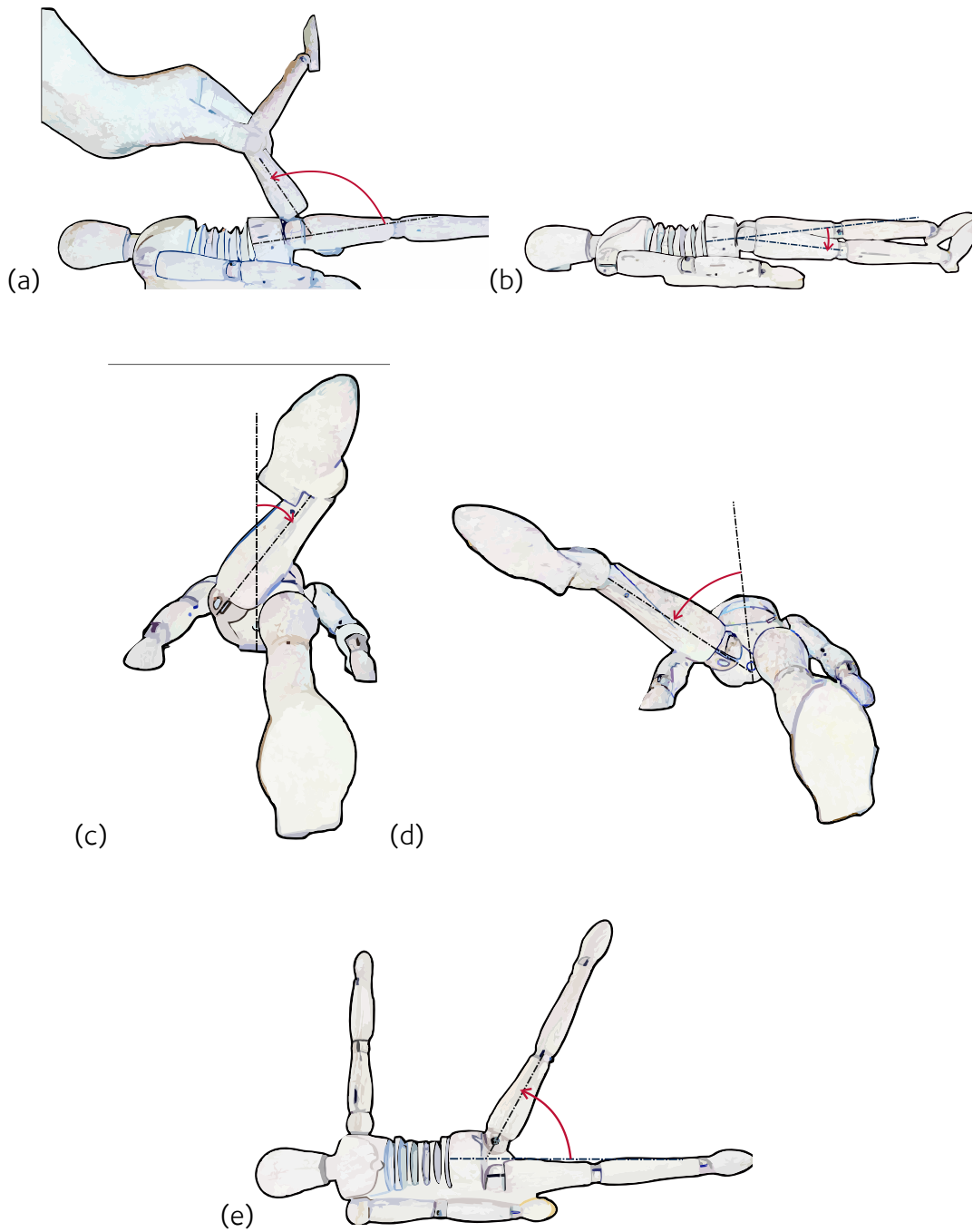


Figure 4.7.: Demonstration of angle measurement conventions at the hip. (a) hip flexion (b) hip extension (c) hip internal rotation (d) hip external rotation (e) hip abduction.

#### 4. Data collection methods

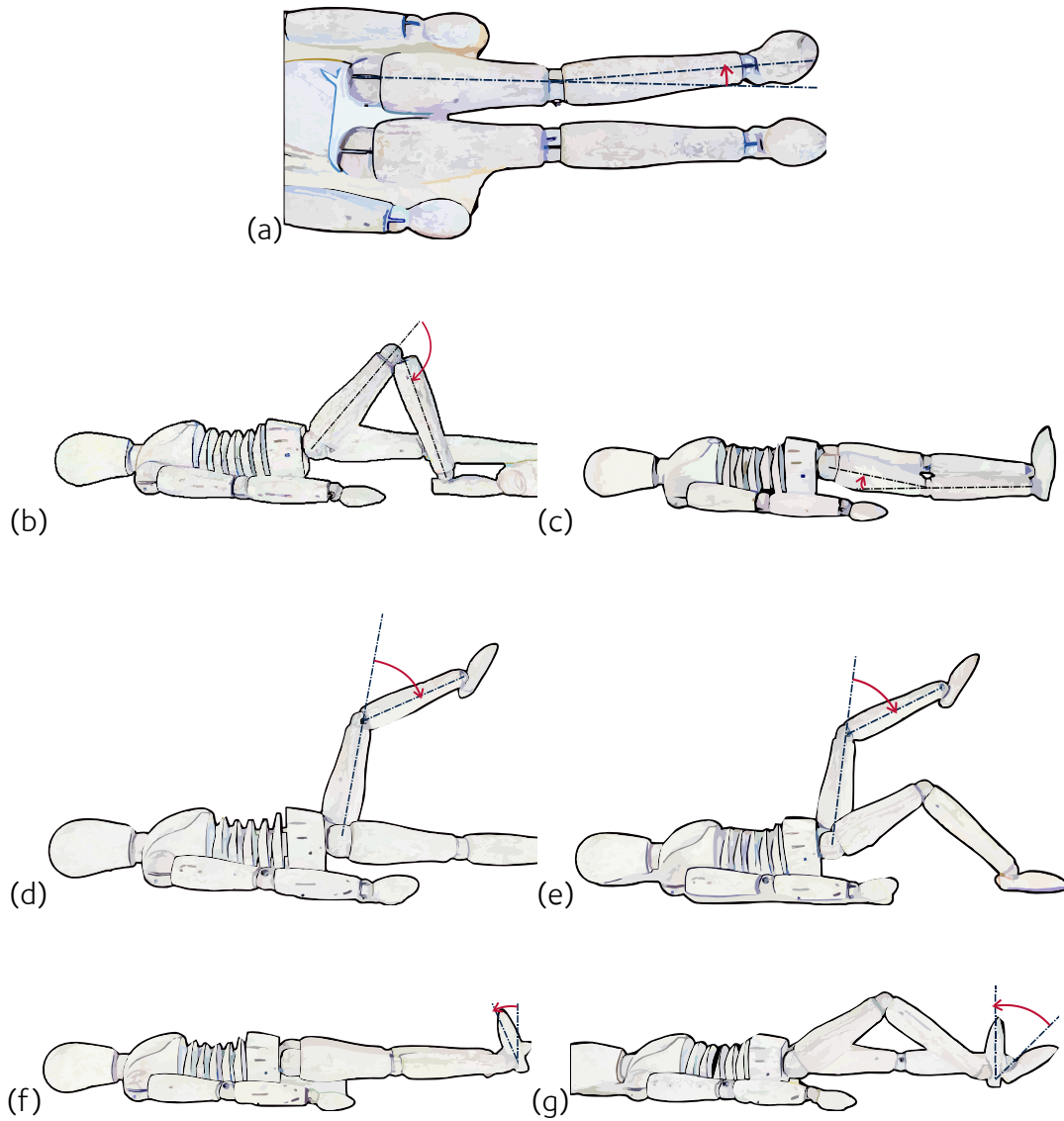


Figure 4.8.: Demonstration of angle measurement conventions at the knee and ankle.  
(a) knee valgus (b) knee flexion (c) knee extension (d) unilateral popliteal angle (e) bilateral popliteal angle (f) ankle dorsiflexion with knee extended (g) ankle dorsiflexion with knee flexed.

#### 4. Data collection methods

(Advanced Mechanical Technology, Inc., Watertown, MA, USA) sampling at a minimum 1000 Hz; a 12 camera Vicon system (Vicon-MX, Oxford, UK) for measuring kinematics, sampling at 100 Hz; and a Novel EMED plantar pressure plate (Novel, Germany) (Fig. 4.1).

Retro-reflective markers of radius 5 mm were placed at known anatomical landmarks of the body. Most children (n=104) had the full body Vicon Plug-In Gait model (PIG) [176] (Fig. 4.10). For children with feet of sufficient size (n=86) the Oxford Foot Model (OFM) [167] was applied bilaterally (Fig. 4.11).

The OFM is a clinically tested and validated model which has been developed by the NOC and Oxford University [167]. This is a three segment foot model: two main foot segments – hindfoot and forefoot – plus a separate hallux segment. A marker was also placed on each navicular tuberosity in an attempt to quantify midfoot movement and calculate NH (2 extra markers). For the purpose of Arch Height Index calculation a marker was placed on the top of each foot at 50% Foot Length (2 additional markers) during static trials only.

The rest of the body was tracked with the PIG marker set (Fig. 4.10) (6 segments in the lower limb, 19 additional markers on the upper body). Twelve infra-red cameras (Vicon MX-Vicon, Oxford, UK) were used to measure three-dimensional motion of these markers. Cameras were sampled at 100 Hz. Two (or later, three) AMTI (Advanced Mechanical Technology, Inc., Watertown, MA, USA) force plates were used to collect GRF data, sampling at 1000 Hz.

Pressure data was also collected simultaneously with the marker trajectory data. Plantar pressure data was collected using the Emed<sup>®</sup> system from novel at 50 Hz with 4 sensors / cm<sup>2</sup> collecting pressure within range 10-1270 kPa.

##### 4.3.3. Participant protocol

Because the study required the cooperation of a number of young children, it was

#### 4. Data collection methods

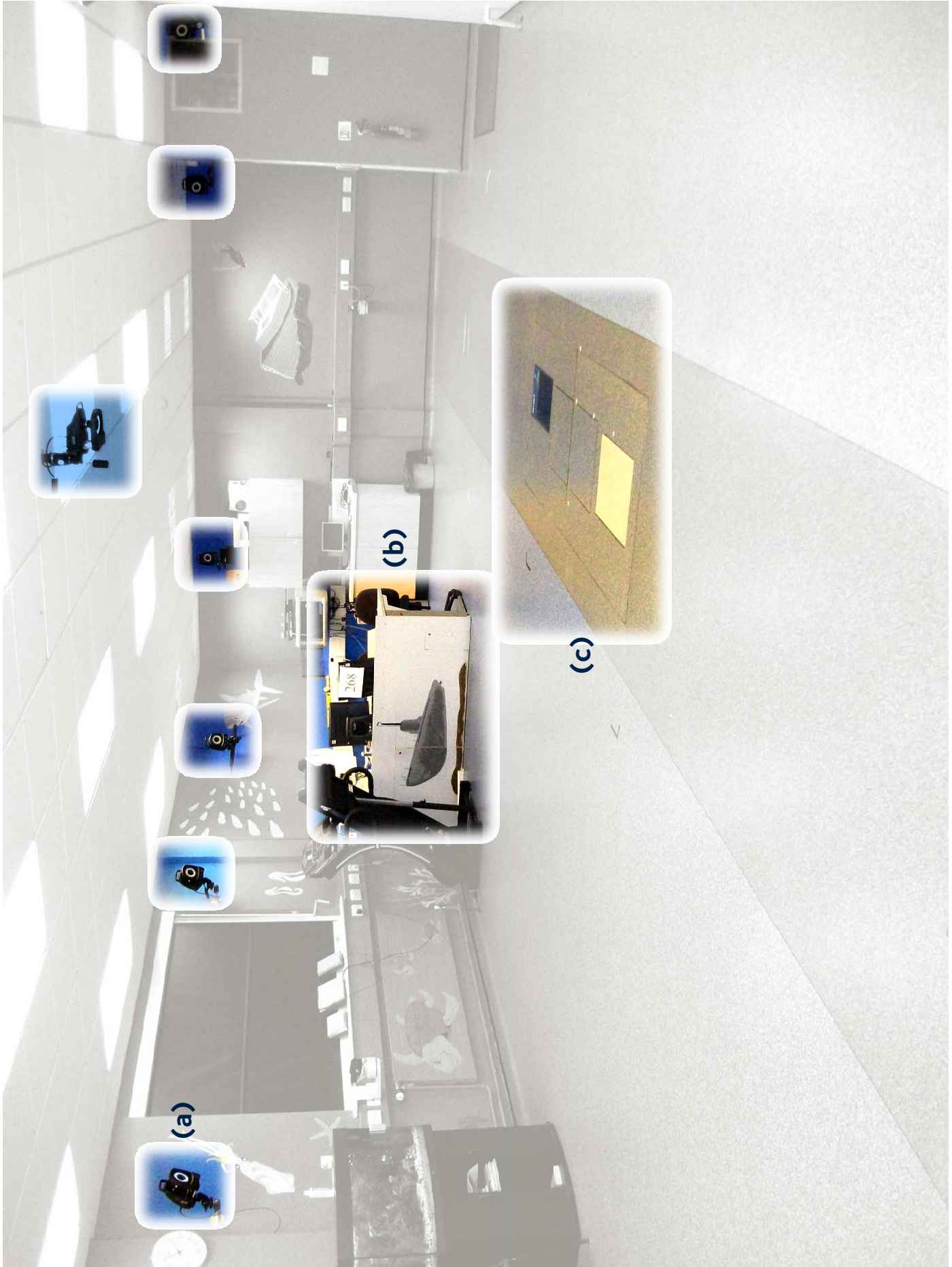


Figure 4.9.: Photograph of laboratory. (a) seven of 12 Vicon cameras, (b) capture workstation, (c) (from top) Novel EMED pressure and three AMTI force plates.

#### 4. Data collection methods

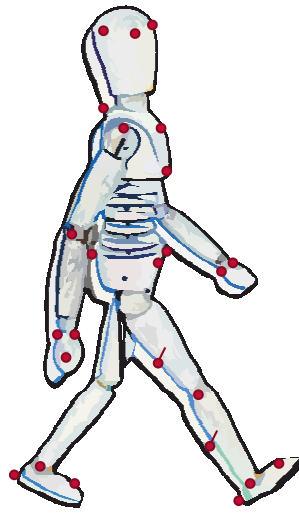


Figure 4.10.: Markers for Vicon Plug-In Gait model.

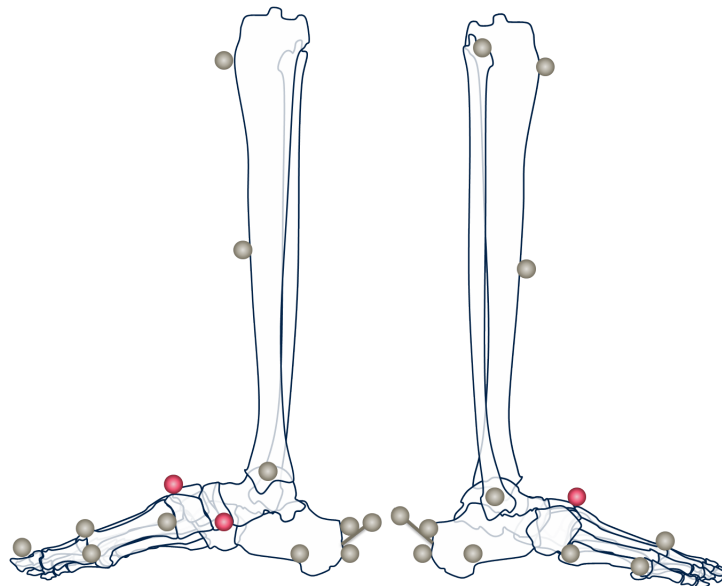


Figure 4.11.: Oxford Foot Model (grey) and additional Navicular Height (NH) and Dorsal Arch Height (DAH) marker (red) positions. Left - medial view. Right - lateral view.

## 4. Data collection methods

particularly important to streamline the process. At each session, prior to the arrival of any participant, the laboratory was calibrated, and equipment checked. The markers and electrodes were prepared. Multiple children were often in the lab at once, with different elements of the process occurring concurrently, and a number of people were involved in the data collection. Typically the order of events was general examination, foot structure evaluation, gait analysis (Fig. 4.12).

For straight level walking trials, a minimum of four clean force and pressure plate strikes per leg were required. The walking trials over the force plates involved walking the length of the lab (the “mid-gait” approach). The trials walking over the pressure plate were collected using the two step method (essentially because the active area of the pressure plate was smaller, and so the margin for error was reduced). The two step method has been found to be comparable to mid-gait concerning pressure when three to five trials were acquired [96].

### 4.3.4. Processing protocol

For each subject the trials were processed using Vicon Nexus software (Fig. 4.13). Gaps, if small, were handled by interpolation using cubic splines [113]. Larger gaps were filled by assuming constant distance between markers on the same segment [39]. Trials with very large gaps in relevant trajectories were excluded. A Woltring filtering algorithm was used [188]. Foot strike and foot off events were determined using the force-plate data (with a tolerance of 20 N) where possible, and otherwise manually. Thigh wand offsets were iteratively determined with the assumption of minimal ab-/ad-duction occurring at the knee [5].

## 4.4. Symptomatic participants

Data for the symptomatic population was extracted from existing patient records.

#### 4. Data collection methods

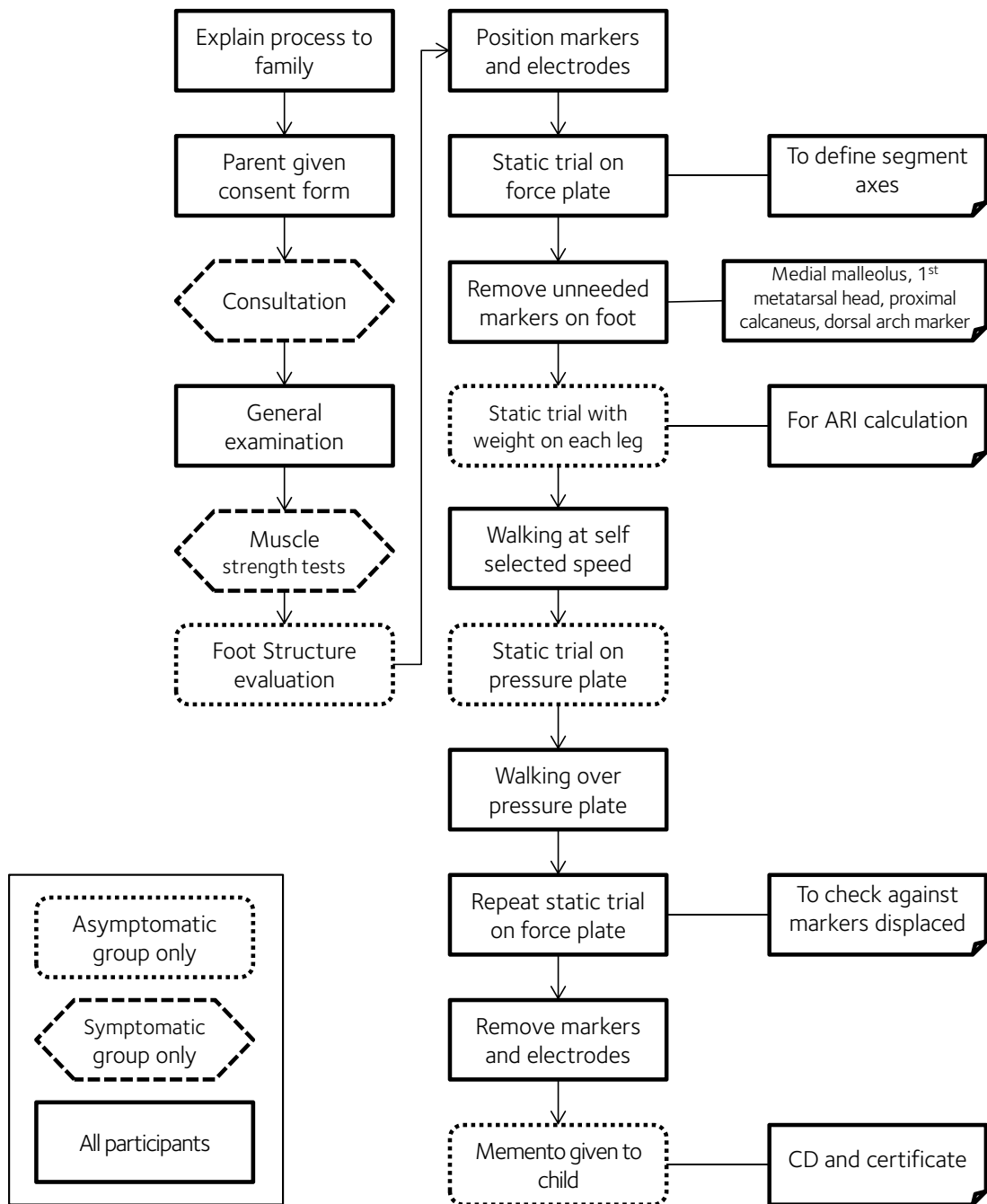


Figure 4.12.: Participant protocol flowchart. Dotted curved items only apply to asymptomatic volunteers. Dashed hexagonal items apply only to symptomatic patients. All other items refer to both groups. Notes exist on the right hand side.

#### 4. Data collection methods

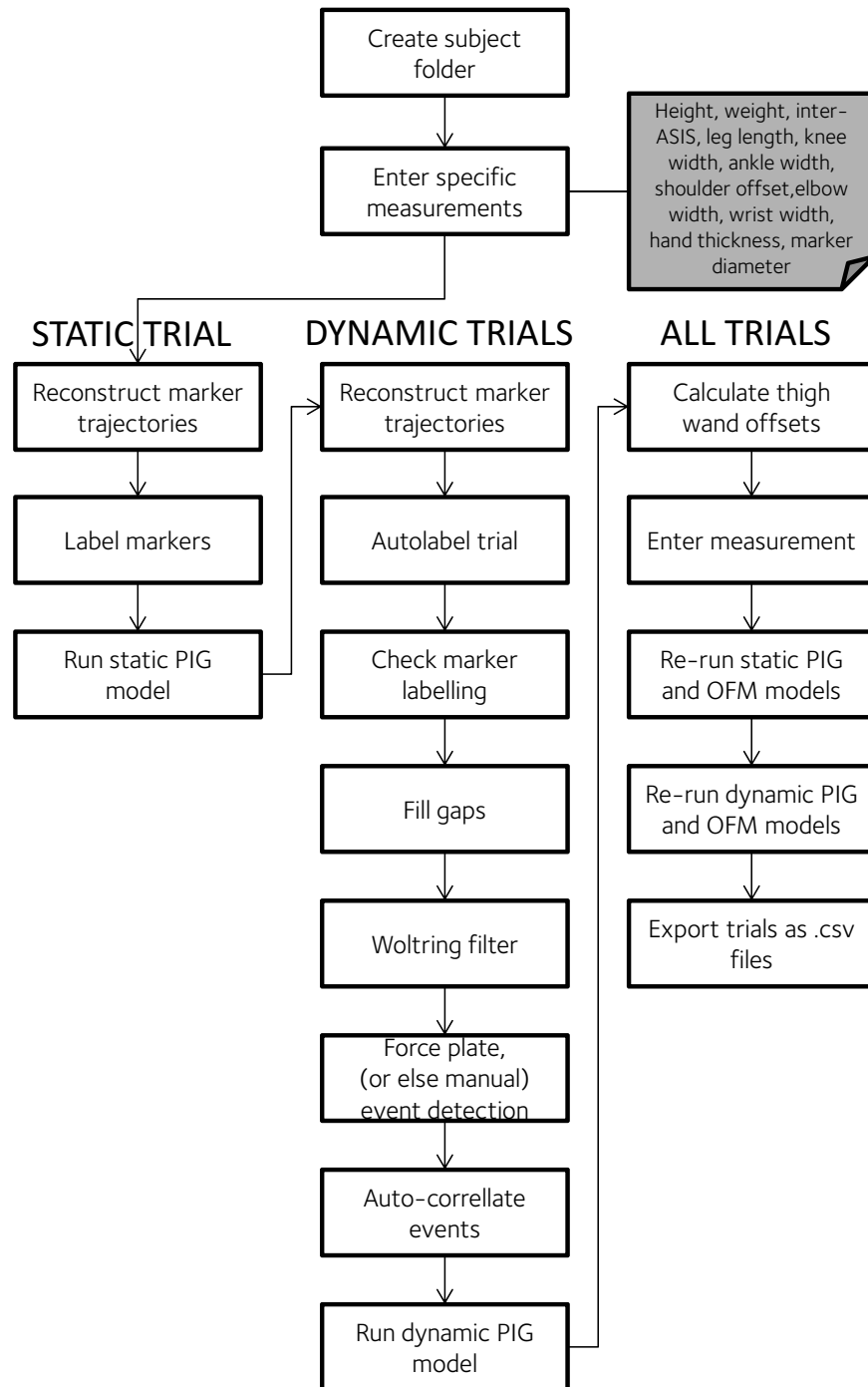


Figure 4.13.: Vicon processing method for subject kinematic and kinetic data.

## 4. Data collection methods

The database was searched for children with a referral for idiopathic flatfoot, and whose parent or guardian had signed to allow the use of the data for research purposes. This resulted in 23 flatfooted (yet otherwise normal) subjects, all except one of whom displayed symptoms to varying degrees. This group had the same general examination procedure as those recruited from the general population. There tended to be a more detailed foot description available for these subjects describing rear-, mid-, and fore-foot. The kinematic, kinetic, EMG, and pressure data for this set was similar to the normal data set. The same marker sets - OFM and PIG - were used.

There were several limitations to this retrospective data collection. The navicular and dorsal arch markers were not used. There was no record of FPI. Static pressure prints were not recorded. The lack of traditional quantitative foot posture assessment techniques meant correlations or regressions for severity would not be possible in this data set, nor could the difference between severity of foot types be quantitatively assessed. There were several accessories to the protocol. There were additional tests for strength, the Windlass effect, and presence of midfoot breaks.

### 4.4.1. Strength testing

Muscle strength was quantified. The Medical Research Council of Great Britain (MRC) system is the most commonly used manual muscle strength grading system. Following the Second World War, 12 surgeons created a manual to illustrate major muscle actions and testing methods [142], and a scale to grade the action (Table 4.2). The action of the hip flexors, extensors, abductors, and adductors, knee flexors and extensors, ankle dorsiflexors and plantarflexors, foot pronators and supinators was assessed by a physiotherapist on this scale.

### 4.4.2. The Windlass effect and midfoot break

The Windlass effect is the recovery of the arch when the toes are dorsiflexed, pri-

#### 4. Data collection methods

Table 4.2.: MRC Scale [142].

Grade	Muscle State
0	No contraction
1	Flicker or trace of contraction
2	Active movement against gravity eliminated
3	Active movement against gravity
4	Active movement against gravity and resistance
5	Normal power

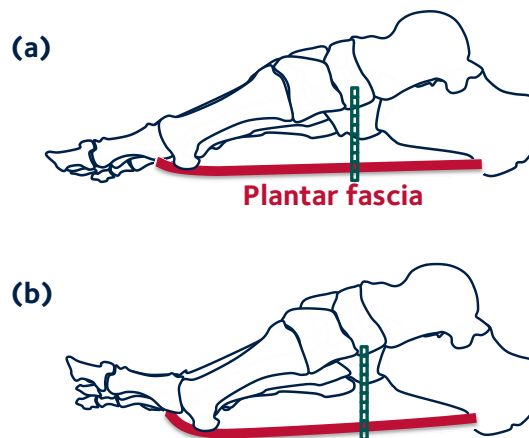


Figure 4.14.: Illustration of Windlass mechanism. (a) Foot in resting position with plantar fascia. (b) foot with dorsiflexed toes, pulling on the plantar fascia, shortening the length of the medial arch, and consequently raising the position of the navicular.

marily via the tightening of the plantar fascia (Fig. 4.14). The plantar fascia is a thick connective tissue that connects the tuberosity of the calcaneus to the proximal phalanx. When the toes are dorsiflexed the fascia is pulled in the directions of the phalanges, thereby reducing the distance between the calcaneal tuberosity and the heads of the metatarsals. This effect was tested by asking the participant to stand on their toes and looking for the recovery of the arch. If the arch does not reconstitute this implies that the Windlass effect is absent. Midfoot break is associated with

## 4. Data collection methods

severe flatfoot, and if present, it was noted.

### 4.5. Summary

Four groups were included in the study: three Asymptomatic (Neutral feet, Mild flat feet, and Flat feet - these subgroups will be defined in Section 6.1), and one group of idiopathic Symptomatic Flat feet. All participants completed a general examination which included foot structure and flexibility. Where possible the children completed static standing and dynamic walking gait analysis with EMG, tri-axial force-plates, PIG and OFM markers. Plantar pressure during walking was also recorded.

Asymptomatic children also had FPI evaluation, and markers on the navicular tuberosity and the dorsal surface of the arch. Static trials on the pressure plate were also conducted for the asymptomatic group.

The symptomatic group completed an additional standard patient consultation, manual muscle strength tests, and assessing for the Windlass mechanism and midfoot break.

The methods for the data collection having now been explained, the data can begin to be analysed (Chapters 5-11). The first of these chapters will focus on characteristics of the data-set that are only available in a subset (symptomatic patients or asymptomatic volunteers). These provide a better description of the populations being investigated and help to guide subsequent steps in analysing the gait data.

## 5. Characteristics of the patients and volunteers

This chapter details the known symptoms in the patients and quantitative foot posture in the volunteers. Firstly, the patient symptoms are described by location, this is compared with the result of the audit to learn more how representative the gait laboratory population is of other patient populations (Section 5.1). Secondly, the noted strength in the limbs of the patients is considered (Section 5.2). Thirdly, quantitative measures - the Foot Posture Index, Arch Height Index, Normalized Navicular Height, and static footprints - which were measured in the asymptomatic volunteers are described (Section 5.3). This information, while not revealing potential causes of symptoms (as it cannot compare asymptomatic and symptomatic populations), helps understanding of the population and how representative the it is.

The information in this chapter is asymmetrical: one could assume there are no symptoms or weaknesses in the asymptomatic volunteers however this was not recorded; the quantitative foot posture assessments were unfortunately not standard procedure for patients. In the patient population the symptoms experienced are crucial to

## 5. Characteristics of the patients and volunteers

the interpretation in terms such as theorizing causality and assessing impact and relevance of results. The strength in the patient population has also been recorded and although this is intended to be referenced to normal there are problematic aspects to that.

Flatfoot has traditionally been assessed by appearance, or by a method arising from that appearance. Clinicians have recognized idiopathic flatfoot in patients experiencing pain. The assessment methods described in Section 2.1 were developed in clinics to better define and quantify this impression. As assessments of foot pronation and arch construction, it would be expected that the FPI, AHI, and NNH correlate strongly with each other and with the physiotherapist description of foot posture.

AHI and NNH should reflect the lowering of the arch. FPI appears to include many of these criteria in its construction (abduction of the forefoot, lowering of the arch, heel eversion).

All of this information, while being asymmetric, can still help define which populations our study represents and therefore the relevance and applicability of any results from the rest of the study.

### 5.1. Symptoms of the symptomatic population

The patient notes of the symptomatic group where available were reviewed to determine the symptoms and other relevant characteristics of those involved (Table 5.1). Foot pain was the most common symptom, with pain becoming less frequent further away from the foot. The tendo-Achilles was of frequent concern. Balance problems were fairly common too, as had been identified previously in the audit (Chapter 3). Midfoot break was common but not always present. Absence of the Windlass mechanism (Fig. 4.14) was present in 26% of subjects. One patient was asymptomatic

## 5. Characteristics of the patients and volunteers

Table 5.1.: Symptom frequency among symptomatic group (n=34 feet) where data was available.

Symptom	Frequency
Foot pain	78%
Ankle pain	28%
Knee pain	17%
Hip pain	11%
Tendo Achilles pain	14%
Fatigue	17%
Balance problems	22%
Developing or present midfoot break	55%
Absent windlass mechanism	26%

and was recategorized to the AF group.

Comparison between the study group, and the audit group reveals similarities between populations (Fig. 5.1). The pain reported by the orthotic department more closely resembles the frequency described by the patients in the main study. However, the patients of the main study were selected on the basis of having painful flat feet so it is not perhaps surprising that this population has a higher percentage reporting pain, particularly at the foot. The percentages reporting balance or falling problems were similar among the physiotherapy department and SF population. This phenomenon was not reported in the orthotics population, perhaps because this was not of concern to the orthotists, or was not recorded as a tick box was not included on the form. Absence of the Windlass mechanism was of similar frequency in the physiotherapy department and SF population, though this was never a concern among the orthotic population that was sampled.

### 5.2. Strength and the symptomatic population

Strength in the SF group was manually tested on the MRC Scale (Fig. 4.2) [142]. The strength of hip flexion, extension, and abduction; knee flexion; ankle dorsiflexion and

## 5. Characteristics of the patients and volunteers

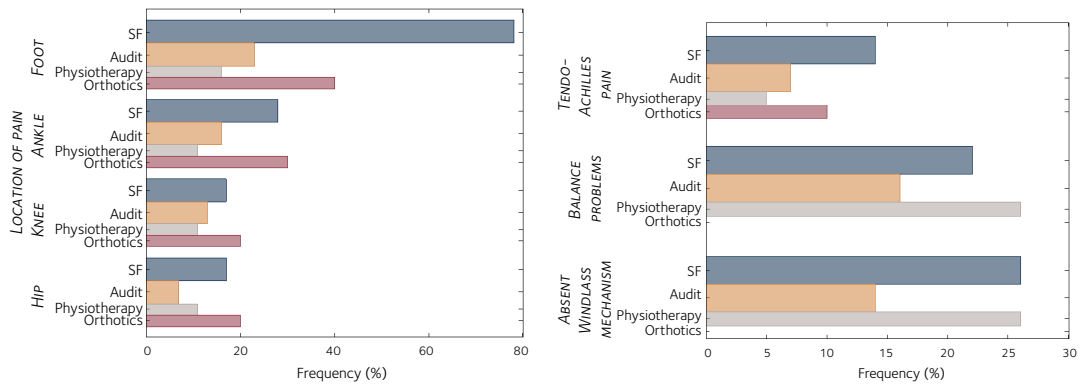


Figure 5.1.: Comparison between symptoms in the main study and audit populations. Percentages reporting pain at the hip, knee, ankle, foot, and tendo-Achilles as well as those reporting balance problems and absence of the Windlass mechanism.

plantarflexion; foot pronation and supination were gauged manually by a clinician (Fig. 5.2).

Several scores were recorded of 2+, 3+, or 4+ (Figs. 5.2). These scores have little meaning on the original scale. The MRC scale is ordinal and the differences between grades were not assumed to be constant. It is widely acknowledged that differences between grades 3 and 4, or 4 and 5 are wide and difficult to quantify. Yet it leaves an unclear message whether, at 2+ the subject was able to act against gravity or not, at 3+ whether they provided additional resistance or not, and at 4+ to what extent resistance was abnormal. Alternatively, the score may have indicated something else, for example at the shoulder it may be possible to provide resistance to the testing (grade 4) without having enough strength or strong enough synergists to provide full motion against gravity (grade 3) [71].

The minimum score at the hip was 2+ and at the ankle was 3. The system was developed to monitor recovery from paralysis, so the scale focuses on severe weakness (scores 0-3). Particularly in children, wide variability in muscle strength, makes it difficult to judge normal power. Since we had no data on the control group it was practical to interpret scores of 4-5 as potentially within normal bounds of variation for children of the age in question.

## 5. Characteristics of the patients and volunteers

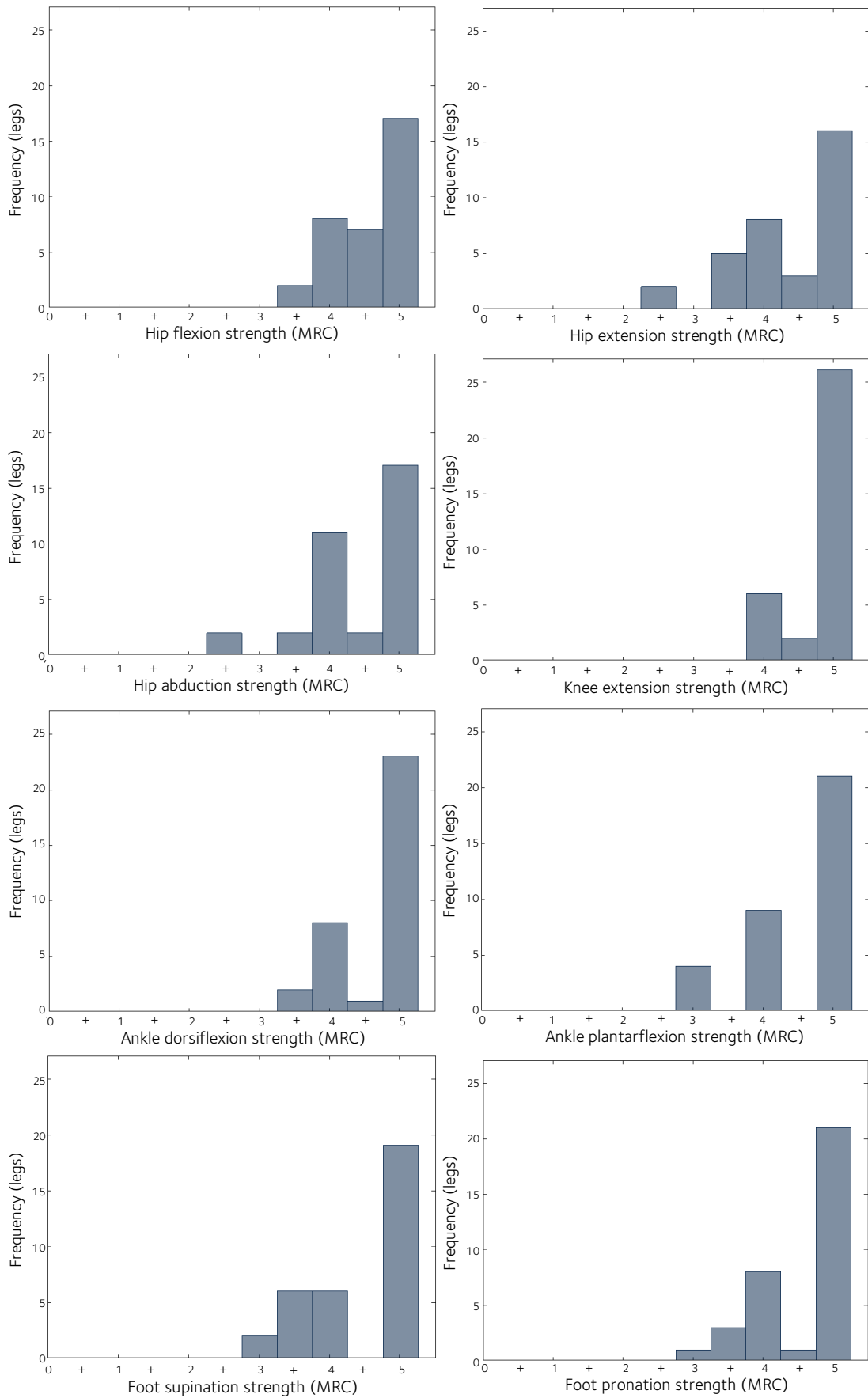


Figure 5.2.: Histograms of SF strength at hip, knee, ankle, and foot. Categories based on MRC scale (Fig. 4.2) [142].

## 5. Characteristics of the patients and volunteers

Classifying scores below 4 as (most likely) “abnormal” reveals foot supination and hip extension to be weak in 24% and 21% of the SF group. The association of flatfoot with reduced supination is established [104]. Weak supinators have been suggested as a cause of flatfoot [72]. This weakness may predict and correlate with reduced supination during gait and static stance. It could not be assumed that the weakness is causative, since the weakness could equally be the result of a lack of use. The weak hip extensors require further explanation.

Poor ( $MRC < 4$ ) hip abduction, ankle plantarflexion, and foot pronation were recorded in 12% of the symptomatic group. None of these has previously been associated with flatfoot to the knowledge of the author. This may be a normal rate of incidence, but unfortunately we have no record of these scores within the asymptomatic population for comparison. Hip flexion, knee extension, and ankle dorsiflexion were “normal” ( $MRC \geq 4$ ) in more than 90% of the symptomatic group.

### 5.3. Quantitative foot posture assessment in volunteers

Traditional assessments were collected as described in Chapter 4. The quantitative assessments selected and collected were the FPI, AHI, ARI, NH, NNH, and static footprints.

Despite the total sum of the FPI having good to excellent repeatability, the individual components are unreliable and its relation to dynamic function is disputed (Table 2.2). It is a popular comprehensive and semi-quantitative method that is simple to implement so was included. AHI, ARI, NH, NNH, are highly reliable with moderate correlation to clinical definitions and prediction of dynamic functions (Tables 2.3 and 2.4). These measures correlate well with “gold standard” radiographic techniques so were included. Static footprints are well respected and very reliable, although correlation with dynamic function is not good (Table 2.6).

## 5. Characteristics of the patients and volunteers

For further justification of the selection of quantitative methods of assessment please refer to Section 2.1 (in particular Section 2.1.4).

### 5.3.1. Methods

#### *Foot Posture Index*

The FPI was recorded for 63 asymptomatic volunteers. Each of the six components was assessed (Table 2.1). The total sum was then used to categorize feet, applying the standard limits (equation 2.1):

- less than zero - “supinated”/other,
- between zero and five - “normal”/neutral,
- between six and nine - “pronated”/mild,
- above nine - “highly pronated”/flat.

#### *Static footprints*

The static footprints recorded from the Novel pressure plate proved to be unsuitable for use with traditional methods. For the vast majority of asymptomatic volunteers, the footprint appeared to be of the type classically associated with a high arch (Fig. 2.2). This could be due to several reasons: firstly, the threshold of 10 kPa on the Emed pressure plate could have been too high to record midfoot contact pressures while standing in children, and other methods may be more sensitive; secondly, the calculations have previously been based on an ink print or maximum pressure print which may include loading response and motion to provide a picture of the maximally loaded area, not a snapshot of genuine static contact at the midfoot area.

Of the footprint-based methods, only the Arch Index is sensitive enough to differentiate degrees of “high” arches (one with no or broken contact in the midfoot region). The Alpha angle requires a concave join between the forefoot and midfoot which is

## 5. Characteristics of the patients and volunteers

not always apparent. The Chippaux-Smirak and Staheli Indices rely on the ratio of the narrowest part of the midfoot region to the width of the hindfoot or forefoot. In the data collected for this study, the narrowest part of the midfoot was almost invariably zero, and therefore the measure was not sensitive enough to pick up differences between the majority of prints. Static plantar pressure prints for the (symptomatic) patients were not available, as they were not routinely collected.

### *Measuring AHI and NNH using markers*

The AHI and NNH have several measurements required: the Foot Length (FL), Truncated Foot Length (TFL), Dorsal Arch Height (DAH) at 50% FL, and Navicular Height (NH) (Fig. 2.1). There are several methods used to make these measurements. This section will explain how the method for collecting this data (calipers for FL and TFL, markers for DAH and NH) was arrived at.

The most commonly used method is to use calipers for all measures [185]. When this method was tried several issues were found. For FL the trouble was in which direction to measure, parallel to the medial side of the foot or parallel to the principal axis of the foot (from calcaneal tuberosity to second metatarsal head). We chose to measure parallel to the principal axis. For feet with a midfoot break, it was thought that this method would be more straightforward. Since the principal reason for the measurement was in our case flatfoot it seemed prudent to be prepared for this eventuality. Given that the principal axis of the foot is approximately perpendicular to the horizontal curve of the calcaneal tuberosity, the cosine function indicates rotation exceeding  $18^\circ$  would be required for a 5% change in length measurement. Thus this specification makes little difference to the final result.

The second problem with the caliper method, is the TFL. Traditionally described as “foot length minus toes”, this is often measured from heel to the first metatarsophal-

## 5. Characteristics of the patients and volunteers

langeal joint. This joint was found difficult to identify with any repeatability. A more repeatable measure was found to be to the most distal weightbearing surface proximal to the joint. It has been reported that in the absence of toe deformity, truncated arch height ratios can be estimated using the full Foot Length [98]. It therefore should not be problematic to use a more repeatable measure of length except, possibly, in terms of comparison with other studies.

The third problem with using calipers occurs when measuring DAH and NH. This was found to be a finicky procedure, awkward and difficult to get the measurement in the vertical direction. One method which has been attempted to solve some of these problems is to attach graph paper to a set square and to mark the height on the paper [37]. However, again this was an awkward and time consuming procedure inappropriate for use with participants. Another method which could have been used was photography [123] although calibration is an issue. The AHIMS device appears to be a reliable method [132]. The marker system was a reliable, accurate, and dynamic system readily available to us, with no manufacture or awkward procedures necessary, so this was used. This additionally allowed us to monitor the behaviour over time and gait.

### *Method for testing repeatability of marker and caliper based AHI measurements*

As is described above, TFL and FL were measured with calipers parallel to the principal axis of the foot. A marker was placed at 50% FL on the dorsum of the foot and the position was recorded for 3 seconds by the Vicon camera system. Three females participated in the study: CK, JL, and JB. They were similar in height, foot size and age - approximately 1.64 metres, UK size 4/5, and mid to late 20s, respectively. CK measured, and applied markers, to the left and right feet of JL and JB five times. JL and JB measured and applied markers to the other two participants once.

## 5. Characteristics of the patients and volunteers

Table 5.2.: Intra- and inter-tester repeatability of the measurements involved in the AHI calculation.

Standard Deviations	Mean				Maximum			
	FL (mm)	TFL (mm)	AH (mm)	AHI	FL (mm)	TFL (mm)	AH (mm)	AHI
Intra-tester	1.21	2.99	1.57	0.01	1.60	4.90	1.81	0.01
Inter-tester	0.93	3.81	2.34	0.02	1.84	7.28	5.09	0.03

The AHI was calculated by dividing the mean (over the three second static trial) 50% FL dorsum height, as measured by marker (with an offset due to marker diameter and base), by the TFL.

This sample size is too small (and homogeneous), to calculate intra-class correlation coefficients for intra-tester and inter-tester repeatability. It was decided, therefore, to analyse this data by examining the standard deviations associated with various measurements, and comparing the deviation to the range in the population which participated in the data collection of this project.

### *Repeatability results and discussion*

Standard deviations of each of the four measurements and six feet were calculated intra- and inter-tester. The mean and maximum standard deviations were then determined for each of the four measurements (Table 5.2). FL was found to be a repeatable measure, with all standard deviations less than 2 mm. TFL was a little different though with significant inter-tester variability for one foot in particular leading to a standard deviation in excess of 5 mm; however, the mean deviations were less. The variation in DAH was generally speaking low, excepting one measurement which exceeded 5 mm. Within the final AHI calculations, the error was very low (0.01 intra-tester, and 0.02 inter-tester) compared to the range of indices recorded in our subject group (0.13 to 0.43).

McPoil et al. previously reported full results in terms of repeatability [98]. They used

## 5. Characteristics of the patients and volunteers

Table 5.3.: Comparison of standard deviations of intra- and inter-tester differences (i.e. all possible differences between two measurements as appropriate, e.g. the difference between the first and second measures of subject B Foot Length taken by tester one (an intra-tester difference), or the measures of subject B Foot Length taken by testers one and two (an inter-tester difference)) with another study [98].

Standard deviation (mm) of differences	Intra-tester		Inter-tester	
	Our Study	McPoil (mean)	Our Study (mean)	McPoil (mean)
Arch Height	2.12	1.80	3.16	1.37
Foot length	1.76	3.63	1.07	2.97

Table 5.4.: The intra-tester limits of agreement analysis of AHI measurements.

Intra-tester	Standard Deviation
Foot length (mm)	1.76
Truncated foot length (mm)	4.13
Arch height (mm)	2.12
Arch height index	0.01

a photographic method and measured two parameters in common with our study: DAH and FL. Comparing the mean standard deviations reveals similarity between the results (Table 5.3). The McPoil study had a far greater number of feet tested (550). Additionally, only one photograph was taken per subject, reducing variability in the resulting estimate of AHI. The McPoil paper obtained very good intraclass correlation coefficients.

Further analysis of the limits of agreement revealed that one of the main sources of bias is the TFL (Tables 5.4 and 5.5). The procedure of measuring this emerged organically (as described previously in this section's introduction), so affirming the method prior to the start of the data collection could reduce this effect. Again, compared to the range of values collected from subjects within the main study, variation within the Arch Height Index is minimal. Further study could be warranted to better assess the use of markers and calipers to calculate AHI in children, as well as to test the repeatability of the NNH when measured this way.

## 5. Characteristics of the patients and volunteers

Table 5.5.: The inter-tester limits of agreement analysis of measurements.

Inter-tester	Bias (mm)			Standard Deviation (mm)			
	CK vs. JL	CK vs. JB	JL vs. JB	CK vs. JL	CK vs. JB	JL vs. JB	Mean
Foot length	0.14	0.45	2.15	0.37	2.19	0.64	1.07
Truncated foot length	2.29	3.03	8.65	0.04	7.36	2.33	3.25
Arch height	5.21	0.42	-2.05	2.81	2.48	4.17	3.16
Arch height index	0.02	0.00	-0.03	0.01	0.03	0.03	0.02

### 5.3.2. Results

#### *Foot Posture Index*

The FPI was recorded for 126 asymptomatic feet. Individual components of the FPI were concentrated on scores of zero and one (Fig. 5.3). Despite the limited range of individual component scores, the total scores ranged from -2 to +11 within this asymptomatic population (Fig. 5.4). More variation was recorded within the male population than the female.

The trouble with this measure is perhaps that it is not particularly sensitive. The distribution may reflect a reluctance of the testers to give a score less than zero or greater than one in any particular category, or reflect the rarity of meeting the criteria of a score that is not zero or one. After applying the standard criteria there are relatively few feet that were not classified as neutral (Fig. 5.4). It may be interesting to note, that even while the FPI is ordinal in nature, the total scores were very strongly aligned to the non-weightbearing clinician's description of foot posture. FPI score is related to the summarized groupings, but the distinction between Asymptomatic Mild and Flat feet disappears (when weightbearing foot posture becomes the main driver of foot classification). Under the normal classification system (equation 2.1) 3 feet (2%) were highly supinated, 98 (79%) were neutral, 22 (18%) were pronated, and 1 (1%) was highly pronated.

## 5. Characteristics of the patients and volunteers

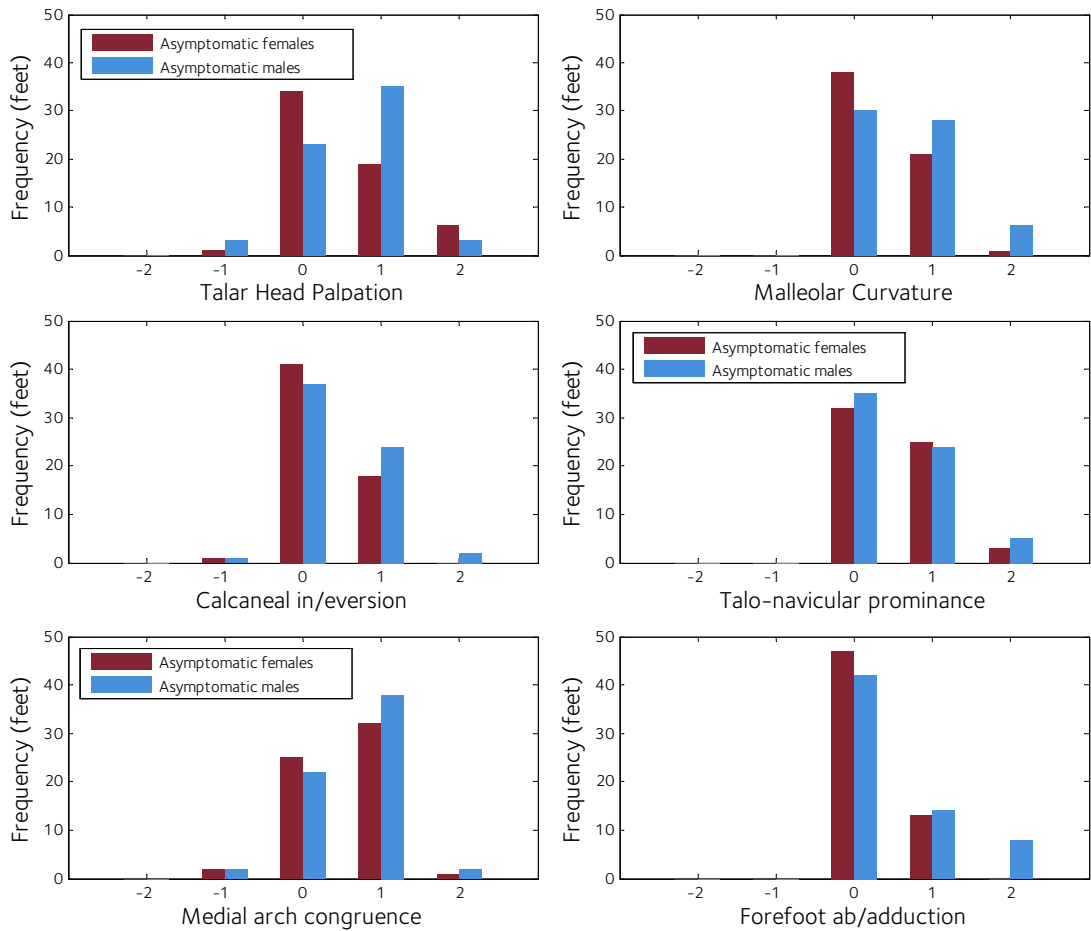


Figure 5.3.: Frequencies of individual components of the FPI within asymptomatic male and female populations.

## 5. Characteristics of the patients and volunteers

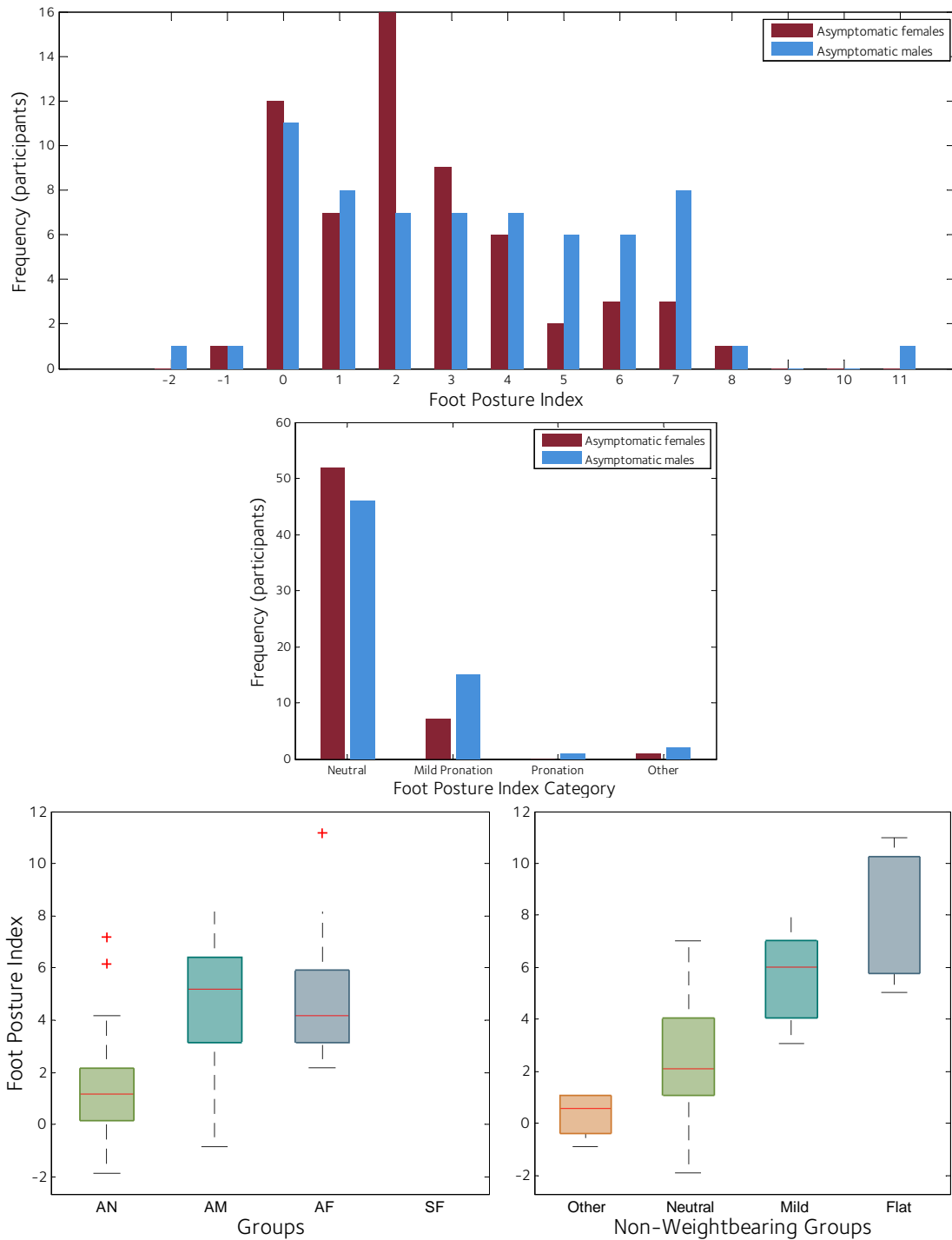


Figure 5.4.: FPI score frequencies within asymptomatic male and female population. Categories: Other < 0,  $0 \leq \text{Neutral} \leq 5$ ,  $6 \leq \text{Mild Pronation} \leq 9$ ,  $10 \leq \text{Pronation}$ . On the box-plot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

## 5. Characteristics of the patients and volunteers

### *Normalized Navicular Height and Arch Height Index*

NNH was recorded in 102 asymptomatic feet. NNH ranged from 0.11 to 0.34 (Fig. 5.5). This makes them to be mostly low and neutral according to Murley et al. [115]. Under the Murley et al. sorting 31 (30%) feet would be classified as “flat” ( $NNH < 0.17$ ), 34 (33%) as “neutral” ( $0.22 < NNH < 0.31$ ), 37 (36%) would be excluded from their study.

Arch Height Index was recorded in 117 feet (a few participants did not have Foot Length measured bilaterally), all from the asymptomatic population. AHI ranged from 0.25 to 0.43 (Fig. 5.5). There were no clear age trends, it was normalized to TFL, and this supports the research that says the arch has developed by the age of five. There were a couple of outliers for the AHI, which could be the result of difficulty in placing the dorsal arch marker (because of its proximity to the proximal head of the first metatarsal which already requires a marker for the OFM). According to the classification of Howard and Briggs [67] 15 (13%) of the feet tested were low arched ( $AHI \leq 0.275$ ), 17 (15%) were high ( $AHI \geq 0.356$ ), 85 (73%) were neutral.

Both AHI and NNH show similar patterns to the FPI. The values are strongly correlated to non-weightbearing foot posture description (Fig. 5.6). However, with the grouping system (which is largely based on weightbearing foot posture), there appears to be no difference between Asymptomatic Mild and Flat feet. It is unclear why this is the case. It could suggest that the descriptor “mild” was not applied with precision by clinicians when assessing weightbearing posture, only in cases of uncertainty. Or it could indicate relative arch height during weightbearing, or indeed the weightbearing posture itself, was not used as the indicator of “mild-ness”.

## 5. Characteristics of the patients and volunteers

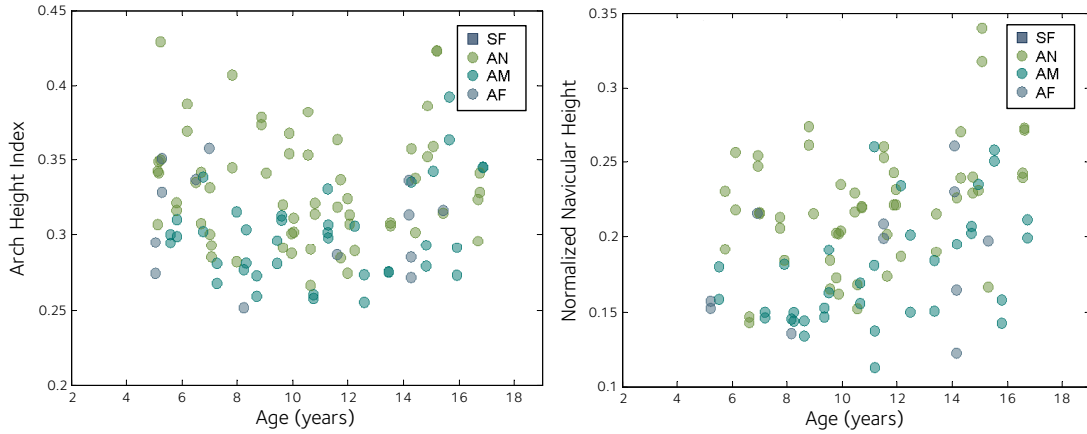


Figure 5.5.: Arch Height Index (left) and Normalized Navicular Height (right) within asymptomatic population versus age. The classification system used to colour this figure will be discussed in Section 6.1.

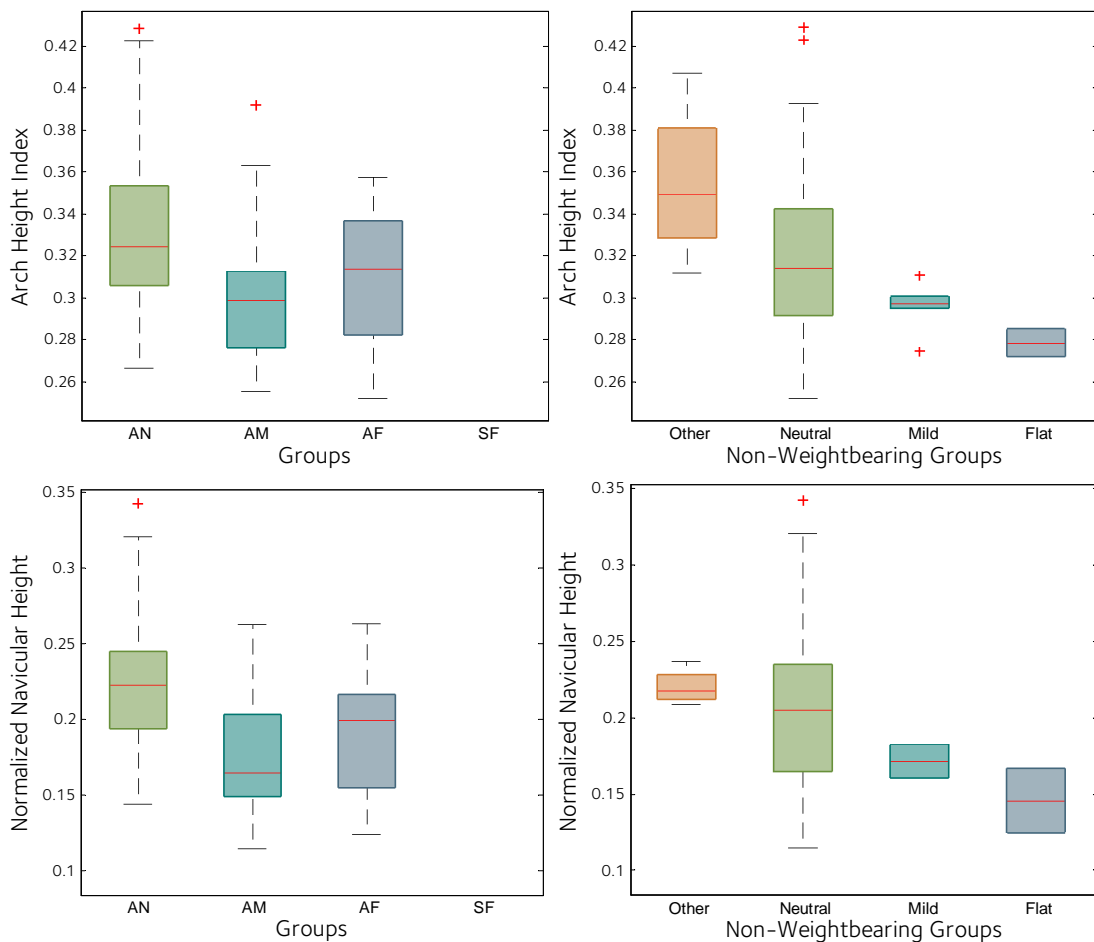


Figure 5.6.: Normalized Navicular Height and Arch Height Index comparison between groups. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

## 5. Characteristics of the patients and volunteers

Table 5.6.: Correlations between Arch Height Index (AHI), Normalized Navicular Height (NNH), and Foot Posture Index (FPI).

	FPI-AHI	FPI-NNH	NNH-AHI
R <sup>2</sup> statistic	0.147	0.266	0.433
F statistic	18.76	34.84	75.62
P value of F statistic	0.0000	0.0000	0.0000
Estimate of error variance	0.0013	0.0015	0.0011

### *Correlations and comparisons*

The different quantitative measures returned different ratios of classifications (Fig. 5.7). This reduces the value of investigating co-classification. The FPI is most conservative, clinical classification by way of the mild group (which will be discussed in Section 6.1) and Normalized Navicular Height are less so. Although Murley et al. [115] is highly conservative in terms of classification when considering the high number of uncategorized subjects (37%). The quantitative and semi-quantitative methods may still be compared using regression.

The traditional continuous variables were correlated by linear regression (Fig. 5.8 and Table 5.6). Since these are linear correlations, the FPI was linearized according to Keenan et al. [79]. NNH and AHI were moderately correlated (perhaps unsurprising considering the similar nature and constituent parts of the calculation). The correlations with FPI were low. Possibly there was difficulty in the placement of the markers because of its nearness to the proximal first metatarsal marker (which took precedence), creating a source of error that was not present during the tests for repeatability (Section 5.3.1).

Medial arch congruence is a visual approximation of arch structure. NNH is a quantitative assessment of arch height. NNH clearly agrees with this FPI category (Fig. 5.9). It may have better repeatability, but is more time consuming to collect. The other constituents of FPI were not in strong agreement with quantitative static measures (such as from the OFM).

## 5. Characteristics of the patients and volunteers

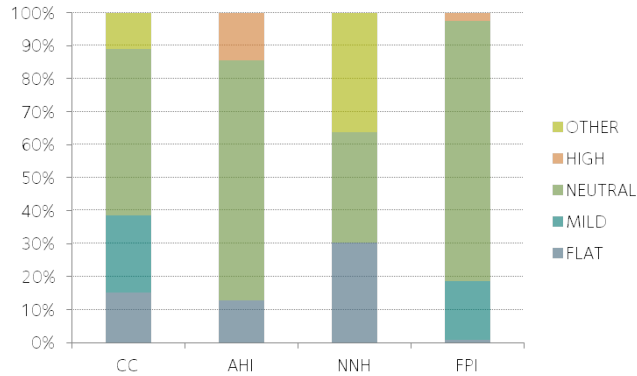


Figure 5.7.: Frequency of various outcomes using four foot classification methods in the neutral population. CC - Clinical Classification (to be discussed in Section 6.1). AHI - Arch Height Index. NNH - Normalized Navicular Height. FPI - Foot Posture Index.

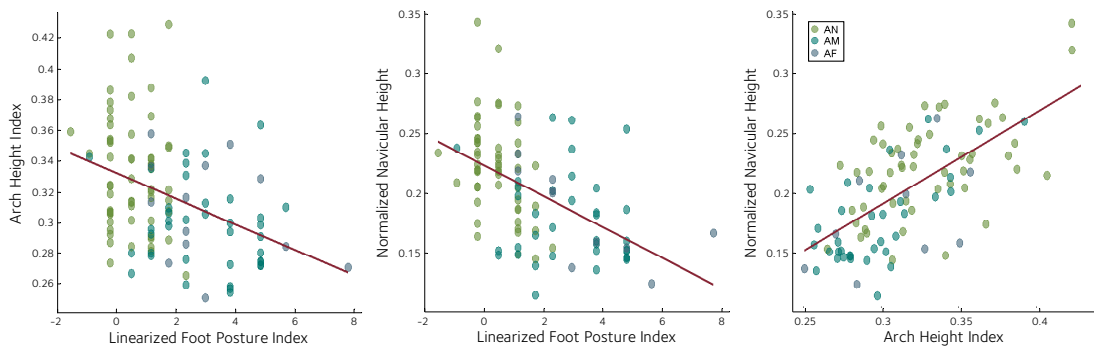


Figure 5.8.: Scatter plots of correlations between Arch Height Index, Normalized Navicular Height, and Foot Posture Index. The classification system used to colour this figure will be discussed in Section 6.1.

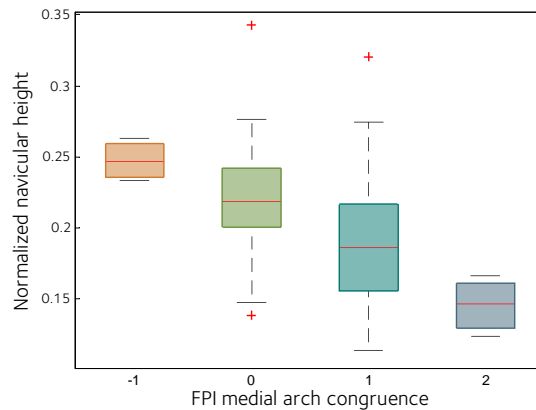


Figure 5.9.: Normalized Navicular Height is a quantitative assessment of FPI medial arch congruence. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

## 5. Characteristics of the patients and volunteers

### 5.4. Summary

Symptoms associated with flatfoot were most commonly foot pain, followed by ankle pain, with continuing reduction in symptoms with increasing distance from the foot. Fatigue and balance problems were also commonly noted.

Strength of foot supinators and hip extensors, appeared to be weak among the symptomatic group. Weak hip abductors, ankle plantarflexors, and foot pronators also presented in this group, but to a lesser extent. However, since there were no control groups with which to compare, drawing firm clinical conclusions is problematic.

A new marker and caliper based method to collect AHI measures was attempted. This method had similar associated standard deviations to another study [98].

Within 63 assessed members of the asymptomatic population, FPI scores of  $-2$  to  $+11$  were recorded. However, the vast majority of asymptomatic feet were within "normal" limits. Therefore this system may not be sensitive enough for the type of cases that are being considered.

Asymptomatic NNH ranged from 0.11 to 0.34, AHI from 0.13 to 0.43. The NNH correlated better with FPI ( $r^2=0.26$ ) than the AHI did ( $r^2=0.18$ ). The NNH and AHI demonstrated a modest correlation ( $r^2=0.43$ ). On these grounds, the NNH being a scalar and objective measure which correlates to other measures, would be favoured when attempting to quantify foot posture.

The symptoms and weaknesses of the symptomatic population have now been described, the quantitative assessment of the foot posture of the volunteers has been presented. This leads us to ask the first questions of the whole data-set - what static and passive differences are there between neutral feet, asymptomatic flat feet, and symptomatic flat feet.

## 6. Passive and static characteristics

The purpose of this chapter is to introduce comparisons between Asymptomatic “Neutral” foot, Asymptomatic “Mild” flatfoot, Asymptomatic Flatfoot, and Symptomatic Flatfoot on the basis of static and passive measurements. Firstly, it considers the foot structure as described by the physiotherapists as the principal method to divide groups (Section 6.1). This lays the ground for all future analyses, and leads to the investigation of the statistical quandary: one subject, two feet (Section 6.2)? Secondly, essential properties of the populations (age, sex, BMI) are examined (Section 6.3). Thirdly, parameters including flexibility and skeletal alignment is tested to see if any of these parameters are related to flat feet or symptoms (Sections 6.4–6.6). The data was collected and processed as described in Chapter 4. Analysis is by way of comparison of groups by ANOVA and correlations between the continuous variables.

It had been noted as early as 1896 that flatfoot was not necessarily debilitating, but sometimes it was extremely so, and that this did not necessarily correspond to the appearance of the foot [88, 184]. It remains a foot type, not a foot condition. There may be underlying differences between the symptomatic and asymptomatic populations which better explain the presence of symptoms.

## 6. Passive and static characteristics

There are very few studies that have compared asymptomatic and symptomatic populations with flatfoot – it tends to be studied either as an asymptomatic or symptomatic condition compared to a neutral asymptomatic foot.

The earliest comparison between symptomatic and asymptomatic flatfoot is from 1997 [41], though is principally concerned with the aetiology of posterior tibialis tendon dysfunction-related symptoms which is not the focus of this study. Three studies between 2009 and 2013 attempted to correlate radiographic properties with symptoms: Pehlivan et al. conclude the talar–first metatarsal angle to be increased in symptomatic young males (n=28, 56 feet) [129]; Moraleda and Mubarak found increased lateral displacement of the navicular in symptomatic patients (n=135) [109]; Yan et al. also found increased lateral displacement of the navicular to be related to the onset of symptoms in children (n=100) [192].

The use of radiographs is controversial in children for relatively minor conditions (even more so in symptomatic cases), it would be helpful if some symptomatic-specific signs could be picked up on by non-radiographic techniques. Given the previous differences found in radiographic studies, it would be reasonable to predict that the differences between the groups (at the feet) will be in the transverse and sagittal planes.

Textbook descriptions of flatfoot [64, 72, 104] additionally provide the following expectations of flatfeet that will be examined closely in this chapter for differences between asymptomatic and symptomatic flatfoot:

- abduction of the forefoot on the hindfoot at the mid-tarsal joint;
- significant lowering of the medial longitudinal arch;
- increased angle of gait (external rotation of the principal axis of the foot – from calcaneus to second metatarsal – relative to direction of travel);
- excessive heel eversion;
- genu valgum (knock knees);

## 6. Passive and static characteristics

- forefoot pronation;
- forefoot supination.

These changes may be related to the presence of symptoms. It could be hypothesized that symptoms will correlate to excessive deviation in some of these aspects. Exceeding a threshold is often related to the development of symptoms in the body.

In terms of the painful symptoms - joint and muscle pains - nociceptors (pain receptors) require a minimum level of stimuli before they trigger a signal, so it could be assumed that this will correlate to an excessive deviation. Abduction of the forefoot and lowering of the arch may place excessive strains on the soft tissues that support the arch. Genu valgum could place excessive loading on the lateral aspect of the knee.

OFM angles and aspects of the clinical assessment may be able confirm these changes, and whether they relate to the presence of symptoms. It could be hypothesized that symptomatic patients with knee pain will display excessive genu valgum and those with foot pain will display excessive forefoot abduction and lowering of the medial arch.

Flat feet demonstrate active peroneus longus, anterior tibialis, and posterior tibialis during standing (Gray [58] as cited by Basmajian and de Luca [8]). This may be an attempt to recover the arch or reduce pronation (Fig. 2.7). This could lead to the reports of fatigue in symptomatic flatfoot. This study does not report muscular activity so it is not possible to assess whether this is the case.

### 6.1. Classification of foot types

There were 127 participants (20 patients and 107 volunteers); 69 were female, and 58 were male. Physiotherapists' descriptions of feet were recorded in non-weightbearing for 108, and in weightbearing in 103 of the children; no description

## 6. Passive and static characteristics

Table 6.1.: Number of feet with various clinical descriptions of foot posture.

Classification	Neutral	Mild	Flat	Other	No description
Non-WB	172	11	28	9	26
WB	89	58	46	13	36

of foot posture was recorded in 14 children. The descriptions, where available, were simplified into four categories. “Neutral”, where no serious deviation from a perceived norm was noted. Mild where a pronated/flat foot structure was noted, but was described as “mild”. “Flat”, where a pronated/flat foot structure was noted. “Other”, where a different type of description was given.

Within our total population, 18% of feet were flat in non-weightbearing, and 54% during weightbearing (Table 6.1). Within the asymptomatic population 7% were pronated during non-weightbearing, and 45% during weightbearing. Flatfoot was universal in the SF group during weightbearing, but not during non-weightbearing (Figs. 6.1 and 6.2).

This may provoke the question: how do these classifications relate to each other? It is somewhat difficult to compare nominal groups. An attempt has been made to present this visually (Fig. 6.3). During non-weightbearing, the majority of feet were classified as “Neutral” feet (Table 6.1). However, during weightbearing, whilst the majority of these feet remain “neutral”, many (43%) are classified as one of the other foot types to a mild flat, flat or other foot type. Feet that appear to be mild flat feet during non-weightbearing may retain this classification or re-classify to a more severe posture upon weightbearing (38%). Non-weightbearing flat feet remained flat upon weightbearing.

The study required a minimum of three groups: neutral asymptomatic feet, flat asymptomatic feet, and flat symptomatic feet (Section 4.2). For the symptomatic group, clinician’s description of foot posture was the only method used to assess foot posture. Therefore, these descriptions allow comparison between asymptomatic and symptomatic flatfoot. If either the non-weightbearing or weightbearing descriptions were

## 6. Passive and static characteristics

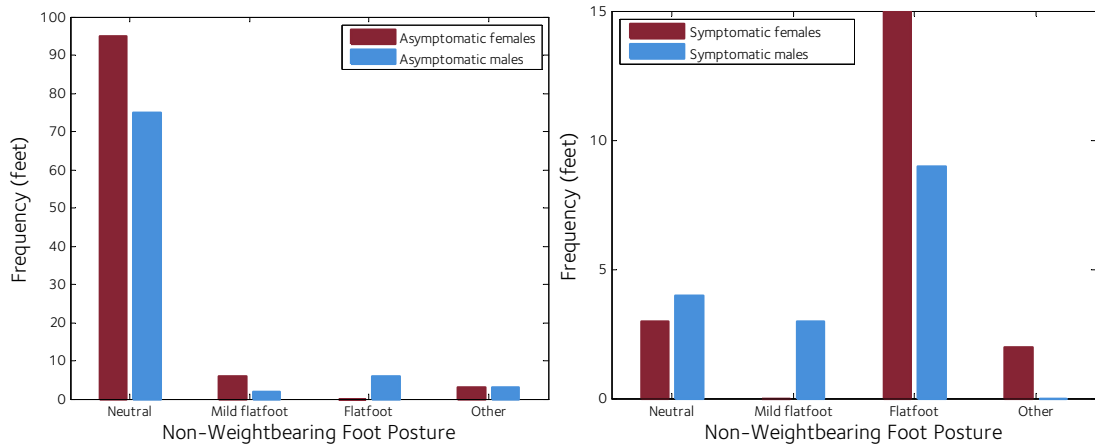


Figure 6.1.: Non-weightbearing clinical descriptions of foot posture in asymptomatic volunteers (left) and symptomatic patients (right). A neutral foot posture during non-weightbearing is less common amongst the flat-footed patients.

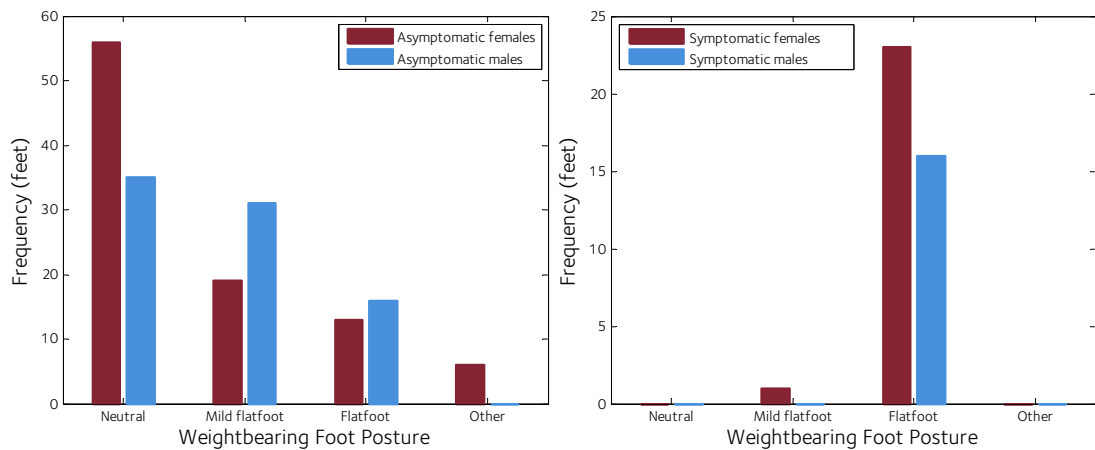


Figure 6.2.: Weightbearing clinical descriptions of foot posture. Breakdown of data for volunteers (left) and symptomatic patients (right). “Mild” flatfoot is rare among the patient population but relatively common among the reference group.

## 6. Passive and static characteristics

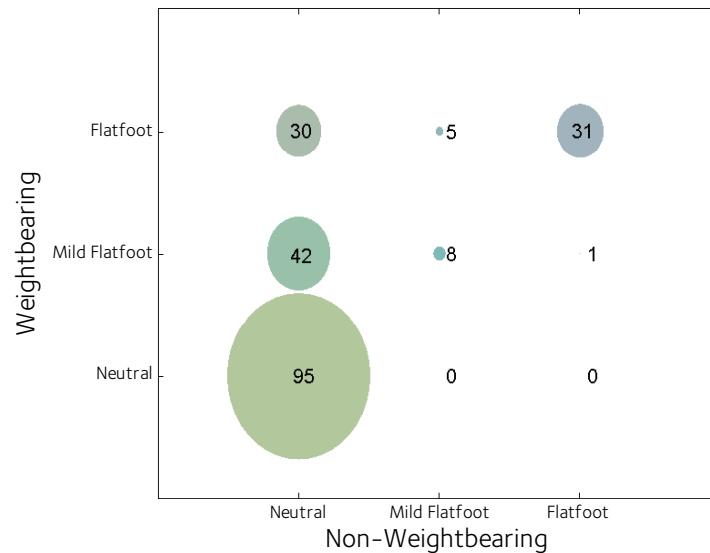


Figure 6.3.: Comparison of non-weightbearing and weightbearing clinician's description of foot postures. Number of participants in a category printed in circles with radius proportional to the size of the group.

used 28 or 38 feet would have been left uncategorized respectively. Using both descriptions allowed us to include all but 24 feet (i.e. 230 feet in total).

The system worked as follows:

1. If subject is a patient (with symptoms attributed to their foot structure), category is patient with Symptomatic Flatfoot (all patients had bilateral flatfoot - in one case it was "mild") (SF);
2. Else if the foot is categorized flatfoot in either weightbearing or non-weightbearing, category is Asymptomatic Flatfoot (AF);
3. Else if the foot is categorized mild flatfoot in either weightbearing or non-weightbearing, category is Asymptomatic Mild flatfoot (AM);
4. Else if the foot is categorized as neutral in either weightbearing or non-weightbearing, category is Asymptomatic Neutral foot (AN).

This resulted in 38 Symptomatic Flat feet, 33 Asymptomatic Flat feet, 50 Asymp-

## 6. Passive and static characteristics

tomatic Mild flat feet, 109 Asymptomatic Neutral feet; and 24 unclassified feet. These are the groups that will be used in future tests between groups. The numbers of subjects that the various types of data were collected on subdivided by category is described in Table 6.2.

Table 6.2.: Detailed description of data collected to compare neutral, asymptomatic flat, and symptomatic flat feet by group. 127 participants were initially included, however some did not have adequate foot posture assessment or had unusual foot posture (that could not be classified as neutral or flat). Only over fives are included in most analysis owing to developmental considerations (Section 2.2). Data is not universal owing to protocol variation, data quality, and compliance issues. The other categories are therefore specific to data type. GRF - Ground Reaction Force, PIG and OFM are marker-based models (Figs. 4.10 and 4.11).

	n	n > 5 y.o.	Spatiotemporal	GRF	Kinematic-PIG	Kinematic-OFM	Kinetic	Pressure
AN	109	100	98	98	98	88	98	35
AM	50	47	47	47	47	47	47	13
AF	33	29	29	29	29	29	29	8
SF	38	38	34	34	37	32	36	16
Total	230	214	208	208	211	166	180	72

### 6.2. One subject: two feet versus one foot

This study quickly encountered a statistical problem. Should both feet be considered, or just one; and if so, which and how? This was quite topical at the time of thesis writing, although no consensus had been drawn [102]. Several simple solutions exist to this problem, each with their own problems (Table 6.3). This problem has been considered for some time in ophthalmology and within that field more sophisticated solutions do exist [78, 86, 147]. At the time of writing, these methods had not been

## 6. Passive and static characteristics

Table 6.3.: Solutions to the two foot problem and issues associated with them.

Solution	Issues
Both feet	May artificially inflate sample size leading to spurious findings
Random foot	Does not utilize full dataset Introduces another source of variability
More extreme foot	Skews samples. Particularly neutral foot sample. Does not utilize full dataset Could miss a compensating contralateral limb effect
Right or left foot only	Results only apply to right or left feet Does not utilize full dataset
Right and left foot separately	Can produce peculiar results which appear to be significant only on one side of the body.
Dominant leg	No evidence dominant leg represents anything Does not utilize full dataset Results only apply to dominant legs
Average representative	Creation of something that never existed "Watering down" effect Difficulty classifying foot type if not symmetric

applied to gait data but this is something that could be considered in the future.

Several solutions select one foot, whether randomly, or not. The random selection does not make use of all the data, and created another source of sampling error. The other methods give results that apply only to one type of foot - left, right, dominant, flatter. Sometimes the left and right feet are analyzed separately; however, this creates quite curious results that appear to only apply to left or right feet, even if there is no significant difference between left and right. It seemed that the data would be best utilized by the cautious interpretation of results, rather than the abandonment of half the data-set seemingly at random.

Two solutions exist for both feet. Taking the average of two feet to create a new intermediary foot makes a new foot, one which never existed in the first place. This could obscure valuable information, and has an additional problem of foot classification if the feet are asymmetric (as was the case in 12.5% asymptomatic cases). The trouble with using both feet as independent samples is that often characteristics of one side of the body are more similar to those on the other than they are to another subject. However, the use of both legs allows the use of additional control

## 6. Passive and static characteristics

or sub-groups (due to larger sample allowing division into multiple subgroups) which can tackle the problem of spurious findings (type I error). A result which appears significant may be marked as dubious if it has unexpected or unexplained interactions with other groups.

Since the data will be tested in groups, and the feet were allocated independently, something to test might be how similar the data is within the groups versus within the subjects (i.e. left and right). If the feet fall in separate groups, repeated samples is not a concern as they are not contributing to the same set. If the groups are sufficiently specific, the similarity within the group may approach or exceed that between feet of a subject which would imply that there was no issue including both feet in the group if they were of the same type as they are no more similar than other limbs in the group.

### 6.2.1. Method

The validity of foot selection techniques, as presented in Table 6.3, in this particular study was investigated. Asymptomatic feet were allocated to groups independently (Section 6.1). For the symptomatic group all cases were bilaterally flat and symptomatic, in any case it would be difficult to attribute many of the symptoms appropriately to a single foot (caused directly by the ipsilateral limb or as compensation for the contralateral foot). The symmetry of foot category was investigated.

A test was created to determine if characteristics of contralateral body sides are more similar to each other than characteristics of random feet. Since the majority of statistical tests of the thesis are categorical, the random foot comparison was taken from the same group. The data tested was taken from some results of this thesis which will show high significance later in the thesis (angles at foot off of Chapter 9). The difference between measures on different sides of the body were calculated. The difference between measures from randomly selected subjects that were within the same group were also calculated. An independent samples t-test was conducted to ex-

## 6. Passive and static characteristics

Table 6.4.: Intra- and inter-subject (within group) differences in angles at foot off. Asterisks highlight the significant results ( $p < 0.05$ ).

		N	Mean	Std. Dev.	ANOVA Sig.			N	Mean	Std. Dev.	ANOVA Sig.
Hip Flexion	Left-right	107	2.57	1.96		HF-TB Inter	Left-right d	98	6.62	7.15	
	Within group	80	6.78	4.91	*.000		Within group	80	7.88	6.37	.216
Hip Adduction	Left-right	108	2.90	2.45		HF-TB Inversion	Left-right	98	5.96	6.41	
	Within group	80	2.83	2.44	.850		Within group	80	6.54	5.20	.508
Hip Internal Rotation	Left-right	108	4.23	3.88		FF-HF Dorsiflexion	Left-right	98	4.45	3.47	
	Within group	80	6.46	5.23	*.002		Within group	80	4.68	3.59	.660
FE-TB Flexion	Left-right	100	3.78	2.80		FF-HF Adduction	Left-right	98	5.14	4.39	
	Within group	80	6.32	5.16	*.000		Within group	80	5.50	4.34	.588
FE-TB Varus	Left-right	100	1.87	1.39		FF-HF Supination	Left-right	98	6.17	4.82	
	Within group	80	3.70	2.62	*.000		Within group	80	6.86	4.81	.345
FE-TB Internal Rotation	Left-right	99	7.85	9.04		HX-FF Dorsiflexion	Left-right	97	9.81	7.92	
	Within group	80	7.92	6.47	.948		Within group	80	14.19	12.00	*.006
HF-TB Dorsiflexion	Left-right	98	3.38	5.38		HX-FF Adduction	Left-right	98	6.82	5.48	
	Within group	80	4.62	3.54	.067		Within group	80	8.73	6.33	*.034

amine if the effect was significantly different. The symptomatic group was excluded from the analysis below, as they had increased intra- and inter-subject variability.

### 6.2.2. Results and discussion

Within the asymptomatic group 87.5% of subjects had two feet of the same category. If the groups remained the same size (109, 49, and 33) and allocations of feet were random, the probability of symmetric foot groups would be 0.42.

The results of the intra-subject versus inter-subject study were mixed (Table 6.4). Six out of 15 measures tested were significantly more similar within subject (left - right difference) than between random subjects from the same group. None of the measures at the hindfoot - tibia or forefoot - hindfoot were more similar between left and right feet, than they were between random subjects within the same group.

#### Conclusion

There are several reasons why left and right measures of a subject are no more similar than those between different subjects. A large measurement error, or strong homogeneity within a group could cause this phenomenon.

At the hip, knee, and hallux all measures except HX hip adduction and knee internal rotation were significantly more similar within the subject. Perhaps high measurement

## 6. Passive and static characteristics

errors create large variance that accounts for the absence of the effect in these cases. An equally plausible explanation would be that these measures are strongly related to subject group, however it will be shown in Chapter 9 that this is not the case.

At the hindfoot-tibia and forefoot-hindfoot no measure was significantly more similar between left and right feet than it was between the feet of subjects of the same group. This is likely explained by strong homogeneity within the group. The groups were after all classified based on foot structure, so it seems reasonable that foot structure is similar within the group.

These results suggest that it is not necessary to discard data from multiple legs. The practice of including the left and right side was not equivalent to multiple samples. At least it was not so at the foot and ankle. Inclusion of both feet, in groups as classified by a physiotherapist, combined with a cautious interpretation of results (particularly at the hip, knee, and hallux) would seem to be advisable. At least, that is, until more sophisticated statistical management of the multiple foot problem has been investigated.

Appendix A shows the effect of different foot selection criteria on statistical significance. For subsequent chapters if the reader is concerned about the validity of the results, they should refer to the appendix.

### 6.3. Age, sex, and BMI

The participants were aged between 0.8 and 17.3 years (Fig. 6.4). The AF group was slightly younger on average than the other groups (Fig. 6.5), but the difference was not significant. There are some age trends in terms of gait. This effect could be removed by regression techniques if necessary; however, it was felt best to keep results transparent as long as results were clear. Many elements of the study exclude the under fives as this group may differ significantly from older participants with regards to elements including fat pad, foot ossification, and GRF. Additionally, it may be

## 6. Passive and static characteristics

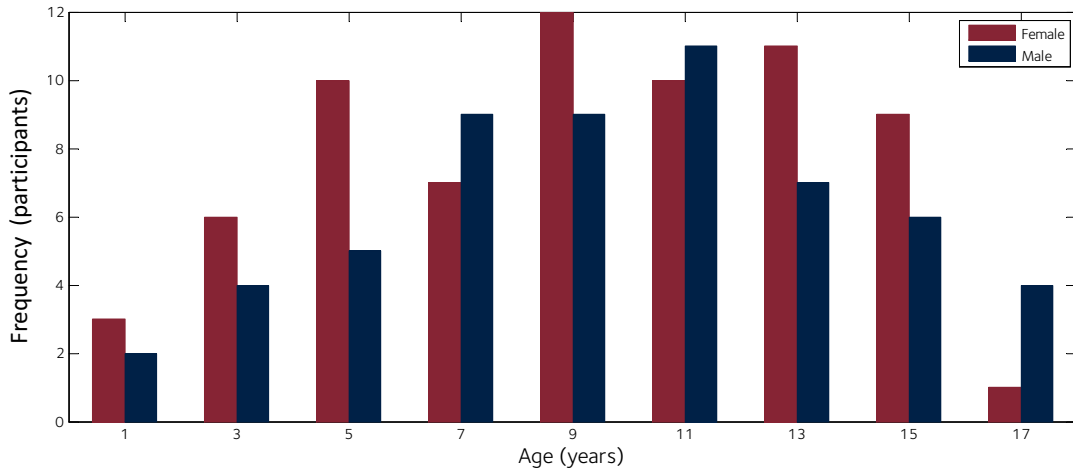


Figure 6.4.: Histogram of ages of children involved in project.

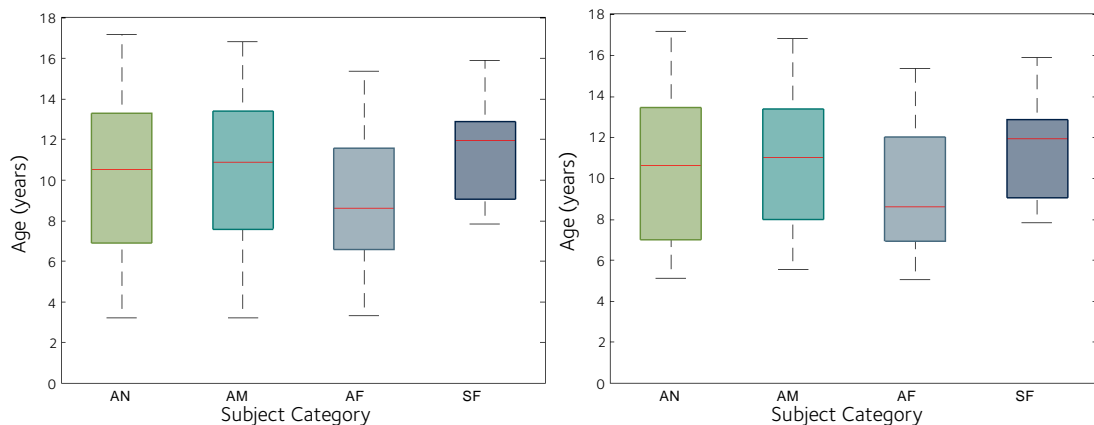


Figure 6.5.: Age distribution of the groups. Left, all subjects (n=127). Right, under 5s excluded (n=109). The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points.

worth considering that the age difference between groups may be a result of symptoms that will not present until an older age. The exclusion of this group reduces the difference between mean ages of the groups (Fig. 6.5). During the remainder of this section, only the over fives will be considered.

There had been concerns that flat and fat feet could be conflated, following the rise in childhood obesity and several publications on the topic [106, 141, 181]. Therefore obesity could have been a confounding factor in this study. Few subjects were found to have Body Mass Indices (BMIs) which were in the obese range according to the

## 6. Passive and static characteristics

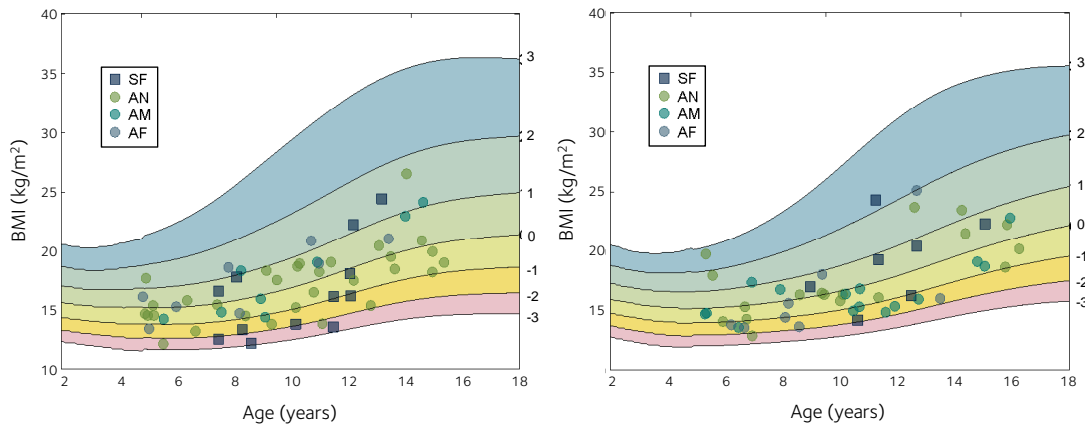


Figure 6.6.: Female (left) and male (right) Body Mass Index (BMI) variation with age. Guidelines and categories based on the World Health Organization child growth standards and growth reference data [190, 191]. Deviation from norm described by standard deviations from  $-3$  to  $+3$  (noted on right hand y-axis of figures).  $\text{BMI} < -3$  SD severe thinness;  $\text{BMI} < -2$  SD thinness;  $\text{BMI} > 2$  SD obese;  $\text{BMI} > 1$  SD Overweight. The categories Asymptomatic Neutral (AN), Asymptomatic Mild (AM), Asymptomatic Flat (AF), and Symptomatic Flat (SF) feet (based on a random selection of representative foot) are depicted.

guidelines of the World Health Organization (Fig. 6.6). Of the female subjects (volunteers and patients), nine were overweight, five were thin, and the rest were within the normal limits. Of the male subjects, two were obese, four were overweight, one was thin, and the remainder were within the normal limits. The prevalence of flat-foot was not related to obesity. The majority of flatfoot within the population could therefore not be attributed to the increase in load bearing caused by obesity, nor could it have been misinterpreted due to excess fat. The obese symptomatic patient had radiographs to demonstrate the flatness ensuring the diagnosis was not a misinterpretation caused by the presence of excessive fat on the foot.

### 6.4. Skeletal alignment

The range of angles recorded was large even within the normal population. Femoral anteversion appeared to decrease with age in our sample (Fig. 6.7). Femoral anteversion peaks between 5 and 6 years of age and lessens thereafter in most children

## 6. Passive and static characteristics

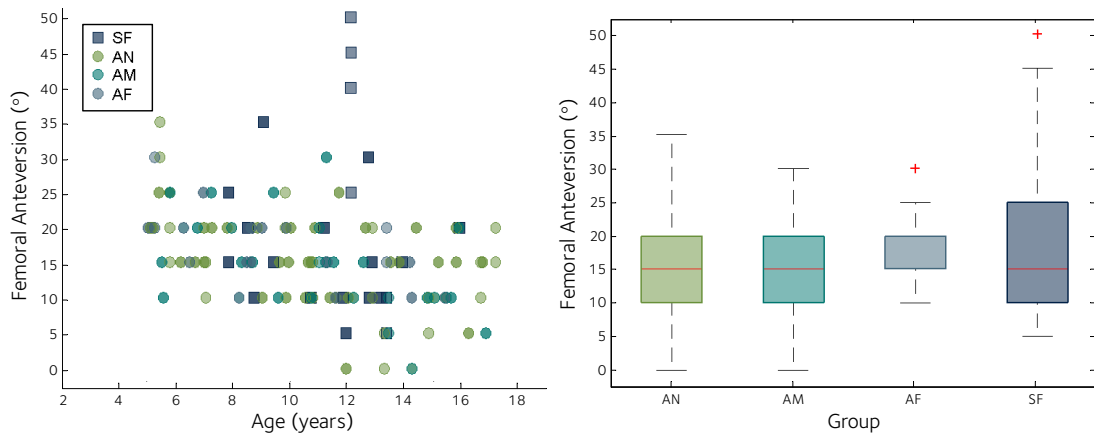


Figure 6.7.: Femoral anteversion decreases with age. It appears to be consistent across groups. Of the box plot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

[161]. It has been reported that flatfoot may be related to increased femoral anteversion through the mechanism of hypotonia associated with developmental delay [194]. Developmental flatfoot (the flatfoot that is outgrown with age) was not the focus of this study, and there were relatively few subjects in the age range with which the paper was concerned (three to six years old).

Knee valgus was more common than varus (Fig. 6.8). “Severe” knee valgus ( $>10^\circ$ ) was mostly associated with the symptomatic population. More generally, varus and valgus knee alignment were fairly evenly distributed amongst the groups. This could be causing the symptoms (e.g. altering loading patterns), caused by the symptoms (e.g. a pain avoidance strategy results in valgus), or correlated with the symptoms (e.g. a common co-morbidity of flatfoot is ligamentous laxity, and this could be influencing both valgus and symptoms independently). However, since the Asymptomatic Flat feet were not associated with excessive knee valgus (the knee valgus was similar to AN and AM groups), it appears from these results that excessive knee valgus is not directly caused by the flatfoot from these results.

Tibial torsion when measured by clinicians appeared to have a relationship with Symptomatic Flatfoot (Fig. 6.9), the mean value for this group was significantly closer to

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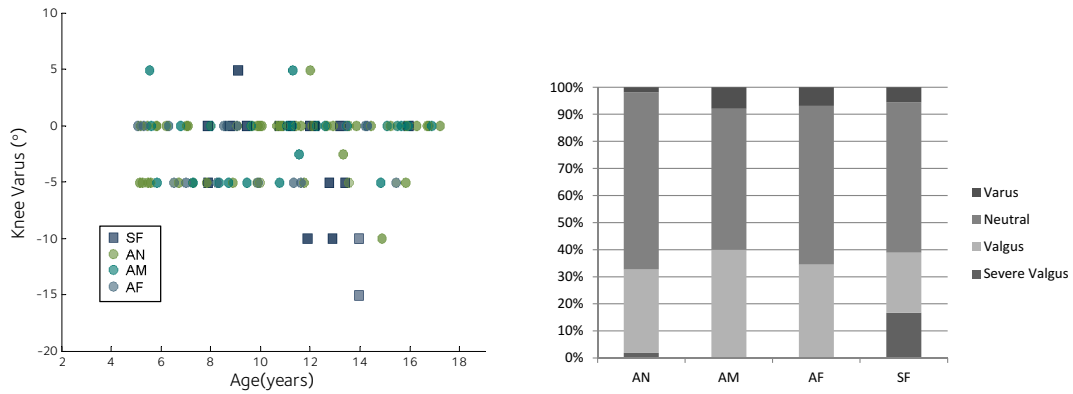


Figure 6.8.: Knee varus with age and categories. Severe valgus  $\leq -10^\circ$ ;  $-10^\circ < \text{valgus} < 0^\circ$ ; neutral =  $0^\circ$ ;  $0^\circ < \text{varus}$ .

zero degrees when measured by clinicians. Studies have found lateral rotation of the tibia increases from approximately  $5^\circ$  at birth to approximately  $15^\circ$  at maturity [164]. The results of our study were therefore a little higher than would be expected in the asymptomatic groups. The clinical measure of tibial torsion is notoriously unreliable, and awkward to estimate. It involves the tester attempting to quantify the external rotational twist in the tibia, by evaluating the axis through the malleoli of the ankle, relative to an axis through the tibial condyles. The OGL has tested and found its accuracy to be  $\pm 20^\circ$ .

The Oxford Foot Model can calculate an estimation of a similar parameter: knee to inter-malleolar axes. This measure is more repeatable as it avoids the awkward estimation procedure that the clinical measure requires. The mean values of this parameter were closer to the expected norms (Fig. 6.10). The reduction in tibial torsion associated with the symptomatic group was insignificant.

Since data on the symptomatic group were collected on average a longer time ago, most likely by different clinicians, this may have affected the clinical estimates. Another explanation would be that the clinicians may have expected a more “deviant” result from symptomatic cases. Finally, since the change in statistical descriptors is small, it may have become “insignificant” purely as a result of chance. Perhaps this could indicate that the study was underpowered, or that the result applies to a par-

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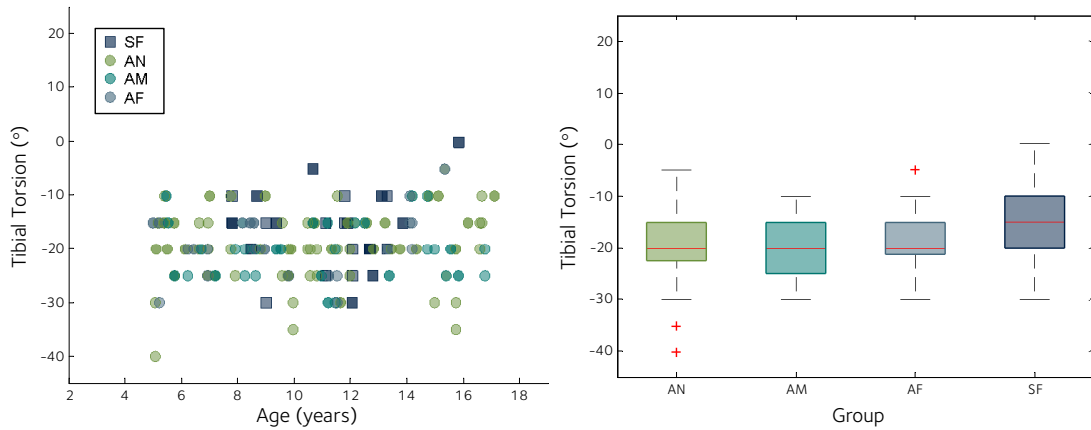


Figure 6.9.: Clinical measure of tibial torsion versus age and between categories. Negative tibial torsion indicates the malleolar axis is externally rotated relative to the axis of the tibial condyles. It appears to be closer to zero in the symptomatic cases of flatfoot. On the box plot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

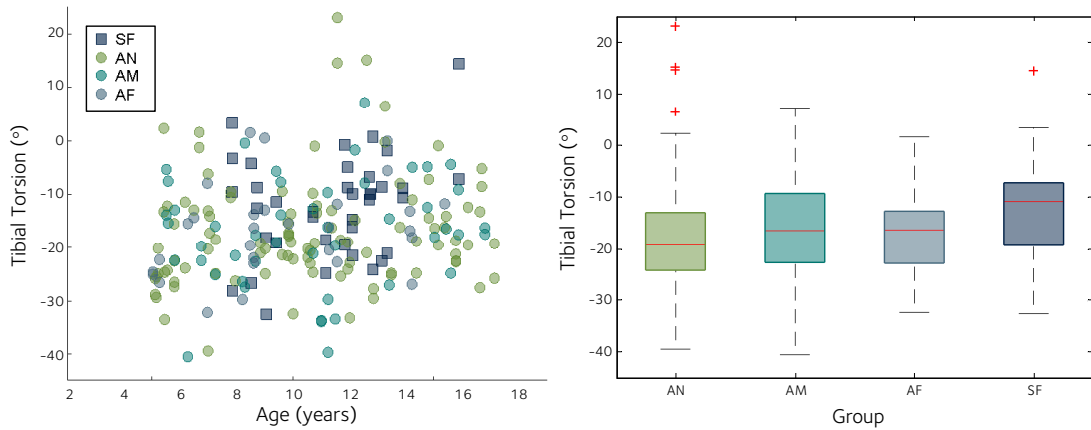


Figure 6.10.: Oxford Foot Model measure of tibial torsion versus age and between categories. Negative tibial torsion indicates the malleolar axis is externally rotated relative to the knee joint axis. The difference between the AN and SF group is no longer statistically significant. Of the box plot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

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ticular subset, therefore this is a “parameter to watch” in future studies. A discovery of bony differences in the SF or AF groups would be highly significant, particularly if beyond the foot.

### 6.5. Flexibility

Again, the range of angles recorded was large even within the normal population. Of the hip angles, there was a decrease in the hip internal rotation and hip abduction with age (Fig. 6.11). This is in line with the decrease in flexibility reportedly occurring prior to puberty [2]. Initially it was thought that the clustering of patients with hip extension of zero degrees or less was significant; however, sometimes this test had been performed on patients as Thomas’s test. Therefore a zero value had been recorded when the subject was able to get to a neutral position or beyond.

Most of the knee angle measurements do not have a large enough range to ascertain a relationship with age (Figs. 6.12); however the popliteal angles do appear to be age related, with the maximum angles occurring around puberty. Knee hyper-extension was more likely to present in the symptomatic population (Fig. 6.13): 15 out of 34 (44%) symptomatic feet had an associated knee hyper-extension greater than five degrees, whereas this presented in only 31 out of 172 (18%) of those in the asymptomatic population, and was particularly rare among those with asymptomatic flatfoot.

Ankle dorsiflexion appeared to decrease slightly with age (Fig. 6.14). However much more striking is the strong association of limited ankle dorsiflexion with the presence of symptoms. With the knee extended, 38% of the normal population had a dorsiflexion angle of 10 degrees or less; 76% of the symptomatic population had this problem. With the knee flexed, the reduced range of motion was present in 10% of the asymptomatic population yet 65% of the symptomatic population. The limited range of motion cannot be attributed to ligamentous laxity - which would normally

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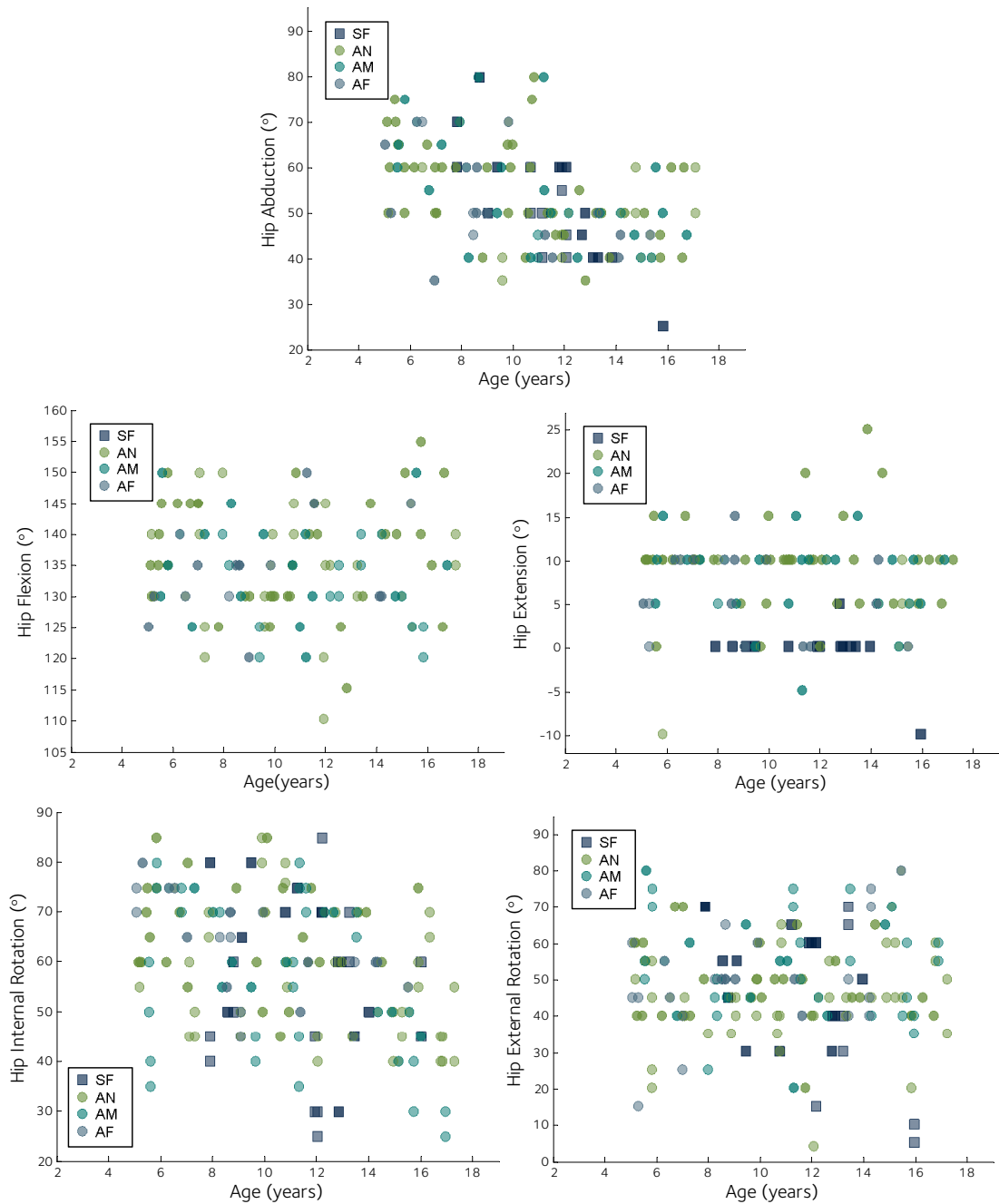


Figure 6.11.: Hip abduction, flexion, extension, internal, and external rotation angles versus age. Ranges of motion may decline with age. Negative hip extension indicates contracture and inability to achieve extension. The patient group records a lower hip extension.

## 6. Passive and static characteristics

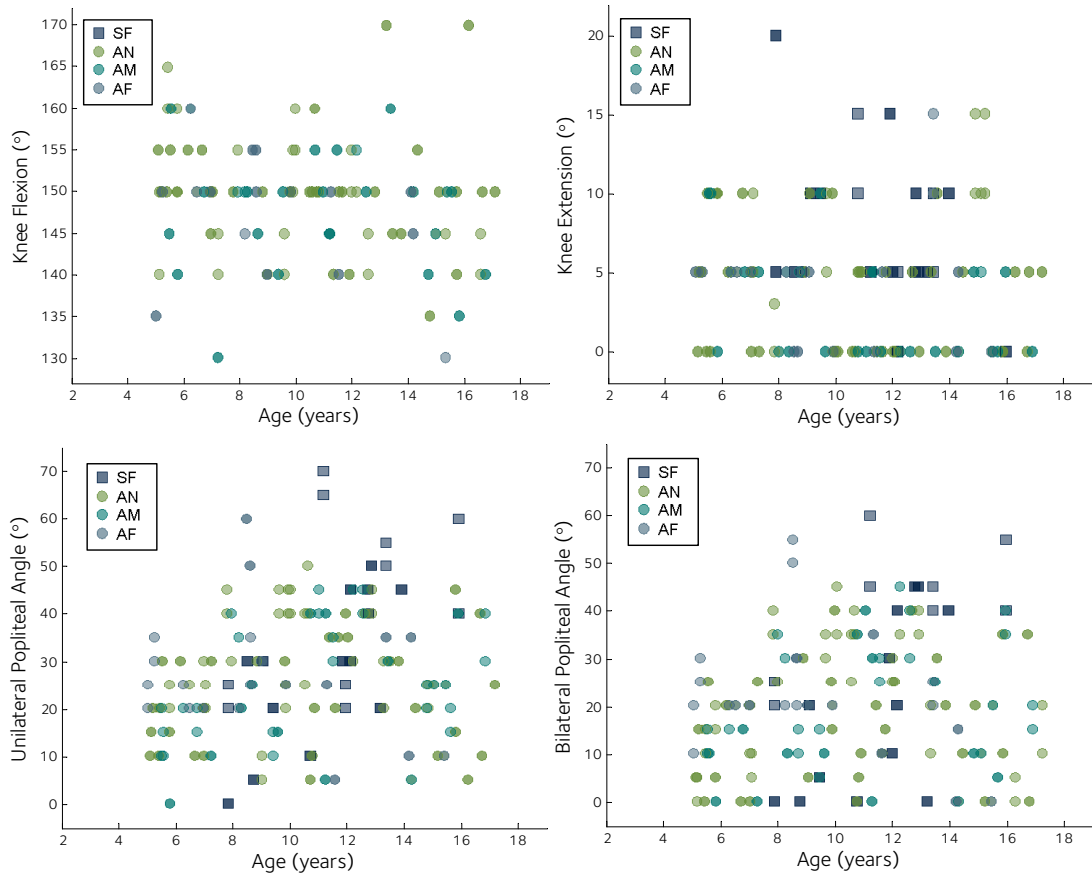


Figure 6.12.: Knee flexion, extension, and popliteal angles versus age.

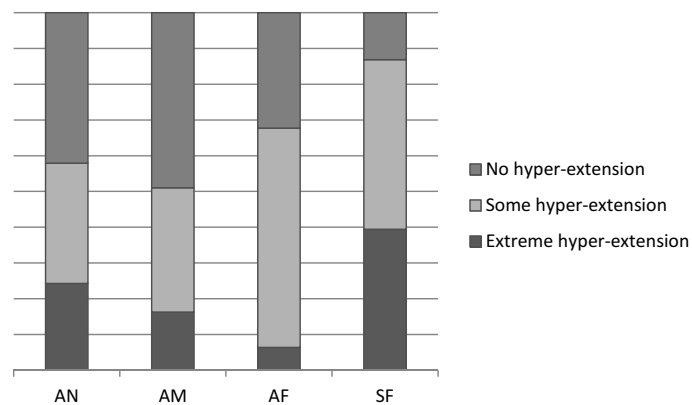


Figure 6.13.: Knee Hyper Extension (KHE) proportions in groups. None -  $KHE \leq 0^\circ$ ; some -  $0^\circ < KHE \leq 5^\circ$ ; extreme -  $KHE > 5^\circ$ .

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be associated with increased, not decreased, mobility. Limited ankle dorsiflexion has long been associated with flatfoot [62]. The length of the triceps surae is usually the cause of the ankle dorsiflexion limit (i.e. gastrocnemius, soleus, and tendo-Achilles). Our results appeared to fit with this picture. There is some evidence that the gastrocnemius muscles of flat feet may be more active, which may lead to contracture. Additionally, the activation of this muscle would result in further collapse of the medial arch owing to the Achilles tendon attachment at the posterior end of the calcaneus. It is not known if the collapse of the arch causes the contraction; however Figure 6.14 may offer a clue. These results may indicate that arch collapse does not cause the contracture, as the asymptomatic flat feet were not associated with the same limitation to dorsiflexion. It has been previously claimed that the shortening is secondary [64], but the evidence is limited.

### 6.6. Using the OFM to assess static foot posture

The Oxford Foot Model (OFM) is a clinically tested and validated model [167] used to assess foot motion during walking. This section aims to use relevant components of the OFM and Plug-In Gait model to provide quantitative foot posture assessment during static stance. An assessment of components which distinguish neutral, flat, and symptomatic flat feet is presented here.

The data collection is described in detail in Chapter 4. Mean values of each of the 14 Euler angles of the lower limbs were calculated during three seconds of quiet standing (frames were excluded if there was a large fluctuation in the Vertical Ground Reaction Force). Each foot was treated as an independent sample and ANOVA tests were used to assess whether angles differed between groups.

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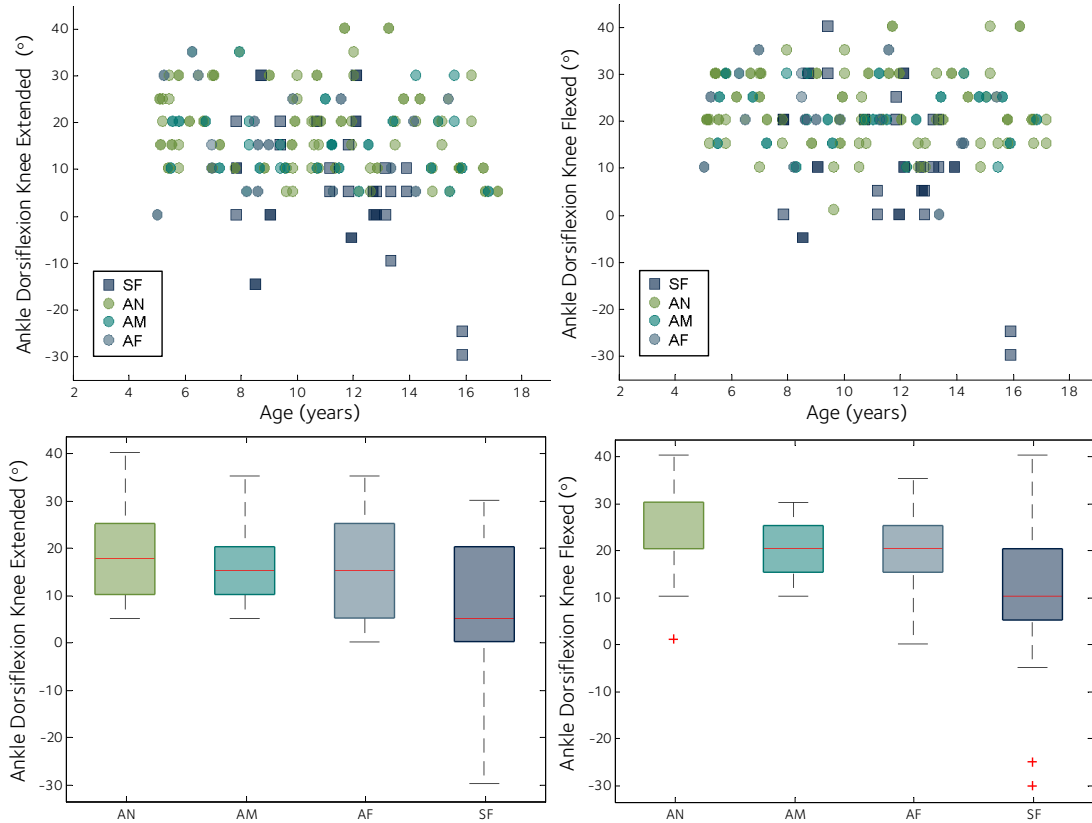


Figure 6.14.: Ankle dorsiflexion variation with age and between groups. Negative values indicate inability to achieve dorsiflexion, this permanent plantarflexion is called equinus, normally due to shortened triceps surae. On the box plot, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

## 6. Passive and static characteristics

### 6.6.1. Multiple statistical tests

Large scale multiple testing of a number of hypotheses can be statistically problematic. The familywise error rate (type I error) is the probability that a significant result may have occurred at random as a result of error (such as sampling error). The theory is that if enough tests are carried out, statistical significance will be achieved even if the finding is erroneous and the result of chance. The popular solution for this is p-value adjustments (reducing the p-value required for statistical significance) such as the Bonferroni correction (generally attributed to Dunn [40]).

The original idea for adjustments was first theorized in the 1920s [120]. Neymen and Pearson were however not concerned with a variety of comparisons, but with repeated tests. In their case, they were interested in repetitive testing within industry - in rates of defective materials, and multiple samples within lots. This is quite a different scenario from what is happening in this research. Indeed if similar tests were being run it would be appropriate to apply such a correction. If only one of twenty papers testing a particular hypothesis found it to have a p-value less than 0.05, it would appear that this type of correction would be appropriate.

However in most science a variety of tests are carried out. So it is unclear over what data the correction should be implemented. Over an author's career? Over a journal? Per statistical test run on one question? If 20 individual papers are produced each running one statistical test with a familywise error rate of 5%, we may expect one of the results to be the result of chance. This is generally acknowledged in science, and one contrary paper is unlikely to alter the consensus.

Additionally, it has been argued that if the chance of making a type I error is reduced, the chance of making a type II error (false negatives) is increased [149]. Unexpected results, may be the false positives that are the result of probability, or may be genuine but unexpected leading to revelations and greater understanding. It may be better to be aware of results that may be proved to be false negatives than to discard those

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false negatives alongside false positives in certain types of study.

So, if false positives cannot be guaranteed against by corrections it would seem more prudent to limit sources of the original error; that is, to concern ourselves with sampling and other errors. Errors caused by equipment, methods, and processing should be limited where possible. And an effort should be made to ensure sampling is representative. Interpretation of results should be cautious of false positives as these can never be eliminated.

An additional note should be made that, while corrections can easily be made when the test statistics are independent, they are overly conservative in cases where data is correlated, such as in this study. For example, heel eversion is associated with external rotation at the heel, and valgus at the knee among other things. If the variability was random and not the result of a network of factors related by causal connections, such as joints, this would be a highly worrying phenomenon and would create significant questions over the understanding of biomechanics. Additionally it should be noted that the presence of a false positive will increase the probability that there are more false positives due to the high degree of interdependence.

In conclusion no corrections will be made to the significance level on the basis of multiple tests for two key reasons. Firstly, it is unclear over which set a correction would be appropriate. Secondly, the measures are highly dependent, and therefore the correction procedures are overly stringent. False positives can never be entirely eliminated, but then neither can false negatives, so cautious interpretation of results is warranted.

### 6.6.2. Choosing statistical tests

Tests for kurtosis and skewness revealed that all of the variables tested were normally distributed (Table 6.5). Non-normality could have been compensated for: skewness can be rectified with the Box-Cox transformation, while kurtosis can be

## 6. Passive and static characteristics

Table 6.5.: Skewness, kurtosis, and homogeneity of variance in static marker based angular measures. All skewness and kurtosis was within acceptable limits ( $-2 < \text{statistic} < 2$ ). Several variables failed the test for equality of variance

	N	Skewness		Kurtosis		Test for homogeneity of variance	
		Statistic	Std. Error	Statistic	Std. Error	Levene Statistic	Sig.
Hip flexion	214	-.050	.166	.730	.331	4.457	*.005
Hip adduction	214	.184	.166	.764	.331	2.631	.051
Hip internal rotation	214	.125	.166	-.105	.331	1.868	.136
FE-TB flexion	198	-.045	.173	-.265	.344	.071	.975
FE-TB varus	198	-.051	.173	.789	.344	3.586	*.015
FE-TB internal rotation	198	.169	.173	.213	.344	.496	.686
HF-TB dorsiflexion	196	-.566	.174	1.832	.346	.222	.881
HF-TB internal rotation	196	-.168	.174	.938	.346	1.864	.137
HF-TB inversion	196	-.263	.174	.340	.346	1.492	.218
FF-HF dorsiflexion	196	.378	.174	1.640	.346	.320	.811
FF-HF adduction	196	-.257	.174	.835	.346	2.184	.091
FF-HF supination	196	.264	.174	-.041	.346	4.652	*.004
HX-FF dorsiflexion	190	.420	.176	.006	.351	2.889	*.037
HX-FF adduction	190	-.368	.176	.280	.351	.937	.424

addressed with a cube root or a sine transformation if it were necessary. However, all statistics were within acceptable limits and were left unmodified.

The next feature of the data tested was the equality of variances between groups – this test is “robust” against non-normality [136]. Levene’s test revealed that some of the variables had unequal variances: hip flexion, knee varus, forefoot supination, and hallux dorsiflexion. This created an issue over what post-hoc tests to use after the ANOVA. It is plausible that the variances are not equal, especially with the symptomatic group which is not fundamentally defined by the severity of the condition but by the presence of symptoms and may represent more extreme as well as a range foot types (there was a mild flatfoot amongst the flat feet of the SF group). Therefore for consistency throughout the thesis it was decided that significant results would have to meet the criteria of two tests: one which assumed the variances to be equal (Tukey) and one which did not (Games Howell).

### 6.6.3. Comparison between AN, AM, AF, and SF

These angles are not commonly reported in static stance so are not compared to reference data. Three tested angles were found to be different between groups (Ta-

## 6. Passive and static characteristics

Table 6.6.: Group sizes, means, standard deviations and one way ANOVA test. Group sizes vary because of variation in marker sets used. Brackets show between which groups significant differences exist by both Tukey and Games Howell post-hoc tests. Segments of the Oxford Foot Model are: FE - Femur, TB - Tibia, HF - HindFoot, FF - ForeFoot, HX - hallux.

STATIC STANCE	Groups	N	Mean	SD	ANOVA Sig.	Groups	N	Mean	SD	ANOVA Sig.
Hip Flexion	AN	96	5.92	8.16	.077	HF-TB Internal Rotation	AN	88	7.28	6.15
	AM	47	7.73	4.59			AM	45	8.94	6.31
	AF	29	7.88	6.06			AF	29	8.38	4.94
	SF	38	4.22	7.29			SF	30	9.70	7.64
	All	210	6.29	7.13			All	192	8.20997	6.30
Hip Adduction	AN	96	-4.21	3.42	*000	HF-TB Inversion	AN	88	-0.93	4.35
	AM	47	-3.53	3.09			AM	45	-4.03	5.23
	AF	29	-3.82	3.36			AF	29	-4.15	4.84
	SF	38	-1.18	4.49			SF	30	-8.38	6.60
	All	210	-3.46	3.71			All	192	-3.31	5.65
Hip Internal Rotation	AN	96	-3.43	6.63	.152	FF-HF Dorsiflexion	AN	88	-2.33	3.44
	AM	47	-5.73	7.30			AM	45	-3.06	3.21
	AF	29	-5.54	7.01			AF	29	-2.37	3.43
	SF	38	-5.84	8.24			SF	30	-3.28	4.82
	All	210	-4.67	7.18			All	192	-2.66	3.63
FE-TB Flexion	AN	88	-5.12	6.96	.471	FF-HF Adduction	AN	88	1.01	5.24
	AM	47	-5.38	6.55			AM	45	-0.07	5.59
	AF	29	-4.66	6.66			AF	29	-3.43	4.41
	SF	30	-3.04	6.99			SF	30	-8.42	6.83
	All	194	-4.79	6.82			All	192	-1.39	6.41
FE-TB Varus	AN	88	-0.04	2.73	.314	FF-HF Supination	AN	88	6.63	4.89
	AM	47	-0.27	3.55			AM	45	7.98	6.56
	AF	29	-0.93	2.52			AF	29	9.11	5.76
	SF	30	-1.11	4.05			SF	30	10.15	7.37
	All	194	-0.40	3.15			All	192	7.87	5.98
FE-TB Internal Rotation	AN	88	-17.47	8.43	.102	HX-FF Dorsiflexion	AN	82	-2.68	6.12
	AM	47	-17.43	9.75			AM	45	-0.03	8.46
	AF	29	-16.68	8.67			AF	29	-1.97	6.48
	SF	30	-12.91	9.59			SF	30	0.34	8.67
	All	194	-16.64	9.06			All	186	-1.44	7.30
HF-TB Dorsiflexion	AN	88	1.74	4.01	.580	HX-FF Adduction	AN	82	-1.14	4.83
	AM	45	1.13	3.94			AM	45	-1.37	5.71
	AF	29	2.42	4.15			AF	29	0.06	6.42
	SF	30	1.24	5.30			SF	30	0.87	6.52
	All	192	1.62	4.23			All	186	-0.68	5.62

ble 6.6). Still no significant differences were found between the AM and AF groups leaving the reasoning behind clinicians categorizing mild flatfoot, and flatfoot unclear. The absence of a significant difference between forefoot abduction in the AN and AM groups (yet differences between other groups) may however indicate that this was one of the deciding factors.

The Symptomatic Flat feet were associated with reduced abduction at the hip (Table 6.6, Fig. 6.15). These results were based around relatively small mean differences, likely the result of changes further down the limb such as knee valgus.

No significant differences were found at the knee during static stance (Table 6.6 and Fig. 6.16). Although excessive passive (non-weightbearing) knee valgus had been

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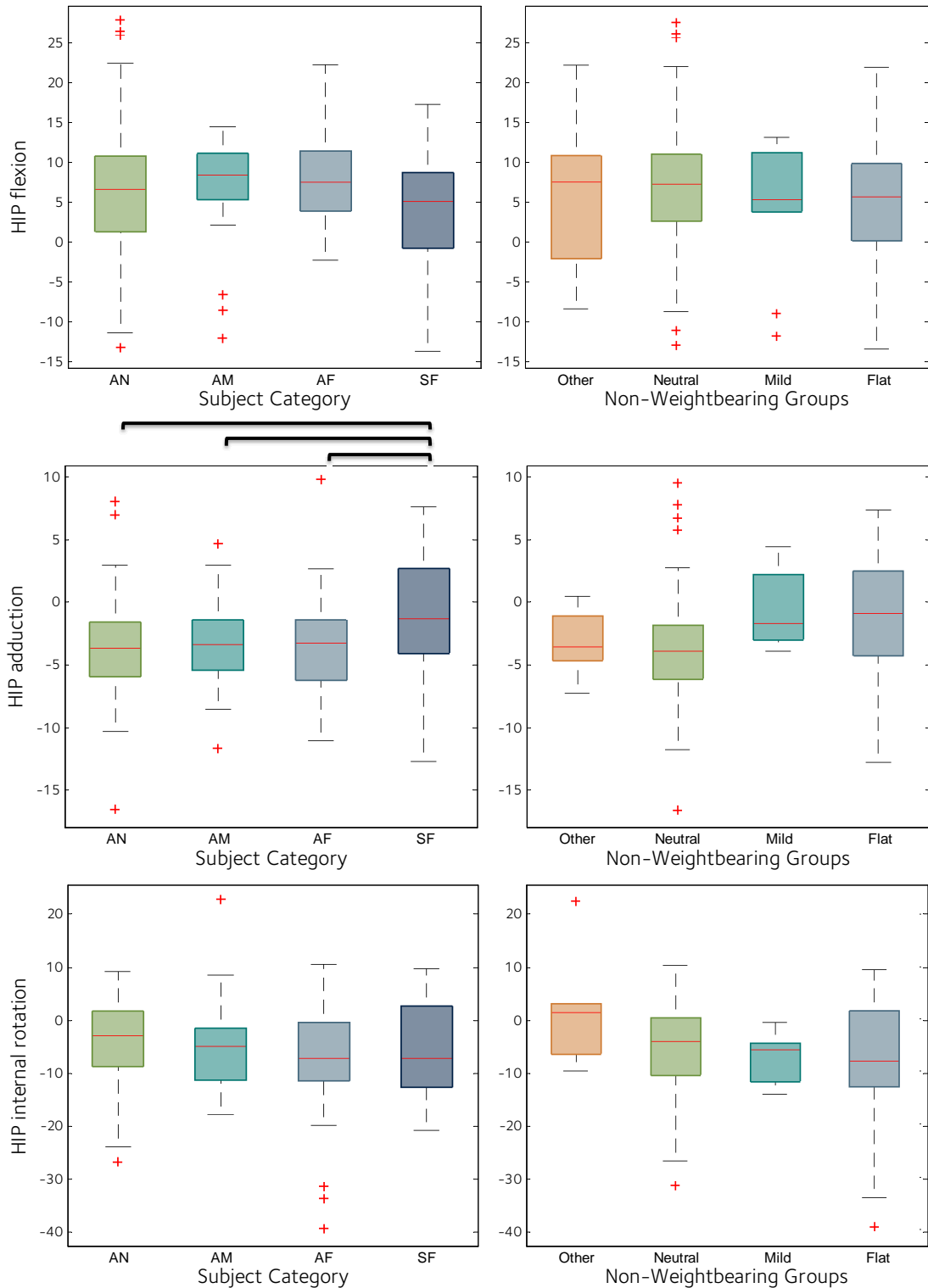


Figure 6.15.: Hip flexion, adduction, and internal rotation during standing. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Overhead brackets show between which weightbearing subject category groups both Tukey and Games Howell post-hoc tests found significant differences.

## 6. Passive and static characteristics

found to be associated with Symptomatic Flatfoot (Section 6.4), this result was not found to be significant during standing, although a trend remained.

Correlating static standing marker-based to non-weightbearing physiotherapist estimates of knee valgus revealed a moderate correlation ( $r=0.445$ , Fig. 6.17). It may have been differences between weightbearing and non-weightbearing posture that was responsible, or error of clinician or marker placement. The non-weightbearing clinician estimates were also within a smaller range. One study specifically investigating non-weightbearing to weightbearing knee motion found a mean  $2.3^\circ$  varus excursions in women and  $1.4^\circ$  in men [158]. Our results did not display this varus bias, and recorded much larger values of excursion perhaps due to large sources of error.

Flatfeet have significantly greater hindfoot eversion relative to the tibia than Asymptomatic Neutral feet (Table 6.6, Fig. 6.18). This may not be entirely surprising since hindfoot eversion is one of the key components the clinicians looked for when assessing flatfoot and one of the components of the FPI - although in the case of the FPI it is compared to vertical rather than to the long axis of the tibia. There was no difference between Asymptomatic cases of Mild flatfoot and Flatfoot. The same trend could be observed in the constituent categorizing methods (FPI, weightbearing and non-weightbearing). Hindfoot eversion is consistently referred to in literature as associated with flatfoot [64, 72, 104].

The forefoot was more abducted relative to the hindfoot in cases of Asymptomatic Flatfoot and Symptomatic Flatfoot (Table 6.6, Fig. 6.19). This was not the case for Asymptomatic Mild flatfoot, which was indistinguishable in this regard from the Neutral group. Perhaps this measure reflects the degree of midfoot break and therefore clinicians regard flat feet without this feature as a mild version. There was only one example of "mild" flatfoot in the symptomatic group. The subject was generally weak on the Medical Research Council (MRC) scale for muscle strength (grade 3-4), had neutral feet non-weightbearing, and one mild flatfoot and one flatfoot during weight-

## 6. Passive and static characteristics

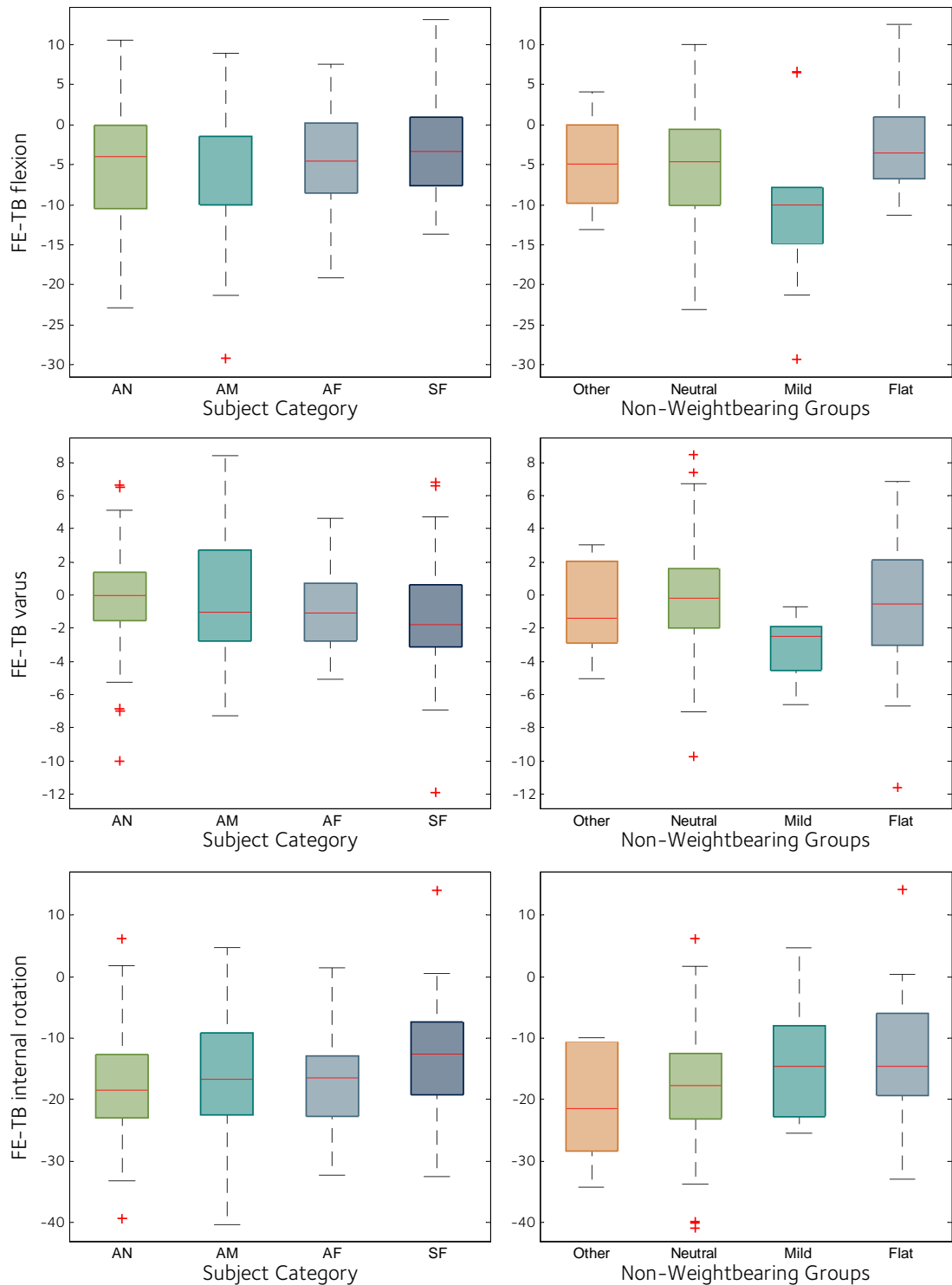


Figure 6.16.: Knee (femur-tibia) flexion, varus, and internal rotation during standing. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. No significant differences were found between weightbearing subject category groups.

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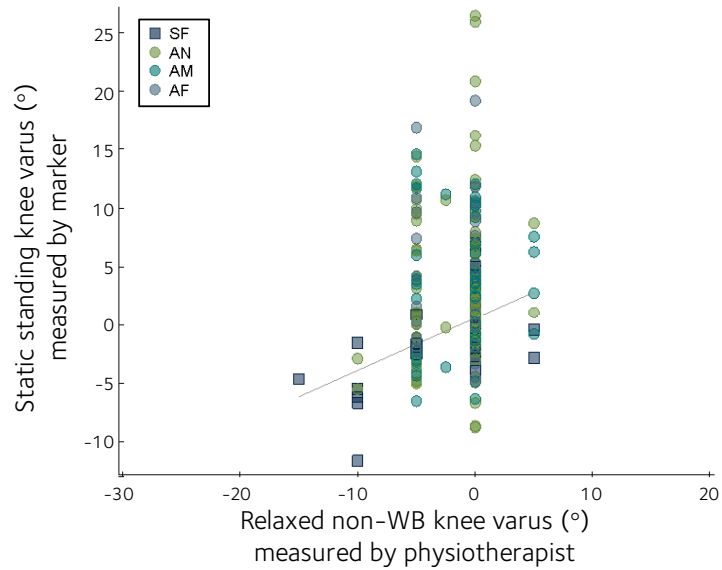


Figure 6.17.: Varus as measured during weightbearing by marker versus non-weightbearing (non-WB) by physiotherapist.

bearing. The flatfoot had forefoot - tibia adduction of  $2.8^\circ$  and forefoot to hindfoot abduction of  $2.3^\circ$ . The forefoot - tibia adduction puts it just inside the 75th percentile for this group. The forefoot - hindfoot abduction is not within the 75th percentile for Symptomatic Flatfoot. It is in fact closer to the mean of a Asymptomatic Neutral or Mild flatfoot. It may be this reduced abduction which led to its classification as a "mild" case of flatfoot. The Asymptomatic Mild flat feet and Neutral feet are similar in terms of abduction by all three classification techniques. The abduction may be reflected in the reports of textbooks of abduction of the forefoot on the hindfoot at the midtarsal joint, and increased angle of gait [64, 72, 104]. This could reflect the same aspect highlighted by previous comparisons between asymptomatic and symptomatic flatfoot - namely increased lateral displacement of the navicular on radiographs [109, 192].

No significant differences were found at the hallux (Table 6.6, Fig. 6.20). The trends in the flatfooted groups were towards dorsiflexion and adduction of the hallux (hallux valgus) relative to the forefoot.

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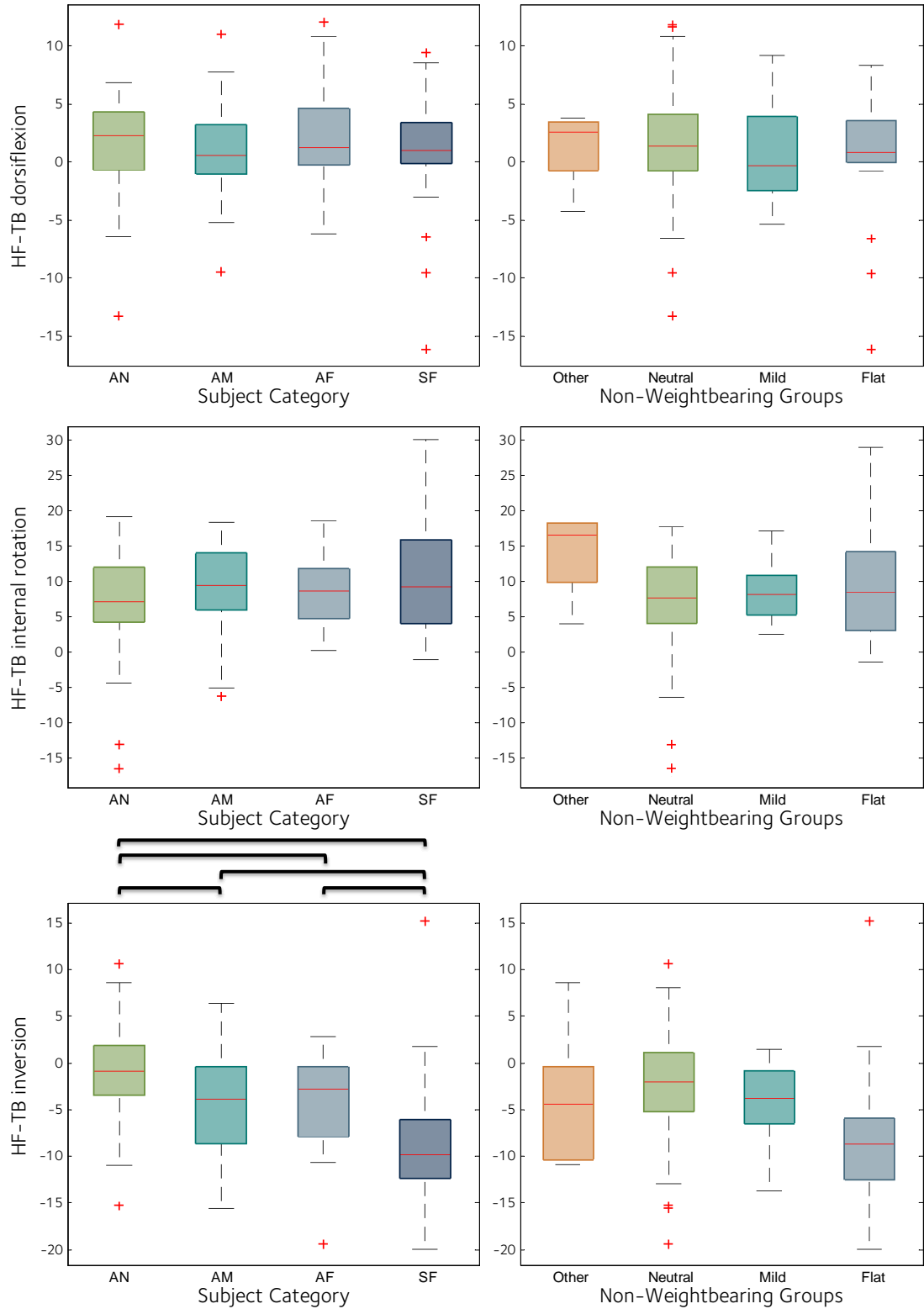


Figure 6.18.: Standing knee dorsiflexion, internal rotation, and inversion during standing. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Overhead brackets show between which weightbearing subject category groups both Tukey and Games Howell post-hoc tests found significant differences.

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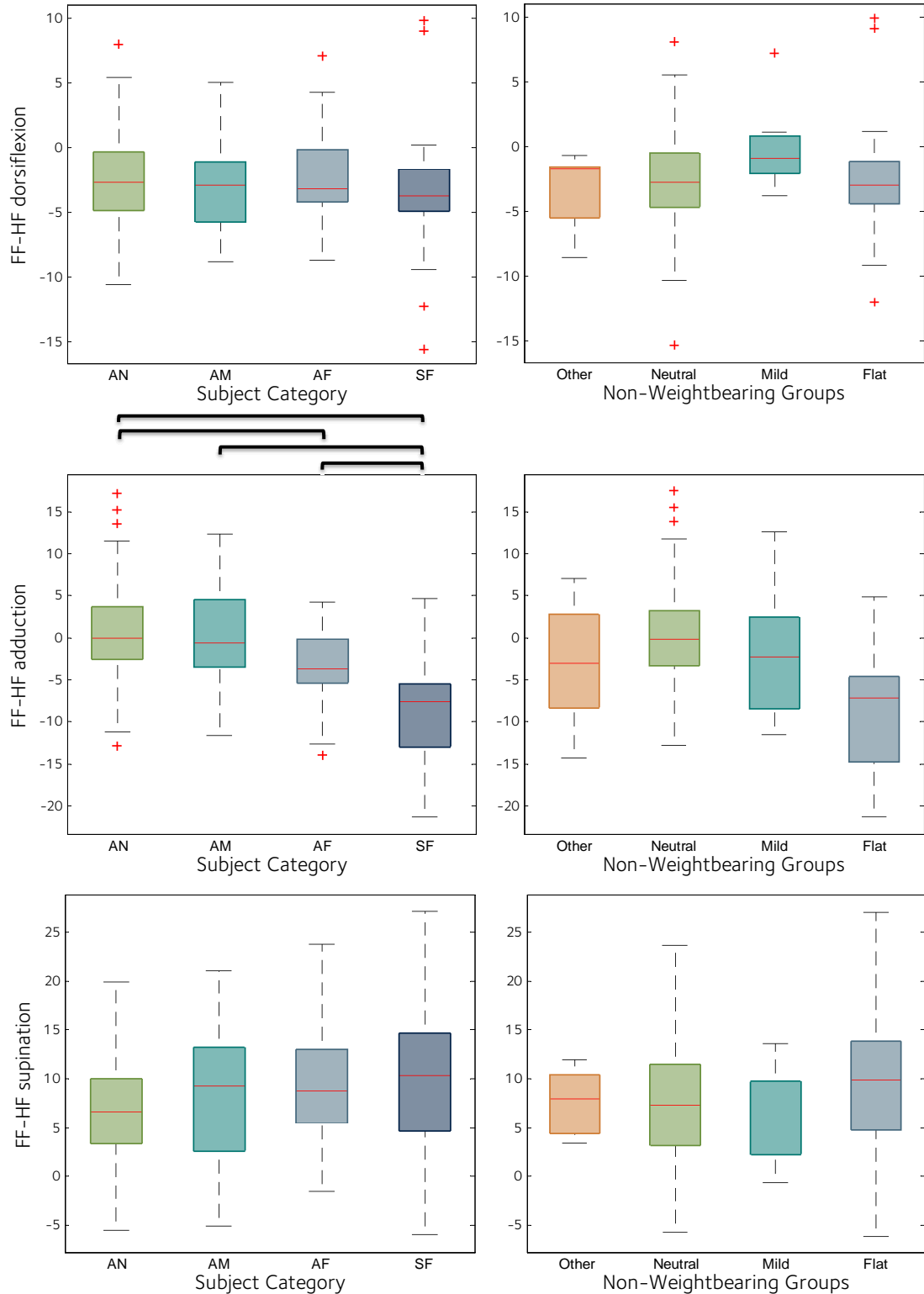


Figure 6.19.: Standing FF-HF dorsiflexion, adduction, and supination during standing. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Overhead brackets show between which weightbearing subject category groups both Tukey and Games Howell post-hoc tests found significant differences.

## 6. Passive and static characteristics

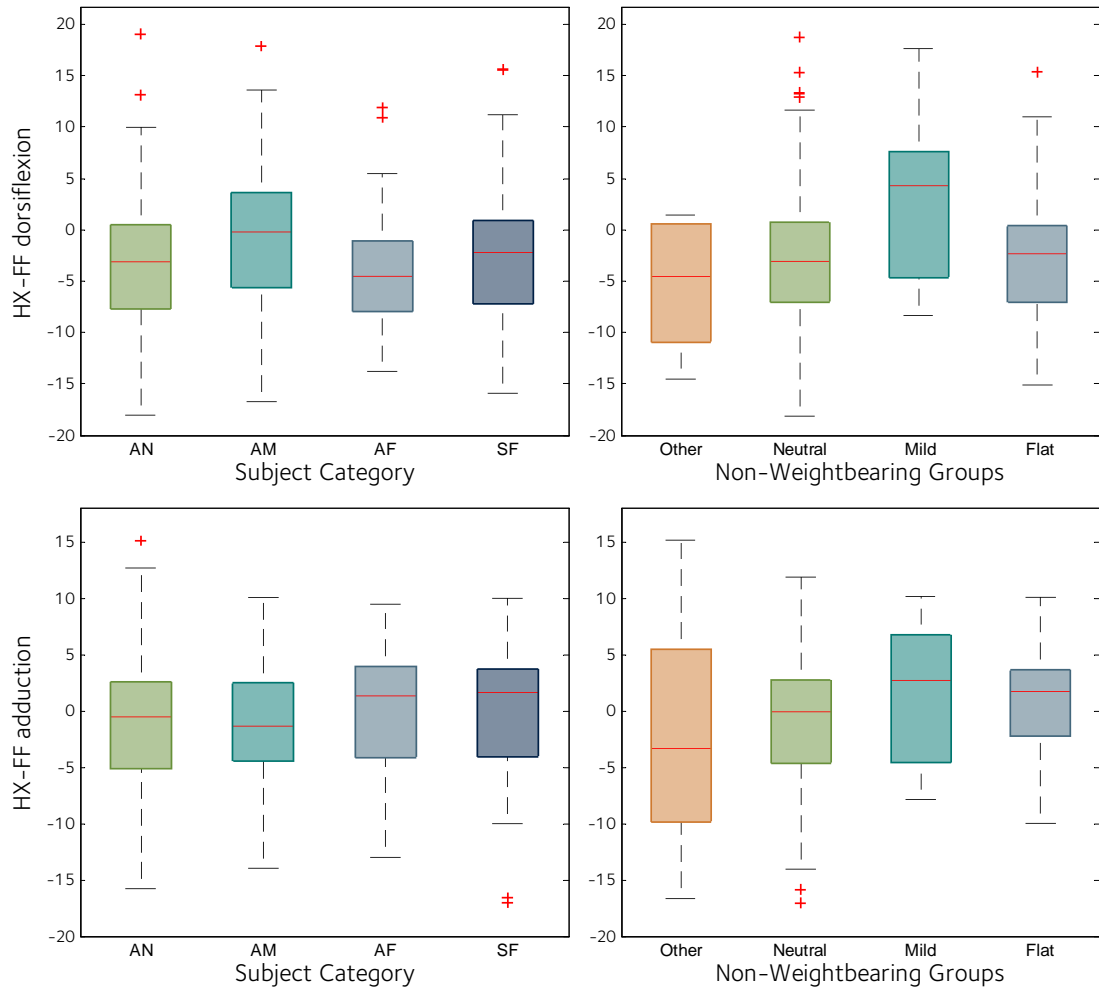


Figure 6.20.: Standing hallux - forefoot dorsiflexion and adduction during standing. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Overhead brackets show between which subject category groups both Tukey and Games Howell post-hoc tests found significant differences.

## 6.7. Summary

One hundred and twenty seven participants aged between 0.8 and 17.3 years were included in the study. Of this group, only two were classified as obese.

Flat feet were common among the asymptomatic population. Feet were more likely to be classified as flat by physiotherapists during weightbearing than non-weightbearing (45% versus 7% for asymptomatic population). Upon weightbearing, 45% of non-weightbearing neutral feet change to a non-neutral foot posture. Of the feet that appear to be mildly flat during non-weightbearing, 45% change to a more exaggerated posture during weightbearing.

Some measures were found to be no more similar among left and right legs of a subject than between left legs of subjects from the same category. This was particularly evident at the foot and ankle, presumably because group homogeneity was stronger than individual homogeneity. It was therefore decided to include measures from both legs in the study, but encourage a cautious interpretation of results (particularly the results at joints which are further from the foot).

Of the clinical examination measures, four presented differently in the group recruited as patients: severe knee valgus, knee hyper-extension, and limited ankle dorsiflexion with knee extended and flexed. Two of these at the knee could potentially be related to ligamentous laxity: excessive knee valgus and hyperextension at the knee. The limited dorsiflexion measures at the ankle may be the product of contracture of the triceps surae. While the contracture is known to exacerbate flat foot, that both groups with asymptomatic flatfoot did not present such extreme values indicates that flatfoot cannot on its own be responsible for the Achilles contracture that results in limited dorsiflexion.

The marker-based assessment produced some significant results. Three measures were distinguishable between groups. Heel eversion was strongly correlated with foot

## 6. Passive and static characteristics

type. Symptomatic Flat feet were differentiated by excessive forefoot abduction and reduced hip abduction. The forefoot abduction may reflect the previous finding of radiographic studies that demonstrated increased navicular displacement was associated with the onset of symptoms [109, 192]. There is good evidence therefore that increased forefoot abduction may be able to predict developing symptoms, a longitudinal study would be required to confirm this. Marker based assessment may provide objective measures of important characteristics. It is more sensitive than the FPI and can quantify not only foot posture but deviations more proximally such as knee valgus and hip adduction.

With passive characteristics and static foot structure having been explored with respect to the differences between asymptomatic and symptomatic populations, the next step is to consider dynamic foot posture in these populations. The chapter to follow will develop methods to analyse the behaviour over the stance phase of gait.

## 7. Event Timings

Time series of data cannot be analysed in the same way as static values can. This chapter explains how specific time points that were suitable for analysis were selected. Firstly the chapter explores the timing of events during the gait cycle. It explores variation in stride and stance durations. It then examines four definitions of midstance: by 50% stance, by foot model markers, by tibia, and by Ground Reaction Force (GRF) event. By analysing the intra-subject variation of these definitions, the GRF-based method is chosen as the most repeatable method, and will be used in subsequent chapters to define midstance.

### 7.1. Introduction

A key aim of this thesis is to study the characteristics of flat feet during walking. To analyse something over a continuous period of time is not trivial.

The first step is to create an exemplar for each subject from the several trials that have been collected. There is natural intra-subject variation in walking patterns. Typically, in the world of clinical gait analysis a “representative trial” is selected by the clinician.

## 7. Event Timings

However, since this selection is subjective, this was not favoured in this study. The SMaRT is one method to select the representative trial [153]. It was chosen for use in the present work as it is objective and can handle any number of variables which do not need to be independent (as the method involves a Principal Component Analysis). This results in the selection of a single trial for all variables.

Selection of a representative trial does not solve the problem of comparing of temporally diverse data. There is significant inter-subject variation in terms of event timing; for example, time to the point at which a maximum value is attained. In this case there was a particular concern because Merriman states that flatfoot is associated with early heel rise [104] (possibly due to tightness of the tendo-Achilles), which could be a confounding factor depending on the method of analysis. The common clinical practice is to calculate an average trace for control subjects ("normal data"). The patient is then compared to the normal data. Calculating an average of temporally diverse data (Fig. 7.1) can result in problems:

- Loss of local features. For example, in the middle of Figure 7.1, the non-averaged trials include a small oscillation which could be important, however, upon averaging this feature is completely obscured. This is very difficult to avoid if large numbers of traces are analysed.
- Record of significantly lower peaks. For example, early peaks of Figure 7.1 range from 9 to 12 with a mean value of 10.4, whereas the average trace has a maximum value of 7, lower than any individual trace. The late peaks range from -10 to -12 with a mean of -10.8, whereas the average trace peaks at -8.4. This averaged trace has a maximum and minimum 67% and 78% of the average of the individual maxima and minima respectively.
- Data sets with greater (temporal) variation average to a flatter pattern.
- Comparisons may indicate differences in magnitude and pattern where there were actually differences in timing. For example, in Figure 7.2, for data sets A

## 7. Event Timings

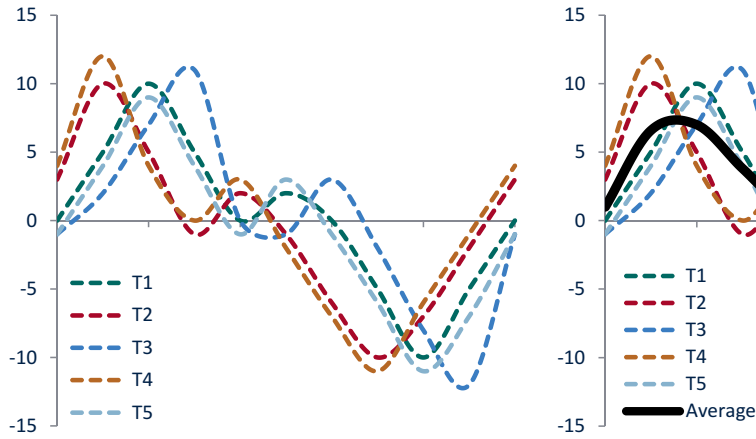


Figure 7.1.: Example data (left) with average trace (right), featuring early peak, local minima and maxima, and late trough. The average trace records lower peak values, the loss of the local peak, and a flatter overall trace.

and B an analysis of peaks would indicate the maxima and minima of the average of A to be 9.3 and  $-8.3$ , compared to those of B to be 11 and  $-11$  respectively. The true average maxima and minima were 11 and  $-11$  for both set A and B. Additionally, comparing at any timepoint would be misleading, as it is clear that set A is shifted temporally. Furthermore, the small oscillation present in the individual traces comprising set A has disappeared during the averaging process. Sets with higher temporal variability, when averaged appear to be sets with lower peaks. Comparison of time points may not result in the comparison of similar features across different groups leading to misleading results.

Taking a simple sine curve it can be shown that it is the timing of events that creates this problem, not variation in magnitude or shift in range. In Figure 7.3, a periodic sine function (equation 7.1) was perturbed by a normally distributed random variable with a standard deviation of 0.2. The function was perturbed in magnitude (equation 7.2), shifted on the y axis (equation 7.3), or shifted on the x axis (equation 7.4):

$$y = \sin(2\pi x), \quad (7.1)$$

$$y_1 = N(1, 0.2) \sin(2\pi x), \quad (7.2)$$

## 7. Event Timings

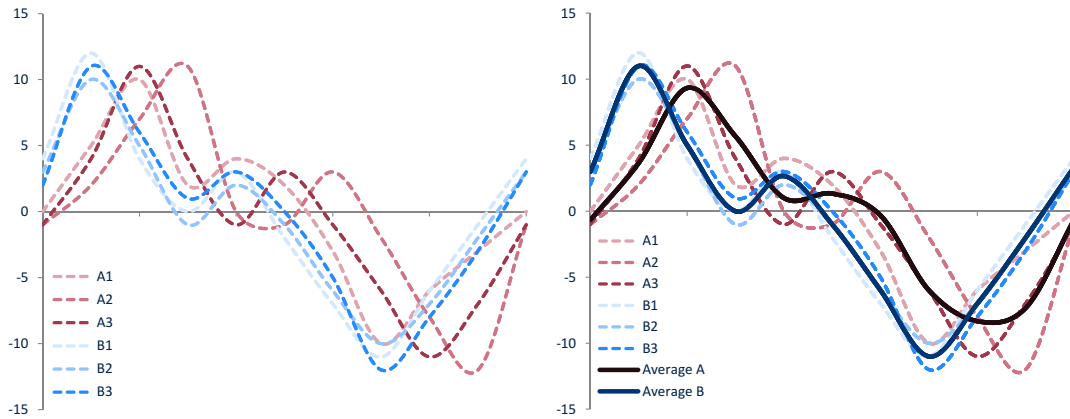


Figure 7.2.: Two sets of example data (left) with two average traces (right), featuring early peak, small feature, and late trough. Average A is the mean of traces A1, A2, and A3. Average B is the mean of traces B1, B2, and B3. The results are confounded by temporal difference, whereas they record differences in magnitude.

$$y_2 = N(0, 0.2) + \sin(2\pi x), \quad (7.3)$$

$$y_3 = \sin(2\pi(x + N(0, 0.2))), \quad (7.4)$$

where  $N(a, b)$  is a normally distributed variable with mean  $a$  and standard deviation  $b$ .

The perturbation of magnitude and shifting the curve vertically will not create a bias in the average. The average trace is an unbiased approximation of the true relationship (Fig. 7.3). The residuals are symmetrical about zero. An average that is based on increased numbers of samples reduces the residual error.

Conversely, horizontal perturbations create systematic bias that cannot be solved by increased sampling. It is clear that the average curves do not represent the unperturbed relationship (Fig. 7.3). Increasing the number of samples does not rectify the problem, in fact increasing the number of samples reduces the likelihood of revealing the true relationship.

It is clear that curves are often complex, and may or may not contain a high level of commonality. The curves can be analysed using a wide variety of techniques [114]. “Registration” can be used to reduce the effect of variation in event timing, but warps

## 7. Event Timings

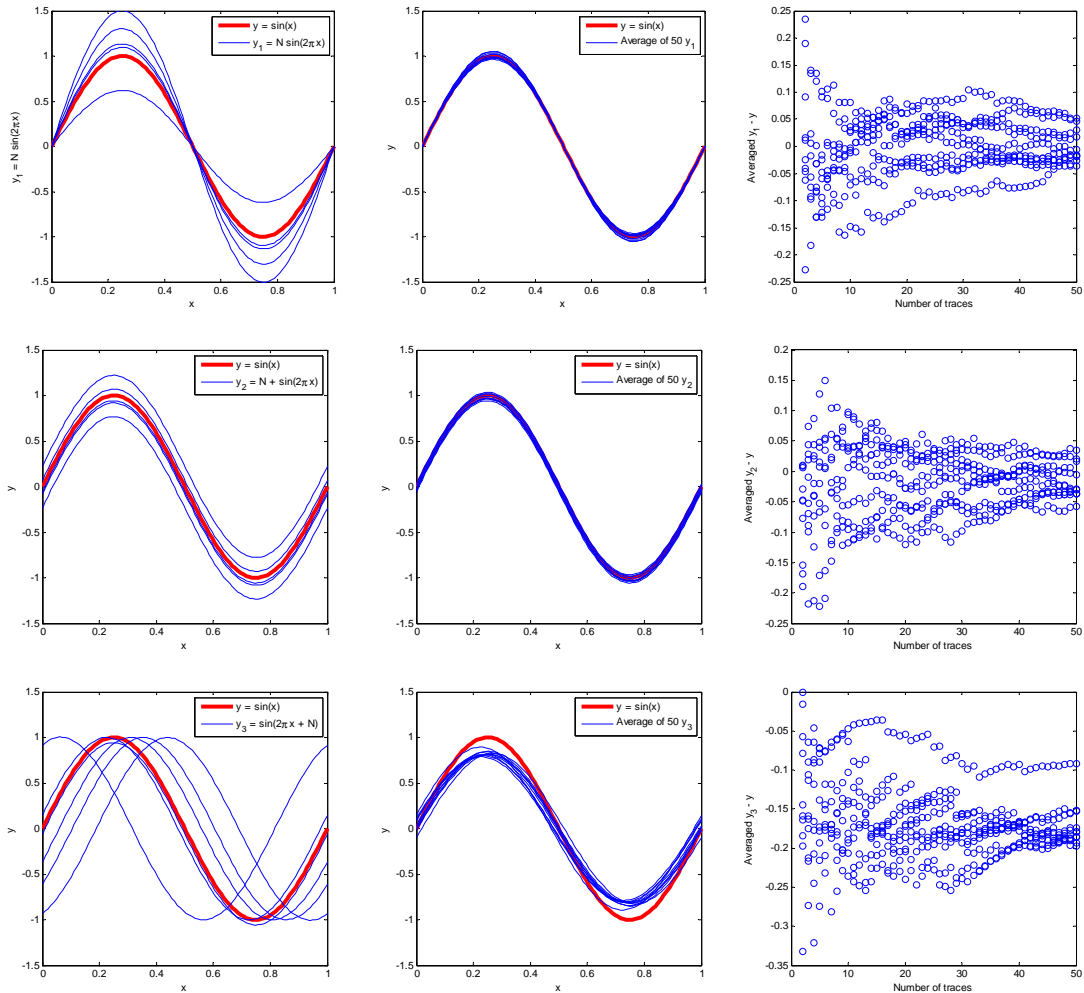


Figure 7.3.: Demonstrating the problems of averaging data which is not in phase. (left) Graphs illustrate five random curves from the distribution. (centre) Graphs show 10 averaged sets of 50 perturbed curves and the unperturbed (true) signal. (right) Graphs show the effect of increasing sample size on difference from unperturbed signal, i.e. the difference between an average trace based on a certain number of samples and the “true” original signal. Perturbations are magnitude (top), vertical shift (middle), horizontal shift (bottom).

## 7. Event Timings

the sample into something unnatural. Bootstrapping has gained some recognition [26], but does not address the issue of temporal variation. Neither method is truly widespread. Since the purpose of this thesis was not to develop or back particular methods, standard, simple, and transparent methods that would facilitate comparison with other studies were used. For statistical purposes the use of tests at functional time points - maxima, minima, foot strike, foot off, etc - would allow valid comparisons that are unaffected by variation in timing.

### 7.2. Gait events

During the gait cycle, each limb goes through a phase of weightbearing called stance, and a period of advancement called swing (Fig. 7.4). Approximately 60% of the time is spent in stance, and 40% in swing in normal adults [116]. The first and last 10% of stance is typically spent with both feet in contact with the floor (double stance) transferring weight from one leg to another.

Progression is principally governed by two forces. The first is generated by the swinging limb which starts with foot off. Foot off is therefore an important source of propulsion, and is a clearly defined and functionally relevant event to investigate. The second is caused by the forward fall of bodyweight which begins as the ankle dorsiflexes during single leg support. The momentum generated by these actions is preserved through the next stance phase by floor contact with the heel. Heel strike is therefore another important functionally relevant well defined event during gait.

During stance, between foot strike and foot off, the heel, ankle, and forefoot can be seen as acting consecutively as rockers; allowing the body to advance over the supporting foot. There are three defined stages. Loading response - the heel rocker - whereby weight is transferred to the leg. Midstance - the ankle rocker - the period, dominated by momentum, with both forefoot and hindfoot in contact with the

## 7. Event Timings

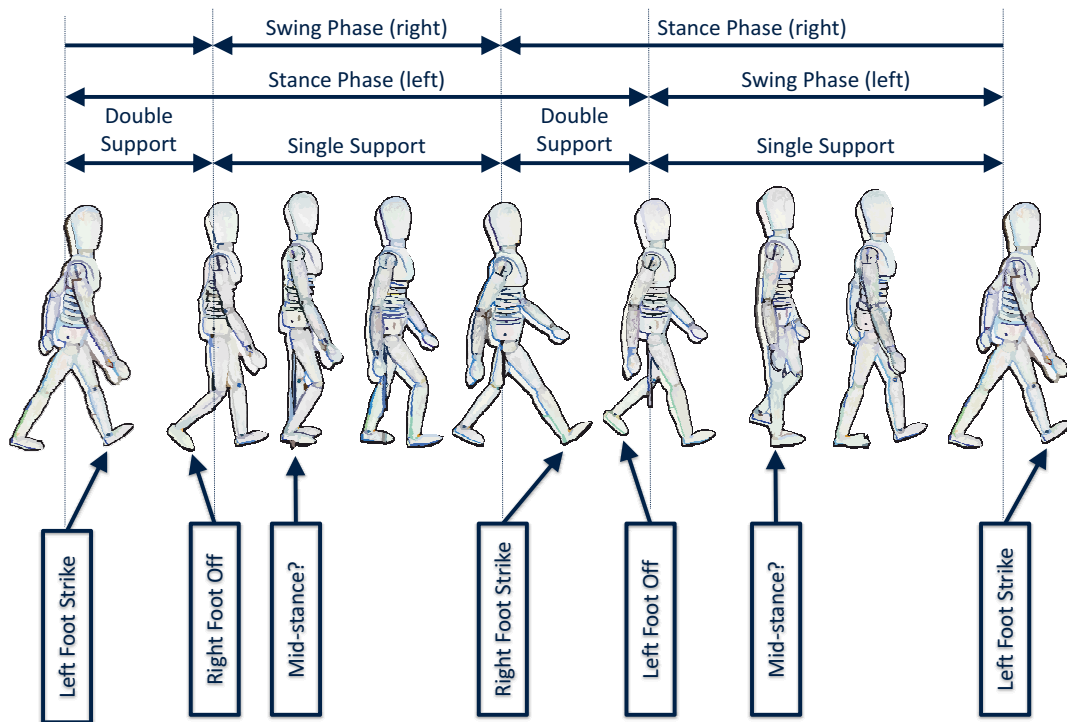


Figure 7.4.: Events during stance and swing phases. Foot strike, foot flat, midstance, foot off, stance and swing phase, single and double leg support.

ground. Terminal stance - the forefoot rocker - starting with heel rise, it relies on stability in the foot for the contralateral limb to propel the body forward with its foot strike. Few of the events that define these periods are easy to detect automatically. However, a point during midstance was thought to provide an interesting comparison to the static stance.

The definition of midstance is not agreed upon. Many consider it to be a period during the cycle, however this is not conducive to our purposes. Another common definition is where the Centre Of Mass (COM) is over the centre of the ankle joint. This is however difficult to assess. Some well defined and accessible methods were investigated in this chapter:

- 50% of stance phase,
- the point where the tibia is closest to vertical,
- the point where foot markers are at their minimum vertical height,
- the local minima of Vertical Ground Reaction Force (VGRF).

## 7. Event Timings

Maxima and minima are commonly reported values of extreme behaviour. The loading extreme postures could be key to unearthing the problems behind flatfoot so will also be included. Swing phase is unloaded, and therefore was deemed unlikely to be the cause of symptoms.

The head, arms, and trunk contribute little to walking. The action of the trunk maintains neutral vertebral alignment. Arm swing is largely a reaction to the generated momentum. The restriction of arm swing does not increase energy costs during walking [135]. The principal actors in walking are therefore the pelvis, lower limbs, and feet, which are justifiably the focus of the study.

### 7.2.1. Foot strike and foot off

Foot strike and foot off are calculated automatically by the Vicon Nexus software if there is a clean strike on the force plate. The point at which VGRF first exceeds 20 N is foot strike (20 N being the threshold). The last point at which VGRF exceeds 20 N is foot off.

If there is no clean force plate strike, the event must be manually identified (Fig. 7.5). This can be done with relative ease for foot strike, but can be difficult at foot off. Once one of each event has been identified in a trial, they can be automatically correlated in Nexus to identify similar events.

### 7.2.2. Midstance

Midstance advances the body over a stationary foot via the ankle rocker. The foot is normally in full (hindfoot and forefoot) contact with the floor. The residual momentum and contralateral limb provide the momentum for the forward motion (Fig. 7.6). The ankle moves from approximately 5° plantarflexion to 10° dorsiflexion during this

## 7. Event Timings

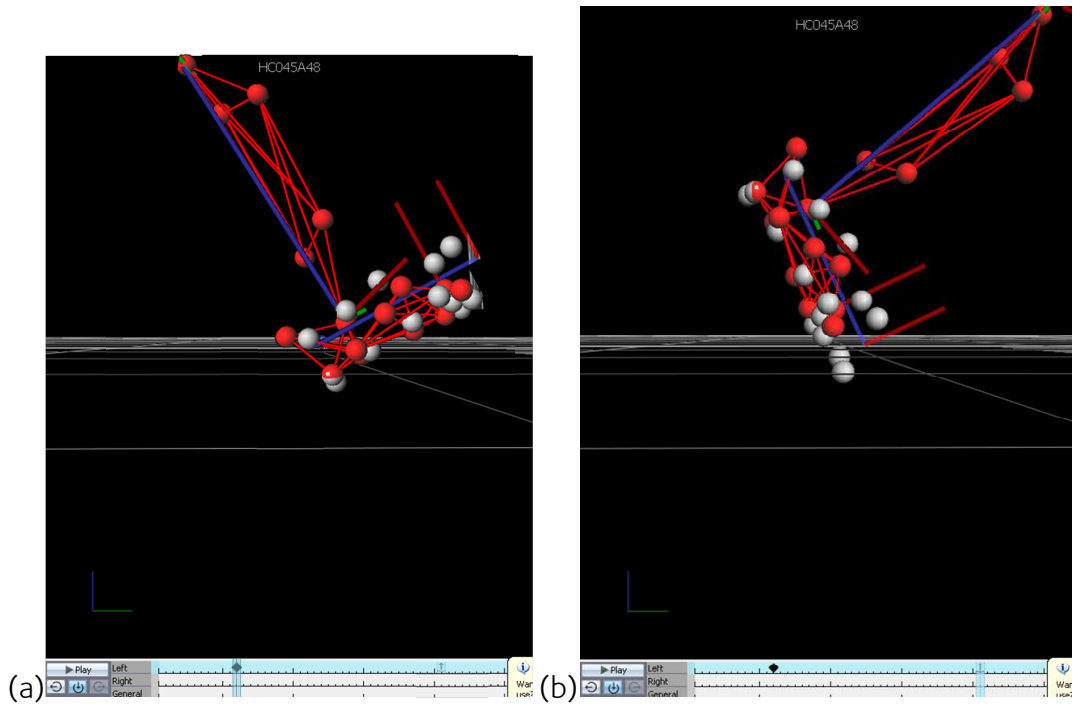


Figure 7.5.: Screen shots of Vicon Nexus while manually selecting events. (a) foot strike and (b) foot off frames.

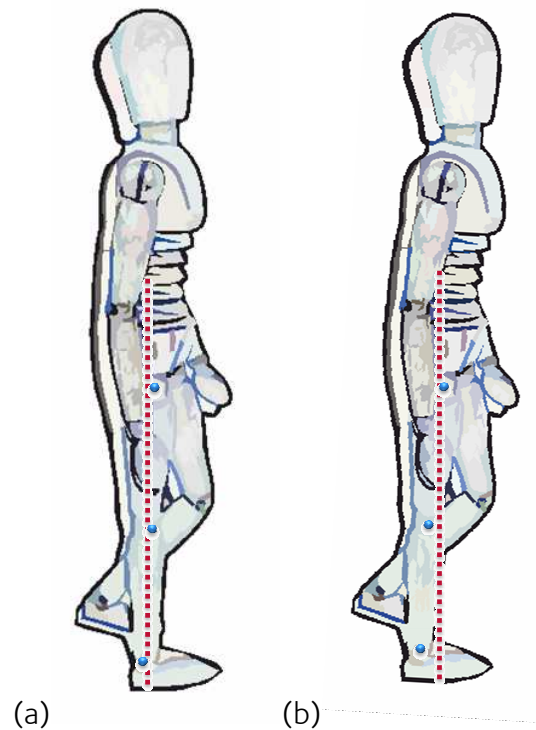


Figure 7.6.: At midstance bodyweight moves along the length of the foot. (a) Early midstance, bodyweight (red dotted line) acts to dorsiflex the ankle and flex the knee. (b) End of midstance, bodyweight is anterior to knee.

## 7. Event Timings

time. The soleus acts to restrain the tibia, the gastrocnemius can assist but will induce flexion torque at the knee. Knee flexion increases to a maximum  $18^\circ$  as single limb support begins, then the knee begins to extend. Once bodyweight is acting anterior to the knee axis, extension can become passive.

### *50% stance*

This is the simplest definition - halfway through stance. This can be calculated based purely on the timing of foot strike and foot off (equation 7.5):

$$t_{midstance(50\% stance)} = \frac{t_{foot\ strike} + t_{foot\ off}}{2}. \quad (7.5)$$

### *Vertical tibia*

The ankle moves from plantarflexion to dorsiflexion with the foot remaining flat during midstance. While viewing from the sagittal plane, the tibia will pass through vertical during walking. If the subject is not walking with a crouch gait, the COM is approximately aligned with ankle joint centre when the tibia is vertical (Fig. 7.6).

To define the long axis of the tibia, firstly a plane is defined by the markers on the head of the fibula, the lateral malleolus, and the medial malleolus (Fig. 7.7). The tibial tuberosity marker is then projected onto the plane. The long axis runs from this projected point to a point halfway between the malleolar markers. The other axes are at right angles to this axis, and along and perpendicular to the plane. During stance, when the long axis is at its closest to the vertical of the global axis of the laboratory, this time-frame is recorded as midstance.

### *Foot marker minimum*

The marker-based minimum uses the vertical height of the markers on the foot (in-

## 7. Event Timings

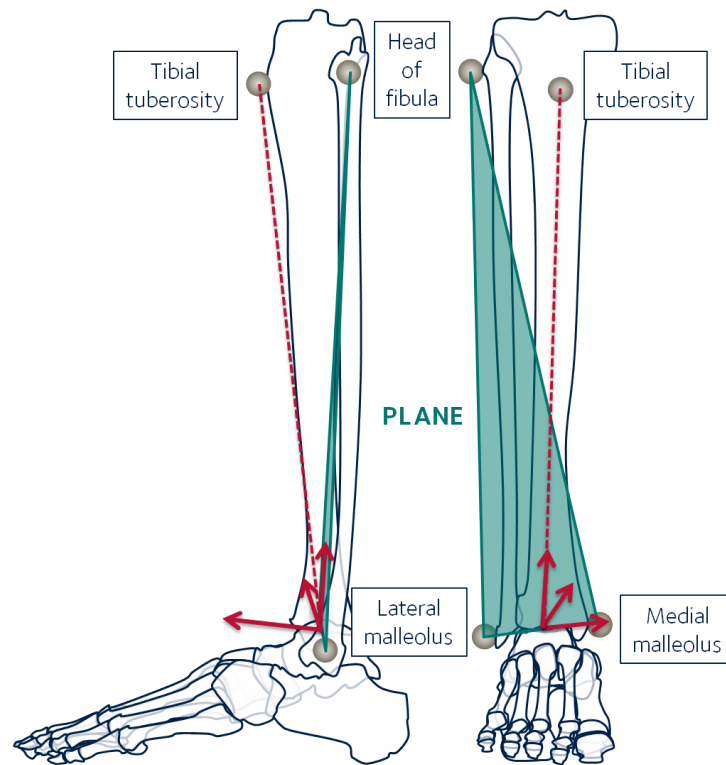


Figure 7.7.: Vertical tibia axis.

cluding the navicular marker when present, but excluding the calcaneal wand) to define midstance. It defines midstance as the frame with the minimum sum of the vertical height of the markers during stance phase (the marker heights included in the calculation were the lateral malleolus, heel, lateral calcaneus, sustentaculum tali, navicular, proximal first metatarsal, proximal fifth metatarsal, toe, and hallux when present).

### *VGRF minimum*

Using the GRF to define midstance was slightly more complicated. Ground Reaction Force patterns are complex and not standard between subjects. In the Vertical Ground Reaction Force (VGRF) there is an expected force pattern with two peaks exceeding body weight, and a local minima less than body weight between them (Fig. 7.8). This local minima could be an interpretation of midstance. There are however some other pattern types, some with large impact peaks (Fig. 7.9 (left) – a feature normally

## 7. Event Timings

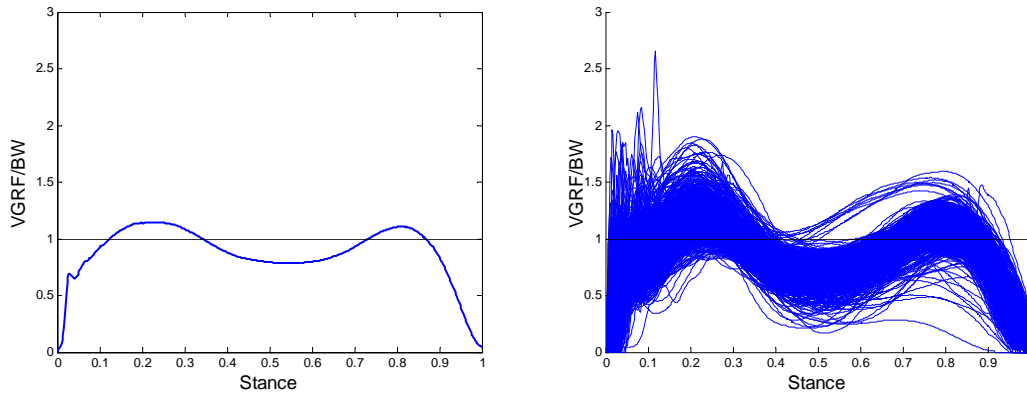


Figure 7.8.: Vertical Ground Reaction Force (VGRF) patterns normalized to Body-Weight (BW). Typical VGRF pattern (left). Black line depicts bodyweight. All VGRF patterns (right).

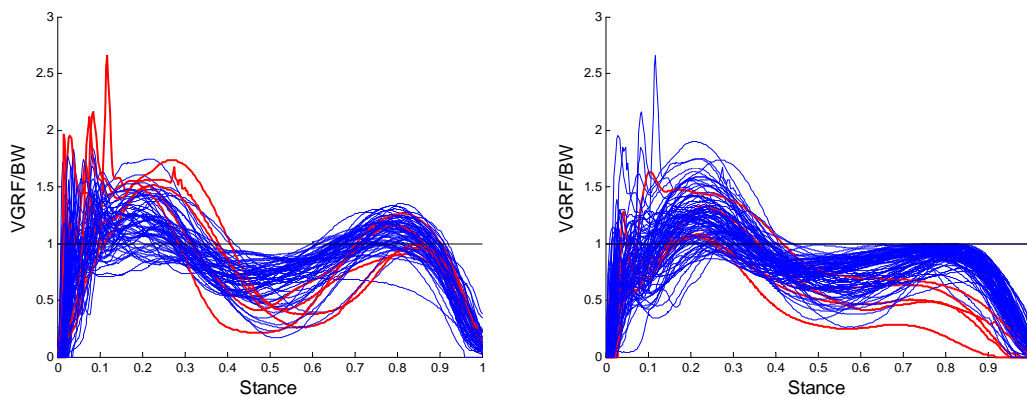


Figure 7.9.: Unusual VGRF patterns. Those which feature impact peaks (left). Those with low Late Stance Peaks (right). Particularly unusual cases in red.

associated with rearfoot-strike running), and some with low Late Stance Peaks (LSPs) below body weight (Fig. 7.9 (right)).

A method to identify the local minima midstance point was developed. The strategy was to find the Early and Late Stance Peaks (ESPs and LSPs) (it was thought that they might be useful in their own right particularly the LSP). Then to find the minima between these points. Smoothing is required as otherwise too many local maxima are detected. The process for each trial with a clean force plate strike (Fig. 4 (a)) was as follows:

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1. Smooth curve with moving average filter with a span of five frames (0.05s) (Fig. 4 (b)),
2. Local maxima of the smoothed curve are recorded (Fig. 4 (c)),
3. Local maxima that are closest to the average percentage of stance where the peaks are found (calculated iteratively over all subjects Fig. 4; all (d) and selected (e)),
4. The absolute minimum between the peaks is taken as the point of midstance (Fig. 4 (f)).

The method is robust at finding the midstance and the LSP. It was weaker at identifying the the ESP correctly, although success is still greater than 90%. Combining this system with the use of a median representative value for each subject, resulted in a genuine midstance event representation for all subjects.

### 7.2.3. Testing for success

The main aim of this investigation was to decide which definition of midstance should be used in future results. It was decided that the best way to assess the success of any timepoint, is that it would define an event in the gait cycle repeatably. If an event could be defined and detected in a non-circular manner (without using the same measure to define the timepoint and measure the outcome of the timepoint), this would be a useful midstance event to investigate. One way to test this would be to see which definition resulted in the most repeatable kinematic result, i.e. which measure defined a point in the gait cycle most repeatably with the smallest intra-subject variation. The angles of the lower limbs were included: hip from the Plug-In Gait model, and those of the Oxford Foot Model (OFM) at the foot and knee. The forefoot - tibia

## 7. Event Timings

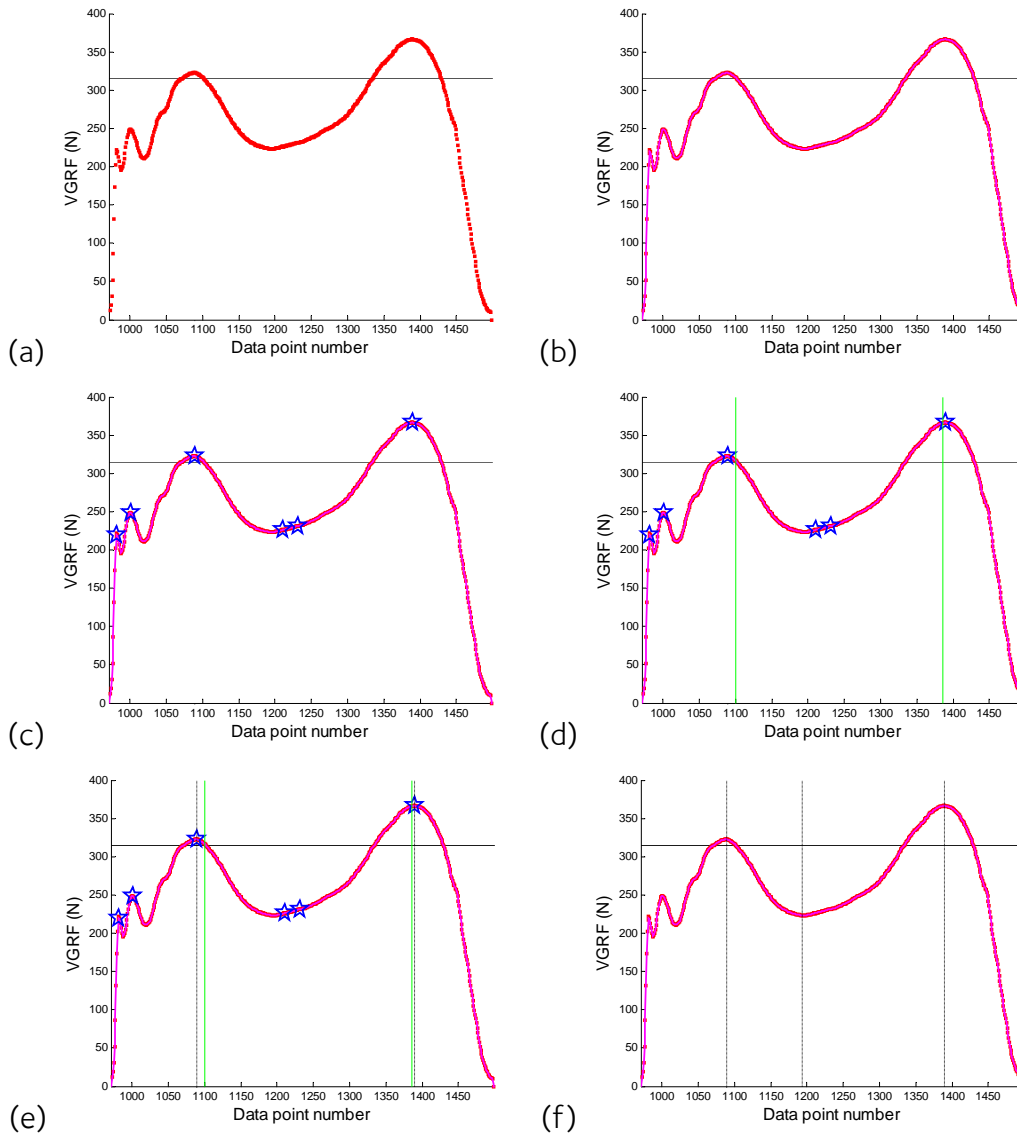


Figure 7.10.: Finding midstance from Vertical Ground Reaction Force (VGRF). (a) raw VGRF (b) smooth VGRF (c) local maxima (d) peak locations (e) Early and Late Stance Peaks (ESP and LSP) (f) midstance from VGRF data.

## 7. Event Timings

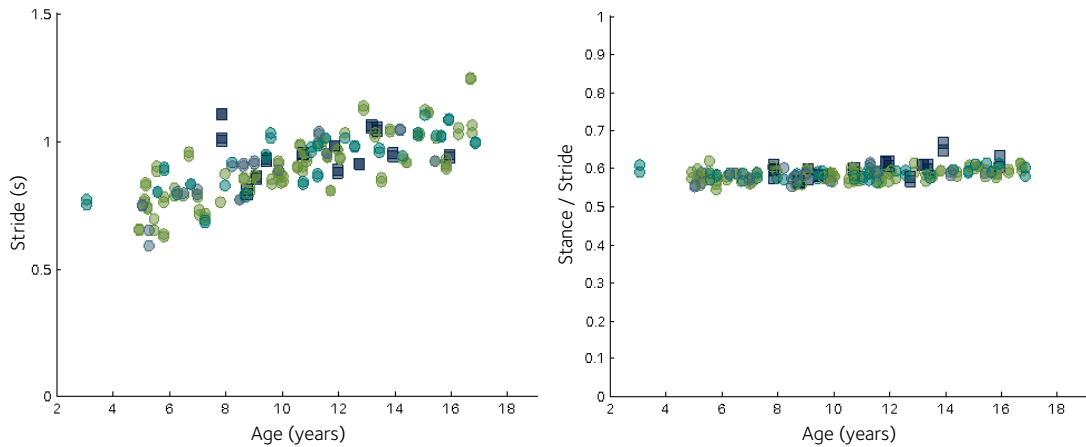


Figure 7.11.: Time spent in stride increases with age (left). Percentage of stride spent in stance (Right).

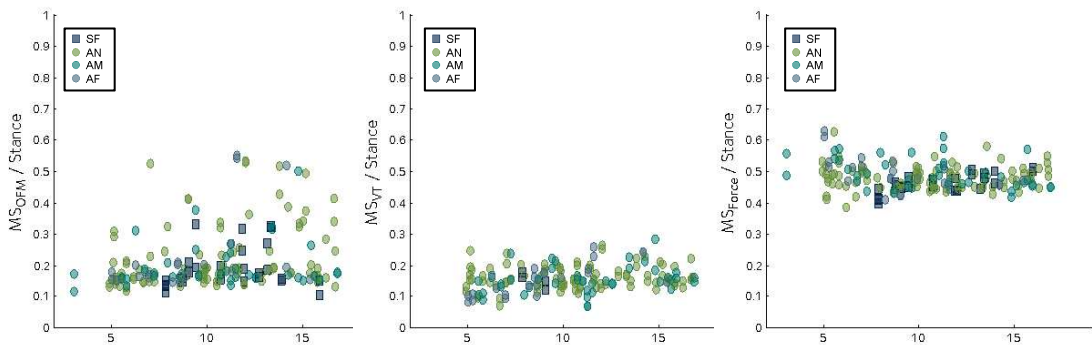


Figure 7.12.: Various definitions of time of midstance as a fraction of time in stance versus age. From left: minimum foot marker sum, vertical tibia, VGRF based definition.

was excluded as it would result in a reiteration of the forefoot – hindfoot and hindfoot – tibia result.

### 7.3. Results and discussion

The time taken per stride clearly increases with age, largely due to increasing leg length (Fig. 7.11 (a)). However the percentage of stride spent in stance phase remains constant (Fig. 7.11 (b)). This will be discussed with respect to the groups in Chapter 8.

The definitions arrived at by the OFM and tibia methods, result in estimations of mid-

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Mean Standard deviations	50 % of stance	Minimum marker position	Vertical tibia	VGRF local minima
Hip	4.47	7.00	6.95	4.38
Knee	3.77	4.91	4.81	3.64
Ankle	4.65	4.87	4.34	4.64
Foot	4.56	4.48	4.55	4.52
Overall	4.36	5.32	5.16	4.30

Table 7.1.: Mean values of standard deviations of intra-subject joint angles at hip, knee, ankle, and foot for different midstance definitions.

stance much earlier than 50% stance (Fig. 7.12). The tibial segment definition may result in an slight angle relative to the true long axis of the tibia which may cause this in the Vertical Tibia (VT) definition. The foot marker minimum sum occurring this early, is perhaps harder to explain, it may be because the foot starts to re-supinate leading to the “flattest” foot not being at midstance. Sometimes the event occurs closer to 50% stance perhaps because these feet are more flexible during foot flat (and therefore continue to decrease in vertical height sum), than those with earlier “midstances”. The VGRF-based definition is centred about the 50% stance point. The definitions do not detect an age related trend.

The result of testing intra-subject variability was that the lowest SD was associated the forceplate-based definition, followed very closely by the 50% stance definition (Table 7.1). The relative success of the 50% stance definition indicates that despite the simplicity of the method, it is a repeatable event at least within subject. Controlling for the variability in features associated with midstance may not reduce the variability in the result. During the following chapters, the forceplate-derived definition will be used.

### 7.4. Summary

To solve the problem of variation in timing, identifiable features and time points were recommended for statistical testing. Clearly-defined events during walking were se-

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lected including maxima, minima, foot strike, foot off, and midstance (Fig. 7.4).

Four definitions of midstance were investigated: 50% stance, minimum sum of foot marker height, Vertical Tibia, and the local minima of the Vertical Ground Reaction Force. These definitions were tested for intra-subject variability of kinematics. The lowest intra-subject variability was associated with the VGRF and 50% of stance definitions. VGRF had a slightly lower deviation at all tested joints and was therefore selected.

Now that methods and problems associated with testing continuous data have been explored, and relevant data-points selected, continuous gait data can now be analysed. The following chapter will investigate the Ground Reaction Forces and the variation in timing between groups.

## 8. Spatio-temporal parameters and Ground Reaction Force

This chapter explores differences in Ground Reaction Force, some spatial characteristics (stride length, step width), and some temporal characteristics (stride duration, percentage of stride in stance, and the timing of various midstance definitions within stance) in various populations. GRFs are investigated in globally- and anatomically-defined coordinate systems. Peak and representative values as well as continuous (and double stride) data are investigated. The spatio-temporal and GRF parameters in children with symptomatic, flat, and neutral feet will be tested here using ANOVA in a similar manner to a previous chapter (Chapter 6).

### 8.1. Introduction

Ground reaction force (GRF) is the force exerted by the ground upon a body in contact with it. Generally, this is an equal and opposite force to that applied. In a case where the only forces acting are vertical, such as static stance on a flat surface, this is known

## 8. Spatio-temporal parameters and Ground Reaction Force

as the normal force. When the force acting is more complex, there is a component of friction acting in the horizontal plane, therefore the GRF becomes a vector that is non-vertical. Thus ground reaction has two essential components: a horizontal frictional component, and a normal reaction component.

Some people have associated reduced propulsive force with flatfoot [104], and thus, it was theorized that the second peak of the Vertical component of the GRF (VGRF) may be reduced. The pattern of an Early Stance Peak (ESP) VGRF above bodyweight, followed by a midstance trough, then a smaller Late Stance Peak (LSP) VGRF below bodyweight is known as “Ben Lomonding” (the pattern resembles the silhouette of a Scottish mountain, Fig. 8.1) [186]. The second peak indicates the leg is adequately stable, supporting bodyweight, and is slowing the downward acceleration of the Centre Of Mass (COM). If the magnitude of the second peak is under bodyweight, it would indicate that these children have lost stability following midstance and collapse would occur if correction was not taken by the contra-lateral leg.

Spatio-temporal parameters can be a repeatable and inexpensive assessment of gait. A variety of equipment can record these types of parameters. A previous study demonstrated that asymptomatic flatfoot is associated with longer stride and reduced cadence [85]. Stride length (the distance between footsteps of the same foot, Fig. 8.2) varies with height, so should be normalized to height or leg length. Step width (Fig. 8.2) does not vary with age or leg length. Stride duration (the time spent for each complete stride, e.g. right foot strike to right foot strike) was previously found also to vary with age (Fig. 7.11), though the principal source of this effect (e.g. age, height, weight) was not investigated. Percentage stance and the percentage of stance at which the various definitions of midstance occurred, were found not to be age related (Fig. 7.12).

Merriman states that flatfoot is associated with reduced propulsive force and early heel rise [104]. In terms of spatiotemporal parameters it could therefore be hypothesized that the flatfooted subjects will display reduced stride length and percentage

## 8. Spatio-temporal parameters and Ground Reaction Force

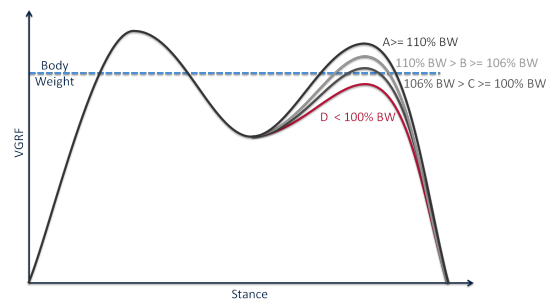


Figure 8.1.: VGRF “Ben Lomonding” patterns relative to bodyweight. Categories for LSP based on Gibbs et al. [52].



Figure 8.2.: Definition of stride length (blue) and step width (green) for right foot step (pink). Step width is measured in the direction perpendicular to the direction of progression.

## 8. Spatio-temporal parameters and Ground Reaction Force

stance as well as an earlier midstance event. These may be reflective or indicative of symptoms (e.g. fatigue and tightness of tendo-Achilles) rather than causative.

### 8.2. Methods

It was perceived as desirable to limit methods of statistical analysis for clarity. Therefore, similarly to previous analyses, only results which satisfied the 0.05 level of Tukey and Games-Howell post-hoc tests were classed as significant.

#### *Spatio-temporal parameters*

The spatial variables - step width and stride length - were calculated. Step width was calculated as the distance between the heel at foot strike and the position of the contra-lateral heel at the following foot strike perpendicular to the direction of progression. Stride length was calculated as magnitude of the vector between heel marker coordinates over consecutive heel strikes projected onto the horizontal plane. This was normalized to leg length which had been measured during the clinical examination.

Duration of stride was the time that passed between the stride length events. Time in stance was calculated as the time between foot strike and foot off (as measured by a force exceeding 20 N on the force plate). Percentage stance was defined as time in stance divided by duration of stride. For the midstance events that had been identified in Chapter 7, the time between the event and the preceding foot strike was normalized to the time in stance. A median value over a minimum of three trials was used to represent each subject. These parameters were subjected to ANOVA between the groups (in a method similar to previous chapters).

## 8. Spatio-temporal parameters and Ground Reaction Force

### *Ground Reaction Force*

Ground Reaction Forces (GRFs), in terms of multiples of body weight, do not change with age after the age of five years [9], and therefore subjects under the age of five were excluded. In those aged 5-12 years old, GRFs are characterized primarily by speed (normalized to height), not age [165]. Therefore ANCOVA (ANalysis of CO-Variance) controlling for a speed-related parameter, relative stride length, was required as a significant difference between groups had been found for this parameter (Table 8.1, Fig. 8.4). The VGRF is highly repeatable within subjects [183]. GRFs were recorded using two or three OR6 (AMTI, USA) 400×600 mm<sup>2</sup> tri-axial force plates at a sampling rate of 1000 Hz (Chapter 4).

Median values for each subject for the magnitude of the ESP, midstance trough, and LSP VGRF were detected (method described in Section 6.6.3). The second peak was further investigated using the categories developed by Gibbs et al. [52] to investigate the presence of “Ben Lomonding” (Fig. 8.1). This data was subjected to ANOVA and ANCOVA (controlling for the relevant parameter - relative stride length).

Horizontal (frictional) GRFs were also considered. Individual antero-posterior median values of the minima and maxima were measured. Early and late stance medio-lateral maxima and minima were also measured. This data was subjected to ANOVA and ANCOVA (controlling for relevant parameter relative stride length).

Additionally, for each subject, a representative trial was selected to allow visual analysis of the complete stance phase. The SMaRT method was used to select the representative trial [153]. This method relies upon principal component analysis [73] of the data-set for each subject; followed by the minimization of the sum of the euclidean distance from median to trial score. This is a repeatable method but can be sensitive to outlying areas, and cannot adapt to variable patterns. The result of the selection was not subjected to further statistical analysis; it was analysed visually. To create representations of the characteristics of the groups, cubic spline interpolation

## 8. Spatio-temporal parameters and Ground Reaction Force

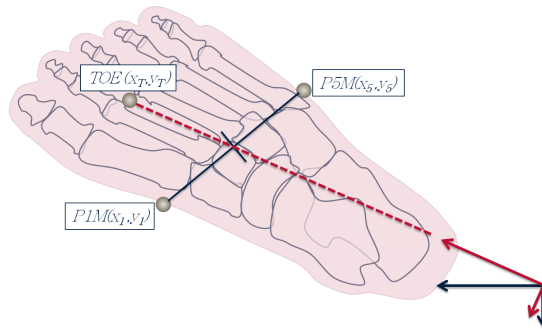


Figure 8.3.: The axis of the forefoot. Toe marker lies between second and third distal metatarsal heads. Other markers lie on first and fifth proximal metatarsal heads. The axis runs from toe marker to the bisection of the line between the first and fifth proximal metatarsal head markers. The axis is projected into the horizontal plane for the purpose of resolving the frictional Ground Reaction Force to the axis and is therefore not the same as the Oxford Foot Model axis.

of the original curves normalized the number of frames to 100 over stance phase.

One issue with the horizontal ground reaction force is that it is reported relative to the laboratory or to the direction of travel. This is perhaps not the most helpful way to view the data as one of the features of flatfoot is an increased angle of gait [104] reducing the comparability of the data. The kinetic data that will be later calculated only reports flexion moment as the foot is included in the model as a vector. Since many expected differences are in the transverse plane this is unfortunate. Therefore an attempt was made to reorient the frictional components to anatomical axes in the hope that this might detect some of the transverse differences.

The frictional GRFs in the medio-lateral and antero-posterior directions were resolved to the axis of the forefoot (Fig. 8.3) to focus on late stance and the loading of the foot at that point. The midpoint of the proximal metatarsal markers is found (equation 8.1),

$$\overrightarrow{PM}_{midpoint} = \frac{\overrightarrow{r}_{P1M} + \overrightarrow{r}_{P5M}}{2}. \quad (8.1)$$

The forefoot antero-posterior axis in the horizontal plane is then described using this

## 8. Spatio-temporal parameters and Ground Reaction Force

point and the toe marker (equation 8.2),

$$\begin{aligned}\vec{b} &= \vec{r}_{TOE} - \vec{PM}_{midpoint}, \\ \overrightarrow{AP\ axis} &= \begin{bmatrix} b_1 & b_2 & 0 \end{bmatrix}^T\end{aligned}\quad (8.2)$$

The dot product of the HGRF and the unit vector of the forefoot axis then describes the HGRF with respect to the antero-posterior horizontal forefoot axis - i.e. antero-posterior to the foot rather than to the laboratory (equation 8.3),

$$AP\ component\ of\ \overrightarrow{HGRF}_{forefoot} = \overrightarrow{HGRF} \bullet \widehat{AP\ axis}. \quad (8.3)$$

The medio-lateral component is the dot product of the HGRF with a unit vector perpendicular to the antero-posterior axis, i.e. the medio-lateral axis (equation 8.4),

$$ML\ component\ of\ \overrightarrow{HGRF}_{forefoot} = \overrightarrow{HGRF} \bullet \widehat{ML\ axis}. \quad (8.4)$$

The patterns of load transfer associated with low LSP VGRF were further investigated. The patterns were compared between various groups.

### 8.3. Results and discussion

#### 8.3.1. Temporal parameters in AN, AM, AF, and SF

Three parameters were found to be significantly different between groups: stride length relative to leg length, step width, and time in stance relative to time in stride (Table 8.1, Fig. 8.4). The cadence of the groups was not significantly different, nor was the timing of any events identified in Chapter 7, although there was considerable variation among subjects (Fig. 8.4, Fig. 7.12).

Relative stride length was significantly shortened in the SF group compared to others

## 8. Spatio-temporal parameters and Ground Reaction Force

Table 8.1.: Mean, standard deviation, and ANOVA results for temporal parameters. Square brackets indicate between which groups post-hoc testing revealed statistically significant differences.

	Group	N	Mean	SD	ANOVA Sig.		Group	N	Mean	SD	ANOVA Sig.
Stride length	AN	94	1.63	0.14	]]]]]] *000	Time to MS <sub>OFM</sub>	AN	98	0.22	0.11	
	AM	47	1.69	0.15			AM	47	0.19	0.07	
	AF	29	1.63	0.20			AF	29	0.22	0.12	
	SF	34	1.47	0.21			SF	38	0.19	0.06	
	All	204	1.62	0.18			All	212	0.21	0.10	
Leg length	AN	98	72.73	24.47	]]]]]] *002	Time to MS <sub>VT</sub>	AN	88	0.17	0.04	
	AM	47	70.65	27.68			AM	45	0.15	0.04	
	AF	29	70.38	32.29			AF	29	0.15	0.05	
	SF	34	90.78	25.57			SF	32	0.15	0.04	
	All	208	74.88	27.33			All	194	0.16	0.04	
Step width (m)	AN	98	0.89	0.13		Time to MS <sub>E</sub>	AN	98	0.46	0.14	
	AM	47	0.92	0.11			AM	45	0.49	0.05	
	AF	29	0.89	0.13			AF	27	0.47	0.04	
	SF	38	0.95	0.08			SF	33	0.46	0.03	
	All	212	0.90	0.12			All	203	0.47	0.10	
Stride duration (s)	AN	98	0.58	0.02	]]]]]] *000	Time to MS <sub>COM</sub>	AN	96	0.44	0.13	
	AM	47	0.58	0.01			AM	46	0.43	0.12	
	AF	29	0.58	0.02			AF	27	0.42	0.14	
	SF	38	0.60	0.02			SF	0	.	.	
	All	212	0.59	0.02			All	169	0.43	0.13	
Time in stance	AN	98	0.58	0.02		Time in stance	AN	96	0.44	0.13	
	AM	47	0.58	0.01			AM	46	0.43	0.12	
	AF	29	0.58	0.02			AF	27	0.42	0.14	
	SF	38	0.60	0.02			SF	0	.	.	
	All	212	0.59	0.02			All	169	0.43	0.13	
Time in stride	AN	98	0.58	0.02		Time in stance	AN	96	0.44	0.13	
	AM	47	0.58	0.01			AM	46	0.43	0.12	
	AF	29	0.58	0.02			AF	27	0.42	0.14	
	SF	38	0.60	0.02			SF	0	.	.	
	All	212	0.59	0.02			All	169	0.43	0.13	

(Fig. 8.4). Percentage time in stance phase was increased in this group relative to the AN group, i.e. the relative time spent in swing was reduced. This created a picture that the reduction in stride length was associated with a small reduction in the period of time required for swing. These results contradict the findings of Lvinger et al. [85], who found a longer stride length and reduced cadence to be associated with asymptomatic flatfoot. The findings of Lvinger et al. may be less reliable as the statistics were calculated over fairly small groups (n=10 and n=9), achieved less significance ( $p=0.07$ ), were not normalized, and there was an imbalance of gender between the groups. Our results created concern about the propulsion and conservation of momentum in the SF group. However, the group also featured increased step width, which may indicate a reorientation to a more mediolateral direction of

## 8. Spatio-temporal parameters and Ground Reaction Force

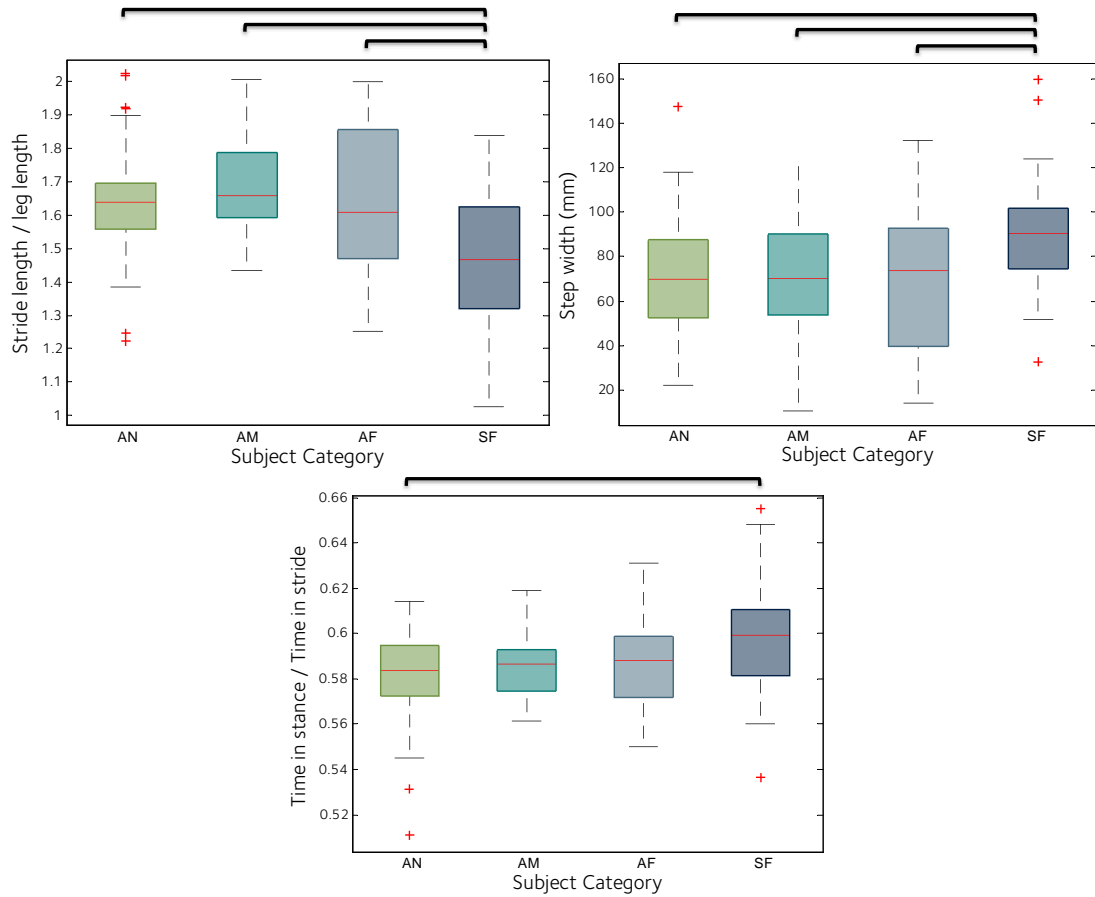


Figure 8.4.: Temporal parameters where significant differences were found. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Overhead brackets show between which subject category groups both Tukey and Games Howell post-hoc tests found significant differences.

## 8. Spatio-temporal parameters and Ground Reaction Force

Table 8.2.: Mean, standard deviation, ANOVA, and ANCOVA of GRF parameters. Square brackets indicate between which groups post-hoc testing revealed statistically significant differences. The ANCOVA refers to the results when relative stride length was controlled for. BW – BodyWeight.

	Group	N	Mean	SD	ANOVA Sig.	ANCOVA		Group	N	Mean	SD	ANOVA Sig.	ANCOVA		
VGRF ES peak (*100/BW)	AN	98	121.4	14.5	]	*016	*001	ML GRF	AN	98	5.6	2.6	)]	*001	.146
	AM	45	122.7	14.0				AM	47	5.1	2.5				
	AF	27	128.8	19.6				AF	29	5.3	2.5				
	SF	34	116.8	9.4				SF	32	3.4	2.1				
	All	204	121.9	14.7				All	206	5.1	2.6				
VGRF MS minimum (*100/BW)	AN	98	67.4	11.5	)]	*006	.970	ML GRF	AN	97	-7.1	2.4	)]	.346	.059
	AM	45	65.6	9.8				AM	47	-6.4	1.8				
	AF	27	67.4	15.1				AF	29	-7.3	3.0				
	SF	34	74.0	5.3				SF	32	-6.9	1.3				
	All	204	68.1	11.2				All	205	-6.9	2.2				
VGRF LS peak (*100/BW)	AN	98	111.8	10.6	)]	*000	*006	ML GRF	AN	97	-5.6	1.8	)]	.751	.969
	AM	45	113.0	10.7				AM	47	-5.5	1.6				
	AF	27	113.2	13.1				AF	29	-5.3	2.4				
	SF	34	103.9	7.7				SF	32	-5.8	1.7				
	All	204	111.0	11.0				All	205	-5.5	1.8				
AP GRF Minimum (*100/BW)	AN	98	-24.5	6.9	)]	*000	*014	ML GRF	AN	97	1.4	0.9	)]	*000	*002
	AM	47	-23.7	4.5				AM	47	1.6	0.8				
	AF	29	-26.4	6.1				AF	29	2.0	1.6				
	SF	32	-20.1	4.2				SF	32	0.9	1.0				
	All	206	-23.9	6.2				All	205	1.5	1.1				
AP GRF Maximum (*100/BW)	AN	97	23.8	3.0	)]	*000	.158								
	AM	47	24.1	3.6											
	AF	29	24.7	4.5											
	SF	32	20.3	4.5											
	All	205	23.4	3.9											

propulsion at foot off. The GRFs may further illuminate this problem.

### 8.3.2. Peak and continuous GRF in AN, AM, AF, and SF

#### *Analysis of peak GRF*

Our findings are in agreement with previous studies which found the typical VGRF peaks and features to be in the region of 120% of bodyweight (ESP), 70% (mid-stance), and 110% (LSP) [165]. The peak values from the force plate were significantly lower in the SF group, the midstance VGRF being closer to bodyweight (Table 8.2, Fig. 8.5).

The flattening of the VGRF curve was thought to be likely related to the reduction in relative stride length. However, after controlling for relative stride length (the speed related parameter that varied between groups), two of the three differences in VGRF remained: ESP and LSP values (Table 8.1).

A 29% incidence of “Ben Lomonding” was found in the SF population, compared to

## 8. Spatio-temporal parameters and Ground Reaction Force

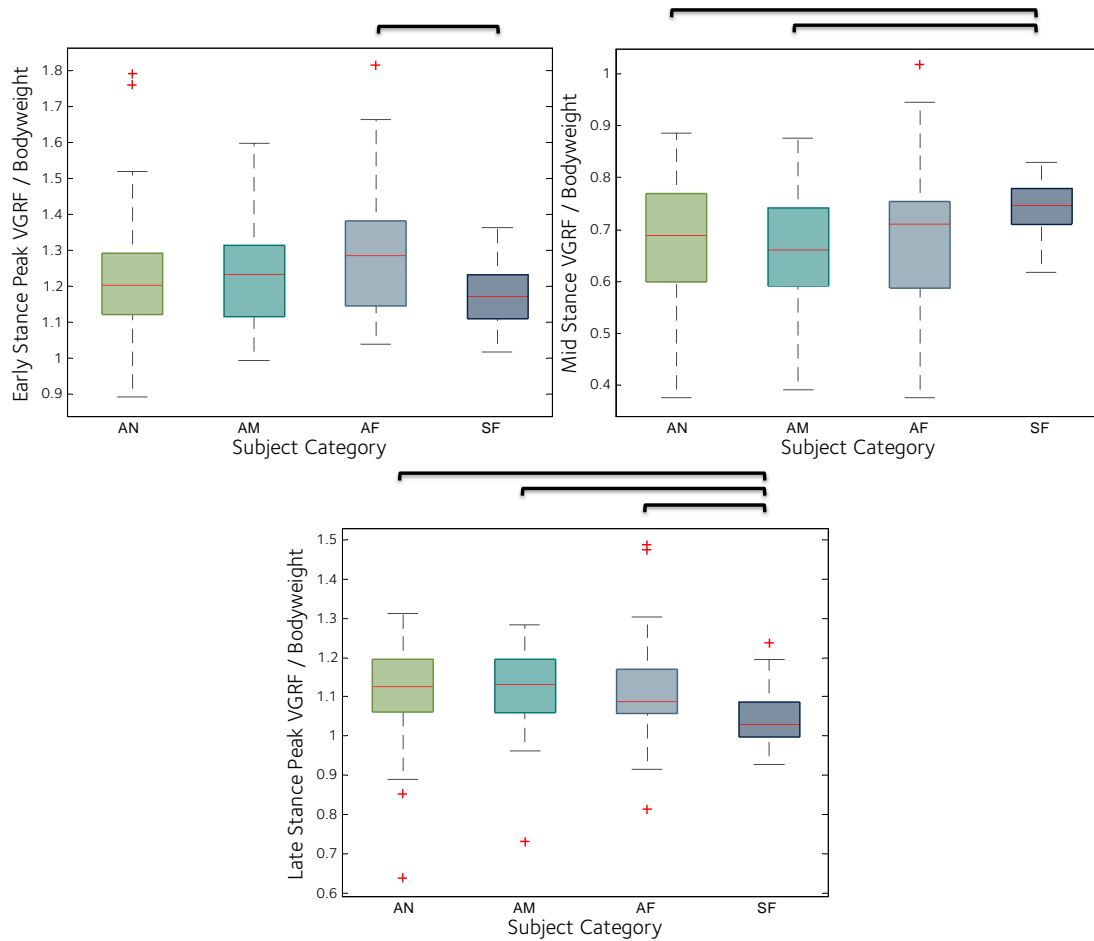


Figure 8.5.: Vertical Ground Reaction Force (VGRF) peak comparison between groups. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

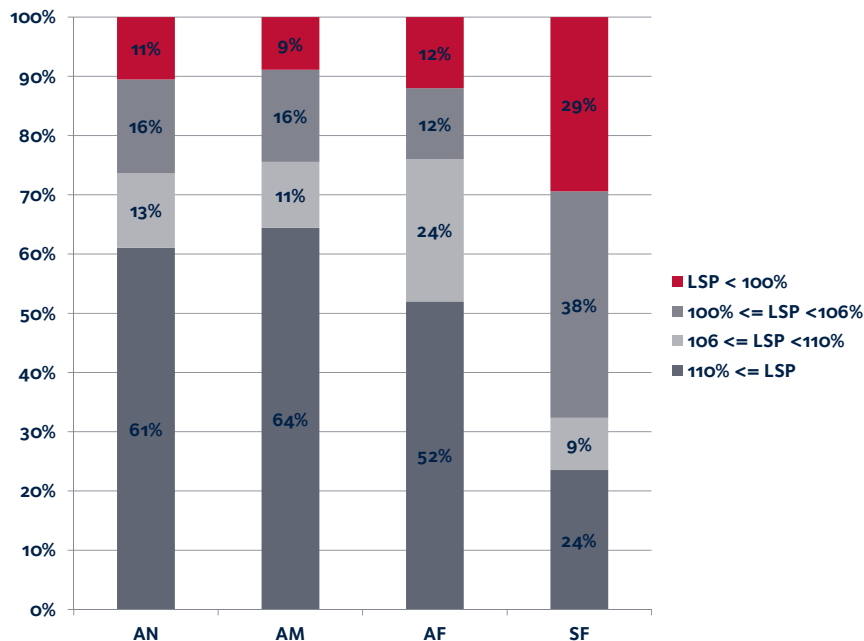


Figure 8.6.: Ratio of "Ben Lomonding" among groups.

## 8. Spatio-temporal parameters and Ground Reaction Force

around 10% in the other groups (Fig. 8.6). To compare this with another study, there is an incidence of 39% among children with cerebral palsy (based on a worst-case rather than representative trial) [52]. However in that study the variance among the population was greater. By the criteria that normal LSP  $\geq 110\%$  of bodyweight [165] only 25% of these symptomatic children act with normal late stance VGRF patterns, compared with around 60% of the asymptomatic cases. This finding is significant, and it suggests that many of the children are unable, or find it difficult, to support bodyweight and resist the downward fall of the COM in late stance, and will rely upon corrective action from the contra-lateral limb.

In the antero-posterior direction, the peak values are also reduced in the SF group (Table 8.1, Fig. 8.7). However, after controlling for relative stride length, this effect diminishes at late stance.

The maximum lateral GRFs are reduced in the SF group (Table 8.2, Fig. 8.8). This indicates a limited or absent lateral impulse. After controlling for relative stride length, this effect is diminished in early stance, but remains in late stance.

### *Continuous GRF*

Considering the continuous traces, averaging over the usual groups revealed little extra information (Fig. 8.9). The peaks that were identified as reduced in the previous analysis remained so.

The second medio-lateral GRF peak was near zero or absent after averaging over stance (Fig. 8.9). The effect of time-based averaging was clear here; the individual peaks after averaging were considerably smaller. Without alternative analysis it would have been unclear whether this was the result of differences in timing, magnitude, or both. Previously reduction in magnitude had been found between groups (Fig. 8.8); any further reduction in the peak is the result of variation in timing.

## 8. Spatio-temporal parameters and Ground Reaction Force

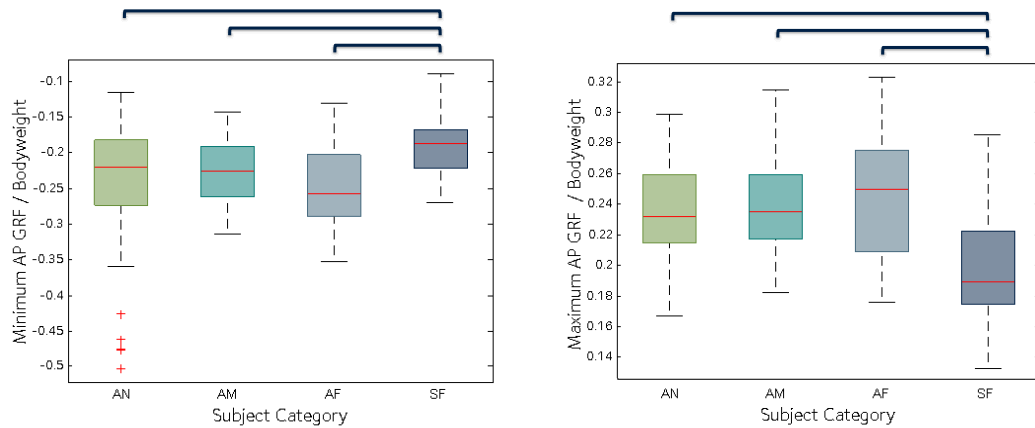


Figure 8.7.: Antero-posterior GRF comparison between groups. Forces in the anterior direction are positive. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

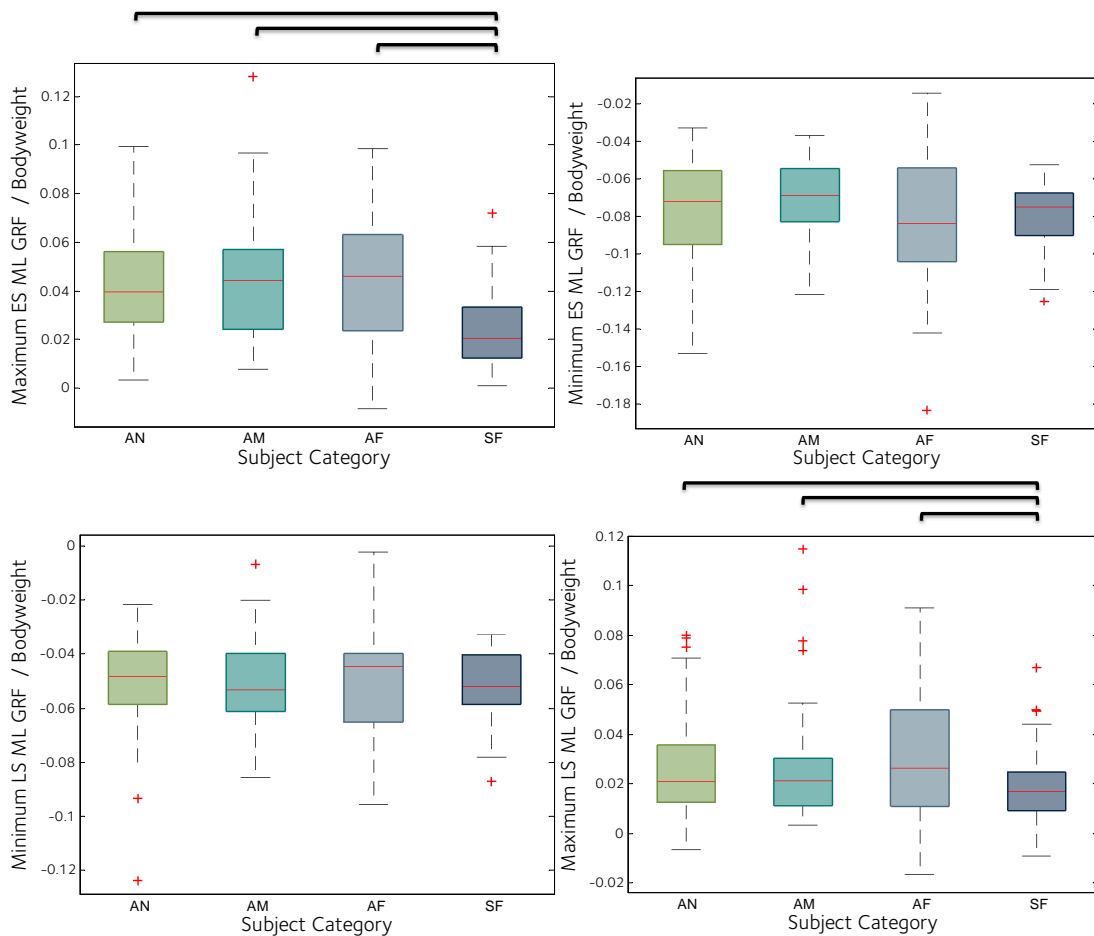


Figure 8.8.: Medio-lateral GRF comparison between groups. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

## 8. Spatio-temporal parameters and Ground Reaction Force

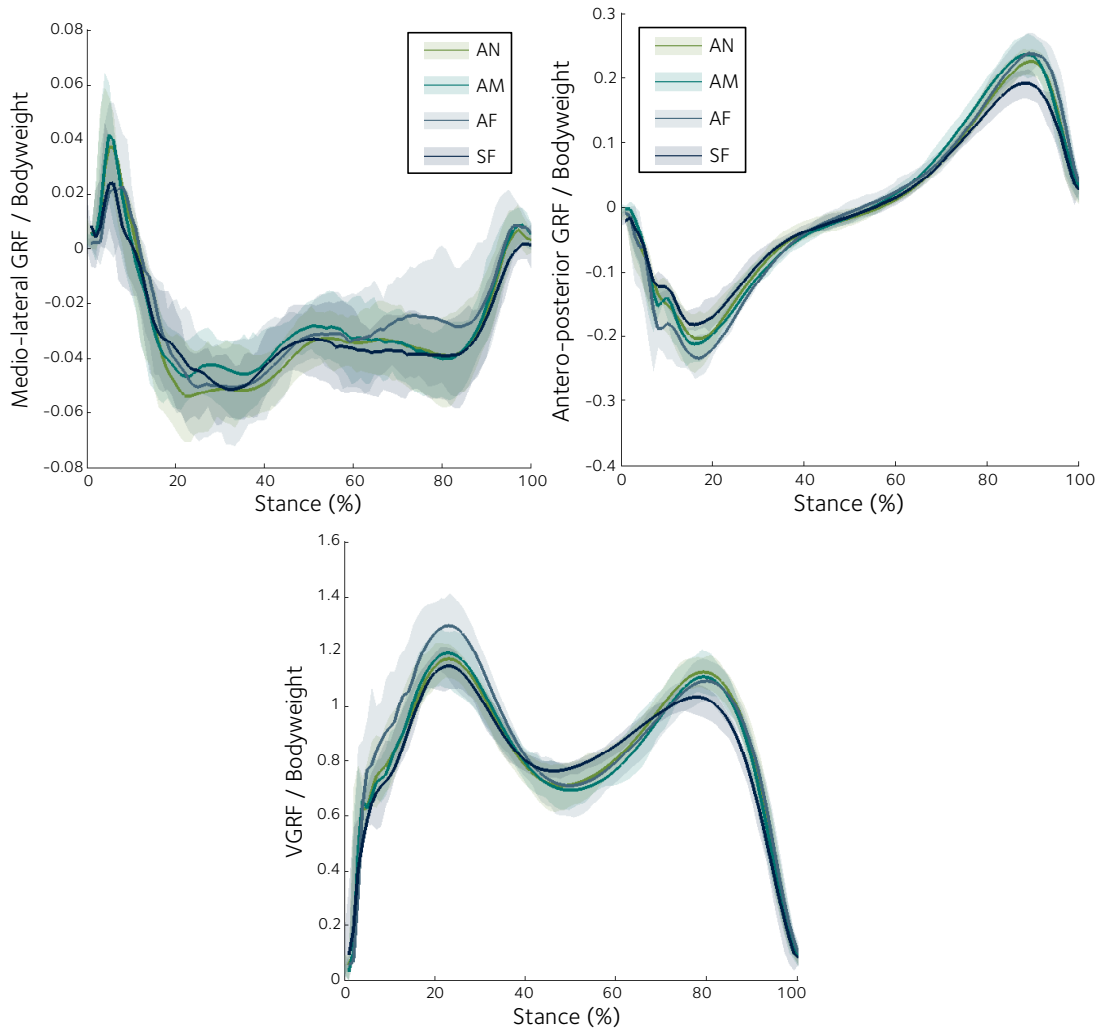


Figure 8.9.: Continuous traces of medio-lateral (ML, lateral GRF is positive direction on axis), antero-posterior (AP, anterior GRF is positive on axis), and vertical (V) GRF, normalized to bodyweight over the stance period. Stride selection based on SMaRT selection of representative trial for individual subjects. Bands represent median average deviation. Groupings and colours are as previously presented.

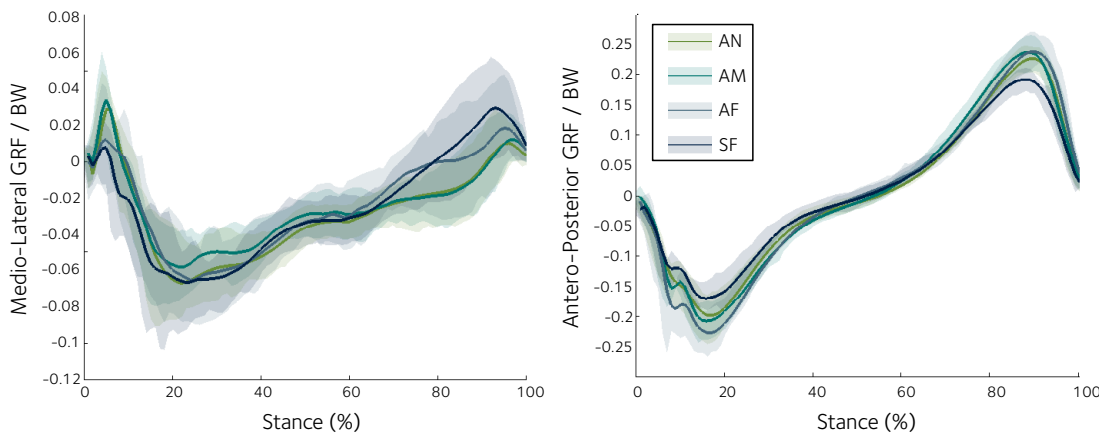


Figure 8.10.: Horizontal (frictional) Ground Reaction Forces (GRFs) reoriented to the ForeFoot (FF) axis. The axes are the long (antero-posterior, anterior GRF is positive on axis) axis of the foot, and the perpendicular (medio-lateral, lateral GRF is positive on axis) axis.

## 8. Spatio-temporal parameters and Ground Reaction Force

The antero-posterior GRF peaks were also reduced in the SF group (Fig. 8.9). The early stance small feature was present in all groups, but any apparent differences could not be distinguished from the effects of time averaging.

The vertical component reductions remain (Fig. 8.9). It appeared as though the timing of midstance and LSPs may have been earlier in the SF groups, however previous analysis had ruled this out (Table 8.1) so again this could be attributed to the effects of time averaging.

### *Continuous frictional GRF reoriented to the axis of the forefoot*

The reorientation of the horizontal GRF patterns to the axes of the forefoot changed little in the long axis (Fig. 8.10). The late stance medio-lateral forces were significantly altered. This is because external rotation of the forefoot increases in late stance in all groups. Perhaps most notable was the increase in lateral peak GRF near foot off when oriented relative to the axis of the forefoot in the SF and, to some extent, AF groups. The increased loading from this perspective, despite reduced stride length, may cause some of the symptoms associated with flatfoot (for example fatigue and foot pain). Or it may be a coping strategy to reduce medial loading, leading to the reduction in propulsion.

### *Investigating the effect of low late stance VGRF*

The patterns associated with "Ben Lomonding" (late stance VGRF peak below body-weight) were selected for further analysis. The analysis was limited to symptomatic subjects to eliminate other sources of variation. The analysis was of the transfer of weight between limbs, so two consecutive clean force-plate strikes were required. The number of subjects in the groups was fairly small: five subjects were identified for the "Ben Lomonding" group, 15 subjects had LSP VGRF above bodyweight. Low

## 8. Spatio-temporal parameters and Ground Reaction Force

LSP VGRF is associated with stability issues so compensation strategies would be expected in the following foot strike. During initial stance medial and posterior spikes as well as a perturbation in the VGRF pattern of the second limb were detected in the low LSP group, which would be consistent with an attempt to regain stability (Fig. 8.11). These groups are however fairly small, so apparent effects may be unreliable.

The process was repeated to see if this effect was still apparent within the Asymptomatic Neutral-footed group (Fig. 8.12). In the three cases, when the LSP VGRF fell below bodyweight the effect was even more pronounced, with a early stance VGRF pattern more closely resembling that of running (with an impulse spike).

### 8.4. Summary

Relative stride length was found to be significantly reduced in the SF group compared to others. This group spent slightly longer in stance compared with the AN group, and tended to have shorter strides than the other groups. This indicates that the swing phase of gait has been curtailed in terms of time and distance travelled. There was also an increased step width.

After controlling for the difference in relative stride length, ESP VGRF was found to be increased in the AF compared to the SF group, while LSP GRFs were found to be significantly reduced in the SF group compared to the asymptomatic groups. This may be interpreted as the cause of the reduced stride length observed. When oriented to axes of the forefoot, increased lateral GRF was found in the groups of flat feet.

The symptomatic group's reduced LSP could be a result of two phenomena: pain avoidance, or some sort of inability to apply or tolerate the load.

The presence of "Ben Lomonding" may favour one explanation. Almost three times as many symptomatic subjects registered a LSP VGRF below body-weight as within

## 8. Spatio-temporal parameters and Ground Reaction Force

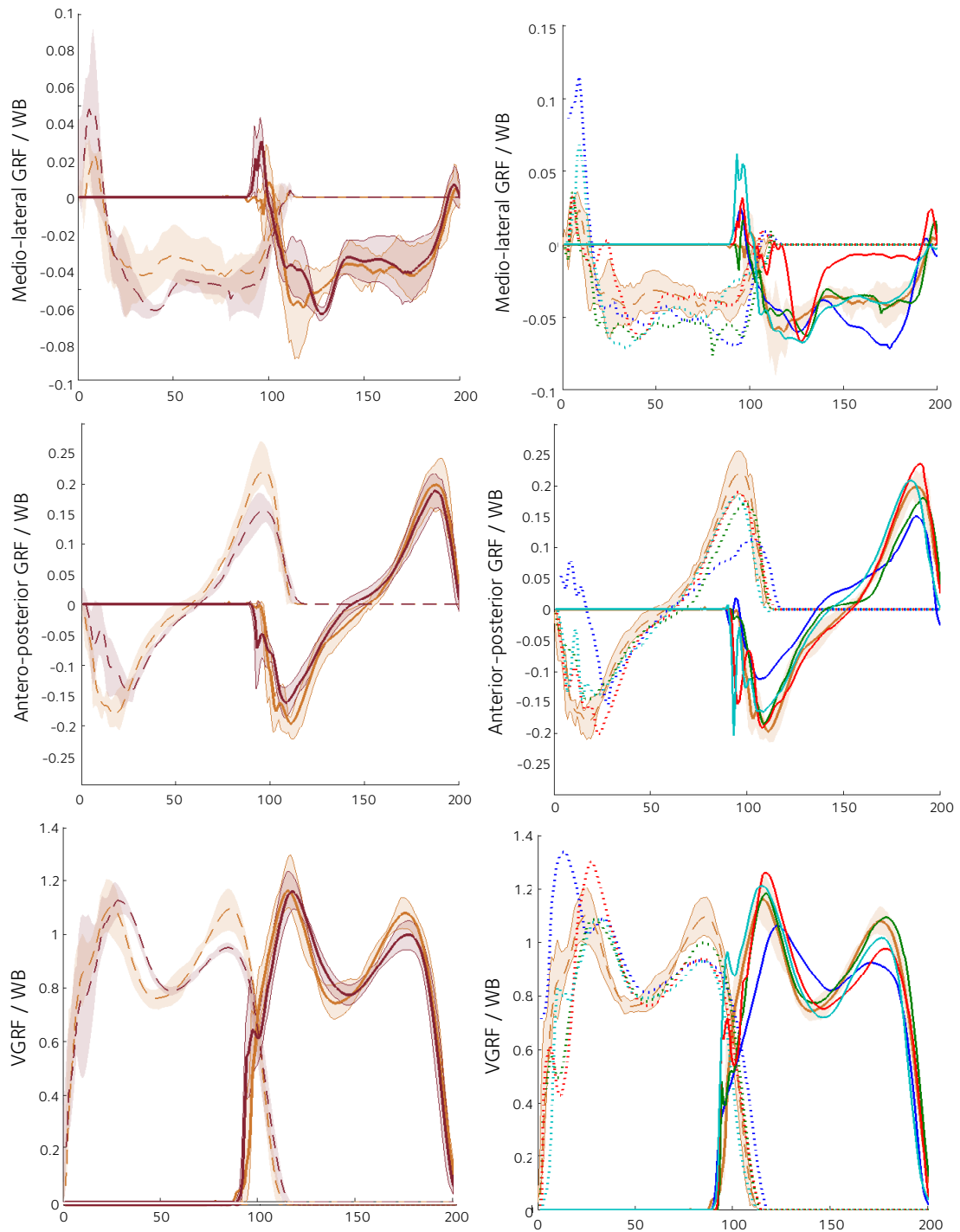


Figure 8.11.: GRF transfer patterns of SF subjects with Late Stance Peak (LSP) Vertical Ground Reaction Force (VGRF) below and above bodyweight. Dotted trace is the first step. (left) Averaged traces of groups below bodyweight (red,  $n=5$ ) and above bodyweight (orange,  $n=15$ ). Bands refer to inter-quartile range. (right) individual low LSP traces superimposed with non-low LSP VGRF bands behind (orange).

## 8. Spatio-temporal parameters and Ground Reaction Force

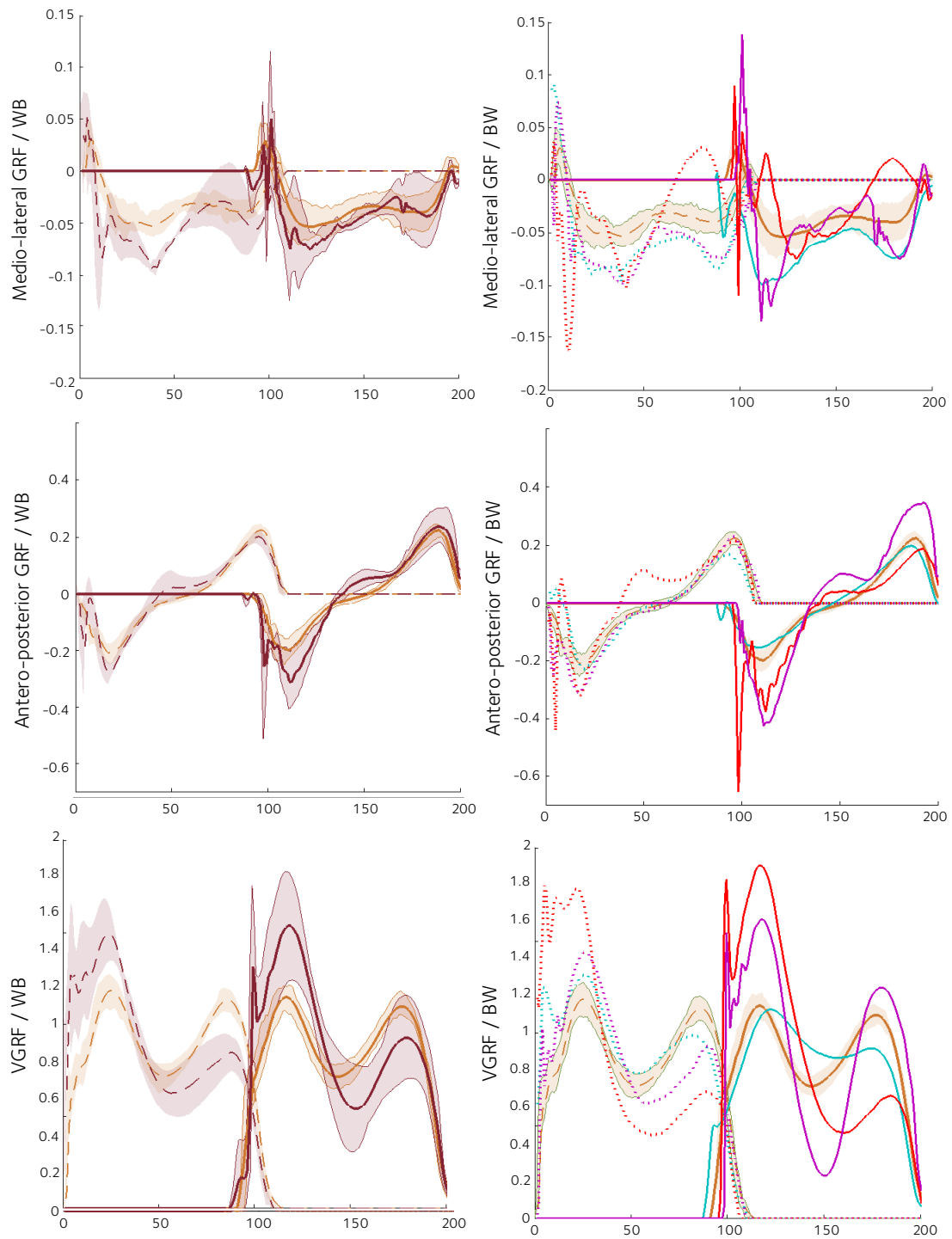


Figure 8.12.: Ground Reaction Force (GRF) transfer patterns of Asymptomatic Neutral feet (AN) with Late Stance Peak (LSP) Vertical GRF below and above bodyweight. Dotted trace is the first step. (top) Averaged traces of groups below bodyweight (red,  $n=3$ ) and above bodyweight (orange,  $n=33$ ). Bands refer to inter-quartile range. (bottom) individual low LSP traces superimposed with normal bands behind (orange).

## 8. Spatio-temporal parameters and Ground Reaction Force

the asymptomatic population. This group would be deemed to have lost stability following midstance, and were not supporting body-weight, and slowing the downward acceleration of the COM. They rely on the corrective action of the contra-lateral limb. This effect was visible during initial contralateral stance in “Ben Lomonding” SF subjects (compared to non-“Ben Lomonding” SF subjects). This corresponds with a finding from the audit (Chapter 3) and symptom summary (Section 5.1) that balance issues and frequent falling were often associated with flatfoot. This appears to favour an explanation of instability as causative of the reduced LSP VGRF. The MRC scores indicate it is unlikely to be a result of muscular weakness as the scores were generally between 4 and 5. Therefore, the most plausible explanation at this stage is that there is structural instability at the time of foot off (at least in a significant portion of subjects).

Basic variation in step characteristics, speed, and timing have been investigated. Differences in Ground Reaction Forces have been revealed. Now the differences in kinematics can be investigated, with a focus on the most pertinent differences, and an attempt to understand the cause of some differences.

## 9. Kinematic measures

This chapter explores kinematic differences between Asymptomatic Neutral (AN), Asymptomatic Mild flat (AM), Asymptomatic Flat (AF), and Symptomatic Flat (SF) footed populations during walking. The data was collected and processed as described in Chapter 4. Discrete time points at foot strike, midstance (as defined in Chapter 7), and foot off, as well as continuous data will be investigated here using ANOVA. The continuous data will also be explored for further insight.

There are five other papers that the author is aware of that have used multi-segment foot models to investigate flatfoot (Table 9.1). The traits detected in previous studies include increased forefoot plantarflexion, supination, and abduction; and at the rear-foot; increased internal rotation, abduction excursion, eversion excursion, and inversion excursion. Alarmingly, the studies do not provide any clear points of agreement. This may be due to the use of different models, different (yet highly specific) groups, or different analysis methods. This is a significant problem in gait analysis. If the authors can draw no more important result than the significant differences, and do not agree on those differences, it is difficult to understand what can be made of these discoveries. It may therefore be considered important in this study to go one step further than the angular differences, and consider the implications of any results.

In addition, Merriman clearly describes seven (unverified) gait analysis signs of flat-

## 9. Kinematic measures

Table 9.1.: Previous multi-segment foot model flatfoot studies. Upwards pointing arrows indicate relative increases, downwards pointing arrows indicate relative decreases.

Article	Year	Groups (age in years±SD )	Results associated with flatfooted group
Shih et al. [156]	2012	20 Flexible Flatfoot (9.7±0.9)	↓ peak hip internal rotation excursion
		10 Normal (9.6±1.2)	↑ peak knee internal rotation
Twomey and McIntosh [174]	2011	12 Low Arched (12.2±0.4)	↑ hip external rotation
		12 Normal (12.2±0.4)	↑ knee valgus
Levinger et al. [85]	2010	10 Normal (24.3±8.7)	↑ rearfoot internal rotation
		9 Flat Arched (20.1±1.3)	↑ late stance peak forefoot plantarflexion
			↑ midstance peak forefoot abduction ↓ terminal stance peak forefoot adduction
Twomey et al. [173]	2010	25 Normal Arched (11.1±1.2)	↑ medial arch angle
		27 Low Arched (11.2±1.2)	↑ forefoot supination
			(some left or right side specific results)
Cobb et al. [34]	2009	11 Typical (25.2±3.2)	↑ "pre-swing" rearfoot inversion excursion
		11 Low Mobile (24.5±6.1)	↓ "pre-swing" rearfoot eversion excursion ↓ midstance calcaneo-navicular abduction excursion

foot [104]. These signs are listed below, alongside a commentary of how they may be relevant to flatfoot and the development of symptoms:

- "Medial heel contact" – this may indicate non-ideal position as the contact may be medial to the (open chain) axis of the talo-calcaneal (subtalar) joint resulting in moments being generated around the joint.
- "Subtalar joint pronation at heel strike" – may lead to internal rotation of the tibia and eversion of the calcaneus (for more information on subtalar joint neutral please see paragraph 2 of the Normalised Navicular Height part within Section 2.1.1).
- "Reduced or negative re-supination" – "re-supination" before push off is important to provide a stable platform for propulsion by way of the "joint locking mechanism" (see below).
- "Abductory twist" – the abduction of the heel after the foot flat period.
- "Early heel lift" – a shortened foot flat period may be related to tightness of the

## 9. Kinematic measures

tendo-Achilles.

- “Reduced propulsive gait” – less propulsive force provided at foot off.
- “Increased genu valgum beyond physiological norm” – excessive knee valgus or knock knees may cause pain, instability, or weakness by altering the way the force is transmitted through the joint.

### *The joint locking mechanism*

There are at least two proposals of how the joint locking mechanism works. The mechanism is supposed to work to “lock” the foot and provide a rigid lever at push off. The unlocked posture is important for the purposes of shock absorption and adaptation to uneven surfaces.

The first theory, proposed by Root et al. [145], is that it is the mid-tarsal joints that are central to the stability. They state that the axes of the talo-navicular and calcaneo-cuboid joints must be parallel to be unlocked. However this depends on both joints behaving as hinge joints, which is disputed. The talo-navicular joint in particular is thought by many to be closer to a ball-and-socket joint and examination of the constraints of this joint seems to support this assertion.

The second theory, promoted by Glaser et al. [54, 55], claims that the motion of the talus on the calcaneus is the crucial aspect. The posterior facet of the talus (Fig. 9.1) move in a helical manner upon the cone shaped surface of the calcaneus. As the foot pronates, the loading moves to the middle and anterior facets. The spring ligament (from sustentaculum tali to navicular tuberosity, Fig. 9.2), at this point, maintains the talus in position and, by this mechanism, the ligament provides shock absorption. The re-supination moves the loading back over the posterior facet which is more stable.

The second theory is more in line with common theories of flatfoot. Rose identified

## 9. Kinematic measures

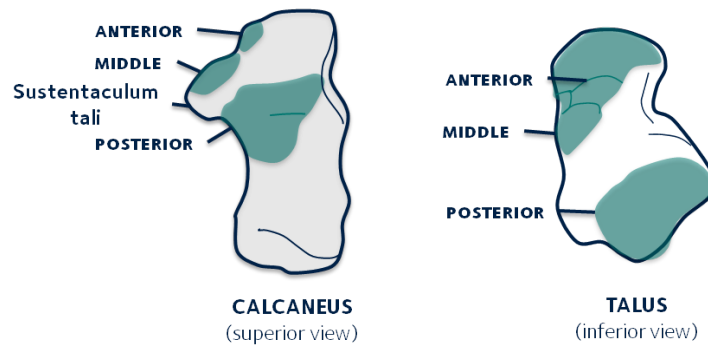


Figure 9.1.: Facets of the talo-calcaneal (subtarsal) joint. (left) superior view of calcaneus with three talar facets visible and sustentaculum tali. (right) superior view of the talus with three calcaneal facets visible.

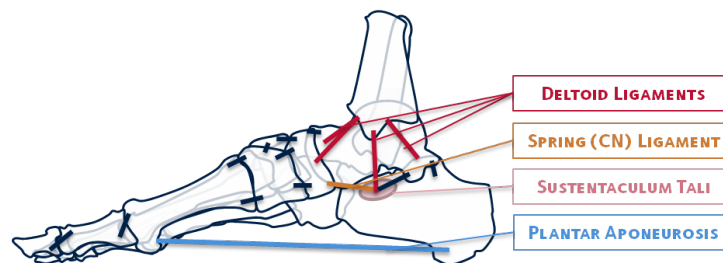


Figure 9.2.: Ligaments of the medial side of the foot. Those which Jay [72] identifies as most important in maintaining arch integrity are highlighted and labeled.

## 9. Kinematic measures

joint laxity as the primary cause of flexible flatfoot [146]. According to Jay [72], the most important factor to arch integrity is the sustentaculum tali, the second strongest factor - the posterior tibial tendon integrity. Other important supporting factors include the deltoid ligaments, inferior calcaneo-navicular ligament, and plantar aponeurosis (Fig. 9.2). The identification of the importance of the sustentaculum tali and spring (calcaneo-navicular) ligament integrity in terms of preventing flatfoot, surely support the second theory, which relies on these structures when the talo-calcaneal joint is unlocked to prevent total collapse.

Several studies have examined the motion of the foot bones with cadaveric and bone pin studies to reveal considerable inter-subject variability (reviewed by Nester [118]). In-vivo studies found the talo-tibial motion not to be limited to dorsi-/plantar-flexion even during dynamic tasks: mean range of motion in the transverse plane was between 7° and 10°; mean range of motion in the frontal plane was between 8° and 15° [4, 89, 119]. Those studies found more transverse and frontal plane motion in the talo-tibial than talo-calcaneal joints of many subjects indicating the roles of these joints are quite interchangeable. The talo-navicular joint is not limited to sagittal motion, and (to a lesser extent) neither is the calcaneo-navicular joint [4, 89, 119]. An additional highlight of these studies was the finding of significant lowering of the lateral arch during gait. These findings indicate that the (mid-tarsal joint locking) theory of Root et al. [145] is certainly over-simplistic. They do not call the (talo-calcaneal joint locking) theory of Glaser et al. [54, 55] into dispute, although they highlight inter-subject variability.

### 9.1. Methods

The data was collected and processed as described in Chapter 4 and representative values were found for statistical testing (Fig. 9.3). As detailed in Chapter 7, the times analysed were foot strike, midstance (as defined by the Vertical Ground Re-

## 9. Kinematic measures

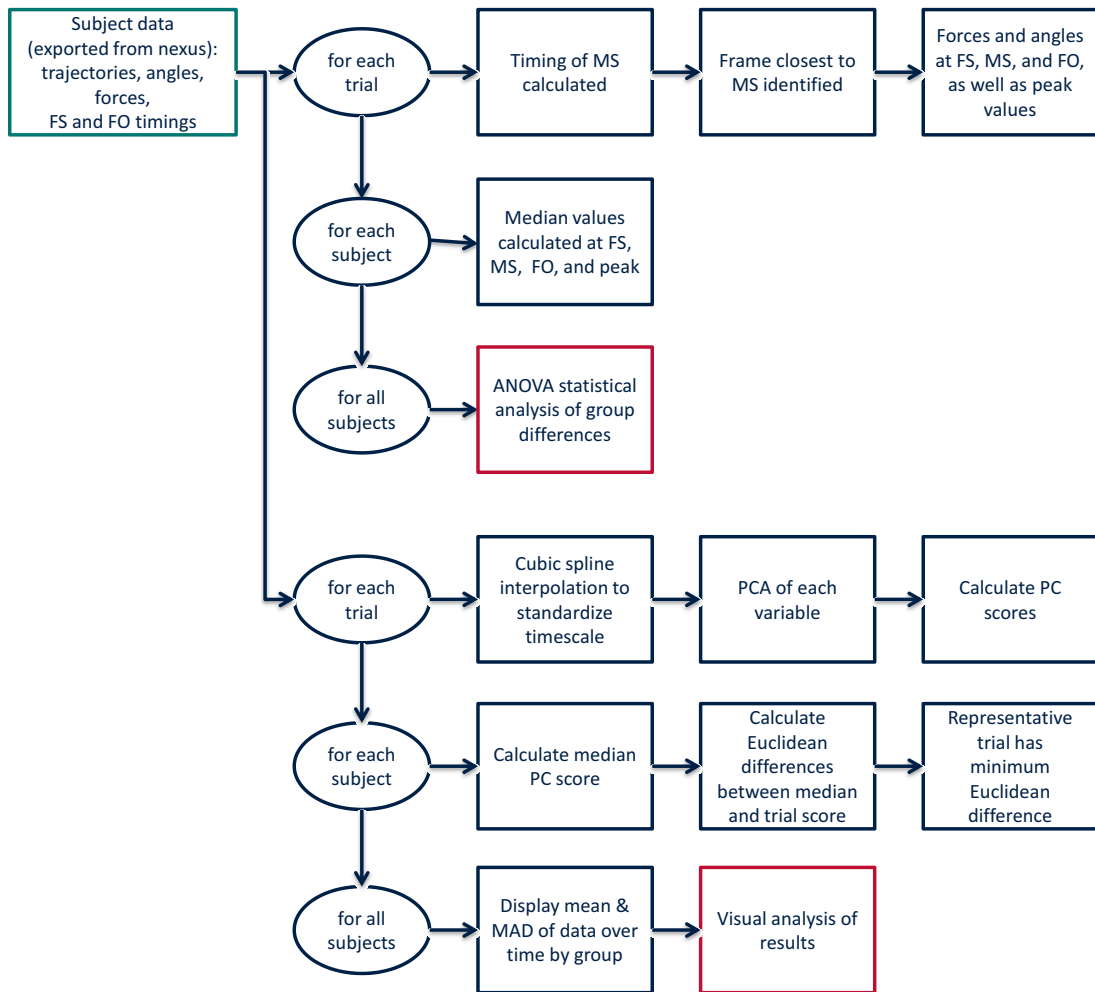


Figure 9.3.: Flowchart showing simplified data processing system. MAD stands for Median Average Deviation.

action Force), and foot off. Median values are calculated for each subject at these times. In addition median peak values were analysed to facilitate comparison with the aforementioned studies (Table 9.1, ).

Additionally, for each subject, a representative trial was selected to allow visual analysis of the complete stance phase (Fig. 9.3). This required creating a cubic spline interpolation of the original curves to normalize the number of frames. The SMaRT method was used to select the representative trial [153]. This method relies on principal component analysis [73] of each measure of each subject; then minimization of the sum of the Euclidean distance from median to trial score. This is a repeatable method but can be sensitive to outliers, and confused by variable patterns. The result of the selection was not subjected to further statistical analysis, it was analysed

visually.

### *Statistical Analysis*

Statistical analysis was done between the groups as previously defined, in a similar manner to the process in Section 6.6.2. ANOVA was performed on the four groups and for the result to be considered significant, they had to pass two post-hoc tests: Tukey and Games-Howell. To avoid developmental flatfoot, participants under the age of five were excluded.

## 9.2. Results and discussion

### 9.2.1. Comparison between AN, AM, AF, and SF

Applying the same test as in Section 6.6.2, revealed no skewness, but some Kurtosis in the hip angles - particularly adduction. It was perceived as desirable to have one standard method of statistical analysis for clarity. Therefore only results which satisfied the 0.05 level of both Tukey and Games-Howell post-hoc tests were counted as significant.

#### *Foot strike*

At foot strike four angles were revealed to have significant differences (Table 9.2, Fig. 9.4), with one difference at each of the joints (hip, knee, ankle, and foot).

The AF group recorded increased hip flexion (Table 9.2, Fig. 9.4), as had been previously been found in static stance. Since found in static stance and heel strike, it is possible that this reflects the position of the pelvis. Considering only one of the

## 9. Kinematic measures

Table 9.2.: Mean, standard deviation, and ANOVA results at foot strike. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

FOOT STRIKE	Groups	N	Mean	SD	ANOVA Sig.		Groups	N	Mean	SD	ANOVA Sig.	
Hip Flexion	AN	98	32.55	6.48	.013	]]]]	HF-TB	AN	87	7.78	9.47	.572
	AM	47	34.66	4.77			AM	45	9.58	7.87		
	AF	29	36.71	6.10			AF	29	7.85	5.16		
	SF	35	33.86	7.33			SF	32	9.49	8.29		
	All	209	33.82	6.36			All	193	8.49	8.37		
Hip Adduction	AN	98	-2.16	3.50	.121	]]]]	HF-TB	AN	87	-0.47	6.38	*.017
	AM	47	-1.93	3.07			AM	45	-1.93	5.17		
	AF	29	-1.05	2.85			AF	29	-2.83	4.62		
	SF	35	-0.78	3.43			SF	32	-4.09	6.04		
	All	209	-1.73	3.34			All	193	-1.76	5.94		
Hip Internal Rotation	AN	98	-9.46	6.55	.317	]]]]	FF-HF	AN	87	-3.05	4.37	.546
	AM	47	-10.43	6.07			AM	45	-2.21	3.97		
	AF	29	-9.73	7.52			AF	29	-3.05	3.86		
	SF	35	-11.81	6.24			SF	32	-3.57	4.49		
	All	209	-10.11	6.54			All	193	-2.94	4.22		
FE-TB Flexion	AN	88	4.29	4.18	*.046	]]]]	FF-HF	AN	87	1.27	5.55	*.000
	AM	47	4.77	5.22			AM	45	0.46	4.97		
	AF	29	6.20	4.28			AF	29	-2.50	4.23		
	SF	32	6.69	5.46			SF	32	-8.50	8.45		
	All	196	5.08	4.74			All	193	-1.11	6.79		
FE-TB Varus	AN	88	-0.63	2.60	*.008	]]]]	FF-HF	AN	87	5.46	5.13	.062
	AM	47	-1.12	3.35			AM	45	7.90	6.48		
	AF	29	-1.79	2.19			AF	29	7.20	6.51		
	SF	32	-2.67	3.87			SF	32	8.22	7.61		
	All	196	-1.25	3.05			All	193	6.75	6.20		
FE-TB Internal Rotation	AN	88	-15.55	11.45	.085	]]]]	HX-FF	AN	88	11.03	9.63	.483
	AM	47	-16.25	10.35			AM	45	11.24	11.56		
	AF	29	-12.92	9.37			AF	29	7.74	9.81		
	SF	32	-10.74	10.10			SF	32	10.28	11.66		
	All	196	-14.54	10.79			All	194	10.46	10.46		
HF-TB Dorsiflexion	AN	87	-1.81	6.45	.665	]]]]	HX-FF	AN	88	-7.21	7.40	.174
	AM	45	-1.25	3.07			AM	45	-5.86	6.46		
	AF	29	-2.46	3.46			AF	29	-5.27	6.64		
	SF	32	-2.54	4.82			SF	32	-4.04	8.65		
	All	193	-1.90	5.15			All	194	-6.09	7.35		

## 9. Kinematic measures

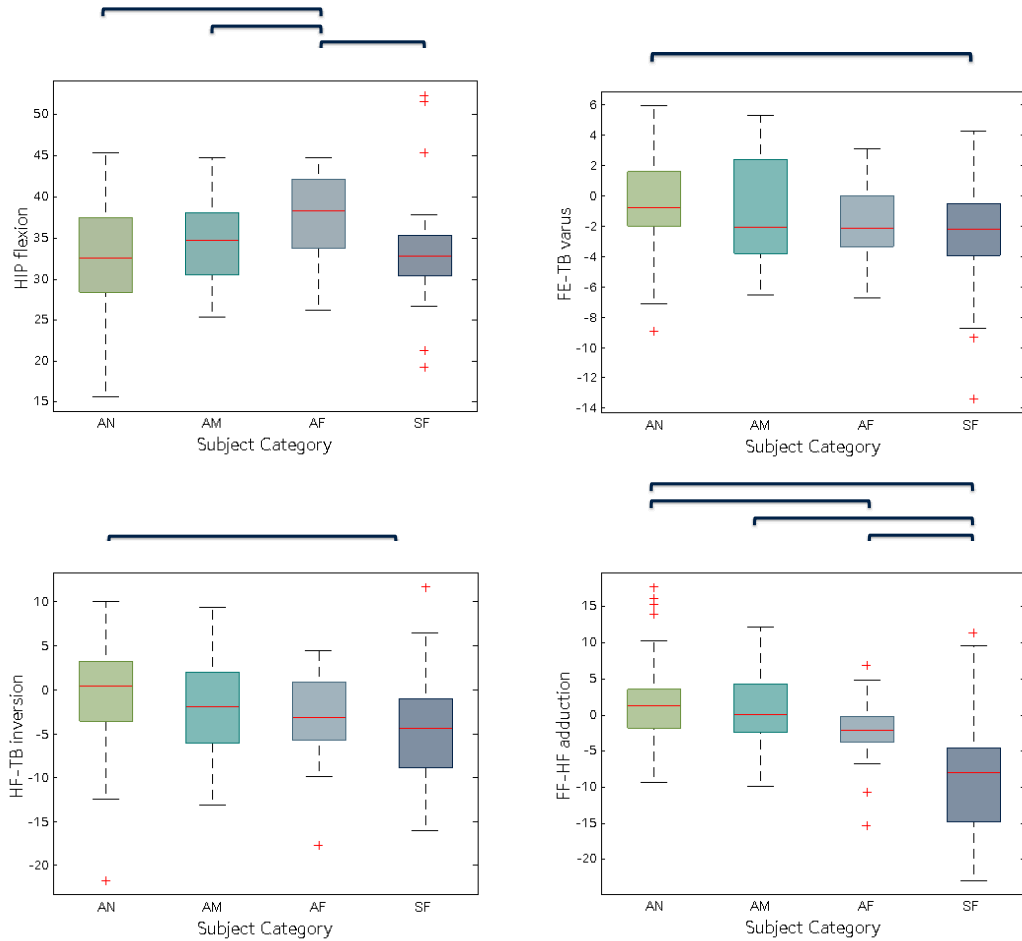


Figure 9.4.: Angles at foot strike where significant differences were found. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

## 9. Kinematic measures

asymptomatic groups of flat feet is showing this trend, it is possibly a false positive and does not reflect a genuine phenomenon.

The SF group had significant knee valgus compared to the AN group (Table 9.2, Fig. 9.4). Examination of the data suggests the trend is for all flat feet to be associated with knee valgus. A previous kinematic study found knee valgus to be associated with flatfoot [174], and it is commonly referred to in textbooks. Section 6.4 recorded “extreme” valgus to be more commonly associated with symptomatic (rather than asymptomatic) flatfoot. However, measuring this with the marker system in the static case did not record such a subtle difference. This was attributed to either a clinician expecting valgus therefore recording valgus, or a result of error and uncertainty in the model. The reappearance of a significant difference dynamically corroborates the presence of increased valgus in the population.

Greater eversion of the hindfoot was recorded in the SF group than in the AN group (Table 9.2, Fig. 9.4). This appeared to be a trend in all flat footed populations and had been expected. Heel eversion forms a significant component of the foot assessment procedure, therefore was likely to appear in the results; however this was more evident in static stance (Fig. 6.18).

The only angle which distinguished the symptomatic from all other foot groups was the abduction of the forefoot relative to the hindfoot (Table 9.2, Fig. 9.4).

### *Midstance*

At midstance, five of fourteen measures demonstrated significant differences between groups (Table. 9.3, Fig. 9.5). One hip measure, two knee measures, one ankle, and one foot measure.

At the hip, during midstance, flat feet were associated with more hip flexion; the MF group did not demonstrate such a change.

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Table 9.3.: Mean, standard deviation, and ANOVA results at midstance. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

MIDSTANCE		N	Mean	SD	ANOVA Sig.		N	Mean	SD	ANOVA Sig.
Hip Flexion	AN	98	6.65	6.78	]]	HF-TB	AN	87	2.64	9.97
	AM	45	7.29	5.51			AM	43	5.10	8.14
	AF	27	10.42	6.34			AF	27	4.70	6.19
	SF	34	10.75	7.64			SF	31	5.35	8.06
	All	204	7.98	6.80			All	188	3.95	8.82
Hip Adduction	AN	98	4.09	3.25	.326	HF-TB Inversion	AN	87	-3.61	4.94
	AM	45	4.69	3.17			AM	43	-5.81	6.14
	AF	27	5.13	2.65			AF	27	-6.52	4.62
	SF	34	4.91	3.12			SF	31	-7.80	6.88
	All	204	4.50	3.14			All	188	-5.22	5.73
Hip Internal Rotation	AN	98	1.25	7.19	.071	FF-HF Dorsiflexion	AN	87	1.04	4.09
	AM	45	-0.86	7.47			AM	43	0.71	3.91
	AF	27	0.29	8.33			AF	27	1.51	3.97
	SF	34	-2.69	9.31			SF	31	1.12	5.37
	All	204	0.00	7.87			All	188	1.05	4.24
FE-TB Flexion	AN	88	5.82	4.65	]]]]	FF-HF Adduction	AN	87	0.29	5.29
	AM	45	6.36	5.40			AM	43	-0.18	5.42
	AF	27	6.74	5.95			AF	27	-2.54	4.35
	SF	31	10.61	4.68			SF	31	-8.26	8.24
	All	191	6.85	5.27			All	188	-1.63	6.53
FE-TB Varus	AN	88	-0.39	2.73	]]	FF-HF Supination	AN	87	3.92	5.14
	AM	45	-0.90	3.13			AM	43	5.57	6.27
	AF	27	-1.27	2.52			AF	27	6.78	5.57
	SF	31	-2.82	4.47			SF	31	6.54	7.47
	All	191	-1.03	3.23			All	188	5.14	5.98
FE-TB Internal Rotation	AN	88	-13.61	11.89	.260	HX-FF Dorsiflexion	AN	88	-2.08	8.51
	AM	45	-11.95	9.48			AM	43	0.42	8.84
	AF	27	-11.58	8.42			AF	27	-4.28	7.66
	SF	31	-9.30	9.43			SF	31	-2.48	10.02
	All	191	-12.23	10.57			All	189	-1.89	8.79
HF-TB Dorsiflexion	AN	87	6.21	4.01	.591	HX-FF Adduction	AN	88	2.62	6.99
	AM	43	6.29	3.13			AM	43	3.23	5.97
	AF	27	6.13	3.47			AF	27	3.16	7.27
	SF	31	5.18	4.42			SF	31	5.34	7.78
	All	188	6.05	3.81			All	189	3.28	6.96

## 9. Kinematic measures

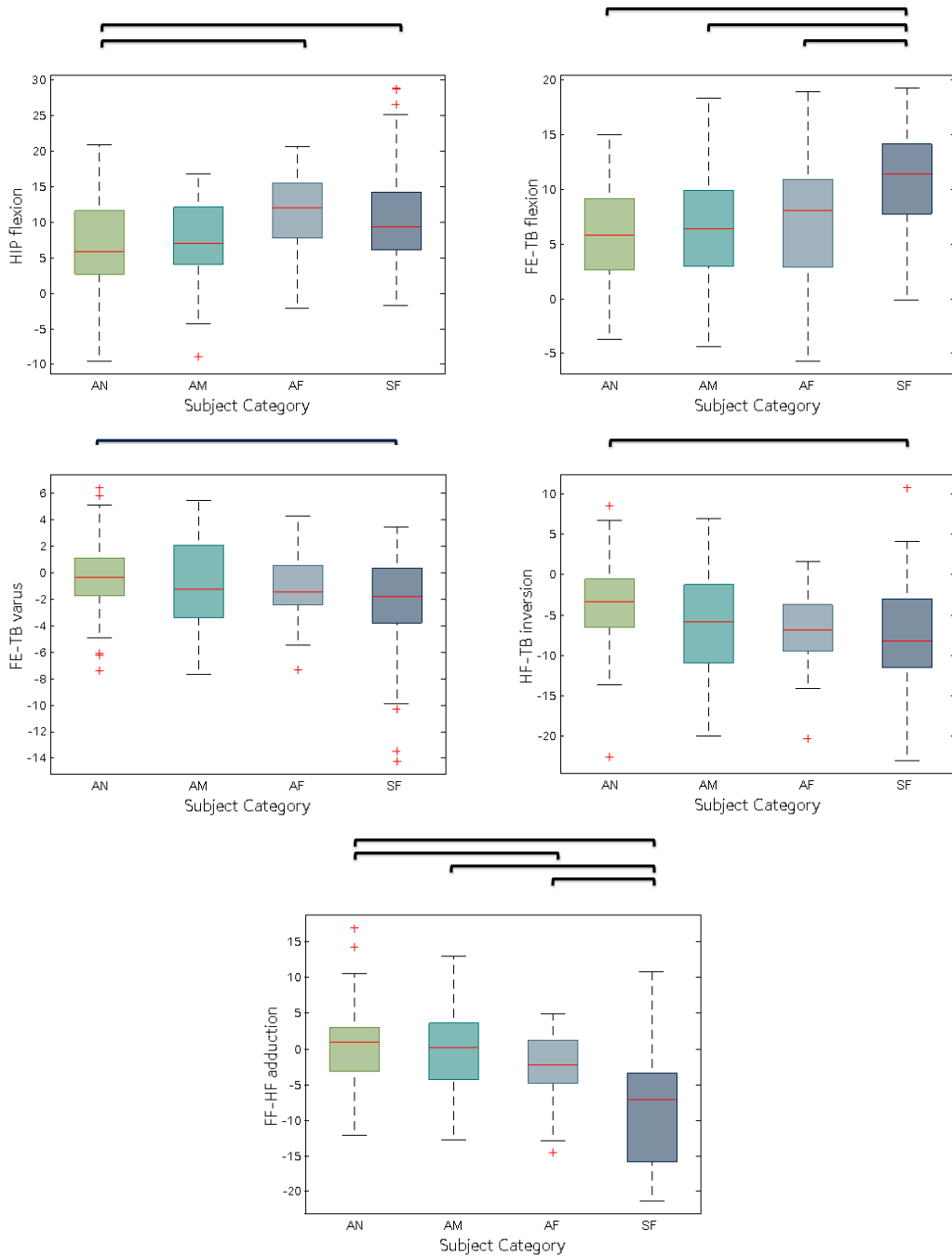


Figure 9.5.: Angles at midstance (as defined by the force-plate) where significant differences were found. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

## 9. Kinematic measures

At the knee more flexion and valgus was found at midstance in the SF group (Table 9.3, Fig. 9.5). This is in agreement with a previous kinematic study which found knee valgus to be associated with flatfoot [174], and it is commonly referred to in textbooks. The knee was found to be more flexed at midstance only in the symptomatic group, which was perhaps surprising considering this group was previously found to have a larger passive hyperextension of the knee (Fig. 6.13). This may be an over-compensation of the symptomatic population to provide stability or avoid strain. Similar to foot strike, knee valgus at midstance was associated with the symptomatic population (though with a relatively small mean difference).

Similarly to static stance and foot strike, the hindfoot in the flat feet was found to be more everted relative to the tibia.

Similarly to static stance and foot strike, the forefoot was shown to be abducted in the symptomatic population. The increased forefoot abduction of the flat feet at this point reflects the findings of a previous study [85].

### *Foot off*

It is at foot off where the differences were most clear, with significant differences in seven out of fourteen angles (Table 9.4, Figs. 9.6 and 9.8). Most significant differences were associated with the symptomatic population – two at the hip, two at the knee, two at the ankle, and one at the foot.

There was reduced abduction and extension at the hip (in line with the results at static stance and foot strike) (Table 9.4, Fig. 9.6). The reduced hip extension at foot off is probably related to the reduction in relative stride length (Section 8.3.1, Fig. 8.4). Indeed a strong correlation exists (correlation coefficient =  $-0.55$ , Fig. 9.7).

There was increased flexion (as had been found at midstance) and reduced external rotation at the knee. This may reflect the finding of Shih et al. of increased peak

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Table 9.4.: Mean, standard deviation, and ANOVA results at foot off. Square brackets indicate between which groups post-hoc testing revealed statistically significant differences.

FOOT OFF	Group	N	Mean	SD	ANOVA Sig.		Group	N	Mean	SD	ANOVA Sig.	
Hip Flexion	AN	98	-5.95	6.96	*001	]]	HF-TB	AN	87	5.11	9.40	*005
	AM	47	-6.56	5.71			AM	45	7.15	8.60		
	AF	29	-2.60	6.95			AF	29	6.57	7.11		
	SF	37	-0.75	10.94			SF	32	0.16	8.60		
	All	211	-4.71	7.83			All	193	4.99	9.01		
Hip Adduction	AN	98	-5.50	2.54	*025	]]	HF-TB	AN	87	3.18	7.16	.134
	AM	47	-5.46	2.97			AM	45	3.02	5.57		
	AF	29	-5.18	2.93			AF	29	3.07	4.43		
	SF	37	-3.87	3.32			SF	32	0.12	7.47		
	All	211	-5.16	2.88			All	193	2.62	6.57		
Hip Internal Rotation	AN	98	1.42	6.58	.336	]]	FF-HF	AN	87	-9.45	4.62	.241
	AM	47	-0.54	6.74			AM	45	-10.22	4.42		
	AF	29	1.32	6.02			AF	29	-8.81	3.22		
	SF	37	-0.03	7.65			SF	32	-8.12	5.92		
	All	211	0.72	6.75			All	193	-9.31	4.66		
FE-TB Flexion	AN	88	31.45	5.68	*000	]]]]	FF-HF	AN	87	7.55	5.81	*000
	AM	47	31.20	7.04			AM	45	7.58	4.91		
	AF	29	32.84	7.31			AF	29	3.75	4.94		
	SF	32	39.37	7.00			SF	32	-5.22	9.19		
	All	196	32.89	7.08			All	193	4.87	7.75		
FE-TB Varus	AN	88	0.27	3.40	.197	]]]]	FF-HF	AN	87	2.66	4.99	*033
	AM	47	-0.97	3.63			AM	45	3.92	6.84		
	AF	29	-0.56	3.91			AF	29	4.89	5.95		
	SF	32	-1.16	5.63			SF	32	6.23	7.88		
	All	196	-0.38	3.98			All	193	3.88	6.23		
FE-TB Internal Rotation	AN	88	-14.23	10.48	*024	]]	HX-FF	AN	88	14.49	12.61	.108
	AM	47	-13.18	8.84			AM	45	17.05	16.36		
	AF	29	-12.04	8.55			AF	29	13.64	14.09		
	SF	32	-8.04	10.19			SF	32	21.20	16.22		
	All	196	-12.65	9.96			All	194	16.06	14.50		
HF-TB Dorsiflexion	AN	87	-10.60	6.49	*001	]]	HX-FF	AN	88	-6.27	8.21	.213
	AM	45	-10.12	4.44			AM	45	-3.93	10.31		
	AF	29	-9.06	5.34			AF	29	-2.49	7.22		
	SF	32	-5.81	6.22			SF	32	-4.48	11.34		
	All	193	-9.46	6.06			All	194	-4.87	9.21		

## 9. Kinematic measures

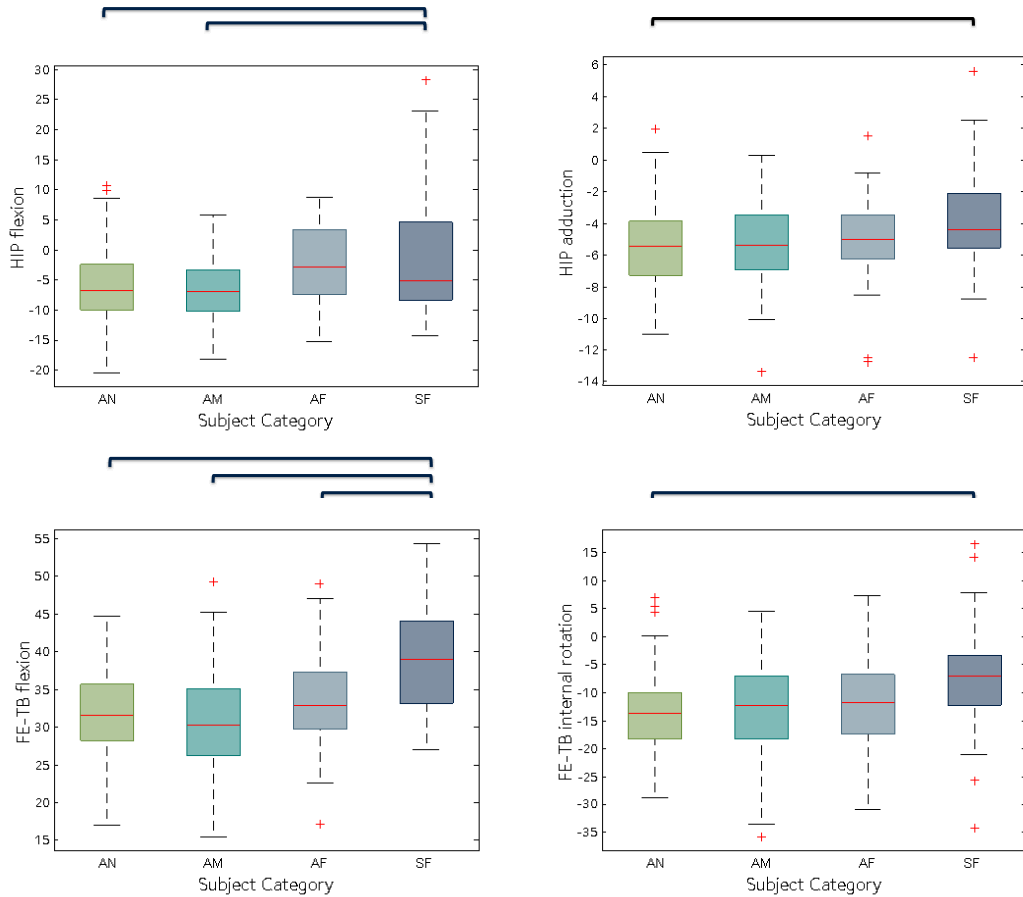


Figure 9.6.: Hip and knee angles at foot off where significant differences were found. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

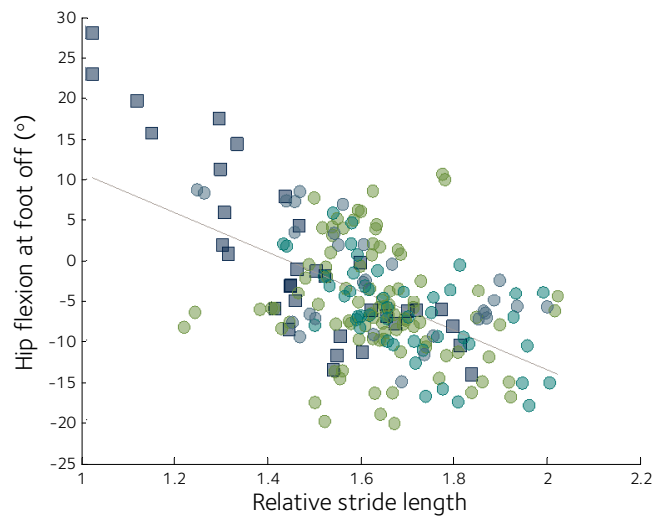


Figure 9.7.: Correlation between hip flexion at foot off and relative stride length. As relative stride length increases, hip extension increases. Linear correlation in grey, correlation coefficient =  $-0.55$ .

## 9. Kinematic measures

knee internal rotation in flat feet [156]. The rotation of the tibia may be related to rotations at the ankle.

At the ankle, the SF hindfoot was less plantarflexed relative to the tibia and the AF group had more internally rotated hindfeet than the SF group (Table 9.4, Fig. 9.8). The reduced plantarflexion appears again to relate to the reduced propulsion identified in the previous chapter. The finding of reduced internal rotation may appear at first to be contrary to the findings of Levinger et al. [85], however, that study found the increase in asymptomatic flat feet relative to neutral feet, which is not contradicted (but in fact suggested) by our findings – it is the symptomatic flat feet which demonstrate reduced internal rotation relative to the asymptomatic groups in our case. Upon reflection this is perhaps an interesting finding as it may suggest a compensatory strategy of internal hindfoot rotation may benefit the population, or that allowance of external rotation (“abductory twist”) in terminal stance is not desirable.

Again, there was increased abduction of the forefoot in the flatfooted groups especially SF and AF (as had been found at all other time points). This is in agreement with Levinger et al. in AF-AN [85], and Hunt and Smith in SF-AN [68]. All groups were significantly different from each other in this regard except AN and AM.

### 9.2.2. Visual analysis of continuous traces in AN, AM, AF, and SF

Inspection of hip angles over time reveals further information (Fig. 9.9). The significant differences were found for flexion; and it is evident that the range of flexion is slightly reduced in the symptomatic subjects. This is probably related to the reduced relative stride length. The hip internal rotation graph reveals the second peak to be missing in the flatfooted subjects. This increased internal rotation of the hip relative to the femur is caused by the contralateral leg taking the next step and therefore rotating the pelvis. The absence of such a feature could have been related to the

## 9. Kinematic measures

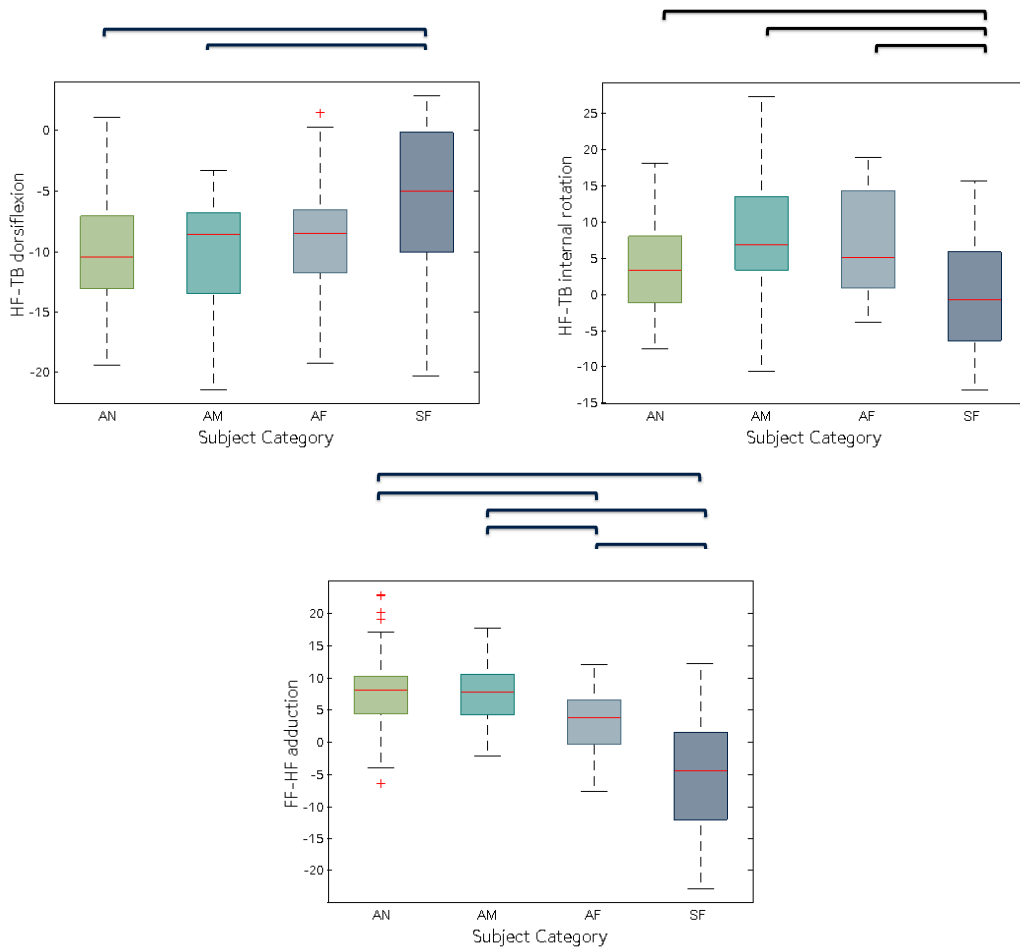


Figure 9.8.: Ankle and foot angles at foot off with significant differences. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

## 9. Kinematic measures

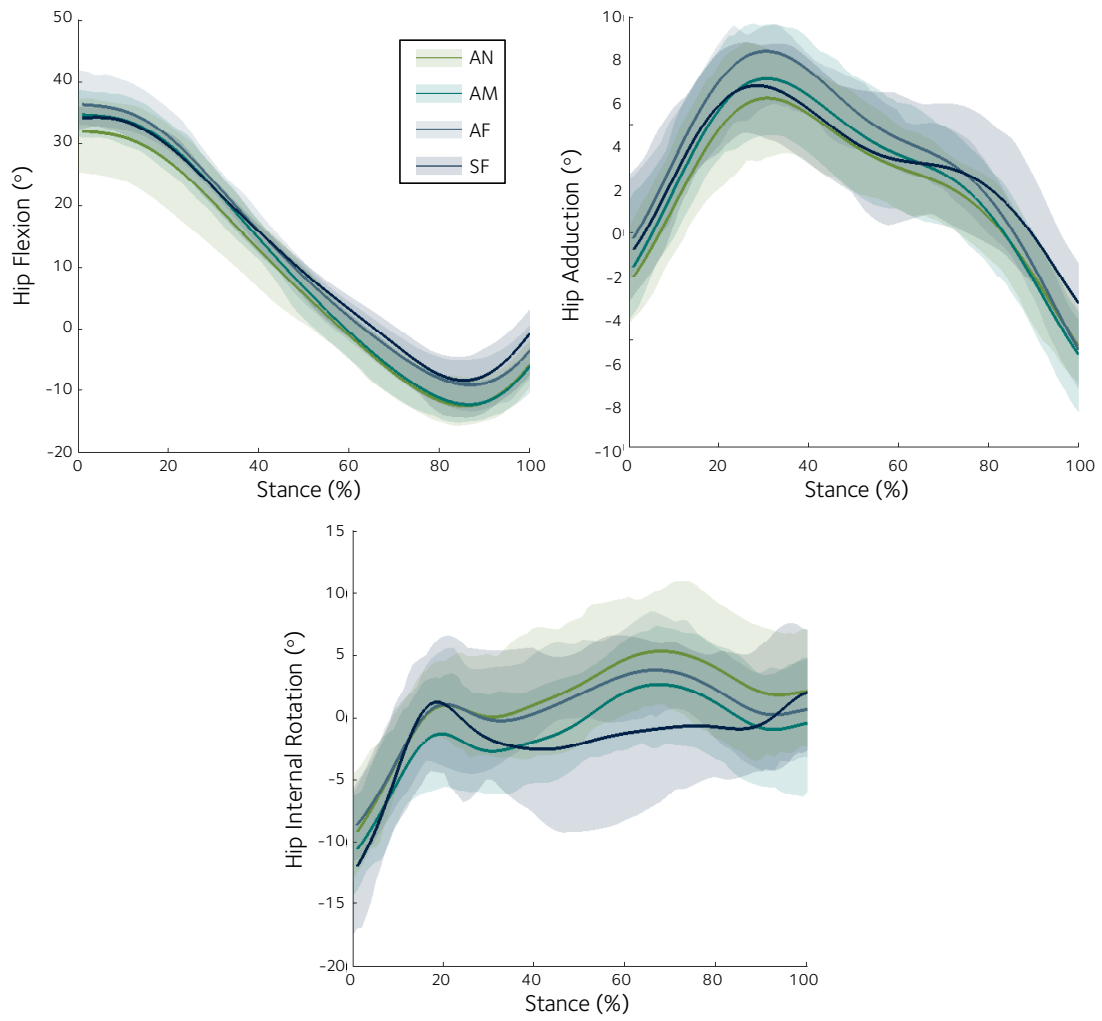


Figure 9.9.: Hip angles versus percentage stance. Group mean and inter-quartile range.

## 9. Kinematic measures

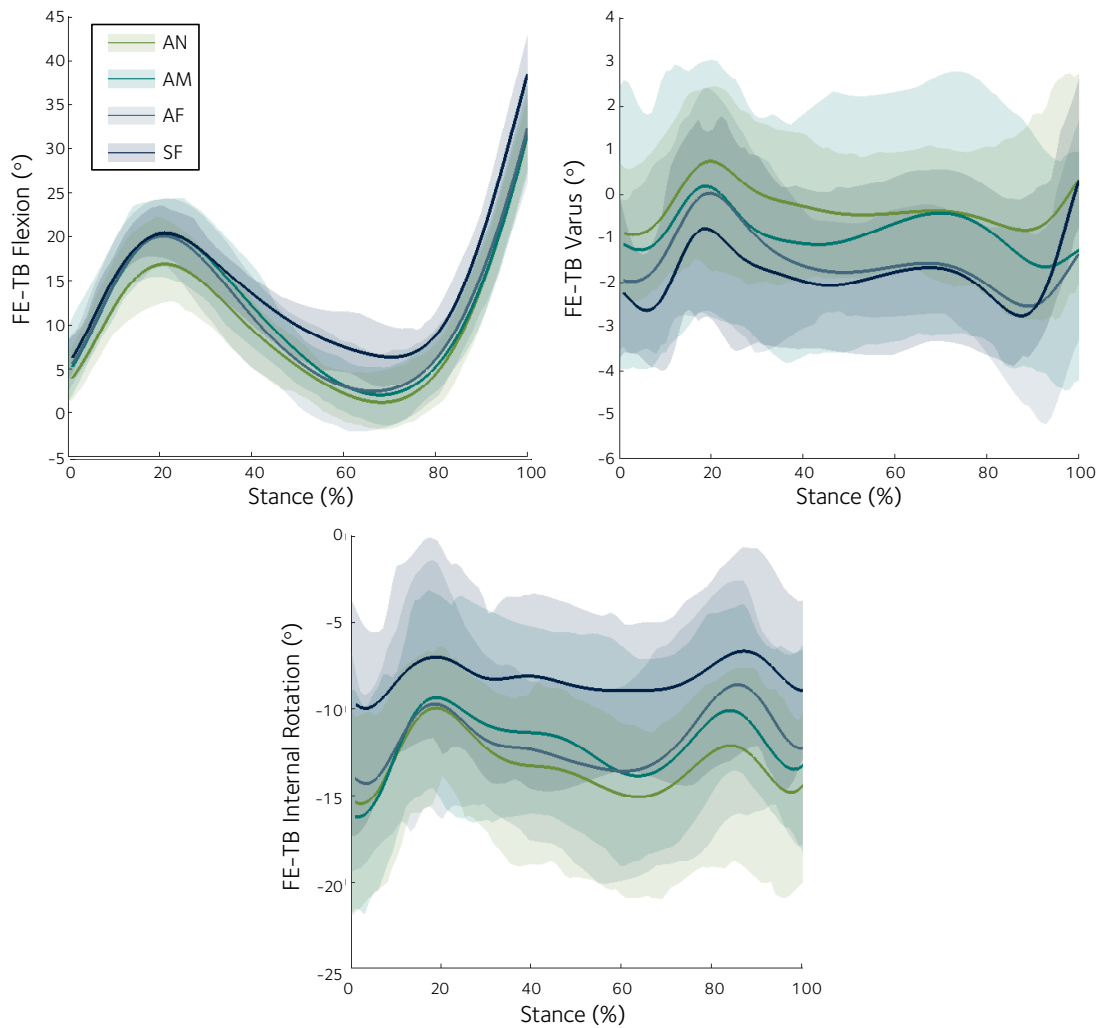


Figure 9.10.: Knee angles versus percentage stance. Group mean and inter-quartile range.

reduced stride length in the symptomatic subjects (Section 8.3.1, Fig. 8.4).

At the knee, the continuous information provides little additional insight (Fig. 9.10). It appears that the valgus associated with SF group rapidly corrects in terminal stance.

The ankle curves reveal that in the SF group, towards foot off, the hindfoot externally rotates relative to the tibia (Fig. 9.11). This is a feature which is not associated with all subjects, but with a significant number (Fig. 9.12). This may be what has been described by Merriman as “abductory twist”. The divergence into two patterns within the SF group may explain why the asymptomatic groups of flat feet were highlighted as significantly different from the SF group but were not from the AN group.

## 9. Kinematic measures

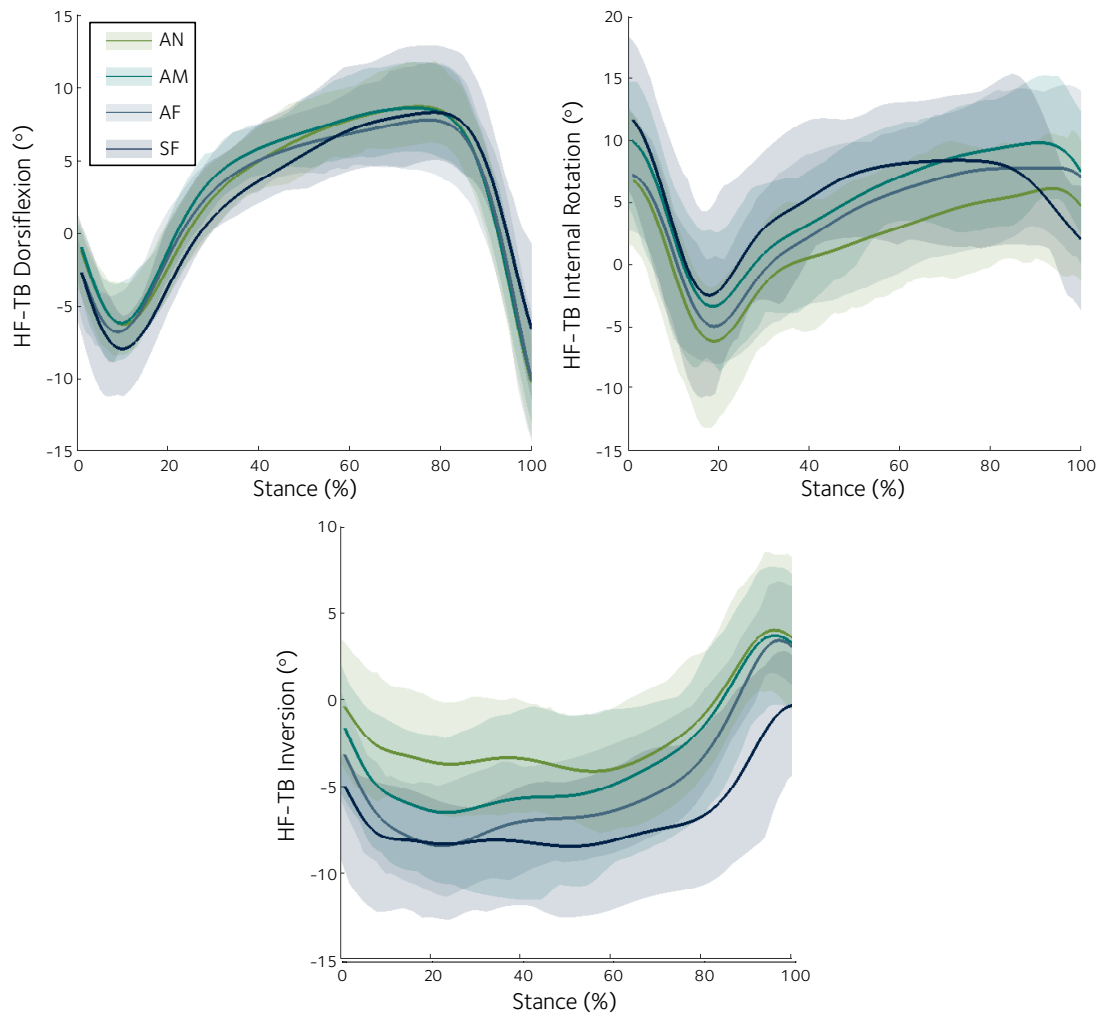


Figure 9.11.: Ankle angles versus percentage stance. Group mean and inter-quartile range.

The averages of the magnitudes of the AN group very were close to the findings of Levinger et al. [85], with the exception of hindfoot internal rotation which had been reported as much more external within the neutral group of the aforementioned study. The trends seen in our symptomatic groups were similar to the flatfoot group of the other study though there are differences.

Though eversion at foot off had not been found to be significantly different (Table 9.4), this may have been the result of the test point selection as there appears to be a timing difference (Fig. 9.11). The asymptomatic groups are evertng as foot off approaches whereas the symptomatic group are in the process of inverting. Indeed when the peak value was tested,  $p=0.016$ . The inversion process appears to

## 9. Kinematic measures

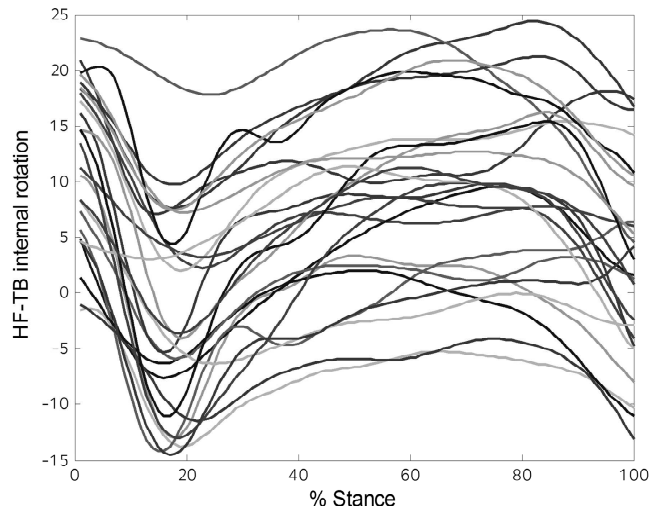


Figure 9.12.: Symptomatic Flatfeet, HF-TB internal rotation versus stance.

be slower in the SF group, perhaps supporting the theories that forefoot abduction may have impaired initial supination or that the supinators may be weaker.

Within the foot, forefoot-hindfoot angles are as expected, with the clear association between FF-HF abduction and the SF group (Fig. 9.13). The averages of the AN group are in close agreement with the neutral group in Levinger et al. [85], the symptomatic group are closer to the flatfoot group from the same study.

At the hallux, the abduction during terminal stance reflects and mirrors the HF-TB external rotation pattern in the SF group (Fig. 9.14). This may be related to friction leading to the opposite behaviour at the hallux.

### 9.2.3. Summary of results and further implications

In summary (Table 9.5), the increased hindfoot eversion and forefoot abduction present in static stance were found throughout gait in the SF group. Additional changes included the presence of increased hip flexion and knee valgus among other things. The differences were most apparent at foot off. The only differences directly supported by previous research are forefoot abduction (as few studies have been conducted on

## 9. Kinematic measures

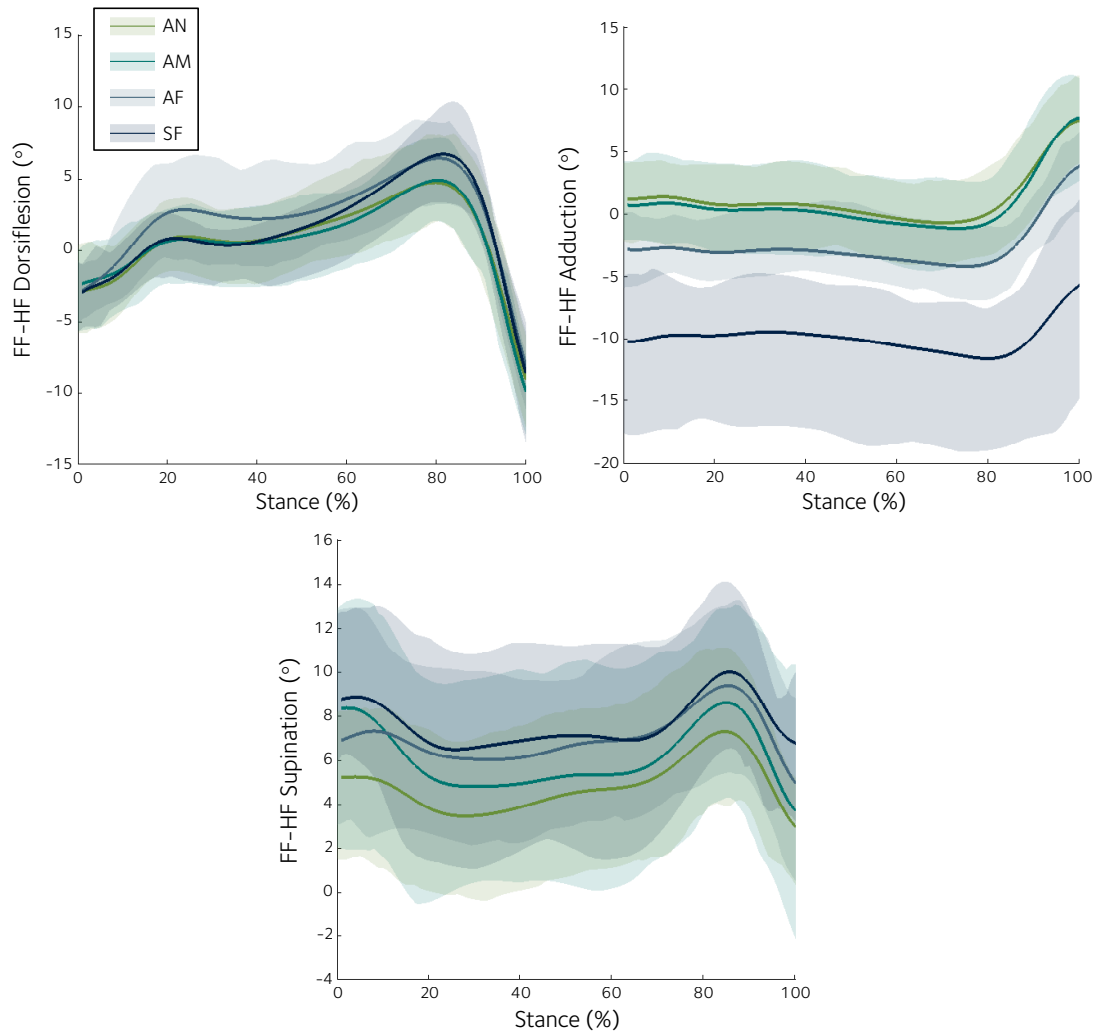


Figure 9.13.: FF-HF angles versus percentage stance. Group mean and inter-quartile range.

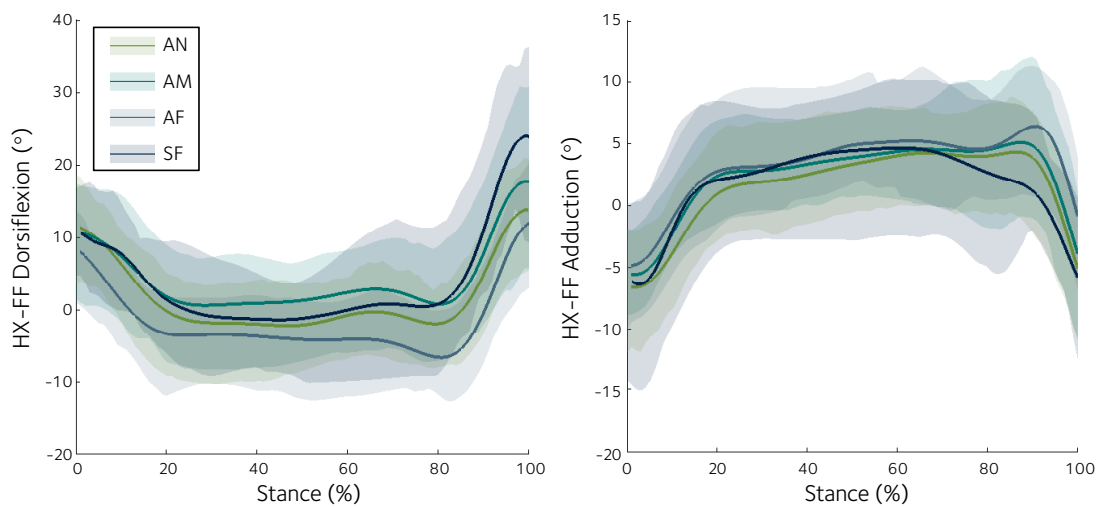


Figure 9.14.: HX-FF angles versus percentage stance. Group mean and inter-quartile range.

## 9. Kinematic measures

Table 9.5.: Summary of significant angular differences in static and dynamic stance (while walking). A significant difference is indicated between groups A and B as A-B. If there is also a difference between A and C the terminology is A-B/C. The group on the left hand side of the hyphen displayed the characteristic listed, e.g. increased hip flexion compared to the group on the right hand side. \* supported by radiographic studies [192, 109]. \*\* supported by kinematic study [68]. \*\*\* supported by a kinematic study [85].

	Static stance	Foot strike / early stance	Midstance	Foot off / late stance
↓ hip abduction	SF-AN/AM/AF			SF-AN
↑ hip flexion		AF-AN/AM/SF	SF-AN, AF-AM/AN	SF-AN/AM (↓ hip extension)
↑ knee valgus		SF-AN	SF-AN	appears to correct
↑ knee flexion			SF-AN/AM	SF-AN/AM/AF
↓ external knee rotation				SF-AN
↓ hindfoot plantarflexion				SF-AN/AM
↑ hindfoot eversion	SF-AN/AM/AF, AF/AM-AN	SF-AN	SF/AF-AN	temporal variation of peak
↑ external hindfoot rotation				SF-AM/AF
↑ forefoot abduction	SF-AN/AM/AF*, AF-AN	SF-AN/AM/AF, AF-AN	SF-AN/AM/AF	SF-AN**/AM/AF, AF-AN***/AM
↑ forefoot supination	?			?

symptomatic non-posterior tibialis tendon dysfunction which is where most of the significant results appeared).

### *Foot strike*

During initial contact pre-tibial muscles (tibialis anterior, extensor hallucis longus, extensor digitorum longus, and peroneus tertius; Fig. 9.15) should contract to maintain neutral ankle posture. The hindfoot eversion could be attributed to an imbalance between these muscles. This can also be interpreted as an attempt to compensate for the shortening of the tendo-Achilles by reducing the distance between calcaneal tuberosity and tibia, however correlation between passive ankle dorsiflexion and static hindfoot eversion was weak. The presence of increased forefoot abduction could be attributed to structural differences.

### *Foot off*

At the knee, increased flexion, and decreased external rotation were found in the SF group. The flexion may be the result of the decreased hip flexion or activity (Section

## 9. Kinematic measures

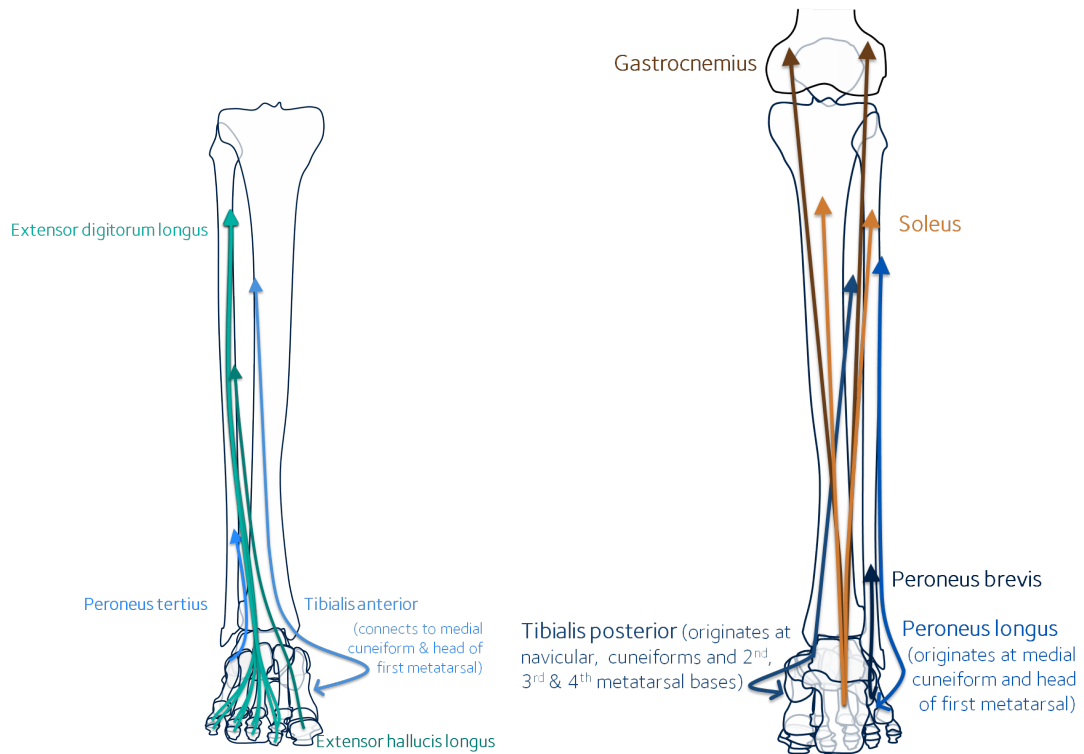


Figure 9.15.: Insertion and attachment points of (left) pre-tibial muscles and (right) some muscles involved in foot off. Pre-tibial muscles are - extensor digitorum longus, tibialis anterior, extensor hallucis longus, peroneus tertius, and tibialis anterior - which act to maintain neutral ankle alignment at foot strike. Foot off muscles - gastrocnemius, soleus, peroneus brevis, tibialis posterior, and peroneus longus - which act to maintain an inverted foot posture at foot off and propulsive force.

## 9. Kinematic measures

6.5, Fig. 6.14), and it could also be related to the late stance instability identified in Chapter 8.

The external rotation in the symptomatic group indicates a failure to “re-supinate”. Though no significant differences were found in terms of supination, this may be due to large error in this measure. Additionally there is no tracking marker near the proximal first metatarsal (it is removed after the static trial) – which may be necessary to adequately describe forefoot supination. Inversion or supination is important to gaining stability or stiffness in the foot. The soleus and gastrocnemius normally act to maintain ankle position against the torque provided by body-weight [170]. A foot that is not stiff cannot provide support against which these muscles can work to provide propulsive power and ankle stability.

Inversion of the subtalar joint creates stability in the foot either by mid-tarsal or talocalcaneal mechanisms (Section 6.6.3). Inversion of the foot is prompted by the obliquity of the second to fifth metatarsal heads ( $28^\circ$  anterior to the coronal plane [70]). The metatarso-phalangeal joint flexes  $20^\circ$  at the end of terminal stance, which would lead to approximately  $6^\circ$  supination (given the  $20^\circ$  flexion and  $28^\circ$  obliquity of the metatarsal heads). The inversion is supported by action of the soleus and tibialis posterior, this action is balanced by the action of peroneus longus and brevis (Fig. 9.15). Foot supinators were found to be weak in 24% of SF subjects (Section 5.2). The support of the arch via the Windlass mechanism (Fig. 4.14) also contributes to stability. A weak Windlass mechanism was recognized in 26% of SF subjects (Section 5.1).

If the foot is unstable, there is no support against which the tendo-Achilles can work to provide propulsive force. Instead the calcaneus will be able to rotate about the tibia (if it is assumed that the talo-calcaneal locking mechanism is the relevant one). This will result in strain of the passive structures of the foot. Potentially leading to exacerbation of the condition, and symptoms such as foot pain, plantar fasciitis, fatigue, and stability issues.

The forefoot was abducted in the SF group, as had been the case in standing and

## 9. Kinematic measures

throughout stance, however the difference at this point in time was greater than had been reported previously [85]. Adduction was also reduced in the AF group. This may explain the increased late stance lateral (relative to forefoot) GRF patterns in the SF, and to a lesser extent, AF groups (Section 6.6.3, Fig. 8.10). The external rotation of the forefoot may interfere with the initial supination provided by the obliquity of the second to fifth metatarsal heads. This may require further effort from other supinators (tibialis posterior and soleus), leading to fatigue and overwork. Some believe posterior tibialis tendon dysfunction can be caused by flatfoot, with overwork of the tibialis posterior being the root cause of this. Abduction in the AF group may be an indication that symptoms will develop in these subjects and monitoring or conservative management may be warranted.

It is perhaps the external rotation of the hindfoot which provides the most important indicator of the difference between asymptomatic and symptomatic flatfoot. Levinger et al. [85] found more internal rotation in their asymptomatic flat foot relative to neutral group; our difference is not significant but supports their result. Our study found the SF group have significant external rotation relative to the asymptomatic groups indicating the possibility of a “coping strategy”. The external rotation after foot flat may be a consequence of moments produced by the excessive abduction of the forefoot. The tibia is in effect internally rotated relative to the hindfoot. This is associated with pronation by way of the subtalar joint axis, not supination which is desirable for stability. Thus the foot is unstable at the point of push off resulting in large strains being placed upon passive structures of the foot. The alternative to the effect dissipating at the talar joints is for the tibia to rotate at the knee which is also sub-optimal. By contrast, internally rotating the hindfoot should result in the tibia being externally rotated relative to the hindfoot leading to supination and therefore greater stability at foot off. These findings suggest the first things to be attempted may be correction of the forefoot abduction, or perhaps considering internal rotation of the hindfoot at the point of foot off. Furthermore, it indicates that the common finding of in-toeing with flatfoot may be desirable and not something to be corrected

in isolation.

### 9.3. Summary

Many significant differences were found between angles throughout stance. At foot strike hip flexion, knee valgus, knee eversion, and knee abduction were associated with flatfoot. At midstance, hip flexion, knee flexion, knee valgus, HF-TB eversion, and FF-HF abduction were associated with flatfoot. At foot-off, hip flexion, hip adduction, knee flexion, knee internal rotation, HF-TB dorsiflexion, HF-TB external rotation, and forefoot rotation but not HF-TB eversion were associated with flatfoot. Many of these differences may be attributed to the reduced stride length.

It is not surprising that it was at foot off was the most significant timepoint, nor the previous results of poor propulsion and stability if the problem is considered logically. It is believed that the foot has two modes: one being more flexible and one more rigid - rigid being associated with a more supinated posture. It is believed that the rigid mode is required to provide a stable structure for push off. Flat feet are more pronated and are therefore more likely to be in a flexible mode at the time of foot off. Flat feet may therefore not be able to provide the rigid lever required for push off. This results in poor quality of propulsion, instability at a time of single support, and necessitates many kinematic adaptations.

Eversion of the hindfoot was significantly different in the SF group at foot strike and midstance, but not foot off. This appeared to be caused by slow re-supination in this group. Testing of the peak value revealed a significant difference. The slow re-supination may be due to the external rotation of the forefoot preventing regular progression over the foot and impairing the initial supination normally caused by the obliquity of the second to fifth metatarsal. Forefoot abduction is significantly different in SF subjects in both static and dynamic stance. It may be the best predictor of symptoms.

## 9. Kinematic measures

Some SF subjects displayed rapid external twist of the hindfoot relative to the tibia in terminal stance while the asymptomatic groups with flatfeet tended to retain hindfoot internal rotation. The rapid and perhaps free external rotation of the hindfoot may be a consequence of moments created by excessive forefoot abduction and may lead to pronation by way of the subtalar joint impeding inversion and stability of the foot. It may be advisable in the future to separate such groups both for analysis and treatment.

Now that kinematic and GRF differences have been analysed, kinetic differences will be investigated. The following chapter relies on marker and forceplate data to compute kinetics which are analysed in a similar manner.

# 10. Kinetics

This chapter explores differences in forces and kinetics in the flat-footed populations. Temporal differences that were previously found (relative stride length, Chapter 8) will be taken into account. The data was collected and processed as described in Chapter 4. The analysis between the four populations will be by way of ANOVA, ANCOVA, and visual assessment.

Kinematic differences from the hip to the foot were reported in the previous chapter (Chapter 9). Differences in Ground Reaction Forces (GRFs) were summarized in the antecedent chapter (Chapter 8). This raises questions over what effect this will have on forces and moments acting at the joints.

On the basis of kinematic and GRF data, inverse dynamics can estimate the moments acting on the joint. Classical (forward) dynamics uses the knowledge of external (e.g. GRF) and active loads (e.g. muscle forces) to predict the movement of the body. Inverse dynamics uses body kinematics and external loads to calculate joint moments and muscle forces. The pioneers of this analysis were Braune and Fischer [16]. Inverse dynamics is now a relatively common practice in gait analysis.

One previous study of flatfoot without posterior tibialis tendon dysfunction found kinetic differences between flatfoot and neutral populations [68]. This study compared

## 10. Kinetics

15 adult males with a history of musculoskeletal symptoms attributed by a clinician to planus or pronated static foot posture, to 18 normal adult males. The peak plantarflexor ankle moment and inverter moment were higher in the group with flat feet. The study could not conclude on whether these differences were associated with symptomatic flatfoot or flatfoot generally.

The kinetic differences in children between symptomatic, flat, and neutral feet will be investigated here using ANOVA and ANCOVA (controlling for relative stride length) in a similar manner to previous chapters.

### 10.1. Methods

It was perceived as desirable to have one standard method of statistical analysis for clarity. Therefore, similarly to previous analysis, only results which satisfy the 0.05 level of Tukey and Games-Howell post-hoc tests were classed as significant.

Testing moments and powers at foot strike, midstance, and foot off may not be appropriate as there is little loading in the body at these points. Therefore, maxima and minima during the stance phase were selected to be tested. In total, 15, measures were selected for ANOVA (Fig. 10.1). These were evaluated using local and global maxima and minima algorithms.

### 10.2. Results and discussion

#### 10.2.1. Comparison between discrete points in AN, AM, AF, and SF

Nine of the 15 kinetic measures tested were found to be significantly different between groups (Table 10.1). However, after controlling for relative stride length, only

## 10. Kinetics

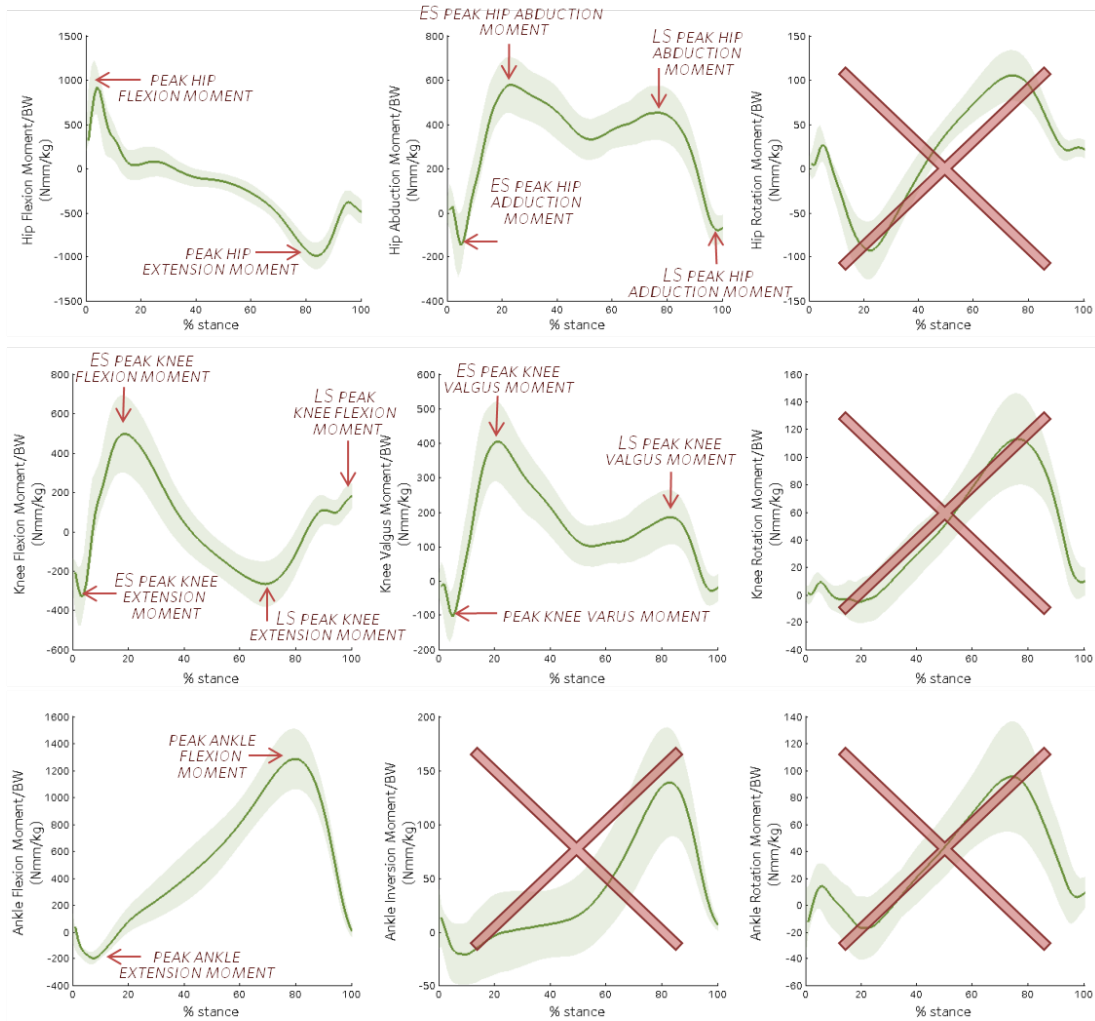


Figure 10.1.: Demonstration of hip, knee, and ankle moment maxima and minima. Hip, knee, and ankle rotation moments were ruled out due to large sources of uncertainty associated with transverse plane joint moments. Ankle inversion moments ruled out due to modelling the foot as a vector. Reference data: group mean from AN subjects  $\pm$  median average deviation.



## 10. Kinetics

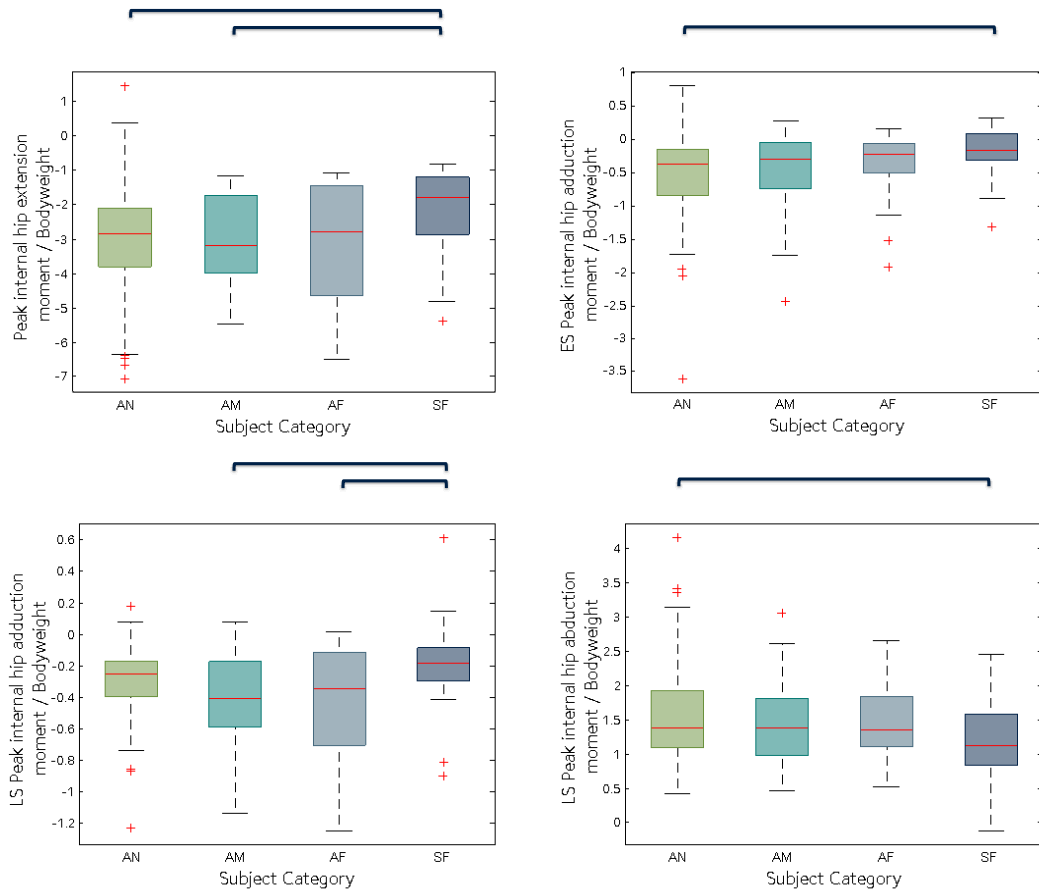


Figure 10.2.: Peak hip moments where significant differences were found. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

## 10. Kinetics

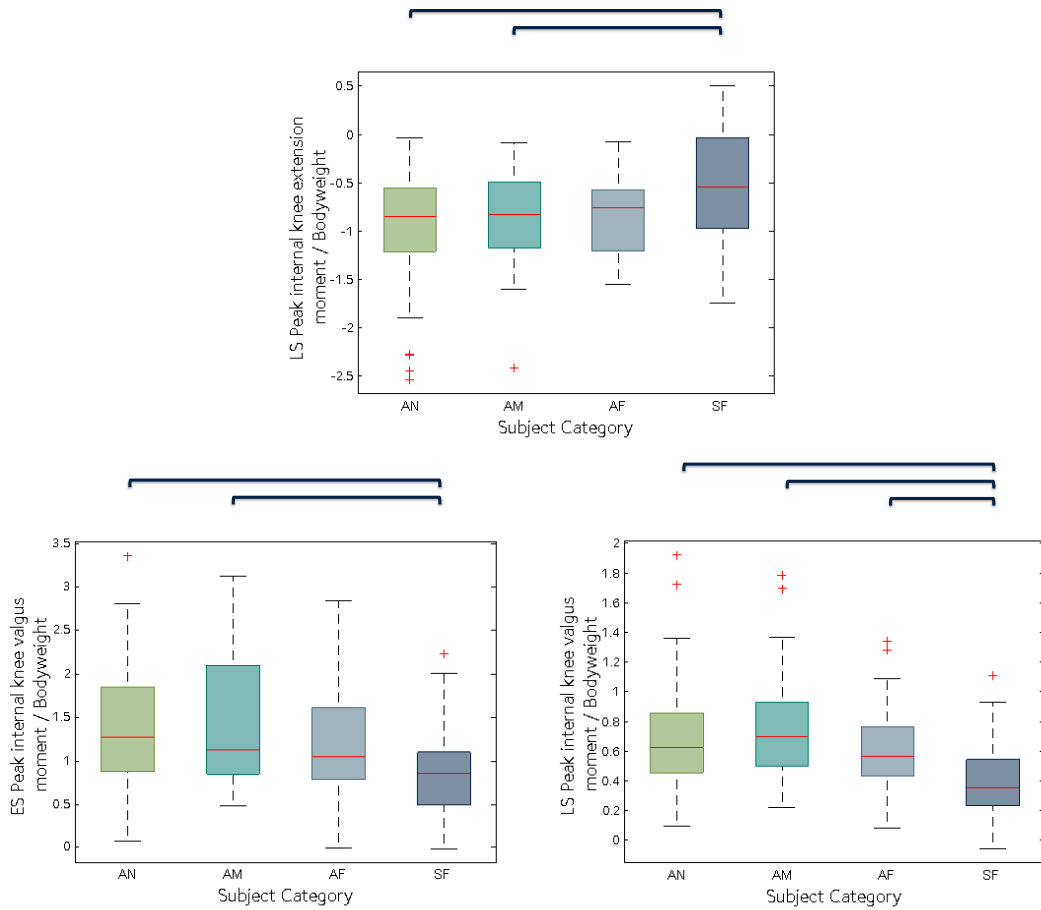


Figure 10.3.: Peak knee moments where significant differences were found. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually. Square brackets indicate between which groups (Tukey and Games-Howell) post-hoc tests revealed significant differences.

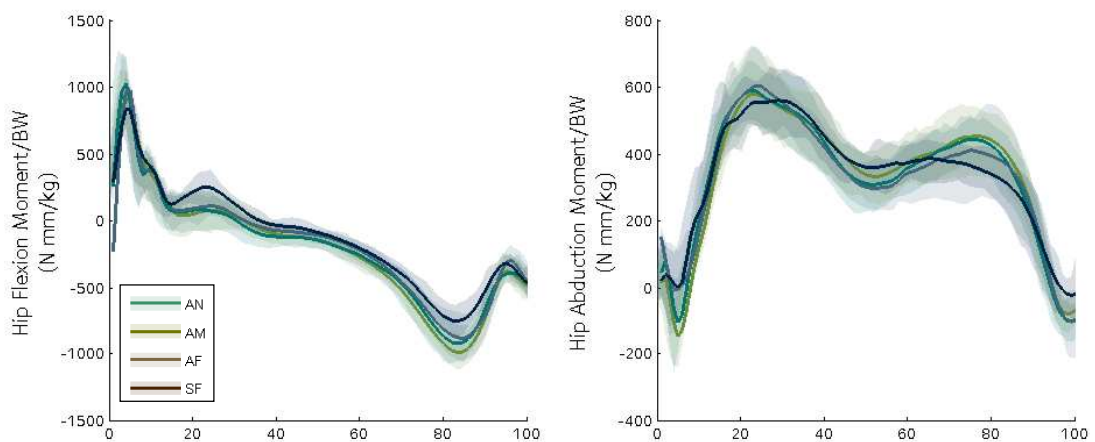


Figure 10.4.: Moments acting at the hip as multiples of bodyweight over stance phase of gait. Bold lines represent mean values, bands represent inter-quartile range.

stride length, as they were only significant when controlling for stride length.

At the ankle, peak ankle plantarflexion moment was shown to be significantly different, even when controlling for stride length. Tukey and Games-Howell tests did not agree on groups between which the difference was significant. Tukey HSD described the difference between AN and SF to be significant whereas Games-Howell did not. This represented an increase in moment for the SF group, in agreement with the findings of a previous study [68].

### 10.2.2. Visual analysis of continuous data in AN, AM, AF, and SF

The results of the representative trial selection confirm the results of the ANOVA (Figs. 10.4, 10.5, and 10.6). Additionally, the power was also presented in this way (Fig. 10.7).

Generally, peak power was reduced in the SF group (Fig. 10.7). The only potential exceptions to this rule concern relatively small peak values.

## 10.3. Summary

It had been hoped that kinetics could answer some of the questions regarding the propulsive forces. However, because of the high dependency on walking speed, this was not so helpful. The reduction in walking speed, resulted in almost every peak moment or power being reduced in the SF group. While ANOVA suggested nine differences, ANCOVA reduced this figure to two out of the original 15. The first of the two was a dramatic decrease in late stance peak hip adduction moment in the symptomatic compared to asymptomatic flatfooted groups, this is probably caused by the slower late stance hip abduction in the symptomatic group (Fig. 9.9). The other parameter was the only increase, which was in ankle plantarflexion moment,

## 10. Kinetics

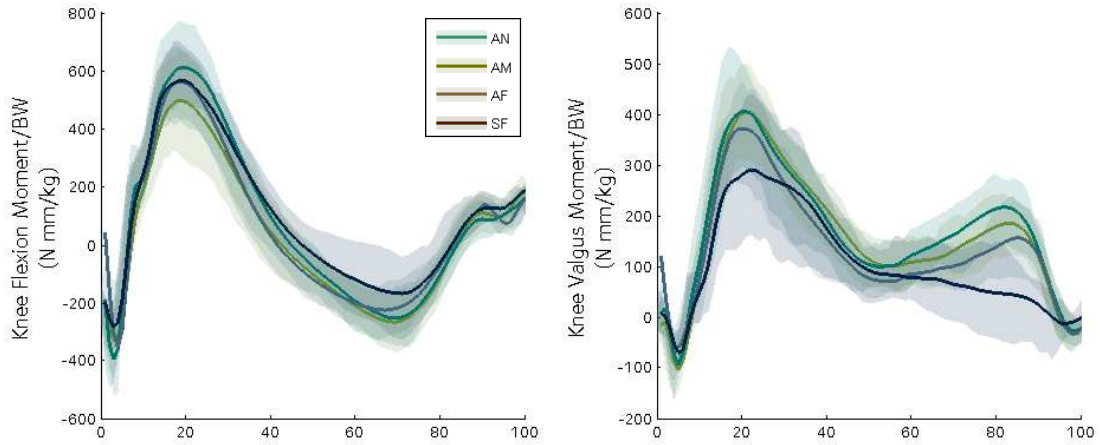


Figure 10.5.: Moments acting at the knee as multiple of bodyweight over stance phase of gait. Bold lines represent mean values, bands represent inter-quartile range.

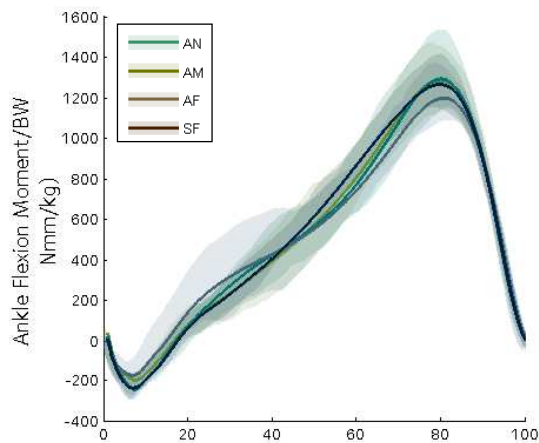


Figure 10.6.: Moments acting at the ankle as multiple of bodyweight over stance phase of gait. Bold lines represent mean values, bands represent inter-quartile range.

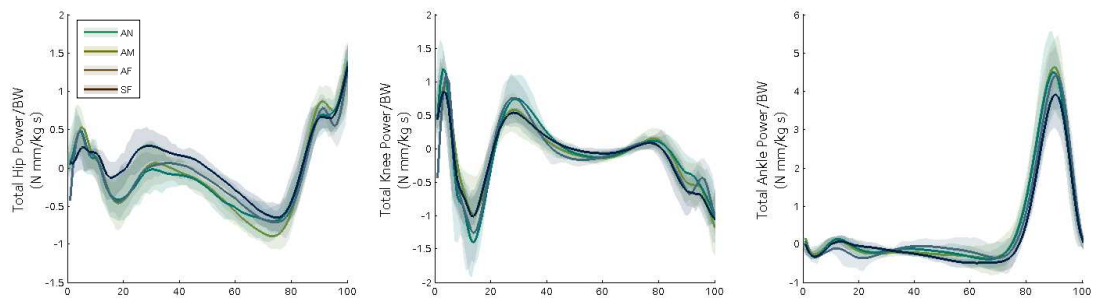


Figure 10.7.: Power generated at hip, knee, and ankle during stance. Bold lines represent mean values, bands represent inter-quartile range.

## 10. Kinetics

this confirmed the results of a previous study [68], it appears that this is related to the Ground Reaction Force which was found to contain spikes to compensate for late stance instability (Section 6.6.3), .

Future studies are recommended to calculate the kinetics of the midfoot as previously the data revealed kinematic differences and GRF differences relating to the foot. Results in the transverse plane would also be desirable (the kinematic results indicated the transverse plane to be the most different).

Now that the kinetic differences have been described. The analysis based on marker and force-plate data has been largely completed. The following chapter will focus on data obtained from another source - the pressure plate.

# 11. Plantar pressure

This chapter explores plantar pressure among the population. Marker data and plantar pressure maps are combined to create a dynamic version of the Arch Index. Peak values of midfoot pressure are also calculated. The data was collected and processed as described in Chapter 4. The purpose of this chapter is to compare dynamic plantar pressure patterns in neutral, “mild” flatfoot, flatfoot, and symptomatic flatfoot.

The Arch Index (AI) of Cavanagh and Rogers [25] is one method used to assess foot arch structure (Fig. 2.4 (a)). Normally AI is evaluated during static stance or based on a midstance or maximum pressure print, but knowing exactly how the AI changes with time during stance could be just as important. The aim of this study was to investigate the variation in AI during walking and to see if this measure has the potential to identify subtle functional differences between children with neutral feet and those with flatfoot.

The other plantar pressure based measures were unable to be applied to pressure prints, mostly due to the resolution, thresholds of the system, and automatic identification of landmarks. The Alfa angle (Fig. 2.3) requires the identification of the point where the forefoot area meets the medial side of the midfoot, which is problematic as it is difficult to automate, and in severely flatfoot with midfoot break or in prints

## 11. Plantar pressure

with no midfoot contact it would be impossible to identify. The Chippaux-Smirak and Staheli indices (Fig. 2.3) were ruled out as even with a print with significant midfoot contact (Fig. 11.1 (b)), the minimum midfoot contact width is likely to be zero or one sensor (5 mm in width), thus not suitable for this equipment and dynamic analysis. The Arch Length Index (Fig. 2.3) was also flawed when considering prints with non-continuous midfoot contact (i.e. cavus), which would have lower ratios along with those with midfoot collapse. Dealing with prints demonstrating midfoot break remains problematic. Footprint Index and Truncated Footprint Index (Fig. 2.4) were eliminated due to difficulty in identifying landmarks and difficulty in handling those with the midfoot break. Martirosov's K index was excluded due to the necessity of identifying no less than 6 independent landmarks some of which are impossible to find without guaranteed toe contact, and can not be calculated in the case of non-continuous midfoot contact. Thus the only possibilities left were the valgus index and Arch Index (Fig. 2.4), which could be calculated by identifying landmarks largely from the Vicon markers rather than from the footprint, and could deal with non-continuous midfoot contact and midfoot break (in fact the valgus index does not require the footprint at all if using markers).

### 11.1. Methods

Data was collected as described in Chapter 4. Spherical reflective markers had been placed at known anatomical landmarks, including the foot [167]. Kinematic and plantar pressure data were collected simultaneously for level walking (and static standing in some asymptomatic subjects). Kinematic data were collected at 100 Hz using a Vicon MX system (Vicon Motion Systems, Oxford, UK) with 12 cameras and processed using Vicon Nexus software. Plantar pressure data were collected at 50 Hz with 5 mm resolution using a Novel Emed-m pressure plate (Novel GmbH, Munich,

## 11. Plantar pressure

Germany). Spatial resolution for adults must be a maximum of 10–15 mm, because of the spatial wavelengths of 20–30 mm, to avoid signal aliasing [87, 127]. This has not, to the author's knowledge, been investigated for children specifically. Across our age range (5–17 years old), according to our data the Truncated Foot Length (TFL) approximately doubles, so a factor of two might be a reasonable assumption to apply to the resolution (i.e. 5–7.5 mm maximum sensor size).

Pressure maps and marker trajectories were exported to Matlab (The MathWorks, Inc., Natick, MA, USA), in which calculations to find the AI and MAI were implemented. Following spatial and temporal synchronization of the data (Fig. 11.3) the principal axis of the foot was calculated from markers on the heel and toe between the second and third metatarsal heads (Fig. 11.1 (a)). The heel and toe markers provide an anatomically relevant and instantaneous axis of the foot, an axis that depends on bony structure (rather than floor contact) and adapts to subtle changes in posture. This definition can be adapted to maintain a pressure mask even when full foot contact is not present.

### 11.1.1. Calculating AI and MAI

The AI and MAI were calculated in Matlab by a multistage process (Fig. 11.3). Firstly, the data was synchronized in space and time. The trajectories and pressure maps were transformed into the same coordinate system using simple translations and reflections (Fig. 11.3). Novel automatically corrects the trajectories for direction of travel, so this was reversed where necessary. The data was synchronized by aligning the heel strike events; that is the first pressure map recording pressure and the heel strike of the marker trajectory. Then the trajectory data (which was collected at 100 Hz compared to the pressure data at 50 Hz) was down-sampled. The heel-toe, or principal, axis, is simply the axis through the projection of the heel and toe markers onto the horizontal plane (Fig. 11.1 (b)). The true position of the heel is 7 mm closer to the toe marker along this axis (owing to the distance between the base and the

## 11. Plantar pressure

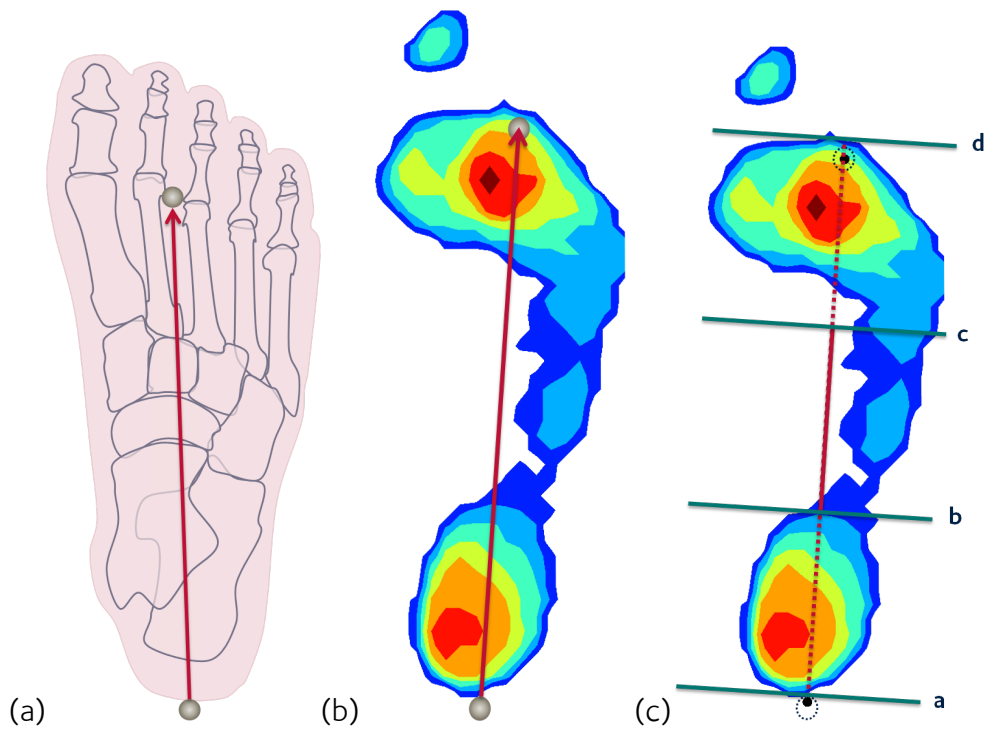


Figure 11.1.: Marker based principal axes, and the divisions of the areas of the Arch Index (AI). (a) Marker based principal axes approximates the axis as that from the heel marker to the toe marker which lies between the second and third metatarsal heads. (b) Application of the axis to a pressure print during midstance. (c) Subdivision of areas of the AI.

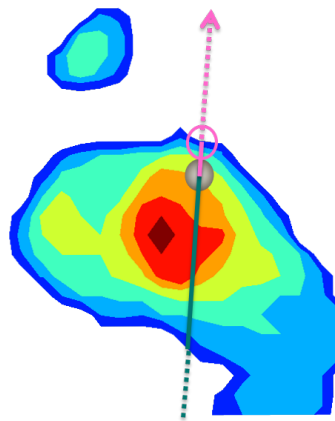


Figure 11.2.: Finding the furthest weightbearing surface of the forefoot (circled in pink). Dark green denotes heel toe axis, pink denotes vector which is searched for the point of interest. Solid line indicates pressure, dotted line indicates no pressure.

## 11. Plantar pressure

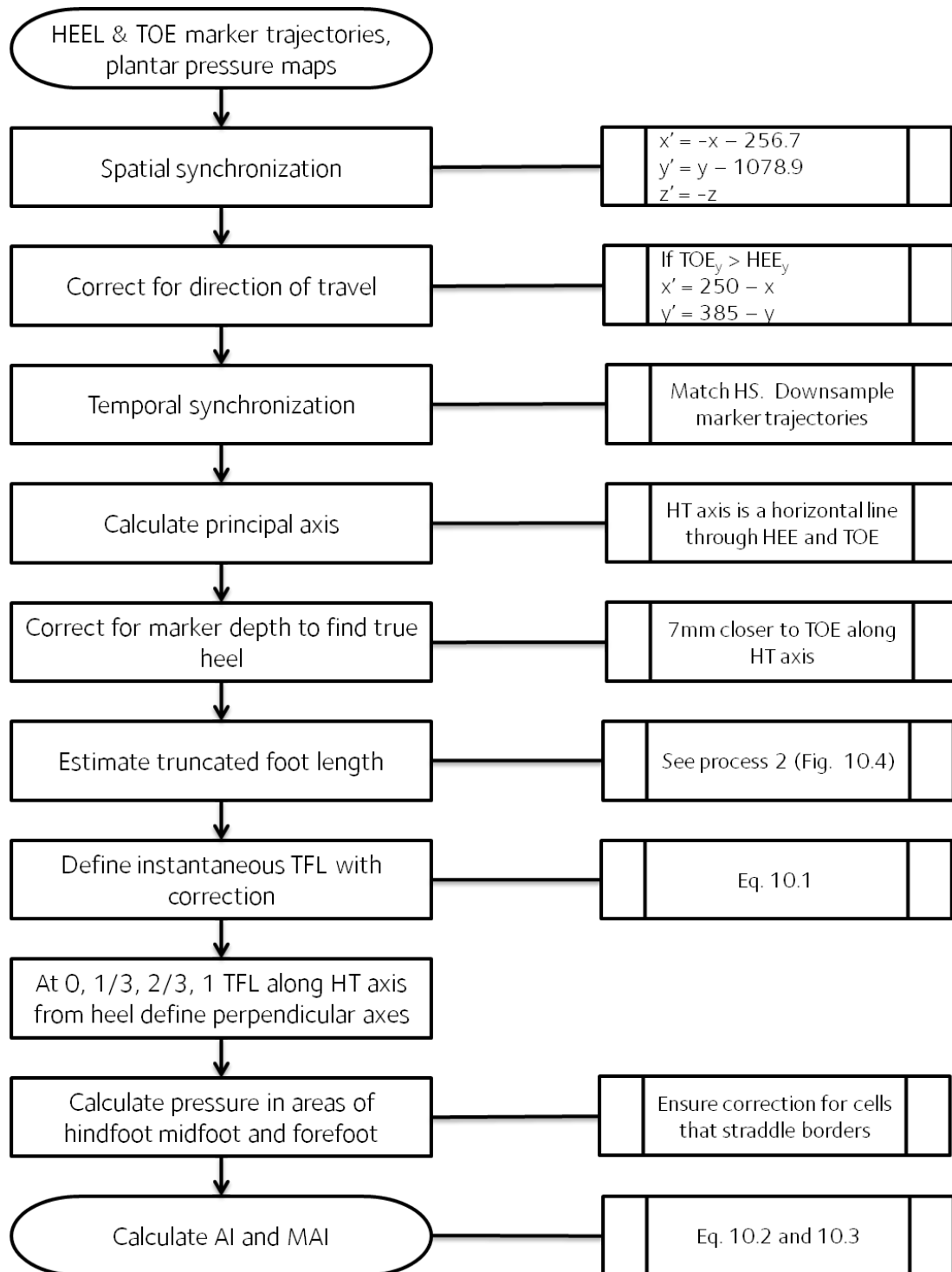


Figure 11.3.: Process to calculate Arch Index and Modified Arch Index.

## 11. Plantar pressure

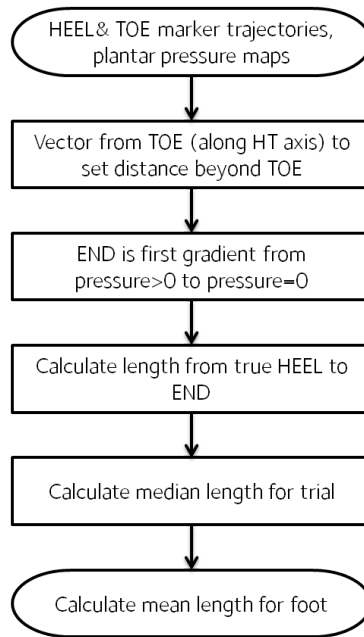


Figure 11.4.: Process to estimate Truncated Foot Length (TFL) based on marker trajectories and pressure maps.

centre of the marker (marker, Fig. 4.1 (d))).

Truncated Foot Length (TFL) is the distance from the true heel to the furthestmost weightbearing surface of the forefoot pad along the principal axis of the foot. This was measured by hand with calipers in 67 asymptomatic subjects (only 131 feet because of occasional unilateral records) with good repeatability (Section 5.3.1). Many subjects, however, lacked this measure so a five stage process was used to estimate TFL for a subject based on plantar pressure maps, and heel and toe marker trajectories (Fig. 11.4). In all further calculations, the five stage mechanised method was used for the TFL.

To estimate TFL, an estimate was created for each frame, then an average becomes representative of the subject (Fig. 11.4). A vector was created from the toe marker to a set distance beyond that marker (along the heel-toe axis). The first point with a gradient to zero pressure is determined as the furthestmost weightbearing part of the forefoot (Fig. 11.2). The selection most proximal to the toe (first point) prevents confusion caused by toe contact. An absence of the gradient event would indicate no forefoot contact, and therefore no estimate is made. The horizontal distance be-

## 11. Plantar pressure

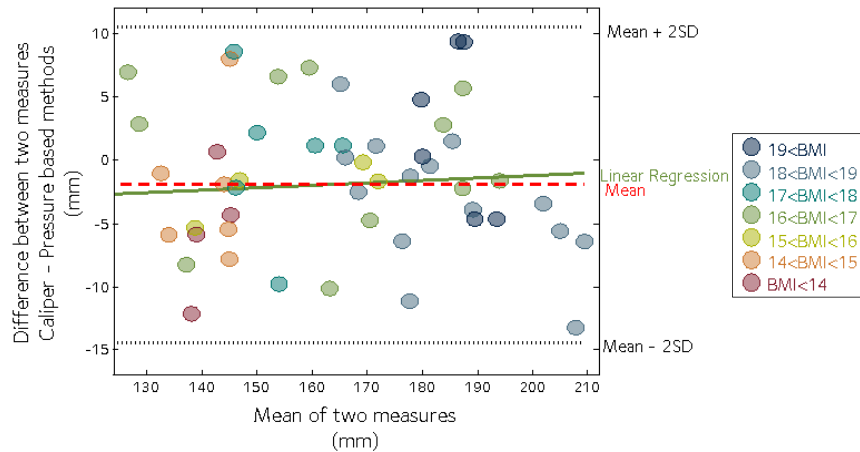


Figure 11.5.: Bland – Altman plot of caliper-based and pressure print-based methods of Truncated Foot Length (TFL) measurement. Mean, standard deviation, and trend with increasing TFL is denoted. Colour of markers indicates BMI.

tween the true heel and the point of the gradient is the frame-wise TFL estimate. The median value for the trial was calculated, then the mean of these values over all trials provides the TFL. These estimates were compared to the caliper-based measures by Bland Altman plots.

Bland–Altman analysis demonstrated good agreement between the measure of TFL based on pressure prints and calipers in 51 feet (Fig. 11.5). The mean difference between the measures was 1.9 mm, with a slight bias for the pressure measure to be longer than the caliper. The standard deviation of the differences was 6.2 mm and most differences were less than 1 cm which was believed to be acceptable, particularly considering the intra- and inter-tester repeatability of the caliper based method (Section 5.3.1). Linear regression revealed no correlation with TFL, although a slight relationship with high Body Mass Index may be evident which may make logical sense considering the effect of the pressure sensor threshold.

It was desired that the method to find AI and MAI would continue to apply even if the forefoot or hindfoot were not in contact with the ground (i.e. outside the foot flat period) so that the whole of stance could be analysed (as it was in other parts of the study). Additionally, it was desired that calculation would be instantaneous

## 11. Plantar pressure

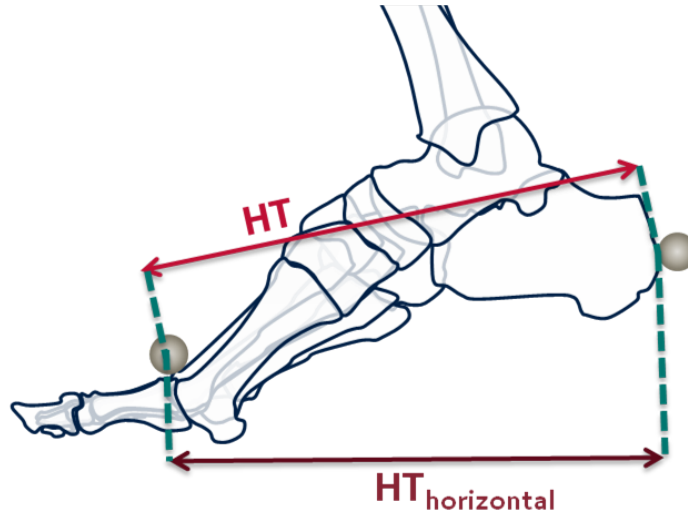


Figure 11.6.: Diagram of 2D and 3D distances between heel and toe markers.

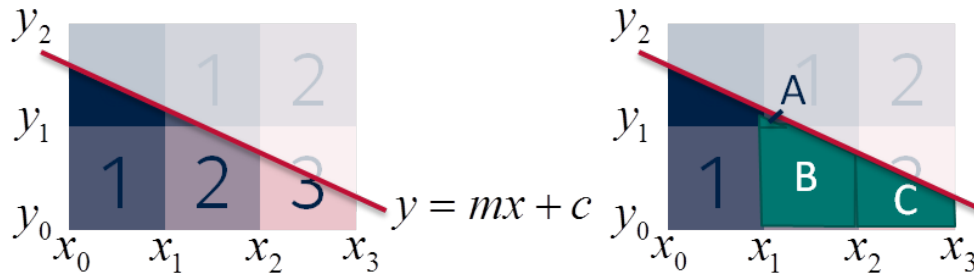


Figure 11.7.: Effect of an axis with a gradient passing through square cells. (left) Demonstration of cells dissected by axis  $y = mx + c$ . (right) Featuring areas of interest: A, B, and C. Area A corresponds to special “if” case (11.5). Area B corresponds to special “else if” case. Area C correspond to simpler “else” case (11.5).

in all respects, with the “mask” adapting frame by frame to account for rotations during stance (particularly internal and external rotation, and the medial heel twist towards foot off). It was assumed that the ratio between the horizontal and three-dimensional distance between the true heel and toe markers (Fig. 11.6) was approximately equal to the ratio between the corrected TFL (that should be used to mask the pressure print) and the TFL estimate. Thus an equation was created to adapt the TFL frame by frame (equation 11.1).

$$TFL_{corrected} = TFL \times \frac{HT_{horizontal}}{HT} \quad (11.1)$$

## 11. Plantar pressure

Axes a, b, c, and d were then defined as perpendicular to the heel toe axis, and passing through points at 0, 1/3, 2/3, and 1 corrected TFL (Fig. 11.1 (c)). Arch Index (AI) and Modified Arch Index (MAI) could then be calculated by simple equations (equations 11.2 and 11.3):

$$AI = \Sigma C_{midfoot} / \Sigma C_{truncated\ foot} \quad (11.2)$$

$$MAI = \Sigma P_{midfoot} / \Sigma P_{truncated\ foot} \quad (11.3)$$

Where  $C$  is the presence of contact, and  $P$  is the actual pressure value.

One issue was cells that were divided by axes (example Fig. 11.7). If calculating the pressure below the line, there are five relevant cells, four of which have pressure greater than zero, and three of those are only partially within the boundary. If the line dissects the cell, the area of the cell, under the line  $y = mx + c$  can be described. The line crosses the lower line of the cell at  $x_{crosslower}$  and the upper line at  $x_{crossupper}$  (equation 11.4):

$$\begin{aligned} x_{crosslower} &= \frac{y_n - c}{m} \\ x_{crossupper} &= \frac{y_{n+1} - c}{m} \end{aligned} \quad (11.4)$$

There are three types of cases (Fig. 11.7). The simplest case is type C, where the line does not cross the upper or lower bounds of the cell. The other cases are where the line crosses the lower bound (type A) and upper bound (type B). As the lines are approximately perpendicular to the direction of travel there should be no cases where the lower and upper bounds of the cell are crossed by the line. Integrals are used to calculate the area, only the positive area is counted (above the lower bound). The area under the line is  $A$  (equation 11.5); the fraction of the cell under the line is therefore  $A/25$  (25 being the total area of the cell). Any cell dissected by the line was included in the sum only in accordance with this percentage. This makes a subtle smoothing effect on the final result (Fig. 11.8), which has more impact on smaller feet or if the

## 11. Plantar pressure

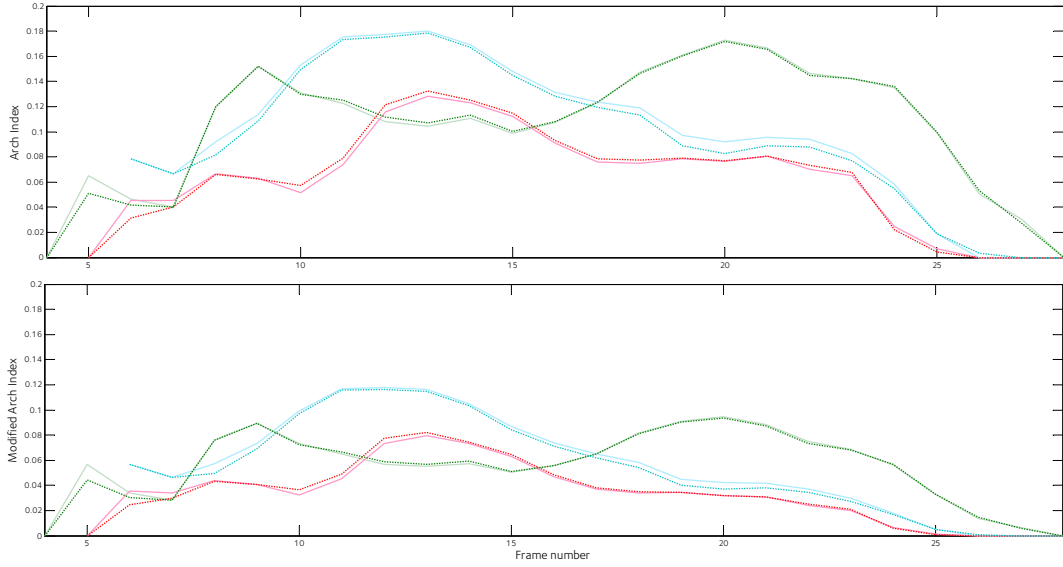


Figure 11.8.: Arch Index and Modified Arch Index while ignoring (solid line), and taking account of (dotted line) percentage of cells within boundaries. Taking account of percentage of cell within boundary has slight smoothing effect on the final trace. When not counting the cell by percentage the pressure in the cell is allocated to the area which the majority of the cell exists in.

cells were larger.

*Case A*    *if*     $x_n < x_{crosslower} < x_{n+1}$

$$A_1 = \frac{m}{2} (x_{crosslower}^2 - x_n^2) + (c - y_n) (x_{crosslower} - x_n)$$

$$A_2 = \frac{m}{2} (x_{n+1}^2 - x_{crosslower}^2) + (c - y_n) (x_{n+1} - x_{crosslower})$$

$$A = \text{maximum}(A_1, A_2)$$

*Case B*    *elseif*     $x_n < x_{crossupper} < x_{n+1}$

$$A_3 = \frac{m}{2} (x_{crossupper}^2 - x_n^2) + (c - y_{n+1}) (x_{crossupper} - x_n) \quad ,$$

$$A_4 = \frac{m}{2} (x_{n+1}^2 - x_{crossupper}^2) + (c - y_{n+1}) (x_{n+1} - x_{crossupper})$$

$$A = 25 + \text{minimum}(A_3, A_4)$$

*Case C*    *else*

$$A = \frac{m}{2} (x_{n+1}^2 - x_n^2) + (c - y_n) (x_{n+1} - x_n)$$

*end*

(11.5)

## 11. Plantar pressure

Each trial was double-checked manually based on the matching of axis definitions to pressure patterns (Fig. 11.9). The common cause of failure was a mismatch between the naming of the plantar pressure and marker trajectory files, and this was easily fixed when noticed.

### 11.1.2. Analysis of results

It was unknown what an AI pattern would look like over time. A simple estimate was made (Fig. 11.10). It was expected to be zero until the point of midfoot contact; this would be followed by a rapid increase as midfoot contact increased. During foot flat, the value was expected to dip with increasing forefoot contact, then to rise again with decreasing hindfoot loading. Finally, a rapid decrease should occur to zero as the midfoot lifts from the ground.

The real patterns, however, turned out to be quite variable. Intra- and inter-subject timing of foot contact events, and timing of peak values varied considerably. The Modified Arch Index was smoother and had more consistent intra-subject peak values. This is probably because the AI sum is unstable because contact varying between on and off makes a big difference to the final score, whereas pressure varying by 5 MPa in a cell makes less of an impact on the MAI. Based on this, five variables were chosen to represent the foot:

- Peak midfoot pressure (median representative per subject),
- Peak AI and MAI during foot flat (median representative per subject),
- A representative AI and MAI trace for each subject (based on minimum root mean square difference from median).

These values and series could then be subjected to analysis.

## 11. Plantar pressure

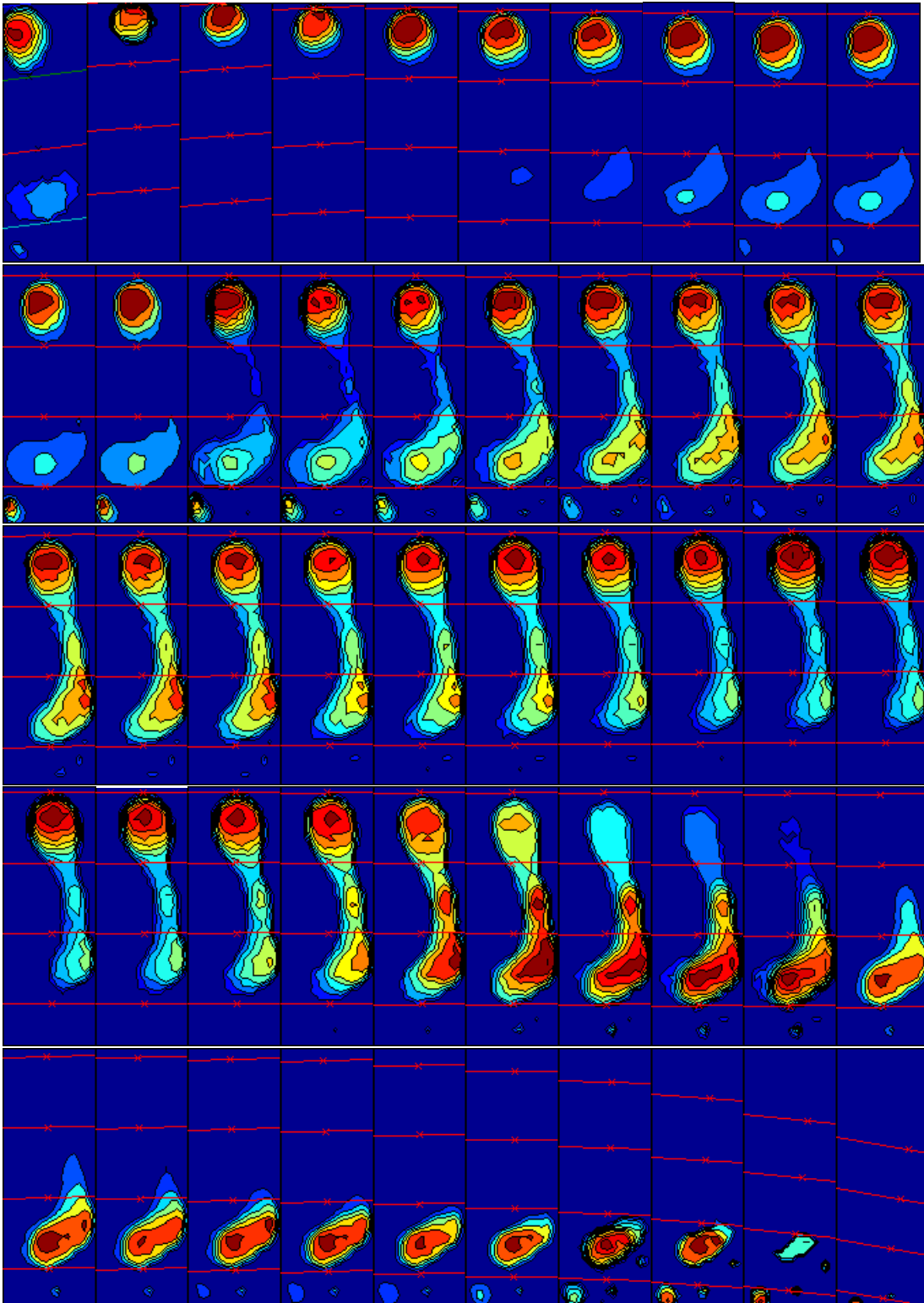


Figure 11.9.: Example pressure pattern over stance with lines. First frame standing, rest through stance. Lines are those used to denote heel, mid, and toe areas.

## 11. Plantar pressure

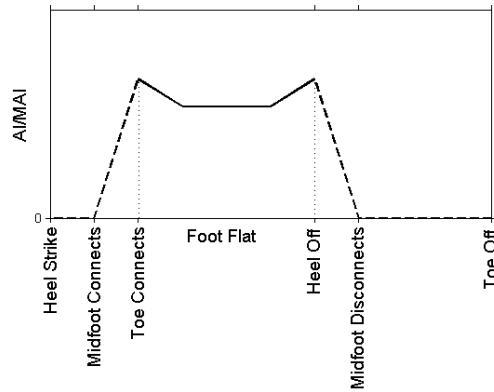


Figure 11.10.: Expected Arch Index or Modified Arch Index pattern over stance. Solid line represents the foot flat period.

### 11.2. Static, peak, and continuous AI in AN, AM, AF, and SF

#### Static AI

The instantaneous static AI was often found to be at or close to zero. This was due to little or no midfoot contact being measured, despite pressure plate thresholds set at 30 kPa. In the cases with non-zero AI, it appeared that a part of the heel intruded on what was classified as the midfoot area.

If the measurements had been made on the basis of maximum pressure print (as is commonly practiced) then a measurement could have been achieved. However, this measurement would have included a loading response and push off characteristics, as well as being dependent on stability. Therefore, it cannot be recommended to use the unfiltered maximum pressure print of stance.

For only one subject out of 15 initially tested was a convincing static AI recorded. As was expected, during 3 out of 4 steps the peak AI for this subject exceeded the static AI. The static footprints were therefore excluded from any further analysis.

## 11. Plantar pressure

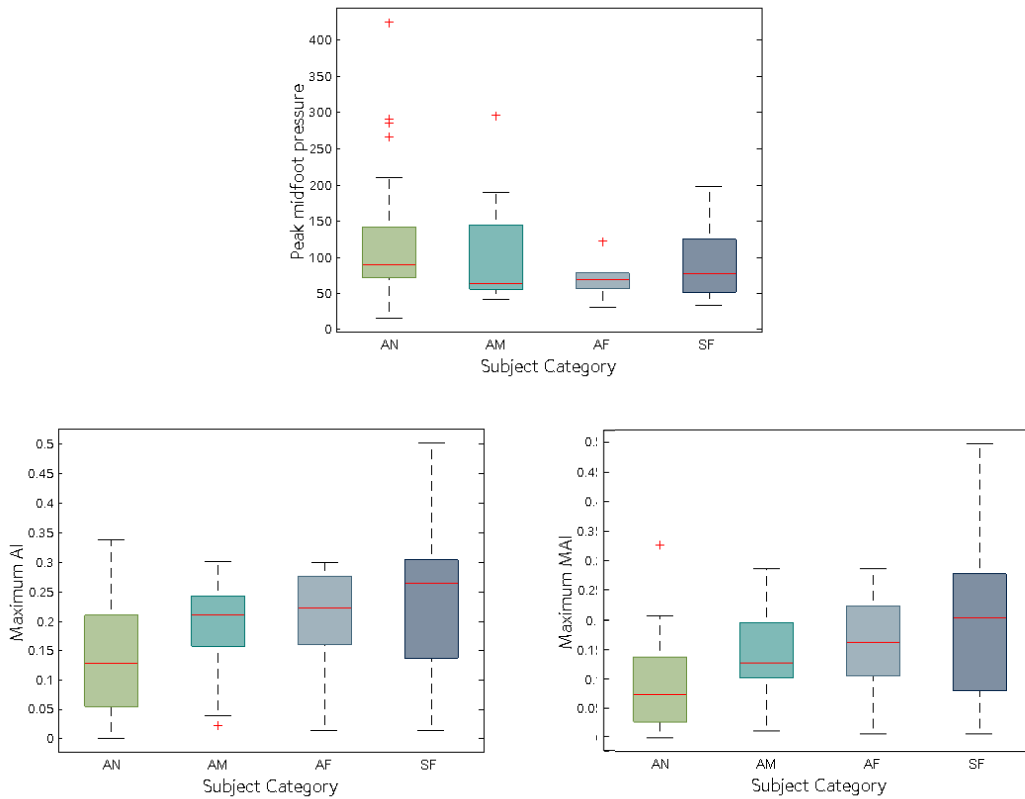


Figure 11.11.: Box-plots of plantar pressure based parameters between groups. (Upper) Peak pressure in the midfoot region during walking. (Lower) Peak Arch Index and Modified Arch Index during foot flat. The central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

### Analysis of peak values in AN, AM, AF, and SF

Seventy two feet were included in this analysis, of which there were 35 AN, 13 AM, 8 AF, and 16 SF. Peak midfoot pressure during walking was no higher in the symptomatic group than in any other (Fig. 11.11). This may indicate that foot pain present in 78% of the symptomatic population (Table 5.1) was not a result of direct foot-floor normal pressure in the midfoot area experienced during walking. However, this does not rule out the causative potential of internal loading and shear forces.

There was, however, a trend for flat feet to have a higher peak AI and MAI (Fig. 11.11). That is to say that while the peak pressure in the midfoot region was not correlated with foot posture, the maximum ratio of midfoot contact to truncated

## 11. Plantar pressure

foot contact was linked to foot posture. This however did not correlate with presence of symptoms nor perceived flatness (mildness). The numbers are too small for full statistical analysis.

### Visual inspection of continuous data form

It had been expected that there would be two local maxima during the foot flat phase (Fig. 11.10); however, this was not necessarily the case (Fig. 11.12). The AI comprised two peaks in only 32% of cases, and one in 18%; more often many peaks were found (Fig. 11.13). For the cases with one peak this may be because of significant flattening of the foot with loading. The cases with many local maxima are often those with a long plateau phase. In three cases, no contact was found in the midfoot region and therefore both indices remained at zero.

There were fewer MAI traces with more than two local maxima (24%), whilst most commonly these traces only contained one local maxima (39%) within the foot flat phase (Figs. 11.10 and 11.13). This difference was most likely caused by the smoothing effect of the modification. This left many fewer cases of the expected pattern, especially when the patterns were examined in more detail (the MAI is a smoother trace, so it naturally has fewer local maxima).

The curves with a single peak were hypothesized to be associated with dynamically flexible flat foot as this would indicate significant flattening of the arch during weight-bearing. A long plateau phase would indicate little additional weight dependent mid-foot contact.

## 11. Plantar pressure

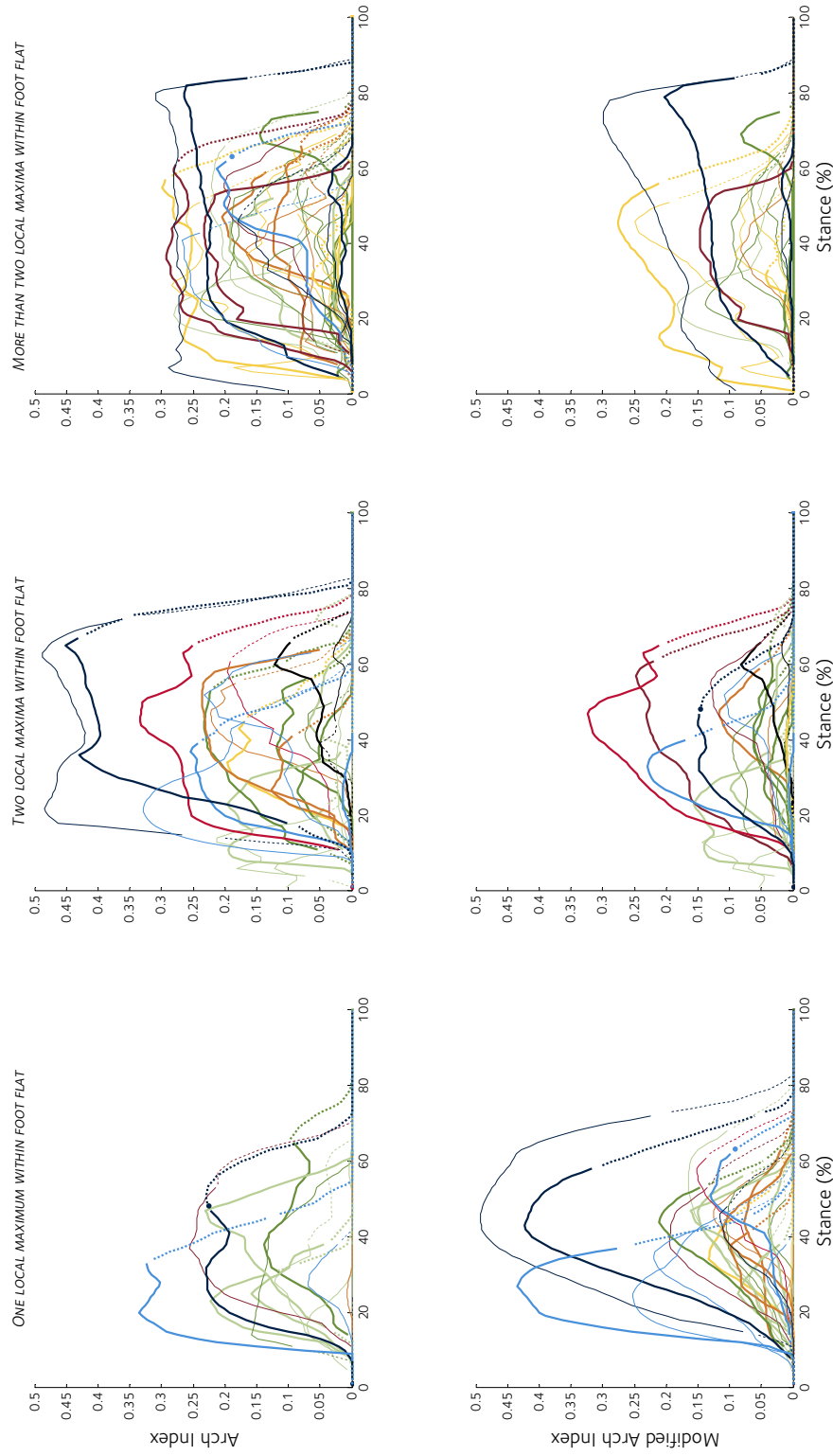


Figure 11.1.2.: Individual traces of Arch Index and Modified Arch Index over stance. Traces are divided into groups with one, two, or more local maxima within the foot flat phase. Each colour represents a different subject with AN in greens, AM and AF in oranges and reds, and SF in blues. Dotted line indicates foot contact incomplete, solid line indicates within foot flat phase. Thicker line indicates right foot.

## 11. Plantar pressure

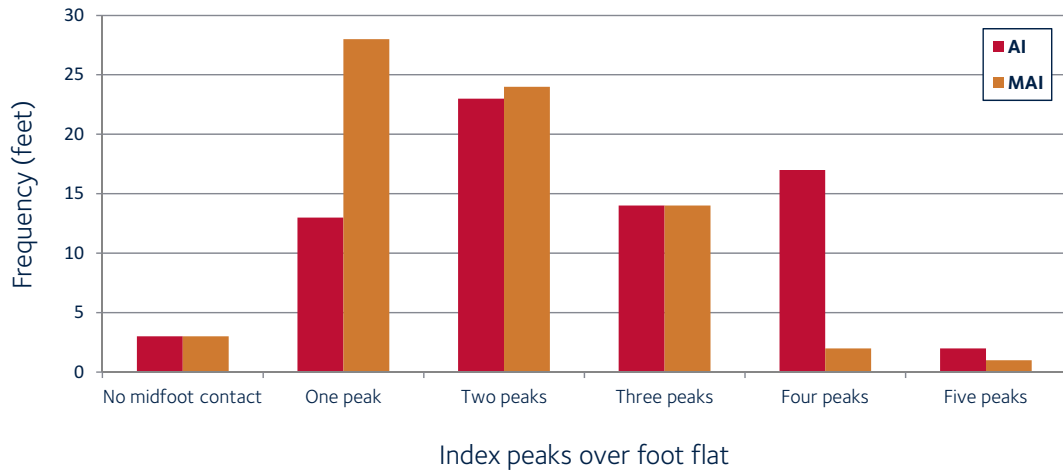


Figure 11.13.: Histogram of number of peaks in Arch Index (AI) and Modified Arch Index (MAI) over foot flat. More peaks were found within AI traces than MAI traces.

### 11.3. Summary

Truncated Foot Length (TFL) could be estimated with good reliability from marker and pressure data. Dynamic (instantaneous) AI and MAI were calculated on the basis of plantar pressure, TFL, and heel and toe marker trajectories.

The AI calculated during walking varied with time through the stance phase. The peak AI value during stance varied considerably between steps for the same subject. There was also considerable variation of AI patterns between subjects.

Contrary to expectations, peak midfoot pressure was no higher in any subgroup of flat feet than neutral feet. On average, all groups of flat feet recorded lower peak midfoot pressure, probably due to the pressure being distributed over a larger area at the midfoot. Peak AI and MAI were higher in groups of flat feet, but differences between symptomatic and asymptomatic groups were not recorded. This indicates that in the majority of cases excessive midfoot plantar pressure is not responsible for the foot pain evident in 78% of this flatfoot population (Table 5.1).

The general shape of the AI curve within subjects had some consistency; however, the shapes of the AI curve tended to vary between those with a plateau feature mostly

## 11. Plantar pressure

seen in the neutral feet, and those that had a more peaked maximum associated with flat feet. The peaked maximum may reflect significant flattening of the foot with loading in the flatfooted population.

The AI is usually assessed at a chosen point in stance or on the basis of a (static or dynamic) maximum pressure print. For most subjects in our study, a reliable instantaneous static AI could not be calculated due to lack of sufficient midfoot floor contact. Static maximum pressure print was not used as this includes loading, unloading and variability characteristics. Dynamic maximum pressure print was also rejected due to the risk of misleading prints caused by foot-floor movements such as the rolling of the heel in early stance, and the late stance medial heel twist. Our results also discourage the use of chosen frame AI values (as was practiced in the Contact Force Ratio), since the features of the curves at 50% stance are inconsistent - some feet at this point recorded their maximum score while others had already lost hindfoot contact (Fig. 11.12).

This chapter shows that it is possible to calculate changes in AI over the stance phase of gait, but that peak midfoot pressure, peak AI, and peak MAI do not reflect symptoms in flat feet. Further work needs to be done to identify subtle differences that might exist between AI patterns in neutral and flat feet, particularly in terms of the peaked feature that may be associated with force-dependent flattening of the foot. With the completion of this final results chapter, the following chapter will summarize the results to provide a complete picture of this study and describe the future work that is needed to answer the questions that remain.

## 12. Summary, conclusions, and recommendations

This chapter will bring together the results of the thesis, noting the strengths and significant discoveries made. It will discuss how parts of the study relate to one another, and the questions that have been answered. Then it will examine the weaknesses and questions unanswered by the work. Finally, the further work and key messages that could be taken on by stakeholders such as research professionals, parents, and clinicians are outlined.

This study sought to answer the question, what is the difference between asymptomatic and symptomatic flatfoot. Along this quest several avenues were explored. Firstly, what are the symptoms associated with flatfoot and how is flatfoot defined? Since flatfoot assessments were usually taken in static stance, which does not necessarily predict dynamic function, the addition of dynamic assessment formed a large part of the thesis. In the end this allowed us to gain insight into whether treatments tackle the symptom-causing features and how flatfoot should be regarded in the clinic and at home.

Three key methods were employed to answer these questions: a review of the literature; a clinical audit; and a large study which compared the clinical, static, and dynamic

## 12. Summary, conclusions, and recommendations

characteristics in neutral, asymptomatic, and symptomatic participants.

### 12.1. Defining flatfoot

Flexible flatfoot has been described as significant flattening of the arch upon weight-bearing. Many assessment methods could be used, most of which are based on some sort of visually-based assessment of flatfoot during static standing.

The background examined the current assessment methods and their various strengths. Clinical examination, Normalized Navicular Height (NNH), and Arch Index (AI) were concluded to be some of the best assessment techniques in terms of repeatability and clinical significance, with the advantage that they avoided the use of radiation.

Flatfoot comes in physiologic and pathologic forms. Previous research on the age of arch development was summarized and the age of five years was decided to be the point at which sufficient development had occurred in terms of the fat pad, arch structure, and gait.

In the main study, traditional quantitative assessments of static foot posture were mostly limited to the asymptomatic population, as the symptomatic population were selected retrospectively from patient records. Static footprints proved to be unsuitable for analysis owing to pressure thresholds. A marker-based method to describe AHI was shown to be acceptable. FPI, AHI, and NNH appeared to correlate better with non-weightbearing than weightbearing clinician-based assessment. NNH proved to be a good proxy measure for medial arch congruence.

### 12.2. The symptoms of flatfoot

Flexible flatfoot was understood to be generally asymptomatic, but occasionally de-

## 12. Summary, conclusions, and recommendations

bilitating. Popular treatments for flatfoot attempted to correct the symptomatic flatfoot to more closely resemble the neutral foot, however this may or may not target the symptom-causing features. The study required an understanding of the symptoms in order to explain the mechanism of pathogenesis.

Review of the literature revealed that the symptoms of flatfoot were generally described as uncommon but the descriptions varied and links to the prevalence of injury were disputed.

The audit was constructed to better understand the symptoms of flatfoot in a systematic and quantitative manner. The most frequent reasons for visits were parental concern, pain in the foot and ankle, as well as hypermobility, frequent falling, and in-toeing. Pain was reported in all cases at the orthotics department, but in only a third of physiotherapy patients, highlighting the need to be aware of non-pain-related concerns such as balance issues and fatigue. The physiotherapy department more closely aligned with the symptom-prevalence described by a previous study than the orthotics department, indicating either a special population or a lack of interest in certain characteristics within the department.

Symptomatic patients with idiopathic flexible flatfoot were included in the main study. Similar to the audit, the most common complaint in the symptomatic population was foot pain (78%). Symptoms were broadly speaking more frequently noted in the main study than in the audit, indicating that this population may have a more severe condition than the average individual presenting to orthopaedic clinics. The MRC manual muscle testing scale indicated potential weakness of the foot supinators and hip extensors, although this is a subjective scale and was not performed on the asymptomatic population leaving questions over the validity of any conclusions that could be drawn.

### 12.3. The differences between symptomatic and asymptomatic flatfoot

The main contribution of the work was to compare symptomatic and asymptomatic flatfoot in a comprehensive, quantitative, and dynamic manner. That is to consider more than the well known visual characteristics, and to extend analysis to dynamic stance.

Three previous studies had investigated the difference between symptomatic and asymptomatic flatfoot, however they were radiographic studies. The studies highlighted talar–first metatarsal angle and talo–navicular coverage angle as predictors of symptoms. The use of radiographs was not acceptable in children with mild or no current symptoms and unsuited to dynamic stance. For this reason the use of non-radiographic techniques to highlight differences between asymptomatic and symptomatic populations was a significant contribution.

The main part of this thesis was a quantitative study that attempted to compare the properties of neutral, asymptomatic, and symptomatic flat feet. Clinicians described 38 Symptomatic Flat feet, 33 Asymptomatic Flat feet, 50 Asymptomatic Mild flat feet, 109 Asymptomatic Neutral feet; and 24 unclassified feet. Overweight and obese participants were uncommon. During the clinical examination, higher ratios of severe knee valgus, and knee hyper–extension were identified in the SF group than in the asymptomatic groups. Less ankle dorsiflexion range was recorded in the groups of flatfeet, and particularly in the symptomatic group.

Further quantitative and comprehensive assessment was undertaken and subjected to statistical testing. The results are summarized in Table 12.1.

Stride length was reduced, step width increased, and percentage of stride spent in swing increased in the symptomatic group, suggesting reduced propulsion. Even after controlling for relative stride length, the Late Stance Peak normalized VGRF was lower

12. Summary, conclusions, and recommendations

Table 12.1.: Summary of differences between neutral, asymptomatic flat, and symptomatic flat feet subjected to statistical testing. A significant difference is indicated between groups A and B as A-B. If there is also a difference between A and C the terminology is A-B/C. The group on the left hand side of the hyphen displayed the characteristic listed, e.g. increased hip flexion compared to the group on the right hand side. The results from the clinical exam (in grey) were not subjected to statistical tests. Kinetic parameters are highlighted in pink. GRF and kinetic parameters were subjected to ANCOVA controlling for relative stride length. \* supported by radiographic studies [192, 109]. \*\* supported by kinematic study [68]. \*\*\* supported by a kinematic study [85]. + generally supported by textbooks.

	Difference	Between groups
	↓ relative stride length	SF-AN/AM/AF
	↑ step width	SF-AN/AM/AF
	↑ percentage time in stance	SF-AN
	Midstance	Late stance
		SF-AN/AM/AF
	Early stance	
c ↓ VGRF	SF-AF	
c ↓ posterior GRF	SF-AN/AM/AF	
c ↓ Lateral GRF		SF-AN/AM/AF, possible ↑ rel to forefoot
	Static stance	
	SF-AN/AM/AF	
↓ hip abduction	Foot strike / early stance	Foot off / late stance
c ↓ peak hip adduction moment		SF-AN
↑ hip flexion	AF-AN/AM/SF	SF-AM/AF
↑ knee valgus	SF-AN	SF-AN/AM (↓ hip extension)
↑ knee flexion	SF-AN	appears to correct
↓ external knee rotation	SF-AN	SF-AN/AM/AF
↓ hindfoot plantarflexion	SF-AN/AM	SF-AN
c ↑ peak ankle extension moment	?	SF-AN/AM
↑ hindfoot eversion	SF-AN	temporal variation of peak
↑ external hindfoot rotation		SF-AM/AF
↑ forefoot abduction	SF-AN/AM/AF, AF-AN	SF-AN**/AM/AF, AF-AN***/AM
↑ forefoot supination	?	?

## 12. Summary, conclusions, and recommendations

in the symptomatic group. In fact a high ratio of “Ben Lomonding” (LSP VGRF below bodyweight) was found in this group indicating trouble resisting the downward fall of the Centre Of Mass, and reliance on the contra-lateral limb for this function. Further analysis of consecutive steps supported this theory with deviations noted in the initial stance of the contra-lateral limb. This instability could explain the lessened propulsion, shortened swing, and stride length.

Analysis of the kinematics revealed several differences that help explain the patterns. At foot strike, increased hip flexion (AF-AN/AM/SF), knee valgus (SF-AN), hindfoot eversion (SF-AN), and forefoot abduction (S-A, AF-AN) were associated with (mostly symptomatic) flatfoot. At midstance increased hip flexion (SF-AN, AF-AM/AN), knee flexion (SF-AN/AM), knee valgus (SF-AN), hindfoot eversion (SF/AF-AN), and forefoot abduction (S-A) were associated with flatfoot. At foot off, reduced hip extension (SF-AN/AM), as well as increased hip adduction (SF-AN), knee flexion (S-A), knee internal rotation (SF-AN), hindfoot dorsiflexion (SF-AN/AM), hindfoot external rotation (SF-AM/AF), and forefoot abduction (S-A, AF-AN/AM) were associated with flatfoot. Probably the most interesting things about the results are that differences are most evident at foot off, forefoot abduction provides the clearest differentiator between asymptomatic and symptomatic feet at any timepoint, and internal rotation of the hindfoot at foot off may be associated with asymptomatic flatfoot as a compensatory strategy. That the results focus upon changes at foot off is logical, as this is when stability in the midfoot is most important.

A theory was proposed. In symptomatic flatfoot, abduction of the forefoot may lead to external rotation of the hindfoot. In turn this leads to either external rotation of the tibia, resulting in knee problems, or internal rotation of the tibia relative to the hindfoot. The internal rotation of the tibia everts the hindfoot by way of the subtalar joint axis and shifts loading to the medial side of the talus, unlocking the midfoot joint-locking mechanism and leaving the foot unstable at push off. The instability leads to overwork of the gastrocnemius and soleus, tightening of the tendo-Achilles (as was demonstrated), and potential fatigue. Additionally the instability may lead directly to

## 12. Summary, conclusions, and recommendations

the instability that was evident in the Ground Reaction Force profiles. The instability is itself self-perpetuating; continual loading of the foot in the “unlocked” position relies on ligaments and tendons to maintain posture particularly the tibialis posterior, spring ligament, deltoids (ankle) ligaments, and plantar aponeurosis. Overuse of these components in positions that place great demand on them could damage them leading to posterior tibialis tendon dysfunction, plantar fasciitis, foot pain, and further flattening of the foot. For this reason the results appear to encourage treatment to focus on correction of the foot off posture if possible, in particular forefoot abduction, and hindfoot external rotation if present.

The results from the kinetic chapter were mostly dependent on the reduced relative stride length and therefore speed. Only one increase was found – early stance peak ankle plantarflexion moment which may be the result of the late stance instability compensatory strategy.

Finally, visual analysis of plantar pressure data (the numbers being too small to support full statistical analysis) showed that increased pressure in the midfoot region was not responsible for the foot pain described by our patients. In fact peak midfoot pressure was lower among the flat-footed populations. Peak AI and MAI were higher in flat than neutral feet, but differences between symptomatic and asymptomatic groups were not convincing.

### 12.4. Other key developments

Different definitions of midstance were investigated. The use of a forceplate-derived definition of midstance marginally improved intra-subject repeatability of kinematic measures over the use of 50% stance as the midstance marker and so was selected.

Truncated Foot Length was estimated on the basis of two markers (heel and toe) and instantaneous plantar pressure maps with success. This was used to calculate the Arch Index over the whole of the stance period.

## 12.5. Limitations

When assessing the existing foot assessment methods the main limitation was gaps in the existing literature. Many measures had been developed and were described ( $n=41$ ), however many of these measures had no information regarding their reliability, consistency, clinical relevance, established reference values, and relationship with dynamic performance. This meant most measures were excluded as possibilities. Additionally, within the ethical framework of working with children, radiographic assessments were not possible despite being regarded by many as the gold standard.

The audit of current practice was limited by poor participation rates in particular departments.

A key source of uncertainty in this thesis is sampling error. The recruitment of participants is a large part of that. This thesis involved two streams of recruitment: the asymptomatic group were volunteers so that has a bias (volunteers being more likely to be of particular ethnic groups and socio-economic backgrounds); the symptomatic group were acquired retrospectively from patient records which is potentially more biased (especially in terms of type of symptoms and background).

The volunteer (asymptomatic, prospective) and patient (symptomatic, retrospective) collection led to an additional limitation of asymmetry in the data available for analysis. The detailed static foot posture assessments (FPI, NNH, AHI, static pressure print) were only collected from the asymptomatic volunteers allowing only ordinal analysis when comparing symptomatic and asymptomatic populations. Strength was only assessed in symptomatic patients. There were also some minor historical differences in terms of the clinical assessment.

The kinetic model used was unable to produce moments with reliability in the important transverse plane. At the ankle the model could only produce moments sagittal plane owing to the simplification of the foot as a vector. No midfoot moments could be produced.

## 12. Summary, conclusions, and recommendations

Data was occasionally absent due to procedural and compliance issues. This particularly affected the pressure analysis as the numbers were too small for statistical testing.

This study focused on particular time-points or events. This left questions over what happens between the events. Although the continuous data was visually inspected, this is subject to the effects of time averaging, and is without indication of statistical relevance.

As a cross-sectional study, it cannot directly measure the progression from asymptomatic to symptomatic flatfoot, nor prove causality. It can only generate theories of a certain level of evidence. As an exploratory study (with a general hypothesis), these theories are not as conclusive as they might be were the specific hypotheses to have been defined in advance.

### 12.6. Recommendations

A better understanding over the current management of flatfoot was developed by clinical audit. Treatment decisions appeared to be strongly related to the department. Departments that irregularly treat idiopathic flatfoot did not produce the volume of data to analyse their methods, but common sense would suggest that the patients should be referred to the departments that are familiar with flatfoot initially (Physiotherapy in this example).

Research professionals

This thesis highlights many issues primarily associated with symptomatic flatfoot (Table 12.1). A theory as to the mechanism of pathogenesis has been suggested. To provide more confidence in the theories and characteristics of symptomatic flatfoot, specific hypotheses should be tested over large groups.

## 12. Summary, conclusions, and recommendations

Longitudinal studies are sorely lacking in terms of flatfoot. To provide better evidence on the development of symptoms, future studies should consider the long term development of the foot (including the shape of the bones) and the development of symptoms. The characteristics highlighted by this work as potential risk factors could be tested to see if they actually were associated with the development of symptoms in flatfoot.

Since flatfoot is common in the under fives, it may be interesting to examine whether there are any compensatory strategies associated with this population beyond the increased fat pad. Within this population, it would be reasonable to examine the effect of kinematics and kinetics on arch development.

This study used ordinal analysis with a simplified representations in terms of the presence of symptoms and of flatfoot. Future studies may wish to collect quantitative descriptions of static foot posture in all subjects (beyond that from OFM, the NNH would be recommended for this purpose). This would allow regression analysis and better accounting for severity. Similarly, in terms of symptoms, the level of severity could be quantified. Alternatively, it may be useful to separate further subgroups such as those with relative forefoot supination or pronation, those with pes planus versus planovalgus, or those with particular symptoms.

Quantitative assessment of strength in all populations could confirm whether there is weakness in the foot supinators and hip extensors of children with symptomatic flatfoot.

The muscular activity during walking should also be analysed. Particular attention could be paid to the muscles highlighted by the kinematic analysis as potential causes of flatfoot and related symptoms - tibialis anterior and posterior, soleus and gastrocnemius, extensor hallucis and digitorum longus, peroneus longus, brevis, and tertius.

The audit could be developed in the future. Repeating the process in different departments and hospitals and improving participation at those departments would add to

## 12. Summary, conclusions, and recommendations

the picture. Retrospective analysis of records could provide much of this data potentially without the need to worry about participation.

In the future, studies could be improved generally in several ways. Researchers should carefully consider forms of recruitment and recruit all populations in the same way and prospectively. In terms of statistics, better solutions to the “two-foot problem” and functional analysis of the whole curve could be attempted. Kinetics of the foot could be calculated from the foot kinematics where many results were found.

### Medical professionals

This thesis supports the concept that flatfoot is usually asymptomatic in children and as such does not necessitate treatment. If the child is symptomatic or demonstrates risk factors such as hyperextension at the knee, knee valgus, reduced ankle dorsiflexion, forefoot abduction, and abductory twist may benefit from a referral or monitoring. The first place to advise treatment should be one used to dealing with flat feet such as a physiotherapist, orthotist, or podiatrist.

The study suggests treatment should focus on the transverse plane and on the position at foot off.

### Physiotherapists

The key notes of this study for physiotherapist are to focus on the transverse plane at the foot and ankle of the individual during late stance and push off where most of the significant differences appeared between the symptomatic and asymptomatic groups. Additionally, during clinical exam severe knee valgus, knee hyper-extension, and reduced ankle dorsiflexion range may be likely to present in the symptomatic population.

Reduced ankle dorsiflexion indicates a tight tendo-Achilles and gastrocnemius so is usually treated by stretching of the tendo-Achilles and gastrocnemius. The thesis

## 12. Summary, conclusions, and recommendations

supports this practice of stretching but notes that it is unlikely to be the source of the problem (although may be involved in the cycle). Therefore it may be desirable to advise this alongside other recommendations.

Gait retraining of the symptomatic population to reduce or reverse external foot rotation at foot off may in future be encouraged although further research would be required.

Asymptomatic children displaying any of the signs (abductory twist, forefoot abduction, knee abnormalities) should be closely monitored and perhaps offered conservative treatment such as gait retraining, strengthening, or orthotics.

Orthotists, podiatrists, and footwear providers

This study highlights the importance of the posture at foot off. It must be noted that it may be difficult for orthotics to treat a problem which is centred around foot off unless they are quite rigid with full length sole. The study suggests it is predominantly in the transverse plane that the pathogenic changes occur in flatfoot so any correction must be tested to ensure action in this plane particularly at foot off.

Additionally the results of the audit indicate a much lower recorded rate of functional limitations and gait disturbances in the orthotics department compared to the physiotherapy department as well as other studies. This may indicate a different population or a lack of awareness of, or interest in, these types of issues. Clinicians may benefit from bearing in mind less obvious symptoms such as fatigue, balance issues, and gait abnormalities, which had been reported elsewhere.

Parents

The main message to parents is that flatfoot is not a pathology in most cases. In children under the age of five this is a developmental norm. Additionally, most children

## 12. Summary, conclusions, and recommendations

in this study without symptoms had little in common with the symptomatic population and according to literature are unlikely to develop symptoms any time soon or have significant pre-disposition to injury.

If symptoms do occur or there is another reason for concern such as family history parents may wish specific advice. Parents would be recommended to initially visit a professional who is regularly treating flatfoot such as a physiotherapist or podiatrist. Conservative treatment options such as orthotics may be supplied by these clinicians which may or may not alleviate symptoms.

### 12.7. Epilogue

Several novel contributions are included in this thesis. The prevalence of symptoms has been quantified. Methods to calculate instantaneous and continuous Arch Index, and estimation of truncated foot length accurately on the basis of pressure were presented. This study has demonstrated differences between symptomatic and asymptomatic flatfoot populations. Differences were most pronounced at foot off. In the symptomatic group, these included kinematic parameters, reduced propulsive gait, and lower late stance peak vertical ground reaction force, indicating stability issues among this population. Implications for treatment and potential risk factors to look for in the asymptomatic population have been highlighted.

## 12. Summary, conclusions, and recommendations

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## A. Foot selection options

The two foot problem has caused significant controversy. Three alternative foot selection policies are presented here side by side (Tables A.1 and A.2). There are 63 variables presented; 18 of the significant results using both feet (29%) were not replicated in every single foot selection technique; six results (10%) were only found when using both feet; three results (5%) were found to be significant in single foot selection techniques but not when utilising both feet.

Table A.1.: Significance of spatio-temporal parameters with different foot selection techniques. Techniques are both feet treated as independent, mean representative value for subject (foot type based on left foot type), left and right feet. p-values from ANOVA tests are listed. Significant results ( $p < 0.05$ ) are shown in bold.

	Both	Mean	Left	Right	GRF / BW	Both	Mean	Left	Right	
Relative stride length	<b>0.000</b>	0.001	0.001	0.000	Vertical	ES max	<b>0.009</b>	0.056	0.064	0.158
Stride duration (s)	0.066	0.162	0.352	0.242		MS min	<b>0.008</b>	0.110	0.051	0.210
Stance/stride	<b>0.000</b>	<b>0.010</b>	<b>0.038</b>	<b>0.009</b>		LS max	<b>0.001</b>	<b>0.027</b>	<b>0.036</b>	<b>0.020</b>
VS_OFM (% stance)	0.145	0.719	0.139	0.793	Medio-lateral	ES lateral max	<b>0.001</b>	<b>0.005</b>	<b>0.004</b>	0.134
VS_VT (% stance)	0.253	0.485	<b>0.046</b>	0.940		ES medial max	0.423	0.334	0.581	0.580
VS_VGRF (% stance)	0.569	0.366	0.706	0.118		LS medial max	0.717	0.851	0.756	0.707
VS_COM (% stance)	0.799	0.619	0.412	0.448		LS lateral max	<b>0.002</b>	<b>0.026</b>	0.105	<b>0.007</b>
					Antero-Posterior	Posterior max	<b>0.000</b>	<b>0.001</b>	<b>0.001</b>	<b>0.010</b>
						Anterior max	<b>0.001</b>	<b>0.014</b>	<b>0.014</b>	0.052

## A. Foot selection options

Table A.2.: Statistical significance of kinematic parameters with different foot selection techniques. Techniques are both feet treated as independent, mean representative value for subject (foot type based on left foot type), left and right feet. p-values from ANOVA tests are listed. Significant results ( $p < 0.05$ ) are shown in bold.

Event	Kinematic measure	Both	Mean	Left	Right	Event	Kinematic measure	Both	Mean	Left	Right
Static Stance	Hip flexion	0.077	0.288	0.215	0.391	Heel Strike	Hip flexion	<b>0.013</b>	0.040	0.145	0.139
	Hip adduction	<b>0.000</b>	<b>0.007</b>	<b>0.003</b>	<b>0.012</b>		Hip adduction	0.121	0.309	0.650	0.089
	Hip internal rotation	0.152	<b>0.389</b>	0.154	0.721		Hip internal rotation	0.317	<b>0.876</b>	0.511	0.406
	FE-TB flexion	0.471	0.610	0.926	0.401		FE-TB flexion	<b>0.046</b>	0.469	0.275	0.251
	FE-TB varus	0.314	0.633	0.620	0.527		FE-TB varus	<b>0.008</b>	0.116	0.198	0.060
	FE-TB internal rotation	0.102	0.240	0.502	0.274		FE-TB internal rotation	0.085	<b>0.422</b>	0.240	0.378
	HF-TB dorsiflexion	0.580	0.971	0.919	0.610		HF-TB dorsiflexion	0.665	0.686	0.097	0.986
	HF-TB internal rotation	0.240	0.052	0.077	0.092		HF-TB internal rotation	0.572	0.495	0.178	0.676
	HF-TB Inversion	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>		HF-TB Inversion	<b>0.017</b>	<b>0.035</b>	0.195	0.068
	FF-HF dorsiflexion	0.511	0.605	0.599	0.499		FF-HF dorsiflexion	0.546	0.469	0.995	0.307
	FF-HF adduction	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>		FF-HF adduction	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>
	FF-HF supination	<b>0.023</b>	<b>0.034</b>	0.092	<b>0.021</b>		FF-HF supination	0.062	0.064	<b>0.025</b>	0.308
	HX-FF dorsiflexion	0.112	0.330	0.314	0.488		HX-FF dorsiflexion	0.483	0.749	0.787	0.362
HX-FF adduction	0.262	0.773	0.555	0.599	HX-FF adduction	0.174	0.412	0.264	0.489		
Midstance	Hip flexion	<b>0.004</b>	0.055	0.162	<b>0.027</b>	Foot Off	Hip flexion	<b>0.001</b>	0.025	<b>0.048</b>	<b>0.028</b>
	Hip adduction	0.326	0.596	0.543	0.656		Hip adduction	<b>0.025</b>	0.053	0.088	0.277
	Hip internal rotation	0.071	0.428	0.282	0.351		Hip internal rotation	0.336	0.843	0.638	0.524
	FE-TB flexion	<b>0.000</b>	<b>0.009</b>	<b>0.050</b>	<b>0.007</b>		FE-TB flexion	<b>0.000</b>	<b>0.000</b>	<b>0.003</b>	<b>0.000</b>
	FE-TB varus	<b>0.004</b>	<b>0.041</b>	<b>0.049</b>	0.106		FE-TB varus	0.197	0.511	0.443	0.314
	FE-TB internal rotation	0.260	0.459	0.493	0.472		FE-TB internal rotation	<b>0.024</b>	0.106	0.072	0.189
	HF-TB dorsiflexion	0.591	0.805	0.590	0.891		HF-TB dorsiflexion	<b>0.001</b>	<b>0.007</b>	0.138	<b>0.016</b>
	HF-TB internal rotation	0.306	0.274	0.084	0.775		HF-TB internal rotation	<b>0.005</b>	<b>0.016</b>	<b>0.004</b>	0.319
	HF-TB Inversion	<b>0.002</b>	<b>0.006</b>	0.085	<b>0.004</b>		HF-TB Inversion	0.134	0.164	0.573	0.157
	FF-HF dorsiflexion	0.897	0.399	0.343	0.747		FF-HF dorsiflexion	0.241	0.360	0.088	0.861
	FF-HF adduction	<b>0.000</b>	<b>0.000</b>	<b>0.001</b>	<b>0.000</b>		FF-HF adduction	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>	<b>0.000</b>
	FF-HF supination	0.053	0.084	0.093	0.117		FF-HF supination	<b>0.033</b>	0.068	0.158	<b>0.034</b>
	HX-FF dorsiflexion	0.162	0.370	0.564	0.346		HX-FF dorsiflexion	0.108	0.388	0.263	0.368
HX-FF adduction	0.317	0.525	0.065	0.674	HX-FF adduction	0.213	0.516	0.160	0.321		

## B. Thesis completion

This appendix documents the completion of the thesis (on custom-designed scale, Fig. B.1).

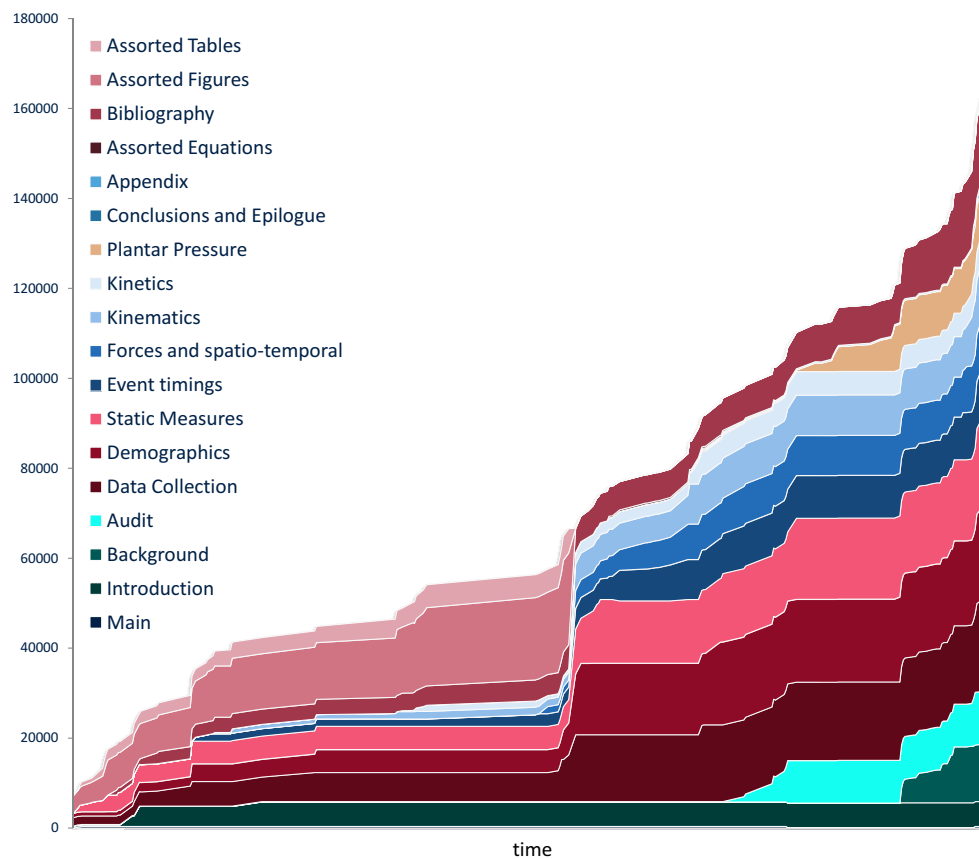


Figure B.1.: Figure of progress in thesis (measured in “points”) over time.