# FOOT POSTURE IN NEUROMUSCULAR DISEASE: DEVELOPMENT AND EVALUATION OF A NOVEL METHOD FOR QUANTIFYING CHANGE IN FOOT POSTURE USING CHARCOT-MARIE-TOOTH DISEASE AS A CLINICAL MODEL

A. C. REDMOND

DOCTOR OF PHILOSOPHY
2004
UNIVERSITY OF SYDNEY

RARE BOOKS LIB

The University of Sydney

## Copyright in relation to this thesis*

Under the Copyright Act 1968 (several provision of which are referred to below), this thesis must be used only under the normal conditions of scholarly fair dealing for the purposes of research, criticism or review. In particular no results or conclusions should be extracted from it, nor should it be copied or closely paraphrased in whole or in part without the written consent of the author. Proper written acknowledgement should be made for any assistance obtained from this thesis.

Under Section 35(2) of the Copyright Act 1968 'the author of a literary, dramatic, musical or artistic work is the owner of any copyright subsisting in the work'. By virtue of Section 32(1) copyright 'subsists in an original literary, dramatic, musical or artistic work that is unpublished' and of which the author was an Australian citizen, an Australian protected person or a person resident in Australia.

The Act, by Section 36(1) provides: 'Subject to this Act, the copyright in a literary, dramatic, musical or artistic work is infringed by a person who, not being the owner of the copyright and without the licence of the owner of the copyright, does in Australia, or authorises the doing in Australia of, any act comprised in the copyright'.

Section 31(1)(a)(i) provides that copyright includes the exclusive right to 'reproduce the work in a material form'. Thus, copyright is infringed by a person who, not being the owner of the copyright, reproduces or authorises the reproduction of a work, or of more than a reasonable part of the work, in a material form, unless the reproduction is a 'fair dealing' with the work 'for the purpose of research or study' as further defined in Sections 40 and 41 of the Act.

Section 51(2) provides that "Where a manuscript, or a copy, of a thesis or other similar literary work that has not been published is kept in a library of a university or other similar institution or in an archives, the copyright in the thesis or other work is not infringed by the making of a copy of the thesis or other work by or on behalf of the officer in charge of the library or archives if the copy is supplied to a person who satisfies an authorized officer of the library or archives that he requires the copy for the purpose of research or study'.

*'Thesis' includes 'treatise', dissertation' and other similar productions.

ACID
FREE
COPY

# Foot posture in neuromuscular disease: development and evaluation of a novel method for quantifying change in foot posture using Charcot-Marie-Tooth disease as a clinical model.

A.C. Redmond

Submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy (Medicine)

2004

Department of Paediatrics and Child Health
Faculty of Medicine

University of Sydney

**Publications arising from work undertaken during the preparation of this thesis.**

## Book chapters

The sections of Chapter 2 covering the physical manifestations of CMT in the lower limb, and the effectiveness of the various treatment approaches, have been published in two co-authored book chapters on CMT:

Chance P., Escolar D., **Redmond A.C.**, Ouvrier R.A. Charcot-Marie-Tooth Disease. in Darras, B, and Jones, R.H..(eds) *Neuromuscular Disorders in Infancy, Childhood and Adolescence.* (Butterworth Heinemann, 2002) ISBN 0750671904.

Ouvrier RA, Ryan M, **Redmond A**. Treatment of Peripheral Neuropathies. In:*Treatment in Pediatric Neurological Disorders.* Ed by: Singer H, Kossoff E, Hartman A, Crawford T., Marcel Dekker, New York (In Press).

*The candidate hereby declares the original and primary authorship of all such lower limb related material published in these co-authored book chapters.*

## Conference proceedings

Preliminary data have been published as:

**Redmond A.C.,** Ouvrier, RA.; *The secondary manifestations of Charcot-Marie-Tooth disease (CMT) and their effect on health related quality of life.* Meeting of the Peripheral Nerve Society, July 26-30, Banff, Canada; Journal of the Peripheral Nervous System 2003: Vol 8; (S1), pp 53

**Redmond,** A., Burns, J. Ouvrier, R.A. Crosbie. J., Peat, J. *An initial appraisal of the validity of a criterion based, observational clinical rating system for foot posture.* "Static and dynamic classification of the foot" Meeting, 19th-20th May 2000, Annapolis, Maryland. Proceedings published in Journal of Orthopedic and Sports Physical Therapy 2001;31 (3) 160

Evans, A., Copper, A., Scharfbillig, R., **Redmond, A.C**., Scutter, S., Williams, M., Sheppard, L. *Reliability of the foot posture index and traditional measures of foot postion.* Proceedings of the 19th Australasian Podiatry Conference - From theory to evidence to practice. Canberra 2001. Australian Podiatry Council, 2001.

The candidate declares the collaborative nature of these publications but also declares that all results presented within this thesis are the product of his own independent analyses.

The candidate also contributed to:

Scharfbillig R., Evans AM., Copper A., Williams M., Scutter S., Iasiello,H., Redmond AC. *Criterion Validation of Four Criteria of the Foot Posture Index* . Journal of the American Podiatric Medical Association 2004;94 31-38.

# ACKNOWLEDGEMENTS

There are many people who contributed to this project. In particular I would like to thank:
My supervising team:

Professor Robert Ouvrier, Petre Foundation Professor of Paediatric Neurology
Associate Professor Jack Crosbie, Department of Physiotherapy
Associate Professor Jenny Peat, Department of Paediatrics and Child Health

For assistance with funding:

The CMT Association of the US, for the Moore Fellowship 2001.
The Podiatrist's Registration Board, New South Wales, Education and Research Account.
The Australian Podiatry Education and Research Fund of the Australian Podiatry Council.
The University of Sydney, Postgraduate Research Support Scheme.

For their practical assistance with the various experimental stages:

The CMT Association of Australia for their assistance with the survey and throughout the latter stages.
The University of Leeds, Rheumatology and Rehabilitation Research Unit, Bioengineering Division for accommodating me within the unit as a visiting researcher, and in particular Dr Jim Woodburn for his assistance with the technical aspects of Chapter Six.
The University of Western Sydney, School of Exercise and Health Sciences, and in particular Josh Burns and Liz Barr for their unfailing support during the experiments detailed in chapters four, five and six.
The University of South Australia, and specifically Angela Evans, Rolf Scharfbillig, Alex Copper and Alison Dalli for their contribution to the reliability studies.
The University of Sydney/Concord Hospital and Dr Garth Nicholson and Dr Kathy Refshauge for their input into the Moore Fellowship application and the clinical trial detailed in Chapter Seven.

Other acknowledgments are also made gratefully to The University of Huddersfield, Latrobe University and to all the clinical staff who input at various stages of the development of the new measure.

All studies were approved as appropriate to the experimental site by the Human Research Ethics Committees of:

The University of Sydney
The Children's Hospital at Westmead
The University of Western Sydney
The University of South Australia

Finally and personally, I would like to thank those close to me who helped me through the PhD process. Great thanks are due to my wife Anne-Maree for her unstinting love and support, and also to Lowri and Nia for coping with me during the tense times. Lastly, in addition to acknowledging his supervisory role formally, I would also like to state my deep personal gratitude to Professor Robert Ouvrier. His wisdom, and the inspirational role model he has provided reached far beyond the PhD process.

# ABBREVIATIONS USED IN THIS THESIS

| | |
|---|---|
| 95%CI | Ninety five percent confidence interval |
| AFO | Ankle-foot orthoses |
| AJC | Ankle joint complex |
| DSD/DSS | Dejerine Sottas Disease/Syndrome |
| CMAP | Compound muscle action potential |
| CMC | Coefficient of multiple correlation |
| CMT | Charcot-Marie-Tooth (disease) |
| CMTAA | The Charcot-Marie-Tooth Association of Australia |
| EMT | Electro magnetic motion tracking |
| FFO | Functional foot orthosis |
| FHSQ | Bennett's Foot Health Status Questionnaire |
| HL | Heel lift |
| HMSN | Hereditary Motor Sensory Neuropathy |
| HRQoL | Health Related Quality of Life |
| HS | Heel strike |
| ICC | Intraclass correlation coefficient |
| JCS | Joint coordinate system |
| MCU | Motion capture unit |
| MNCV/NCV | Motor nerve conduction velocity / nerve conduction velocity |
| MTJ | Midtarsal joint |
| MTP | Metatarsophalangeal (joint) |
| MS | Midstance |
| NCSP | Neutral calcaneal stance position |
| NWB | Non-weightbearing |
| OR | Odds ratio |
| PMP22 | Peripheral myelin protein 22 |
| RCSP | Resting calcaneal stance position |
| RMS (error) | The Root Mean Square (of the error) |
| ROM | Range of motion |
| SD | Standard deviation |
| SEM | Standard Error of the Measure |
| SF-36 | The Medical Outcomes Survey Short Form-36 item questionnaire |
| STJ | Subtalar joint |
| TO | Toe off |
| VAS | Visual analogue scale |
| WB | Weightbearing |

# ABSTRACT

This thesis has two main research aims. The first is to describe the prevalence and scope of leg and foot problems in the most common form of peripheral neuropathy Charcot-Marie-Tooth disease. The second is to identify, develop and validate a method by which structural changes occurring in the lower leg and foot of people with CMT can be quantified in the clinical setting.

A survey of more than 300 people with CMT is presented, which confirmed the high prevalence of foot pathology in the CMT population and provided an insight into the clinical sequelae. The impact of CMT on health related quality of life appears to lie in the mid range for similar chronic diseases. The impact of disease was predicted significantly by severity of leg muscle weakness, and was disease impact was manifest in both the physical and mental health dimensions. Leg muscle cramps were highly prevalent in this sample and also contributed to impaired HRQoL. Footwear is a significant problem for people with CMT, and footwear issues were markedly greater for women than for men. Self-reported structural change in foot structure mirrored the anecdotal literature with a preponderance of CMT feet reported as being high arched.

An extensive review of the literature informed the development of a novel clinical instrument for assessing foot structure, the Foot Posture Index (FPI). In three samples covering early childhood through to adulthood the FPI proved adequately reliable (ICCs 0.89 to 0.57, Measurement error 1.13 to 1.26 units), and was more reliable when used by an experienced clinician in a later CMT sample (ICC=0.97). Concurrent validation against the best available motion analysis solutions demonstrated that the FPI estimates some 64% of true variation in static foot posture, and some 41% of true variance in dynamic function.

The FPI has met with a positive response from the foot health and gait analysis communities and has been rapidly assimilated into the clinical and research communities. The availability of a quick and easy tool that can quantify foot posture presents opportunities for better evaluating foot deformities and treatments in the future.

## TABLE OF CONTENTS

TABLE OF FIGURES PRESENTED IN THE THESIS

TABLE OF TABLES PRESENTED IN THE THESIS

# CHAPTER ONE. INTRODUCTION AND BACKGROUND

---

***Chapter overview***

*Structural foot pathology is so prevalent in people with neuromuscular disease as to be considered almost universal [1-3], and even in the general population the point prevalence of foot related morbidity is some 57% [4], much of which is of structural or functional origin [5]. Despite the high prevalence of foot pathology, there exists at present no widely accepted or adequately validated method for quantifying variation in foot posture in the clinical setting[6]. The continued absence of an acceptable method presents a barrier to clinical assessment, and to the development and evaluation of treatments.*

*In this thesis a novel method for assessing foot posture is described, and its validation in the general population and its specific application to the foot in inherited peripheral neuropathy is detailed.*

---

## *1.1* *INTRODUCTION*

The inherited neuromuscular diseases as a group affect approximately 1 in 1000 people in the developed world, and the most common inherited neuromuscular disease, Charcot-Marie-Tooth disease (CMT), affects approximately 1 in 3000 people [7]. Over the last 20 years, the molecular biology and the genetic basis for a range of neuromuscular diseases have become much better understood. The understanding of the physical effects of these disorders is however, still limited. Many of the treatments aimed at addressing the physical changes associated with neuromuscular diseases have changed little in the past 50 years, although not because of any particular success with existing treatment approaches, and consequently many current treatments remain controversial. Generally, the efficacy of the current treatments has not been evaluated thoroughly. Foot deformities, and their relationship with the inherited peripheral neuropathies are reviewed in depth in Chapter Two.

It is somewhat ironic that while disorders such as CMT have become relatively well understood at the cellular level, basic cardinal data describing the epidemiology of its associated clinical features are limited. Almost all of these patients have foot deformities, including clawed toes and high arched, often painful feet. Similarly, difficulties with balance, temperature regulation, cramps, and so on are reported anecdotally as common, but how common has not been clear. This deficit in knowledge is addressed in Chapter Three with the first large-scale survey of the secondary features of CMT and their effects on Health Related Quality of Life (HRQoL).

There is a broad range of conservative and surgical interventions encountered in the clinical setting, but while a number of surgical series exist in the literature, no quality prospective randomised trials have yet been conducted. Almost no data exist for the efficacy of conservative therapies and the range of treatments in use currently suggests that there is little agreement in the field, a likely consequence of the lack of supporting evidence. Anecdotal reports from patients also suggest variable levels of satisfaction with the treatments currently in use, although in the absence of good data it is difficult to examine this further. With mainstream treatments of variable efficacy, patients report adjunct use of a range of self-administered conservative and alternative therapies, although again, there were no data describing how widespread is the use of these home remedies, nor any indication of their effectiveness. These issues are also examined in Chapter Three.

Good data on the efficacy of interventions for foot pathology is rare in all fields, and the existing concerns are by no means confined to neuromuscular diseases. The complex nature of the human foot, and the difficulties associated with its accurate and objective measurement, have long been barriers to the evaluation of foot pathology in clinical studies. In recent years, organizations such as the Research Council of the American Orthopaedic Foot and Ankle Society have highlighted as a priority, the need for better measures of foot pathology [8]. The Foot and Ankle Special Interest Group of the American Physical Therapy Association published in 2001, a consensus statement identifying priorities for foot outcomes research. The statement identified precisely some of the main characteristics which are felt by experts in the field to be necessary for better evaluating foot posture in the clinical setting[9]. Key points included in the consensus statement were:

1. *The foot is a complex structure, and classification systems should be reflective of this complexity.*
2. *Both dynamic and static methods of describing foot function have identifiable strengths, and both methods have shortcomings that cannot be resolved given the limitations of current technology.*
3. *Some means of standardization of approaches is desirable.*
4. *Where possible, the description of foot structure and function should be based on continuous measures rather than grouping into distinct 'foot type' categories.*

5. *Multifactorial variations in structure and function must be recognised and incorporated into assessment. Measures need to reflect the complexity of the interrelationships occurring within the leg and foot.*
6. *The development of valid and reliable functional assessment tools should be a priority.*

Clearly, foot pathology exists throughout the population at large and so problems with clinical evaluation of foot type, and the novel solution proposed in this thesis, have potential significance beyond any specific application in CMT.

Extreme foot types (such as pes planus and pes cavus) are usually recognised quite readily by clinicians, but subjective foot evaluations are often relatively unsophisticated and result in empiric, dichotomous clinical classifications, not well suited to the thorough evaluation of treatments. Objective, technology-driven solutions have gone some way towards improving the evaluations of foot pathology and related interventions in the laboratory setting, but such systems are not available to the average clinician. High quality, objective analyses are also extremely costly and time consuming to use, leading to concerns over the cost-effectiveness and appropriateness of such technological approaches in clinical decision making. Attempts in the clinical setting, using compromise clinical evaluations to quantify the degree of deformity at initial assessment, or to quantify its progress over time, have generally proven unreliable and inaccurate [10-14].

It is clear that for evaluations of therapies for the foot and ankle to improve, suitable new measures for quantifying the structure and function of the foot must be found.

## *1.2* *AIMS*

The aims of individual component parts of the study are presented as appropriate in each chapter, there were however, two over-arching aims for this thesis.

1. *To obtain comprehensive descriptive data relating to the common physical problems encountered in patients with CMT, with an emphasis on those problems associated with the lower limb and foot.*
2. *To develop and validate a tool for better assessing baseline foot deformity and evaluating existing treatments.*

In this thesis, a novel method is proposed for quantifying standing foot posture in the clinical setting. The new measure produces an index value without units, which describes the standing foot posture in various anatomical segments and planes. It has been named the Foot Posture Index (FPI). The solution derives from a growing consensus in the literature regarding the future direction of foot evaluation in the clinical setting [8 9 15-17], the candidate's sixteen years of experience in the field, and considerable reading. The desirable characteristics are presented and discussed and the basis for the derivation of the measure presented in detail. The validation process is described in terms of a rigorous biomechanical experimental phase and illustration of the clinical application of the measure. Finally the context for its application in the evaluation of CMT is provided, and the utility of the new measure in the clinical setting is evaluated.

## *1.3* *RESEARCH QUESTIONS*

Research questions explored in this thesis:

i. What is the current state of knowledge regarding the effects of CMT on the lower limb and foot?
ii. What are the effects of CMT on sufferers' general HRQoL, and on the health status of the lower limb?
iii. What are the shortcomings of existing measures of foot and ankle posture and function?
iv. What are the desirable characteristics of a clinical measure of foot and ankle pathology?
v. Can a non-technological, low-cost clinical tool provide data of adequate validity and reliability for use in clinical practice?
vi. Can the new measure be used to evaluate the foot deformity of this group of people in a clinical trial context?

This study focuses on people with CMT because the incidence of foot pathology in this group is higher than for almost any other clinical population [3]. In this group of patients, the development of a new tool to quantify foot posture has the potential to make the greatest immediate impact. The applicability of this study is more far-reaching however and the new measure may be suitable for measuring change in foot posture associated with other neurological or musculoskeletal disorders, or to quantify variations in the general population. Quantitative evaluation of foot posture has been so problematic in the past that most objective studies of lower limb function have ignored the intricacies of foot function, simply modelling the foot as a single rigid segment [18]. This approach is justified on the basis of reducing error in these studies, but does little to provide data on the development of the distinct foot types seen in practice. Studies focussing on the foot have attempted to quantify accurately, specific aspects of foot function, but are usually plagued by poor reliability and poor validity [11 13 12 19-25]. If the measure proposed in this thesis proves useful, and its validity is confirmed in wider use, there is some potential for improving the evaluation of foot postures in the clinical setting. This would result in better clinical assessments, but importantly, improved evaluations of treatment, and better data on the suitability of the myriad treatments currently employed.

## *1.4 METHODS*

The methods employed in a complex thesis such as this are necessarily varied, and are therefore considered independently in each chapter.

### *Chapter Two*

The background to the problem was developed in detail from the existing literature. Current limitations in the understanding of the lower limb features of neuromuscular disease were examined, and existing suggestions for methods to address these deficits were appraised.

### *Chapter Three*

The widespread physical manifestations of the most common inherited neuromuscular disease were identified in a large national survey of 324 adults and children with CMT, conducted in conjunction with the CMT Association of Australia. The survey employed the Medical Outcomes Survey "SF-36" [26], a well-validated general measure of HRQoL, and also employed Bennett's "Foot Health Status Questionnaire" [27], along with a series of CMT specific questions to further investigate the impact of CMT on the lower limb. The FHSQ responses provided for the first time, high-quality comparative data on the specific manifestations of CMT in the foot, allowing comparison with a normal population, and highlighting the key areas of concern in the CMT community. A CMT specific section provided an insight into the effects of CMT on the lower limb, and the treatments tried and preferred by patients. This data is a valuable source of empiric, descriptive information about the effects of, and management of CMT in the lower limb.

*Chapter Four*

An alternative method for assessing foot posture was derived from a wide-ranging review of the literature. The construction process is detailed, highlighting the interaction between the component parts, and the selection of component measures.

*Chapter Five*

The feasibility and applicability of the approach was assessed in a small pilot study. The pilot study examined issues such as the empiric reliability of the composite measure, ease of use, and the clinical utility. A small group of practitioners used the first draft of the developmental measure and the consistency of the responses was evaluated empirically. The test-group also evaluated, via questionnaire, the ease of use, ease of understanding, and usefulness of each of the components.

Aspects of the validity and internal component reliability were explored in a study benchmarking the new measure against an existing clinical measure, prior to finalisation of the component criteria. In a moderately large sample (N=131), concurrent measures were taken using the FPI and a second clinical measure (Rose's valgus index). Ordinal regressions were then used to calculate the coefficients of determination for the FPI in relation to the valgus index. This stage of the study program also investigated the validity of the component measures of the FPI, and its internal reliability.

The inter-rater, and intra-rater reliability of the measure was explored in three clinical populations, preschool children, older children and adults (N=89). Either three or four raters measured both limbs of three samples of participants on two separate occasions. Intra class correlation coefficients, measurement error, and mean-difference plots are used to describe the reliability of the measure.

*Chapter Six*

The concurrent validity of the measure was investigated against a bespoke, three-dimensional software reconstruction of the static position of the lower limb. The development of the three-dimensional modelling protocol is outlined, and issues in developing benchmark measures are discussed. The concurrent validity was evaluated further against a more sophisticated static model, and an advanced dynamic evaluation of gait. This experiment was also able to provide, as far as possible, 'gold-standard' data against which the concurrent validity of the FPI is assessed. The internal (inter-item) reliability, the construct validity, sensitivity and specificity were explored in detail.

*Chapter Seven*

A preliminary trial evaluating the effects of night splinting allowed the use of the FPI in a similar context to that in which it may be employed in future. The pilot clinical trial was undertaken ostensibly to evaluate the utility of the new instrument in a clinical setting but also contributes preliminary data on one of the more widely used therapies.

The process of validation described in this thesis is more thorough than that undertaken previously for any other measure of foot posture. The process highlighted some limitations with the FPI, and indeed some limitations in what currently pass for industry-standards. The thesis addresses the key issues of the validation process, but further work will be required to complete the picture. Notably, the reliability of the FPI requires further investigation in each specific population in which the FPI might be applied. As technology permits, and better gold-standards become available, it may also become appropriate to re-visit some of the concurrent validity experiments. Some of the data reported in Chapters Five and Six are less conclusive than would be desired, although the methods tested the boundaries of existing technology, and therefore the results must be considered reflective of the current state of the art. The survey described in Chapter Three was a joint venture between the candidate and the CMT Association of Australia (CMTAA), and the survey design process necessarily reflected compromise between the candidate and the day-to-day activities of the Association. Nevertheless, only well-validated and widely-used surveys were employed for data to be subjected to inferential, comparative analysis, and these data are robust and highly informative. Finally, it is recognised that the pilot study evaluating the FPI in a clinical trial setting outlined in Chapter Seven, is clearly too small to be reported formally as a clinical trial. The full-scale splinting study continues within the department, and for the purposes of this thesis is presented only in so far that it illustrates a use for the FPI, and provides a context for the FPI in practice.

## *1.5 SUMMARY*

In this chapter the outline of the thesis is documented. The introduction highlights the need for a new approach to quantifying variations on foot posture, and overviews the rigorous process to which the new measure was subjected. The particular importance of the foot in peripheral neuropathy has been highlighted to create a context for the thesis, and the complex and varying methods have been outlined.

An overall introductory summary has been presented, which is intended to complement a final section of over-arching discussion and conclusions at the end of the thesis. Where appropriate, each of the experimental chapters includes a more restricted summary of the aims of the specific section, together with an introduction, discussion and conclusion as they relate to that specific section. This enables a concise discussion of the issues relevant to the section at hand without detracting from the broader thesis.

The need for a new approach to evaluating the foot and ankle has been presented and justified, and the relevant arguments will be developed fully in later chapters. The potential impact of the research to the patient with neuromuscular disease and the wider population has also been highlighted. As with the aims, the overall methodologies have been described here, but because of the many approaches employed in this wide-ranging program, details will follow in the appropriate chapters. The general limitations are acknowledged, and again the issues specific to the various experimental phases will be developed in each chapter as appropriate.

On the basis of this outline, the detailed exploration of the thesis will proceed in the subsequent chapters.

# CHAPTER TWO – A REVIEW OF THE LITERATURE

---

***Chapter overview***

*In this review, the literature describing the clinical features of CMT is discussed, with an emphasis on the manifestations of CMT in the lower limb. The limitations of existing treatments for the foot and leg in CMT are also appraised, and later in the review the range of approaches available to the clinician and researcher for evaluating foot posture and function are considered in detail.*

*The review will refer to all forms of CMT and related diseases, but will emphasise the more common, hypertrophic forms of CMT (CMT Type 1), and, in particular, CMT Type1A. CMT1A has been emphasised for several reasons*

*a) it is the most common specific form of CMT*

*b) the ready availability of a diagnostic genetic test for CMT1A, makes it an attractive and confirmable clinical model for scientific study*

*c) CMT1A is reported to be associated with a high incidence of foot deformity, highlighting the relevance of this specific manifestation to the program of work.*

---

## *2.1. DEFINITION OF CMT*

Charcot-Marie-Tooth disease (CMT) was first described in 1855 by Virchow [28], and named after the subsequent work of Jean-Martin Charcot and Pierre Marie in France, and Howard Tooth in the United Kingdom in 1886 [29 30]. A number of CMT sub-types with distinct clinical features were identified during the 20th century. Clinical differentiation was the basis for the seminal classifications of Dyck and Lambert who classified CMT according to its two main phenotypic forms [31 32]. In CMT Type 1, distal weakness and deformity, absent or diminished stretch reflexes, decreased motor nerve conduction velocities and nerve hypertrophy, combine with evidence of segmental demyelination and onion bulb formation on biopsy to create the clinical picture. CMT Type 1 is commonly known as the 'demyelinating' form or 'hypertrophic' form of CMT and its commonest form, CMT1A, has now been shown to be due to a tandem duplication of DNA at chromosome 17 (17p11.2-12) [33 34], or to a point mutation of the gene for peripheral myelin protein PMP22, which lies within this region [35]. In CMT Type 2, the 'axonal' form, nerve conduction velocities are normal or only mildly reduced, stretch reflexes are normally present and there is no nerve hypertrophy. Currently the CMT Type 2 phenotype is known to arise from mutations on chromosomes 1,3,7 or 19 [36-38].

The primary phenotypic classifications remain in widespread use despite advances in the detection of genetic abnormalities. At the time of writing at least 38 genetic variations of CMT are known (summarised in Table 2.1).

*Note: In the genetic, neurological and orthopaedic literature, the terms Hereditary Motor Sensory Neuropathy (HMSN) and CMT are often used interchangeably, despite subtle differences in classification and definition. Debate continues over the accuracy of the nomenclature, but for the purposes of this review the term CMT will be used unless the literature specifically employs the term HMSN.*

**Table 2.1. Sub-classifications of the Charcot-Marie-Tooth syndrome.**

(after Ouvrier 1996, Murakami et al 1996, Bromberg 1997, Auer-Grumbach and Strasser-Fuchs 1998, Vance et al 2000, Chance 2001, Berkhoel 2002, and the US National Institutes of Health “On-line Mendelian Inheritence In Man” database )

| Disorder (OMIM Number) | Inheritance | Chromosomal locus | Pathologic mechanism | Histopathologic features | Clinical features |
|---|---|---|---|---|---|
| CMT1A (118220) | AD | Chromosome 17 1.5Mb duplication at 17p11.2-12 | DNA duplication, PMP 22 protein | Sheath hypertrophy, onion bulb formation | Distal weakness, mild functional impairment, slowing of NCVs |
| CMT1B (118200) | AD | Chromosome 1 1q21-23 | Duffy linked, Myelin Protein P0 mutation | Similar to CMT1A or more severe | Similar to CMT1A or more severe (see Dejerine-Sottas) |
| CMT1C | AD | Chromosome 16p13.1-p12.1 | LITAF missense | | |
| CMT1D | AR | Chromosome 10q21.1—q22.1 | EGR2/KROX20 mutation | | |
| CMT1E (118300) | AD | Chromosome 17p11.2 | PMP22 mutation | | Associated with sensorineural deafness |
| CMT1F | AR/AD | Chromosome 8p21 | NEFL mutation | | Early onset, severe – confused with Dejerine-Sottas syndrome |
| CMT1 | AR | Unknown | | Fewer classic onion bulbs, basal lamina bulbs more frequent. Tomacula present. | Early onset, similar to CMT1A but more complex. |
| CMTX1 (302800) | X linked AD | X Chromosome Xq13.1 | Connexin 32 (gap junction protein GJB1) mutation. NB. GJB1 and P0 mutations have also been found in CMT2 patients. | Demyelination and axonal degeneration. Minimal hypertrophy. MNCVs lower than normal but faster than CMT1A | X linked –absence of male-male transmission. Females mildly affected. Males more severely affected than in CMT1A. |
| CMTX2 (302801) | X linked AR | Xp22.2 | Unknown | | Rare X linked – Only 1 family affected. Females very mildly affected. |
| CMTX3 (302802) | X linked AR | Xq26 | Unknown | | As for CMTX2 but 2 families studied |
| CMT2A (118210) | AD | Chromosome 1 1p35-36 | Kinesin family member gene 1B (KIF1B) mutation | Axonal degeneration | Normal NCVs. Later onset than CMT1A |

| | | | | | |
|---|---|---|---|---|---|
| CMT2B | AD | Chromosome 3q13-q22 | RAB7 missense | Large and small fibre loss | Single kindred, sensory features |
| CMT2B1 (605588) | AR | Chromosome 1q21.2-3 | LMNA missense | | Confined to a small Moroccan pedigree |
| CMT2B2 (605589) | AR | Chromosome 19q13.3 | Unknown | | Confined to a small inbred Costa Rican pedigree |
| CMT2C (606071) | | Linked to Chromosome 12 | Unknown | | Severe, including respiratory failure, and vocal weakness |
| CMT2D (601472) | AD | Chromosome 7p15 | GARS mutation | | Clinically similar to CMT2A, spinal atrophy |
| CMT2E (607684) | AD | Chromosome 8p21 | NEFL gene mutation | | |
| CMT2F (606595) | AD | Chromosome 7q11-q21 | Unknown | | Single kindred |
| CMT2G (607706) | AR | Chromosome 8q13-q21.1 | GDAP1 missense | | 3 kindreds, severe with vocal weakness |
| CMT2H (607731) | AR | Chromosome 8q21.3 | GDAP1 missense | | Pyramidal features, single Tunisian kindred |
| CMT2I (607677) | AD | Chromosome 1q22Chromosome 8q21.3 | MPZ (P0) mutation<br>GDAP1 missense | | Late onset |
| CMT2J (607736) | AR | Chromosome 1q22 | MPZ (P0) mutation | | Sensory and pupillary abnormalities |
| CMT2K (607831) | AR | Chromosome 8q13-q21.1 | GDAP1 missense | | Single Moroccan kindred |
| CMT3 (145900) (Dejerine-Sottas Syndrome) | AR and AD | Chromosome 19q13.1, 17p11.2, 1q22 (a number of specific allelic variants have been reported) | Periaxin (PRX), PMP22, MPZ (P0), EGR2 | Hypomyelination, basal lamina onion bulb formation. MNCVs <10m/s | Clinically severe, infantile onset, global delay, cranial and spinal nerve involvement. (shares common features with severe CMT1A especially in the tetrasomic homozygous variants) |
| CMT4A (214400) | AR – occ AD | Chromosome 8 q13-q21.1 | GDAP1 mutation | Axonal degeneration | Early and severe onset, complete distal (to elbows and knees) paralysis by teens. Often non-ambulatory. |
| CMT4B1 (601382) | AR | Chromosome 11q22 | MTMR2 gene mutation | Congenital hypomyelination, excessive myelin outfolding, onion bulbs, slow NCVs. | Clinically mild to severe, early distal weakness and pes cavus. Cranial nerve signs. Confined to small pedigrees. |
| CMT4B2 (604563) | AR | Chromosome 11p15 | SBF2 mutation | | |
| CMT4C (601596) | AR | Chromosome 5q32 | KIAA1985 mutation | | |
| CMT4D (601455) Lom type | AR | Chromosome 8q24.3 | NDRG1 mutation | | Closed gypsy pedigree, associated with deafness |
| CMT4E (605253) | AR | Chromosome 10q21-22 | EGR2 (Krox20 mouse homolog) mutation | | |
| CMT4F (145900) | AR | Chromosome 19q13 | Periaxin (PRX) | | See CMT3 (Dejerine-Sottas Syndrome) |

| | | | | | |
|---|---|---|---|---|---|
| CMT5 (600631) | AD | Not known. Linkages excluded at Chromosome 1,3,7,10,17 | Unknown | Axonal degeneration. | Two families, pyramidal features, marked leg cramps, and late onset. |
| CMT intermediate A (608340) | AR | Chromosome 8q13-q21.1 | GDAP1 mutation | Intermediate NCVs | 2 Turkish families, mixed axonal and demyelinating features. Fairly mild. |
| CMT intermediate B (606482) | AD | Chromosome 19p13.2-p12 | Unknown | | |
| CMT intermediate C (608323) | AD | Chromosome 1p35 | Unknown | | 2 unrelated families |
| CMT intermediate D (607791) | AD | Chromosome 1q22-q23 | MPZ (P0) mutation | | |
| Hereditary neuropathy with liability to pressure palsies (HNPP) (162500) | | Chromosome 17 1.5Mb deletion at 17p11.2-12 | DNA deletion (or missense mutation) affecting PMP 22 protein synthesis | Presence of tomaculous changes on biopsy with uncompacted myelin. Mild slowing of MNCVs, but conduction block may be present. | Acute onset weakness and sensory loss following nerve trauma. Often the functional deficit is temporary, returning to baseline levels over time. May be episodic. |
| Roussy-Lévy Syndrome (180800) | | Chromosome 17 500Kb partial duplication at 17p11.2 and Chromosome 1q22-q23 | PMP22 or MPZ (P0) mutation | | Similar features to CMT1A but with associated gait ataxia and tremor. In later life may suffer neuropathic foot ulcers. |

## *2.2. EPIDEMIOLOGY OF CMT*

The group of conditions making up the CMT phenotype represent collectively, the most common inherited type of neuropathy, and one of the more common inherited disorders in man. Reports of the prevalence are as high as 1:2,500 in the general population but have shown wide variation. In one Nigerian account of hereditary neurologic disorders among black Africans, a retrospective review of hospital records suggested that this racial group has a prevalence of inherited neuropathy of only 0.15:100,000 [40]. Other studies in the African community [41] suggest however, that the Nigerian data underestimate the prevalence. Conversely the prevalence of 41:100,000 reported in a Norwegian population by Skre [42] probably over-estimates the prevalence. The prevalence of 17:100,000 in a Welsh population [43], and 28:100,000 reported in Cantabria [7] are probably realistic.

Estimates for the proportion of Type 1 to Type 2 cases vary greatly, although the broad consensus in the literature indicates that Type 1 represents between one-half and two-thirds of all cases of CMT [7 43-48].

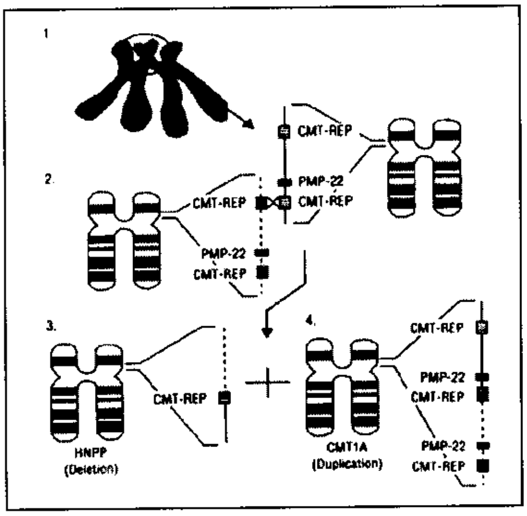
## 2.3. *AETIOLOGY OF CMT*

### 2.3.1 Genetic basis of CMT Type 1 - emphasising CMT1A.

Seventy to eighty percent of cases who present with the clinical picture of CMT Type 1 will test positive for a duplication of a specific region on chromosome 17 [49 50], a figure which is fairly constant for both familial and sporadic cases [49]. The linkage of the genetic basis for CMT1A to chromosome 17 was first reported in 1989 by Raeymakers et al, and Vance et al [33 34]. Subsequent studies [51-56] confirmed this linkage and localised the mutation to a segment of band 17p11.2-12 which codes for a protein Peripheral Myelin Protein 22 (PMP22) (see Figure 2.1). Intragenic point mutations within the PMP22 coding region can similarly result in the same clinical presentation [35 57].

In homozygous (tetrasomic) offspring of two affected parents, the clinical syndrome is usually particularly pronounced [58 59], and has been likened to a Dejerine-Sottas type presentation [60]. This concomitant increase in severity with the double duplication strongly supports the theory of a dose-response relationship [61 62], a relationship demonstrated in mouse models [35 63-65]. In humans the general variability in severity of the clinical presentations does result however, in some overlap between severe heterozygotes and mild homozygotes [59]. An under-dosing effect of PMP22 is seen in the clinical entity of Hereditary Neuropathy with Liability to Pressure Palsy (HNPP) where there is usually a deletion of the same 1.5Mb region found to be duplicated in CMT1A [66].

**Figure 2.1. Genetic duplication in CMT1A and deletion in HNPP (after Chance 1993)**



Other forms of CMT type 1 have been shown to be associated with mutations on Chromosome 1, coding for Myelin protein $P_0$ (CMT1B), and more recently discovered mutations include those on Chromosome 10 in the region coding for EGR2 /KROX20 (CMT1D), on Chromosome 16 coding for Lipopolysaccharide-Induced Tumor Necrosis Factor-Alpha Factor –LITAF (CMT1C), and on Chromosome 8 coding for neurofilament protein, light polypeptide – NEFL (CMT1F). The remaining CMT1 forms are recognised by phenotypic features but have not been localised to specific loci.

Three further forms of forms of hypertrophic CMT have been linked to mutations on the X chromosome (CMTX1,2 and 3). The dominant form (CMTX1) has been localised to a region coding for Connexin 32 (Gap Junction Protein 1) but despite some linkage evidence the genetic basis is not known for the other forms.

CMT type 2, the axonal form, may again be sub-classified according to a large number of genotypic and phenotypic entities as outlined in Table 1.

CMT type 3 is commonly known as Dejerine-Sottas Syndrome (DSS), and a number of allelic variants have been reported for Chromosomes 1, 17 and 19, leading to dysfunction in pathways involving PMP22, $P_0$, Periaxin and EGR2[67-70].

Finally CMT type 4 a relatively uncommon sub type has again been shown to be associated with a range of allelic variants including Chromosomes 5,8,10,11 and 19 [71 72].

### 2.3.2 Patterns of Inheritance

The most common forms of Charcot-Marie-Tooth disease are associated with an autosomal dominant pattern of inheritance, and thus family history is important. Sporadic cases of CMT present some further difficulty to the clinician however [73], as the variability in physical features combines with the absence of a pattern of inheritance to cloud the clinical diagnosis. In many cases, absence of family history can be due to minimal phenotypic expression of an inherited genotype in the parent, however it has been suggested that de novo mutations also account for a significant proportion (5-30%) of sporadic CMT cases [50 70 74-76], and the issue of doubtful paternity must also be considered. Guidelines have been produced which suggest clinical algorithms for the selection of genetic tests, and decision pathways based on clinical findings [77]. Judicious use of genetic testing is required not only to minimise the high cost of the testing, but also because the locus for a number of CMT types remains unknown. While some authors advocate wide ranging genetic screens [70], many types of CMT remain diagnoses of exclusion.

### 2.3.3 Diagnosis of CMT - Electrophysiology

Electrodiagnostic tests used in evaluating CMT include age and temperature controlled assessment of motor and sensory nerve conduction velocity (MNCV and SNCV), latency of evoked response, and amplitude of compound muscle action potentials (CMAP). The tests are described in detail in the literature and will not be reviewed extensively here. They are important, because until the advent of genetic testing, electrophysiological tests formed the basis for CMT classification [46 78]. CMT Type1 is characterised by slowing of nerve conduction velocities, usually to below 38m.s-1, [79]. Decrease in MNCV to pathological levels usually precedes the onset of symptoms, sometimes by many years [80 81]. Normal adult values for MNCV lie in the range of 45/50 to 60m.s-1, a range which is attained in the normal child by approximately 3 years of age [31 82-87]. Some slowing of MNCVs is also often seen in association with axonal forms of CMT, but is less pronounced than that seen in the hypertrophic forms, and is due to the depletion of large diameter fibres [46] rather than the myelin derangement seen in CMT1A.

CMT type 2 is typically associated with marked reduction of compound muscle action potentials (CMAP), although CMAPs will also be reduced in long standing hypertrophic CMT [80 88]. The reduction of CMAPs in CMT type 2 is associated with axonal degeneration alone, and the MNCVs usually remain above 38m.s-1 [31].

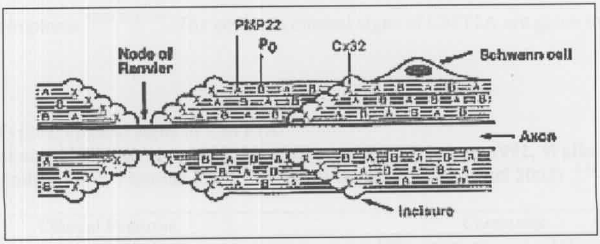
The relationship between long-term axonal loss and disease severity in CMT type 1 as well as in CMT2, is receiving renewed attention, and a number of authors have recently suggested that axonal loss may be more significant than previously thought [89-91].

## 2.4. *PATHOLOGY OF CMT*

### 2.4.1 General pathology

As was outlined in the previous sections, the genetic mutations affect proteins with a variety of functions in peripheral nerve tissue, giving rise to the specific pathologies. A brief outline will be provided for the three most common forms of CMT, CMT1A, CMT2A and CMTX1.

**Figure 2.2 Distribution of major myelin proteins in peripheral nerve (after Roa & Lupski 1994)**



It has been proposed that PMP22 has a regulatory role in the normal development and compaction of myelin,[89 92 93 94] and also appears to aid the adhesion of myelin components [95-98]. In CMT1A, PMP22 dysfunction leads to significant changes in the nerve sheath including Schwann cell proliferation[31 32], and onion bulb formation [63 99]. The mean ratio of axon diameter to total fibre diameter (the so called 'g' ratio) may be altered in CMT1A and Dejerine-Sottas Disease [99 100].

Failed myelin compaction has been noted in HNPP patients [73 95], and in mouse PMP22 knock-out models [101]. Peripheral myelin protein dysfunction is also implicated in the CMT1B sub-type, in which disordered production of Myelin Protein Zero (MPZ or $P_0$) leads to myelin uncompaction [102-104]. A loss of function in the gap junction protein connexin 32, leads to the X linked phenotype CMTX [105 106].

In addition to the changes observed in the myelin sheath, the CMT group of disorders can also be associated with a range of axonal changes. CMT type 2 is characterised by normal myelination but by milder weakness associated with axonal degeneration [107]. Primary axonal degeneration characterises CMT Type 2, although it should be noted that even in the hypertrophic forms of CMT, abnormalities in the myelin sheath will in turn, affect the function of the axon. This is particularly so in the longer fibres in which the axonal effects are more profound [89 90 108]. Over time, muscles innervated by the deficient nerves show progressive functional and histological change [65 109 107]. Fatty infiltration and moderate atrophy are observed [110], with fibre atrophy and fibrosis [2 111].

## 2.5. General Clinical Presentation

The diagnosis of CMT must include consideration of the overall clinical picture because of the incomplete relationship between the genetic/electrodiagnostic testing, and functional deficit and symptoms [45 84 112-116]. The common clinical signs of CMT1A are given in Table 2.3.

**Table 2.2. Typical clinical signs of CMT1A (after Murakami 1996, Alvarez 1998, MacMillan 1994, Nicholson 1991, Walker 1994, Hoogendijk 1994, Thomas 1997, Shy 1999, Ouvrier 1999, Vinci 2003)** [1 43 56 73 80 87 117-120]

| Clinical Features | *Comments* |
|---|---|
| • Insidious onset and slowly progressive motor weakness | *in 18-30% of patients with CMT, weakness is the first presentation. Weakness is demonstrated in 90-97% of CMT cases* |
| • Onset in first two decades of life | *onset in 1st decade in 75-80% and by 2nd decade in 94%* |
| • Tripping and lateral ankle instability | *in 10% this is the first presentation* |
| • Progressive pes cavus | *demonstrated in 80-90% of CMT cases* |
| • Gait changes –steppage or 'marionette' gait | *decreased ankle dorsiflexor power leading to foot drop* |
| • Calf muscle atrophy | |
| • Calf cramps | |
| • Autonomic changes including intolerance of cold and postural hypotension | |
| • Hand weakness –difficulty writing or operating zippers or buttons | |
| • Impairment to, or loss of sensation – with or without neuralgia | |
| • Essential tremor | *demonstrated in 10-25% of CMT cases – (Note the overlap with the Roussy-Levy syndrome)* |
| • Diminution or absence of deep tendon reflexes – Ankle jerk most affected | *demonstrated in 86-94% of cases* |
| • Inability to heel-walk due to weakness of the anterior leg muscles | *demonstrated in 92% of cases* |
| • Slowed nerve conduction velocity | |
| • Nerve thickening and onion bulb formation | |
| • Decreased activity | |
| • Evidence of male to male transmission in some kindreds | *(aids in differentiating CMT1A from CMTX)* |

While the majority of cases have their onset in the first two decades, later onset is not unknown. Late onset cases tend to be associated with a milder phenotype and have less slowing of the MNCVs [86]. The weakness characteristic of CMT is more significant in distal muscle groups than proximal. Weakness is also more profound in the legs and feet than in the upper limbs, and while upper limb strength may be normal in 10-15% of affected individuals, some weakness in the legs is all but universal [119 120]. In the upper limb, decreases in muscle strength range from 20-40% at the shoulder to 30% at the elbow, whereas in the lower limb the decrease in strength associated with CMT eventually, is approximately 50% at the knee (flexion and extension) and 75% at the ankle [121].

Mild sensory loss is a common finding in CMT1A although it rarely causes significant functional impact [122]. The main impact of sensory deficit is the impairment of proprioception and consequently of balance [86].

### 2.5.1 Impact of CMT disease

The impact of CMT is highly variable, whether between people with the same CMT sub-type, within kinships [3 86] or even within homozygous twins [123], and the features can range from the sub-clinical to the highly disabling. One-third of CMT1A patients have reported being unable to run [86], and more than half to have measurable impairments to normal walking [114]. The self-reported impact of the physical aspects of differing CMT types was reported in a Swedish study of patients with CMT Type 1 and Type 2 [45]. More than one-third of Type 1 respondents and slightly more than half of the CMT Type 2 group reported 'moderate' or 'severe' disability.

Only 40% of CMT sufferers are able to maintain full employment and 16% will never work [124], a substantially higher incidence of unemployment than is found in the general population. In one study of disability and quality of life in 50 CMT patients, CMT was reported by 58% of the respondents to interfere with their professional capacity, and 70% indicated that their CMT restricted leisure activities [114].

### 2.5.2 Incidental features of CMT

A number of incidental clinical findings may be associated with CMT. A prevalence of concomitant spinal deformity of approximately 30-50% has been reported in children and young adults with CMT [119] and hip dysplasia is widely reported, [125-127] with an incidence as high as 8-10% [128 129].

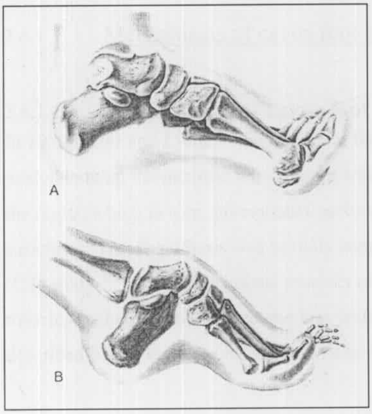
In addition to the typical sensorimotor disorders, patients with CMT often report superimposed autonomic-type changes such as intolerance to cold [130 131]. Abnormal responses to cold have been reported in more than three-quarters of CMT Type 1 patients, although both the patterns and degree of responses are highly variable, and do not necessarily relate to the degree of general disease [130 132]. Muscle cramps, especially in the calf muscles, are a fairly common clinical presentation, but whether such cramps are vascular in origin, or related to other aspects of the neuromuscular disease, is not known [133].

In patients with severe forms of CMT, widespread neuropathy may rarely result in serious presentations such as diaphragmatic weakness and nocturnal hypoventilation, [120 134] pyramidal features, optic disturbance, intellectual impairment and incontinence [120]. These signs are likely to occur only in cases of severe and long standing disease however, and are also unlikely to be associated with duplication confirmed CMT1A.

## *2.6.* PRESENTATION OF CMT1A IN THE LOWER LIMB

Rarely the lower limb in CMT can present with a pes planus, although the typical lower limb presentation in CMT is of a cavus foot type, flexible in the early stages, but becoming increasingly severe and fixed as the disease progresses [1-3 135 136]. The degree of fixation can be determined using the lateral block test of Coleman and Chestnut [137], in which a solid block of material is placed under the lateral forefoot. A rigid cavus fails to adapt to this weightbearing challenge [135]. It has been suggested [1-3 138] that the pes cavus deformity seen in CMT is usually of the 'forefoot' or 'anterior' type in the classification system of Samilson and Dillon [139] This is possibly due to the dynamic nature of the initial deformity, and seems to contrast with the more 'posterior' or 'global' cavus deformity seen in some congenital conditions.

**Figure 2.3. A. Anterior cavus and B. global or posterior cavus (after McCluskey 1989)**



In more advanced stages of CMT, the rearfoot may come to lie in a varus position, with the forefoot in a flexed, valgus position secondary to plantarflexion of the first metatarsal [1 3]. The aetiological processes leading to the formation of a cavus foot are discussed later.

The pes cavus is often associated with other secondary features including pressure lesions on toes due to toe clawing, distal migration of the plantar fat pad with plantar calluses, metatarsalgia, difficulty with shoe fitting, and increased weightbearing on the lateral side of the foot, sometimes with associated stress fractures [1-3 117 136 140-146]. The forefoot may be adducted, and the fibula displaced posteriorly because of external rotation of the ankle and rearfoot associated with rotation of the calcaneus into varus [3]. The calves are usually thin due to muscle atrophy in the lower leg [3], although adipose pseudo-hypertrophy has also been reported in rare cases [133 147] and should be considered when evaluating patients with CMT.

There is still some debate over the precise mechanism by which the cavoid foot changes occur. Dwyer, in 1975, reviewed then current theory on the formation of the pes cavus deformity and presented 23 hypotheses proposed between 1867 and 1953 encompassing neurological and primary bony mechanisms [148]. The modern understanding of the mechanism was better developed and with specific application to CMT by Sabir and Lyttle in 1983 [2] and Mann and Missirian in 1989 [149]. Today, technological limitations still preclude the development of a definitive model, so all explanatory models are hypothetical, based on limited data. The theoretical bases for the more influential models are outlined below, summarised with a working model derived from current consensus in the literature which can serve for application in clinical practice.

## 2.6.1 Mechanisms of cavus foot changes

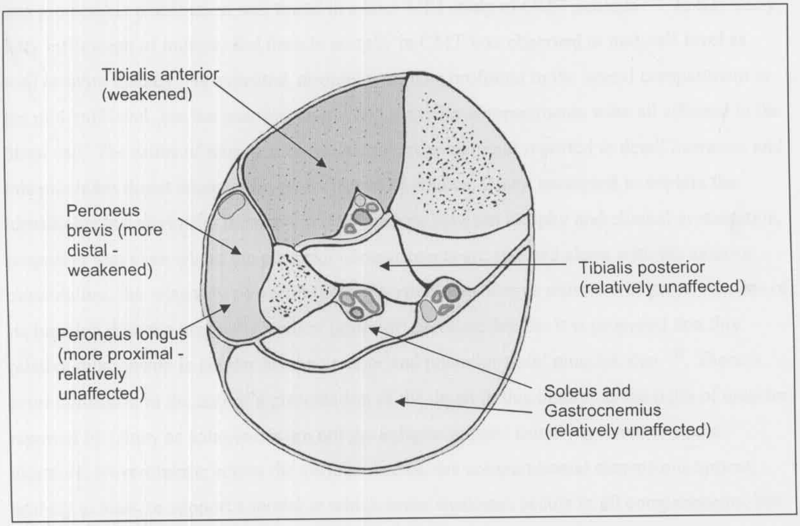
### 2.6.1.1 Mechanisms of cavus foot changes - centrifugal weakness model

In 1982, Sabir and Lyttle [2] suggested that the pattern of weakness was centrifugal. They postulated that the intrinsic musculature was the first affected, and that this caused clawing of the digits, which in turn, precipitated cavus changes through tightening of the plantar structures. This hypothesis was initially supported by a subsequent computed tomography (CT) study [150] in which the distal muscles of the foot appeared to be affected earlier than the muscles in the leg, but has become less widely accepted recently as the compartmental model described below seems to offer better fit to the clinical picture.

#### 2.6.1.2 Mechanisms of cavus foot changes - compartmental weakness model

A more compartmental pattern of denervation and muscle weakness was proposed by Mann and Missirian in 1988 [149].

**Figure 2.4. Compartments implicated in the formation of the cavus deformity associated with CMT.**



The compartmental model proposes that anterior compartment weakness combines with normal tibialis posterior and peroneus longus function, to produce a relative over-pull of the postero-medial musculature, causing a consequent imbalance in the direction of inversion, adduction and plantarflexion. The compartmental model has received support from studies exploring cadaveric muscle weight [151], and later, cross sectional muscle area on magnetic resonance (MR) images [152 153]. Using MR imaging, the relative cross sectional areas in patients with pes cavus, when compared to normal controls, were similar to the pattern of atrophy predicted by the model of Mann and Missirian. Specifically, the ratio of the cross sectional area of the peroneus longus muscle to the tibialis anterior muscle was significantly increased over normal, suggesting atrophy of tibialis anterior and dynamic overpull of the peroneus longus. This finding was evident in patients with CMT, in a group with other neurogenic causes of pes cavus, and in a small group with idiopathic anterior cavus [153].

### 2.6.1.3 Mechanisms of cavus foot changes – modified compartmental weakness model *(all muscles affected but with varying functional consequences)*

Despite the relatively promising results in the MRI studies of multi-pathology pes cavus, a less predictable distribution was found in a later MRI study of CMT patients [110]. In this study, fatty infiltration of muscle, and muscle atrophy in CMT was observed at mid-calf level as well as more distally. As expected, atrophy was most profound in the lateral compartment at the mid-calf level, but the anterior, lateral and posterior compartments were all affected in the distal calf. The ratios of muscle cross-sectional areas were not reported in detail however, and this precludes direct comparison with other MRI studies. Olney attempted to explain the identifiable but obviously incomplete relationships between atrophy and clinical presentation, proposing that even where the posterior compartments are affected along with the anterior musculature, the relatively powerful (posterior) peroneus longus muscle will preserve more of its function than the originally weaker (anterior) peroneus brevis. It is proposed that this relative relationship is similar for the anterior and posterior tibial muscles also [138]. There is some confusion in the author's presentation of the detail in this theory, as the pairs of muscles reported by Olney as antagonists are not the antagonist pairs usually referred to in the literature. Nevertheless, across the various studies, the compartmental dimensions appear, broadly at least, to support a model in which some weakness occurs in all compartments, but with more profound functional effects occurring in the antero-lateral compartments.

### 2.6.1.4 Shortcomings of existing models

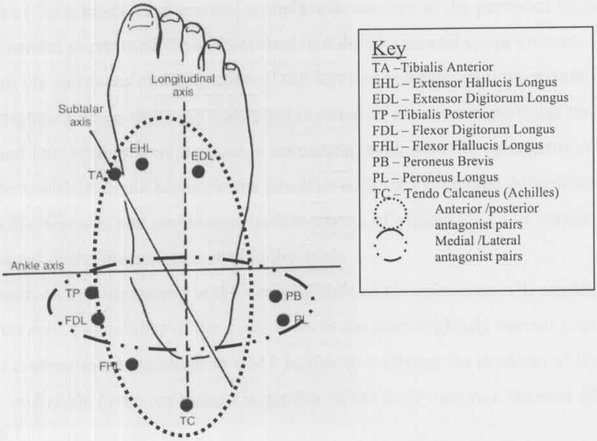
The understanding of the mechanism by which the cavus foot develops is incomplete, and better data in this area are needed to improve predictions of clinical changes in patients, with better planning of treatments to counter them. Furthermore, the generalised evidence in the literature fails to accurately reflect the individuality of the actual presentations of patients in the clinical setting. The gap between theory and clinical presentation is well illustrated by Stilwel et al who report in their series of CMT patients, a visible asymmetry in muscle dimension and degree of fatty infiltration between left and right sides in some subjects, despite symmetrical clinical presentations [110]. Price et al claimed a predictable variation in muscle atrophy on computed tomographic imaging which, it was proposed, can be used to classify the changes according to a predominance of either common peroneal nerve or tibial nerve involvement [150]. These two forms of atrophy should lead to either a pes cavus or pes planus presentation respectively, two highly dissimilar foot types. Even for such a gross distinction as this however, the differences in atrophy were small in comparison to significant factors such as inter-subject variation, age, gender and affected side. The tibial and peroneal classifications proposed were not evident either in the linear regressions the authors employed in their statistical analysis, and were postulated only from the authors' empiric observation of residuals. While the observation of the two types is coherent with current theory, these data cannot be considered strong supporting evidence, and serve to highlight the difficulties in developing a coherent explanatory model substantiated by good data.

#### 2.6.1.5 Mechanisms of cavus foot changes – a practical clinical model

For the purposes of practical application in the clinical setting, a working theoretical model of the progress of the pathology can be derived from existing literature and is well summarised in the reviews of Holmes et al [3], Alexander and Johnson [136], Price et al [150] and Aktas and Sussman [142]. This clinical model proposes that the weak intrinsic musculature combine with the normal long toe flexors to cause clawing of the digits. The relatively normal peroneus longus, inadequately opposed by its weakened antagonist, tibialis anterior, causes plantarflexion of the first metatarsal and the anterior cavus. The strong tibialis posterior is also inadequately opposed by the weakened peroneus brevis, which then acts with the long flexors to adduct the forefoot (See Figure 2.5).

Over time fibrosis and contracture of the plantar structures will also contribute to an increasingly severe and rigid position [1]. It is not clear whether the varus position of the calcaneus is a primary consequence of the tibialis posterior muscle overpull [154 155] or a secondary change resulting from the valgus forefoot [156]. Theoretical arguments have been advanced in support of both explanations [1 136 150] but only limited experimental data exist. The radiographic analysis of the osseous foot changes associated with CMT reported by Aktas and Sussman suggests that while excessive plantarflexion of the first metatarsal on the mid foot is a universal finding, rearfoot involvement is less common. The finding of a consistent pattern of forefoot deformity does tend to support indirectly, aspects of the Mann and Missirian muscle imbalance theory, and supports the contention that the calcaneal varus occurs secondarily in CMT.

**Figure 2.5. Relative mechanical advantage of the musculature around the ankle**



The role of muscle imbalance in the precipitation of a range of deformities about the ankle is equally intriguing when viewed in the broader context of severe CMT and other positional disorders. In the reports of individuals more severely affected with CMT, the more widespread neuropathy leads not to a worsening of the typical pes cavus, but to a weakened 'flail' foot with pes plano-valgus and little soft tissue contracture or bony change.

When muscle imbalance occurs in a pattern reversing that typically found in CMT, i.e. a weakened postero-medial compartment, the counterpoint to the pes cavus typical of CMT is observed. Thus in patients with preserved peroneal function, diminution or absence of tibialis posterior function rapidly results in the development of a severe plano-valgus deformity. Highlighting the importance of dynamic muscle imbalance in this model, Mizel et al reported a small series of eight patients with pre-existing traumatic palsy of the antagonist peroneal group, in whom tibialis posterior tendon transfers were performed [157]. In the peroneal deficient patients, the foot developed little or no structural change post-surgery, despite the medial weakness brought about by the posterior tibial tendon transfer. The authors highlight the similarity in their series to the imbalances seen in CMT, and postulate that in such conditions weakening of the unaffected muscle may prove of benefit to the patient. This has not been confirmed in any clinical studies of CMT cases but makes for an interesting observation.

Two case studies reporting the longer-term consequences of traumatic laceration to the peroneal tendons also provide some insight into the formation of the cavus foot deformity [158] [159]. In both of these cases, undiagnosed complete lacerations of the peroneus longus tendon with involvement of peroneus brevis, resulted in a developmental cavus characterised by inversion of the calcaneus and adduction of the forefoot but with minimal plantarflexion of the first metatarsal. In neither case was reconstruction of the severed peroneal tendon possible, and thus both proved resistant to correction, even with the transposition of other tendons. Both authors again highlight the parallels with the cavus type deformities seen in neuromuscular disease, and emphasise the importance of establishing and maintaining the subtle balances in the musculature around the ankle.

In the cavus foot, any increasing in the varus attitude of the calcaneus will predispose the patient to inversion instability of the ankle even in the neurologically normal population [160]. The lateral compartment weakness in CMT further exacerbates the problem of lateral ankle instability, and ankle inversion trauma is another of the more common features of CMT in the lower limb [1].

### 2.6.2 The effect of CMT on gait

The structural changes are often the most striking feature of the lower limb in CMT, however these static changes reflect important if subtle alterations in dynamic function. The gait pattern in the typical CMT patient is one of a high stepping gait, precipitated by failure of the weak anterior ankle musculature to adequately dorsiflex the foot during the swing phase of gait [1 2 117 139]. The swing phase of this 'marionette' gait pattern, noted in the original paper of Charcot and Marie [29], ends with either a toe-to-heel, or foot-flat loading response [1 141 149], rather than the normal heel-to-toe gait. One study has quantified empirically, drop foot in static single limb stance [117], but studies analysing in detail the gait of CMT patients are rare. Kuruvilla et al presented in 2000, the first video based gait analysis, and report significant differences from normal comparators [161]. Some irregular findings were noted at both proximal and distal joints in the leg during walking. The most profound finding, as expected, is of a significant aberration in ankle motion. The foot falls into plantarflexion through the swing phase, and makes ground contact at the forefoot in a plantarflexed position. The video study confirms previous anecdotal reports that the knee exhibits greater flexion throughout the gait cycle. This is particularly pronounced at toe-off, probably to aid in ground clearance. However, in contrast to previous observational studies and anecdotal reports [1 2], hip flexion and extension was found to be relatively normal, with greater medio-lateral sway at the hip in the CMT group the only abnormal finding. It is not clear whether increased sway is due to a hip abductor/adductor imbalance as part of the CMT neuropathy, is secondary to spinal deformity, or due to a physical compensation for the foot drop.

## 2.7. *TREATMENT OF LOWER LIMB PATHOLOGY IN CMT*

In the absence of quality data to inform clinical decisions, surgical and non-surgical treatments for the lower limb in CMT remain controversial and varied. It has been noted previously in the preceding chapter that addressing this deficit would be aided by the development of instruments capable of better quantifying changes associated with treatments.

### 2.7.1 Non-surgical treatment

A number of suitable goals have been proposed for non-surgical management of the leg and foot in CMT. They include maintenance of function and comfort, protection of weakened joints, ensuring patient safety, and conservation of energy during walking [1 154 162]. Palliative approaches, such as simple cushioning, can be readily adapted from established management principles used in foot pathology associated with other conditions, and will often improve the quality of life of the patient with CMT. Conversely, non-operative strategies aimed at minimising the progression of the structural changes over the longer-term, have been reported to be generally unsuccessful in CMT and in other neurogenic causes of pes cavus development [136 139 156 163]. A range of non-operative treatments including night-splints, ankle-foot orthoses (AFOs) and other orthoses have also been suggested to be relatively unsuccessful [3 164 165] although there are no controlled trials evaluating these approaches rigorously.

#### 2.7.1.1 Strengthening

The weakness associated with the CMT disease process underpins the majority of the clinical signs and symptoms. Strategies aimed at strengthening weakened muscles therefore represent an intuitive approach, and a range of strengthening regimes using both non-weightbearing and weightbearing exercises has been proposed [1]. Gains in thigh muscle strength have been reported over a 24 week training period for one randomised trial of a strengthening program in CMT patients [166 167]. An increase of 21% in the strength of the Maximum Voluntary Contraction (MVC) was found, but the evaluations were performed on proximal leg muscles, those least affected by the disease process in CMT thus presenting a significant limitation to the clinical application of the results.

### 2.7.1.2 Stretching

A range of dynamic and passive, weightbearing and non-weightbearing, stretching approaches is found in the literature. The benefits of stretching the progressively contracting soft tissue structures are intuitive, but data on the efficacy of such approaches in CMT are limited.

#### 2.7.1.1.1 *Stretching - Passive stretching exercises*

Passive stretching exercises are used in a range of conditions associated with soft-tissue contracture. There are no studies of the effect of passive stretching exercises in patients with CMT, but this approach is widely advocated for these patients [1 154 162].

#### 2.7.1.1.2 *Stretching - Splinting*

Night splints are widely used in a variety of conditions which present with limited joint ranges of motion, and although patient compliance can be poor in older children, they are considered a benign approach and are in widespread use. A small number of studies have evaluated the efficacy of splinting in conditions such as cerebral palsy, but the effectiveness of ankle splinting in providing long-term improvements of calf muscle flexibility in CMT is unknown. The serial application of progressive plaster or resin casts over 3-6 weeks has been shown repeatedly, to increase available range of motion at the ankle as a consequence of lengthening the tendo Achilles [168 169]. This has not been investigated specifically in CMT, but consistent results have been obtained in other groups such as children with cerebral palsy and idiopathic toe-walkers [170 171]. Serial casting secondary to soft-tissue surgery in CMT patients has been proposed but not evaluated [163]. While cavoid changes in many pathologies are associated with shortening of the tendo Achilles, it is not clear whether these types of approaches will be applicable to the treatment of foot deformity in CMT. Data from the only radiographic study of the CMT foot to-date suggests that in the anterior-type cavus deformity generally seen in CMT, the ankle joint is already excessively dorsiflexed, with the tendo Achilles already either normal, or of exaggerated length [142]. If this is the case, surgical and conservative treatments currently aimed at improving the plantigrade weightbearing position of the foot may be better directed toward the contracted midfoot than the rearfoot and ankle / tendo Achilles complex.

### 2.7.1.3 Shoe insoles and orthoses

The use of AFOs during daytime walking has a rapid impact on function [172 173], through physical support of the drop foot during walking [1 162]. Worn at night as non-weightbearing splints AFOs have been reported anecdotally to reduce contracture of tendo Achilles (TA) and other soft-tissue [1 154 163]. In patients with foot deformity, the addition of a contoured inner sole surface such as found on an in-shoe orthosis may increase patient comfort [1 174 172]. It has been shown that contoured orthoses redistribute load over the plantar surface of the foot and reduce pressure [175] and such an approach may be appropriate for patients with foot deformity. Shoe modifications have also been described which can assist with this reduction in pressure [136]. Dynamic functional approaches such as lateral forefoot wedging have been hypothesised as being beneficial to the function of the foot, but no quality data are available to support such assertions.

### 2.7.2 Surgical treatment

There is a variety of approaches available for the surgical management of foot and leg deformities seen in CMT. These range from the limited interventions of single tendon transfers, to the substantial interventions of reconstruction and triple arthrodesis [135]. Often the approaches are used in combination [136 176]. Clearly the presence of significant, fixed deformity will require a more aggressive approach, and the management of these feet is less controversial. In the flexible foot however, longer-term issues influencing both the cause and the treatment combine with the theoretical but unproven capacity to prevent or limit future deformity, to make decisions more difficult. Soft tissue procedures which preserve joint motion are attractive in principle because of the theoretical potential for better function post-operatively [1]. The option for further, more radical surgery is also preserved should the initial soft tissue surgery prove inadequate [138]. Conversely, arthrodesis is irreversible and while arthrodeses may produce adequate results in many cases, any approach aimed at selected joint destruction will have some impact on subsequent function.

Arthrodesis is considered an end-stage or salvage procedure in most other conditions, but in CMT the progressive nature of the disorder clouds the issue, and it is widely postulated that because of the inexorable progression of the muscle weakness seen in CMT, soft tissue procedures are doomed to fail from the outset. Proponents of this argument contend that soft tissue surgery provides inadequate control over the muscle imbalances, and that long-term control over the cavus deformity in CMT is best achieved with early arthrodesis [177]. To further confuse the argument however, the few studies to have followed triple arthrodesed patients with CMT in the longer-term, suggest that promising short-term outcomes of arthrodesis are often followed by significant longer-term problems of surgical failure, recurrence and compensatory degeneration of neighbouring joints [128 163 178].

A compromise position suggests that staged surgery, firstly involving soft tissue releases to minimise deformity, later followed by arthrodesis for stabilisation may, in theory at least, result in better outcomes [128 138 165 179 180]. Levitt et al reported 25 years ago, their anecdotal experience that patients undergoing early soft tissue surgery have less severe deformity at the time of subsequent arthrodesis [181] and this has also been reported subsequently [138 182]. The role of early soft tissue surgery in delaying arthrodesis has also been advocated by other authors [128 179 183], but there is little data to support this. In the future, comparative studies employing appropriate randomisation protocols are essential to determine the relative merits of early soft tissue surgery and early arthrodesis.

This part of the review has focussed on the lack of consistent data for CMT; however the confusion over definition, and the lack of outcome measures for treatments applies similarly to most foot-related pathologies. The lack of suitable outcomes for the clinical evaluation of foot posture and function, places significant limits on our understanding of the change process occurring in all postural/functional foot pathologies. By extension, the implications for evaluations of interventions directed at stopping or reversing any change are greater still. At present, the lack of adequate outcome measures for the foot is one of the main barriers to the development of an evidence-based approach for the assessment and treatment of disorders of the foot and lower limb. This is the case not only in CMT but also in the general population [184].

## 2.8. *EVALUATION OF FOOT AND LOWER LIMB DEFORMITY, AND FUNCTIONAL IMPACT.*

The definition, quantification and evaluation of the effect of treatments for foot pathologies require evaluation of a complex musculoskeletal structure. Subjective clinical impressions can be compelling to the experienced practitioner, but are inadequate for quality evaluations of disease and therapy. Obtaining truly objective and criterion based measures presents greater difficulty than might initially be anticipated, and controversies over method and approach remain [16 185 186].

Historically, the most universally accepted classifications of foot type have been based on readily recognised and relatively extreme co-existing pathology, such as the talipes deformities resulting in the clubfoot/ cavo-varus deformity, or pes plano-valgus secondary to cerebral palsy. In these cases the pathology is usually accompanied by identifiable neurological and profound histological change [187], and in the presence of such a characteristic clinical picture, even subjective classifications have strong face validity. Such discrete classifications (for instance, 'clubfoot' versus 'normal' or 'pes planus') are consequently in widespread use.

Greater difficulty arises when there exists in clinical practice, a need for foot posture/function evaluation that relates to more subtle variations from the 'normal' or 'ideal' foot type [187 188], and for exploration of the potential for associations between the foot type and secondary pathology and symptoms. In such situations simple, subjective, dichotomous classifications are generally inadequate.

Ideally, clinical measures of the foot would be based on objective, accurate and valid methods, but in practice the cost and time-consuming nature of objective studies, particularly dynamic studies, have been found to be prohibitive for most clinicians [189]. Until advances in technology provide for a cost-effective and quick objective assessment technique, clinicians will continue to rely on essentially subjective methods for at least the preliminary screening of foot posture in the clinical setting.

There are many types of clinical setting where such a need exists. For example, as well as the pressing need to evaluate progression of disease or success of therapy[189] in neurogenic foot deformities as outlined in the previous section, a wide range of foot types is seen in the otherwise healthy population. There is some weight of evidence linking various foot types with secondary musculoskeletal complaints [145 190-209] but in the absence of objective measures of foot posture, confirming or quantifying such links is impossible.

There is a range of existing measures of foot posture and function, including subjective and pseudo-objective clinical methods, and technology driven, truly objective methods although all have limitations as detailed in the subsequent sections.

## 2.8.1 Subjective measures of lower limb structure and function

### 2.8.1.1 Classification and quantification of gait and standing foot posture

As noted above, early methods of classifying foot type and foot function were usually based on empirical observation such as the presence of the talipes deformities, or specific signs such as the presence of a 'flat' arch or clawed toes. Indeed the subjective observation of dynamic functional events during gait, an important part of any functional assessment, remains much the same to this day [189]. This is true even if the practitioner has access to a well-equipped gait analysis facility for subsequent objective assessment.

Practitioners in the field have long sought to be able to quantify objectively, at least the static foot posture, and the most profound development in this regard was first proposed by Root et al [210 211]. The Root theoretical model was the first pseudo-objective attempt to quantify foot posture and to relate this to models of dynamic function. The model has become widely adopted among practitioners concerned with treating disorders of the foot. In practice, direct measurement of the small anatomical segments of the foot, the underpinning premise of the Root approach, has proved subject to large amounts of error. Unfortunately, a lack of validation of the techniques at the time of introduction led to their widespread adoption before these flaws were recognised. The large errors, coupled with generous clinical interpretations of the supposedly objective results have led to a number of problems with this model, which despite the superficial appearance of objectivity and a scientific base, remains essentially subjective. It has taken some 10 years of consistently critical reliability and validity studies [11 14 15 188 212-215] to convince the clinical professions to lessen their reliance on the pseudo-objective results of this assessment approach.

Many of the difficulties with obtaining accurate clinical measures arise because of the complex structure of the foot. The large numbers of bones and the interdependent nature of many of the joint complexes means that motions often occur about composite and dynamically mobile axes, rather than those of the more readily visualised and constrained joints such as the knee and elbow [216-220].

Kitaoka et al reviewed more than 1000 published papers relating to interventions for foot and ankle pathology, to identify methods used for the grading of the success of such procedures and to determine the applicability of rating scales in reporting clinical results [184 221]. A range of methods was employed, with no consensus as to the applicability, and the authors report that the majority were used with no attempt to determine criterion or content validity. Many measures are reported that are objective or pseudo-objective, but which have little or no relevance to the clinical situation or are invasive, time-consuming or require expensive equipment. Kitaoka identified features considered desirable for a rating system for foot and ankle treatments[184 221]. The key features highlighted by Kitaoka et al are:

- The scale should be reproducible
- It should be comprehensive enough to reflect the complexity of the condition yet simple enough to be user friendly
- It should include subjective and objective clinical factors graded to allow for quantitation
- It should be sensitive enough to detect changes.
- The scale should facilitate statistical analysis.
- It should not be time consuming to use.
- It should not require sophisticated equipment such as a gait laboratory.
- The measures should be taken in a weightbearing posture, as joint responses to input forces are dependent on foot loading [221].

Ideas for solutions to the inherent problems of subjective assessment are many, varied and not all new. Kelly, as early as 1947, had recognised the inadequacy of relying on single measures, and classified the foot using a range of some 32 measures derived from footprints and other indicators obtained with the subject standing, sitting or semi-weightbearing [222]. A multifactorial approach to the static standing assessment of foot type was also proposed by Cook et al, who examined the correlation between three standing measures [223]. In this study the techniques were well described, and the study involved repeated measures on an adequately large sample of 138. However, the reliability analysis was methodologically weak, employing a non-standard protocol which could not support the authors' claim that the results of all three techniques are highly correlated, and that the results are interchangeable.

Dahle et al, in a study of the rating of 77 subjects by three trained clinicians using a criterion based, multifactorial rating schema, found that clinicians were able to classify foot type reliably in the clinical setting [195]. Dahle also made specific mention of the need to define and agree on criteria, and to train the observers. Simple clinical measurement of arch height at a number of sites was found to have high intratester reliability (ICCs 0.87-0.91) and moderately high intertester reliability (ICCs 0.74 –0.79) in a study of 100 subjects undertaken by Saltzman et al [185]. The authors also correlated the clinical measures with comparative radiographic measures. The statistical analysis of this exercise is weak but Pearson's R values are reported for a number of anatomical features. For talar height, which was the only measure in which the radiographic and clinical measures were directly comparable, Pearson's R was 0.81, implying a coefficient of determination of 65% ($R^2$ not reported). This paper would have been more informative had the authors performed a linear regression and reported the results of those calculations. Data have also been reported, in a later study in which various measures of the arch height at 90% of full weightbearing produced intraclass coefficients of intertester reliability of 0.84 and intratester reliability of 0.85 [224].

A wide-ranging, criterion based system for the classification of foot types was proposed by Scherer and Morris, who argue the need for a multifactorial classification system, and presented a comprehensive if complex approach to foot classification [225]. The system of classification is unfortunately presented with no corresponding analysis of its reliability or validity. Given the lack of data supporting its validity and the lack of widespread adoption, the authors overstate their case in their presentation of pathological subgroups, and prediction of the incidence of pathology associated with various classifications. Implementation of the Scherer and Morris system in any form cannot be justified without better data on its reliability and validity.

A number of attempts have been made to produce measurement systems that quantify foot posture in the clinical setting, these are dealt with further in Chapter Four where the background to, and derivation of the new instrument are presented in detail.

### 2.8.2 Objective measures of lower limb structure and function

#### 2.8.2.1 Radiographic measures

Radiographic measures are an initially promising modality as they are widely thought to provide an accurate basis for the quantification of the relationship between bony segments. Radiographic approaches have been widely employed in the evaluation of foot type in the research literature. In the review of the literature undertaken when preparing this chapter, at least 118 papers were found to report the use of radiographic measures to quantify foot posture.

The routine use of radiographic imaging raises ethical issues regarding exposure to ionising radiation, a particular concern for young patients with a progressive deformity. Consequently, while radiography may be used sparingly during the course of progressing foot deformity and in association with particularly aggressive treatment regimens, it is not suitable for routine practice and multiple repeat measures over prolonged periods. Alternative imaging techniques not requiring ionising radiation, such as ultrasound and magnetic resonance imaging are discussed briefly later, but are currently too expensive to be considered a standard clinical assessment.

There are two main areas of methodological concern with plain film radiographic measures of foot posture. The first, magnification associated with source and plate placement [226 227] is usually controlled for. The second significant issue affecting the reliability and validity of radiographic measures relates to identification of the bony morphology. Factors underlying this problem are clear visualisation of bony segments, the effects of parallax and definition of segmental centroids from visible margins [226 228]. Radiographic measures are widely considered among the most reliable of the measures available to the clinician but, because of the problems highlighted above, are still subject to some error [229]. Perry et al reported a parallax effect on the measured length of metatarsal bones of up to 19% and on the measured angles of up to 5°, depending on the position of the foot during exposure of the plate. Cavanagh et al investigated the reliability of 27 radiographic measures and found that between day reliability ranged from ICC=0.44 to 0.98 depending on anatomical site. The orientation of the talus and the navicular and cuboid articulations were among the least reliable measurements (ICC=0.44 to 0.71), but the relationship between large, highly visible bones such as the first and second metatarsal also differed significantly between sessions. Despite conclusions by these authors that the talar inclination angle is not sufficiently reliable for use in evaluations of foot structure, this remains one of the more widely employed measures. Some studies have demonstrated statistically significant and clinically meaningful differences in key radiographic measures, including the talus, in distinct foot types such as pes cavus and pes planus [230]. However, despite some systematic differences in the overall group-means in such studies, significant inter-subject variation precludes the use of many of these measures to define normal or abnormal foot posture, or to define reference values to be applied to individual patients [231]. In Saltzman and El-Ghoury's 1995 study of differences between tibial centre of load to calcaneal contact point in the rearfoot of 57 normal subjects, they found a mean distance of 8mm but a 95%CI for the mean of -7° to +23°. This large between-subject variation is also reported in Vanderwilde's determination of development of radiographic angles in normal children [232], in which eleven radiographic angles were measured, each demonstrating 95%CIs of ± 10° from the mean or greater. In adults, Steel's evaluations further confirm this limitation [231].This between-subject variability highlights the difficulties of making comparisons between individuals from X-ray measures.

A further difficulty with routine X-ray evaluation for objective quantification of foot posture/function is the dependence on the necessary facilities, and the time and expertise required to measure and interpret the results. This is highlighted by an extravagant protocol described by Demp in which a complex method for defining an ellipsoid of best fit is used to define and classify foot types [233]. The complexity of the underpinning calculations and the difficulties associated with imaging all patients appropriately have ensured that the method has not been adopted widely.

As noted previously in this section, alternative modern techniques such as computed tomography and magnetic resonance imaging address many of these deficits and may offer some exciting opportunities in the future [234]. At present however, these techniques are costly, and the axial sections, which are not aligned with the anatomical components of the foot, can be difficult to interpret. Experimental technology can provide highly detailed three-dimensional reconstructions, but these techniques are not yet mainstream [234 235]. One significant current limitation of the techniques is that they can be used currently only to image the non-weightbearing foot and ankle, reducing the validity of the measures [234 229].

One recent study has added a further factor into the equation, as the effects of the Wolfe-Davis law may become relevant in the case of bony measurement following long-standing deformity. Significant morphological differences were demonstrated between the shape of foot bones in individuals with flat feet in comparison to normal controls [236]. It is not clear whether such changes are a cause or a consequence of long term flat footed function but the findings call into question the validity of applying values derived from normal samples in the assessment of flat feet.

#### 2.8.2.2 Laboratory based methods

Since the advent of the microcomputer it has become easier to assess objectively and non-invasively, lower limb dynamic function, although still with limitations. Most systems evaluating dynamic function rely on sophisticated analysis of video film, or tracking of markers using electromagnetic or ultrasonographic techniques [237-242]. While even the gold-standard gait analysis facilities are still subject to larger degrees of measurement error than would be desirable [25 237 243-246], state of the art equipment and methods can now produce acceptable results for joints exhibiting larger ranges of motion such as hips, knees and ankles [237 243 247]. For the smaller, closely inter-related joints of the foot, even state of the art techniques provide less satisfactory objective outputs [243 248]. These issues are discussed later. This introductory review is largely confined to routine clinical techniques, as few clinicians will use instrumented gait analysis as a routine clinical tool, and the aim of this study is to provide a better solution to this specific problem rather than a definitive solution to gait evaluation.

Accurate, objective data detailing dynamic function remains the ideal, but the facilities to produce such objective data are expensive (often in excess of Aus$500,000), and the process of preparing the patients, and then acquiring and analysing the data can be overly time-consuming for routine patient assessment. A more specific review of the relevant gait analysis techniques is presented as appropriate in Chapter Six where the concurrent validity of the new clinical measure is evaluated relative to such a system.

#### 2.8.2.3 Clinical methods

Many techniques have been proposed that are supposed to produce better data than from clinical observation, but without resorting to the expensive and time-consuming methods outlined in the previous section. Without exception these are compromise solutions [6], but they are often more suited to the various demands of the clinical setting, and some have proven popular as screening and preliminary evaluative tools. Also without exception, all have significant limitations [6].

Among the many approaches to objectifying foot posture are those based on inked footprints, or similar methods of preserving an image of the foot in contact with the supporting surface.

Footprints are readily and quickly obtained and, depending on the technique, can often be preserved indefinitely. Many modern techniques use inked foot prints or more sophisticated electronic capture to quantify foot type and estimate function, according to angular relationships of anatomical landmarks, or the calculation of relative area of different parts of the print. These have proved to be relatively reliable [249 250] and can yield useful clinical information with out being unduly time-consuming or requiring expensive equipment. Freychat et al described in detail a method by which such information could be obtained from footprints, and report a relationship between certain transverse plane measures and the associated foot type [250]. They also, however, confine the commentary to this transverse plane relationship between the forefoot and rearfoot and note the incomplete relationship between their transverse plane data and the observed overall foot type. Kouchi and Tsutsumi also explored this relationship in a comparison of transverse plane position of the midtarsal area and three-dimensional foot morphology [251]. In reporting the results of their principal component analysis they state that the single most important variation in human foot shape is the difference between a pronated, flat foot and a normal or arched foot. They report that this feature of flat footedness is correlated with abduction at the midfoot, (similar to Freychat's 'open foot') but they do not quantify the degree of association. Kouchi and Tsutsumi also mention that there are exceptions to the proposed planar associations, noting that some markedly abducted feet maintain a well-developed plantar arch. Subsequent studies by a group including Freychat documented a relationship between the open or closed foot type and leg stiffness when the leg was modelled as a single linear spring, although only 18-22% of the variance in measured leg stiffness was explained by the footprint data [252]. Kernozek also reports a relationship between arch index and the total amount of rearfoot motion occurring during gait [253]. This relationship is incomplete however, and together with the data of Freychat et al, and Kouchi and Tsutsumi implies that while transverse plane motion at the mid foot is an undoubtedly important part of the story, this approach, in common with other measures based on foot prints [14 140 249 254-256], pressure readings [140 257-261] and measures such as the Arch Index [249], fails to take into consideration the many other factors affecting dynamic gait. In a study of the relationship between measures derived from footprints (transverse plane) and directly measured arch height (sagittal plane) this oversimplification was demonstrated by Hawes et al [255]. In multiple footprint measures of 115 subjects it was found that apart from a very general association at the extremes, the footprint parameters were not related to directly measured arch height. Hawes summarised the study with a strongly worded conclusion, "The categorisation of the human foot according to the footprint measures evaluated in this paper represent no more than indices and angles of the plantar surface of the foot itself'. The relationship between two static measures, Arch index and radiographically determined, normalized navicular height was later quantified in a small study, yielding a coefficient of determination of 0.50 [262].

The implication remains however, in common with the findings outlined in the previous paragraphs, that it is probably too simplistic to use observations from only one plane to attempt to give a reliable indication of the overall foot morphology [15 140 263 264]. This is recognised by Cavanagh and Rogers who limit their conclusions regarding the Arch Index (a function of the area of the print in each of the anterior middle and posterior thirds), to its value as a measure of characterizing footprints. Of more concern is the lack of linearity in at least one of the area index measures the Chippaux-Smirak index. In one study including 118 normals aged 15-17 years, both high arched **and** low arched feet demonstrated decreases in the Chippaux-Smirak index in comparison with the mean value from morphologically 'normal' feet [254]. Such a finding calls into question the entire concept of using area measures from footprints as a basis for classifying foot structure. One proposal for foot-type classification based on a footprint index was outlined by Tareco et al [265]. The technique was based on the assumption that the ratio of medial midfoot force to total midfoot force would yield an objective measure of total foot pronation/supination. In this case the new, objective measure was benchmarked against subjective assessment using an undescribed protocol. In practice the technique demonstrated poor sensitivity and misclassified more than 50% of the feet judged clinically to be 'flat'. The coefficient of determination for the prediction of the clinical classification by the footprint index derived measure was 27%, a figure in agreement with much of the data for single plane measures [246 258].

As with radiographic measures, it is important to note the significant between-subject variability in these measures. For one set of angular measures derived from footprints from a normal population of 17 year olds [266], the mean angles of 42.9° to 46.3° were associated with 95%CIs of 23.5° to 65.3°. Area-based measures fare worse still, and the Arch Index yields a 95%CI for the normal range equal to –0.1 to 0.99 for males and 0.13 to 0.93 for females, almost the entire possible range [266], while the Chippaux-Smirak Index yields 95%CIs from –0.02 to 0.60. These broad ranges have also been confirmed in a larger sample [267]. While changes in these measures can provide some indication of group effects in large group studies, individual comparisons must be made with care.

Techniques involving measurement of the angles and positions of anatomical landmarks directly on the foot are probably the most common approaches. Of these techniques, the most common are measurement of the angle relationships of the calcaneus, either relative to the leg or the floor, and measures of arch height.

Measurement of calcaneal angle has been reported widely in the literature. Estimates of the reliability of the techniques vary greatly [268], but the majority of accounts suggest poor reliability [10-14]. Typical figures are provided by Pierrynowski et al when they report data demonstrating that experienced practitioners can place the rearfoot within +/- 3° of the true position on 90% of occasions [269]. While this precision may sound commendable, a range of 6° would encompass error of the order of 50-100% of the total variation encountered in clinical practice. Six repeat measures by the same practitioner bring the error down to an acceptable level but this repeated measures protocol does not reflect the rigour with which the techniques are pursued in clinical practice [10].

The direct measurement of the height of medial arch of the standing foot, has been reported several times and employing a number of different protocols. In its simplest forms this involves direct measurement of either arch height, the height of the navicular tuberosity, or the height of the dorsum of the foot at a specific point. More complex techniques normalise these measures against various interpretations of foot length. Finally, a quasi-functional component is introduced by the use of composite measures such as navicular drop in which the foot is measured in its resting state and again in an artificially induced 'neutral' position, the difference between the two measures providing an estimate of the behaviour of the foot. In theory it is supposed that measurement of arch height is simple in concept and execution, that the measurement should be reliable and that the height of the arch should be a reasonably close indicator of foot function [140].

If the raw height of an anatomical landmark is used however, the value of the measure tends to be limited to repeat measures within individual patients, as inter-subject variation makes between-subject comparisons inappropriate. Composite measures such as navicular drop involve two measures on each individual, one to determine the starting height and a second in a pre-determined reference position such as subtalar joint (STJ) neutral. This approach improves the comparability of the results between subjects but at the expense of decreased reliability, as the repeated measures introduce more potential for error and, as has been discussed in detail above, the establishment of the neutral reference position is itself of questionable validity and reliability. The reliability of double measure techniques such as navicular drop is low for inexperienced practitioners [270], although has been reported to be acceptable in intrarater evaluations of more experienced practitioners [271], yielding an ICC of approximately 0.8 (SEM ~2mm). This figure was in accordance with the subsequent study of Sell et al (ICC 0.83,SEM 1.7mm) [272], who also investigated interrater reliability and found an acceptable level of reliability as evidenced by an ICC of 0.73 (SEM 2.1mm). Intra-rater reliability of raw measures of arch height and navicular height has been found to be acceptably high [14], but again the inter-rater reliability is criticised. In this study the data were collected concurrently with a measurement of valgus index, and it is unfortunate that the relationship between the sagittal plane and frontal plane measures is not reported. The coefficient of determination for navicular drop and composite forefoot /rearfoot position has been described as lying between $R^2= 0.24$ to 0.33 [271], with most of the predictive value derived, as would be expected, from the rearfoot position component. These values are similar to those found by Cavanagh et al outlined previously [258], and suggest that the fundamental limitation associated with measuring motion in only one plane persists over a range of selected paired measures. Early work by Nigg had reported a co-efficient of determination of 0.27, for the explanation of variability in transverse plane shank motion by single plane measurement of arch height [190]. The limitation imposed by single plane measures is supported by the findings of Song et al in their evaluation of two new, experimental methods for assessing foot function. In a discriminant analysis performed by these investigators, inclusion of three measures in the model enhanced the ability of the analysis to classify correctly, planus and rectus foot types in a small sample [273].

Navicular drop is considered by a number of authors to be a more valid indicator of foot function than the traditional rearfoot measurements employed in the Root approach [14 15 272], although it is a single plane measure only and provides an incomplete clinical picture. The reliability of navicular drop has been reported to be acceptable (ICC 0.73 to 0.83) and it is in widespread use[270-272].

The arch angle or the 'Feiss' line is an angle formed by lines drawn from the medial malleolus to the tuberosity of the navicular to the head of the first metatarsal [143 268 274 275]. The arch angle is simply a variation of the other measures of navicular height, with the navicular tuberosity acting in this case as the origin of the angle between proximal and distal landmarks. The angle thus changes as the navicular tuberosity moves either dorsally or plantarward with change in foot posture. The measurement of the arch angle has been reported to be adequately reliable [268], although is not in widespread use. In a novel variation described by Nigg et al, a measure of the rigidity of the arch was also introduced with the proposition of a 'Relative Arch

Deformation' (RAD) statistic, which factors in the degree of change between loaded and unloaded arch height, normalised to body weight [276]. There is a suggestion that stiff arches tend to show higher coupling with leg rotations, with lower arched feet showing less coupling with leg rotations. This degree of coupling is widely recognised clinically, although it remains controversial [14 18 220 221 277-279]. There is possibly some merit in including this factor in assessing foot posture and function, although the formula needs validation and the relative complexity of the approach has precluded its wide uptake.

One other factor that has been widely proposed to affect the degree of coupling between the foot and the leg, is the orientation of the axis of rotation of the subtalar joint [220 230 280 281]. The behaviour of this axis has been demonstrated to be extremely complex in dynamic studies, and a number of in vitro studies have shown substantial variation in axial orientation between specimens [217 218 282 283]. Only one study has demonstrated the axes of rotation in vivo, using permanently implanted Tantalum markers in each of the tarsal bones in healthy volunteers [280], such invasive methods are clearly not applicable to clinical practice. A method for ascertaining the STJ axis of rotation was proposed by Morris and Jones and 1994. The method is highly subjective and unfortunately, the authors report no reliability analysis on the 18 subjects they used to illustrate the application of the technique. The findings of Morris and Jones differ somewhat from the pre-existing data and from their own radiographic benchmarks [279], themselves of doubtful methodological validity. While they attempt to explain the differences theoretically, given the current level of evidence, the technique must be considered of doubtful value. The inclusion of an estimate of rearfoot joint axis is clinically appealing and has been advocated for clinical studies [284], however the reliability of such techniques is questionable.

In addition to the inherent variability in orientation of the axes of rotation, consideration must also be given to the complexity of function associated with reciprocity in many of the coupled systems. The ratio of input to output motion will vary for the rearfoot and midfoot under closed chain conditions, depending on whether the input force is applied to the distal or the proximal part of the couple [285 286]. No attempt has yet been made to factor complex coupling into clinical measurements.

### *SUMMARY*

In this review the background to CMT has been discussed and the implications for the foot developed. The existing measures of measurement of foot posture have been reviewed, and the need for a new instrument for assessing changes in foot structure and function has been demonstrated. Clinical measures are needed to supplement costly and time-consuming laboratory methods as these technology-driven solutions are often impractical in the clinical setting. It has been shown that existing clinical measures are either subjective or largely unreliable, and with few exceptions, the existing clinical measures fail to evaluate the foot in multiple planes, therefore providing an incomplete picture of general foot posture.

As a result of these shortcomings, definitions of foot pathology are weak and often controversial, and evaluations of treatments for the foot remain inadequate. In conditions such as CMT, where foot posture and function may change as the disease progresses, or may be modified by management of the condition, the need for accurate yet easily applied assessment methods is great, yet none of the conventional approaches allow the clinician to quantify the foot posture reliably in the clinical setting.

One consequence of this lack of adequate foot measurement tools is that treatments aimed at addressing foot pathology in the neuromuscular diseases are poorly evaluated, leading to approaches based on 'custom and practice', and which are heavily dependent on the personal experience of the clinician. In the current environment of evidence-based-medicine this is clearly inappropriate. More data are needed in order to establish the relative efficacy of the various surgical approaches, and whether conservative interventions such as stretching, splinting and orthoses have a role in managing the longer-term effects of CMT on the lower limb.

In order to study the foot in CMT, a validated system for quantifying the natural history and response to treatment appears to be an essential pre-requisite.

# *CHAPTER THREE – A SURVEY OF THE MANIFESTATIONS OF CMT AND ITS EFFECTS ON THE LOWER LIMB.*

---

***Chapter overview***

*The secondary features of CMT are widely recognised by neurologists, but good data are scarce. As part of the program of work described in this thesis it was considered appropriate to obtain better data on the impact of CMT on sufferers, with particular emphasis on the effects of CMT on the lower limbs.*

*Due to the relatively low prevalence of CMT in the population and the variety of secondary presentations, it has proved difficult historically, to assemble samples of CMT patients sufficient to collate epidemiological data in face-to-face situations. The CMT Association of Australia (CMTAA) had attempted previously to survey members but had done so without expert assistance, and the results had been unsatisfactory. As part of the candidate's activities with the CMT Association of Australia (CMTAA), a collaborative survey was designed, the Australian Charcot-Marie-Tooth Health Survey 2001. The data reported in this chapter are derived from this collaboration, conducted under the academic and research direction of the candidate.*

*The full Australian Charcot-Marie-Tooth Health Survey, 2001 covers a wide range of clinical features, not just those occurring in the lower limb, and the final report for the full survey runs to more than 150 pages of single space type. Including such a wide-ranging report in full would be inappropriate to the specific aims of the thesis, so only those aims, methods, results and discussion specifically relevant to the effect of CMT on the lower limbs are detailed this chapter.*

*For the interested reader, copies of "The Australian Charcot-Marie-Tooth Health Survey 2001. Results and Final Report" are lodged with a number of CMT organizations including the CMTAA, the CMT Association of the US, and the Peripheral Nerve Society.*

---

## *3.1.* *AIMS*

The aims of the study detailed in this chapter were (with an emphasis on the lower limb):

1. To evaluate the impact of CMT on patients' quality of life.
2. To attempt to provide better information on the range of secondary features reported anecdotally in the literature
3. To estimate the prevalence of the key features of CMT.
4. To identify patient perceptions of the non-surgical treatments currently used in the management of the secondary features of CMT.
5. To identify factors that might be useful as prognostic markers for the course of the disease and relevant interventions.

## *3.2.* *INTRODUCTION*

A number of approaches to the survey were evaluated, including face-to-face interviews, clinician led assessment, and telephone interviews. A repeat of a postal survey was ultimately considered the best option because of the low prevalence of CMT, combined with the geographical spread of patients around the country. The limitations associated with this mode of data acquisition will be considered in interpreting the data. Most significant among these are recall bias, and potential for patient confusion over terminology and therapeutic approaches. It was decided however, that the overall benefits of increasing sample size outweighed the weaknesses of the postal survey approach, but the limitations of a patient completed postal survey must still be considered.

The requirements of the CMTAA executive were initially, to collate simple descriptive information about the secondary effects of CMT and to investigate treatment approaches commonly employed in the CMT community. The CMTAA executive, as a lay group without research expertise, wished initially to design a simple form and to mail it without validation. The candidate's involvement however was the basis for a more rigorous approach.

A first priority was to attempt to source a previously validated tool for the survey. A thorough search of the literature revealed no such tool validated for use in patients with CMT. It was decided instead to employ one of established generic measures of health related quality of life (HRQoL). This would provide information directly useful to the CMT community, but importantly, would also allow for comparison of the impact of CMT on HRQoL with other disorders.

Criteria were identified to determine the most suitable measure, these were:

- Evidence of validation in the general population.
- Validation in a sample with CMT or a similar degenerative neurological disorder.
- Availability of age and gender matched normative values for the Australian population.
- Availability of data for a broad enough range of chronic disorders to enable comparison of the effects of CMT on HRQoL.
- Sensitivity to a range of aspects of HRQoL beyond pain. In particular, the measure used had to be sensitive to the potential effect of CMT on physical function.

Many instruments were potentially suitable. After an initial review, four candidate HRQoL instruments were considered in more detail. The Medical Outcomes Survey, Short Form 36 item version, the SF-36 [287], The EuroQol Group's EQ-5D, The Sickness Impact Profile (SIP) [288], and the Stanford Health Assessment Questionnaire (HAQ) [289].

## The Medical Outcomes Survey, Short Form 36 item version, the SF-36[287].

The MOS SF-36 was developed in 1988 by the RAND corporation from a larger survey of the health of the population in the United States. It is intended to yield a scoring profile, highlighting various aspects of physical and mental status, and quantifying the burden of disease and the effect of treatments [287].

The SF-36 consists of 36 individual questions (items) aggregated into eight dimensions:

1. *Physical function* – the extent to which a person is limited by their health in performing a range of physical activities
2. *Impact of physical health on role performance* – the extent to which physical health affects work or other daily activities
3. *Bodily pain* – severity of pain experienced and the impact on activities
4. *General health* – health status combined with perceptions of health relative to others.
5. *Social functioning* – the effect of health or emotional problems on the quality and quantity of social interactions
6. *Vitality* – perceived levels of energy or fatigue
7. *Impact of emotional health on role performance* – effects of emotional problems on work or other daily activities
8. *General mental health* – the extent of feelings of anxiety, depression or happiness

The eight scores are each expressed on a scale of 0-100 where a higher score equates with greater well-being. The eight dimensions can also be further aggregated into a physical and mental health component summary score (PCS and MCS).

The validity of the SF-36 has been evaluated in a wide range of populations including the USA, UK, and specifically in Australia [290 291]. In 1998 the Australian Bureau of Statistics (ABS) published a large survey of 18,800 people in the 1995 Australian population providing a set of population norms [292]. The SF-36 is validated for postal surveys and self-completion [293 294].

## The EuroQol Group's EQ-5D

The EuroQol group developed a six-point instrument in 1990, modified to the current five-point instrument (EQ-5D) in 1991. The EQ-5D is a self-completion instrument employing five descriptive questions answered by trichotomous closed responses. The EQ-5D yields a single quotient score, which makes it attractive for economic studies. The EQ-5D has been validated in a number of clinical populations [295]. Normative data are available for the United Kingdom [296] and New Zealand populations [297] but not for the Australian population. Euroqol is reported to be outperformed on overall performance profile by SF-36 [298 299].

## The Sickness Impact Profile (SIP)

First described in 1976 [288], the SIP has been widely used as an outcome of general health status and since the survey reported in this chapter was conducted, has been used as a secondary measure in a study of CMT patients [114]. The 136 items in the SIP are grouped into 12 categories describing different functional behaviours. The SIP has been validated comprehensively, and is suitable for use as a self administered instrument [300]. No Australian study or ABS population norms exist for the SIP. The SIP has been thoroughly validated but in comparative studies the SF-36 has been recommended over the SIP [301 302].

## The Stanford Health Assessment Questionnaire (HAQ)

The HAQ, first described in 1980 is primarily intended for use in patients with arthritis [289]. The HAQ focuses on five dimensions and is generally considered to emphasise the upper limbs function over the lower limbs. The HAQ has been validated for self administration and it remains widely used in the arthritis community [303 304].

Ultimately the Australian version of the SF-36 was determined to be the best option for this survey. It is widely used and has been extensively validated, both by the original authors and subsequently by independent researchers. It has also been specifically compared to a range of other measures of HRQoL including the SIP and Euroquol EQ-5D, and deemed to be superior [299 301 302]. It has not been validated specifically in CMT or in any similar chronic neurodegenerative disease, but has been widely employed in a range of disorders. A comprehensive table of normative data exists for the Australian population. The SF-36 also met the requirement of yielding data on the functional impact of disease, as well as allowing the exploration of the psychological effects of life with CMT.

One criticism of generic measures of HRQoL is that they are often less sensitive than would be desirable, to the specific effects of a disease process. It is good practice therefore, to supplement the use of a generic HRQoL measure with a more specific secondary measure [305]. In the case of this study the effects of CMT on the legs and feet was of concern, and an appropriate foot related HRQoL measure was sought.

Since 1991 the most commonly used foot specific measure of HRQoL has been the Foot Function Index, originally developed for use with patients with rheumatoid arthritis. The FFI does however have some recognised shortcomings and is intended to be specific to Rheumatoid Arthritis. More recently, a number of new measures have been developed.

## The Foot Function Index (FFI)

The FFI, published in 1991, was developed as an outcome measure for patients with foot pathology and foot pain [306]. The authors carried out the initial validation of the instrument in patients with rheumatoid arthritis, and because of the specific nature of the items included in the FFI it has proved difficult to justify its use in other patient groups.

The FFI comprises 20 items which aggregate into 3 subscales : pain, disability and activity limitation. The FFI is validated for self-administration and each item is completed by the respondent indicating their perceived response to a question on a 100mm visual analogue scale. The scales are anchored at each end with a verbal statement representing the opposite extremes of the dimension being measured. Scores are derived by dividing the scale line into 10 equal segments and assigning a score between 0 and 9 to each response. The aggregate subscale scores lie between 1 and 100, based on dividing the actual score by the maximum possible score the subscale [306]. As the first foot specific HRQoL measure to be developed, the FFI is in widespread use [307] despite some concerns over its validity in patients without rheumatoid arthritis [308]. The most common persisting use of the FFI outside of the rheumatoid arthritic population is the use of the pain subscale in isolation.

## American Orthopedic Foot and Ankle Society (AOFAS) foot and ankle rating scales

The AOFAS scales were developed in 1994 to better evaluate the outcome of orthopaedic surgery to the foot and ankle [263]. The AOFAS scales are in widespread use in orthopaedics, and the inception of the AOFAS initially appeared to be one of the more promising developments in the evaluation of foot therapies. There are four scales, one each for the ankle-hindfoot, midfoot, hallux and lesser toes.

The AOFAS have presented no validation of the foot and ankle scales however, and one recent report has been highly critical, suggesting that the scoring of the four scales is susceptible to 'bizarre, skewed behaviour' and recommending that refinements of the scales should be sought [309]. The AOFAS scales are completed by the clinician in consultation with the patient, and include a mix of subjective, patient related variables, combined with physician assessment of features and outcome. Hence they are not true HRQoL measures.

## Foot Health Status Questionnaire (FHSQ)

The FHSQ was developed in Australia by Bennett et al and is a foot-specific measure intended to assess change in HRQoL associated with surgical and conservative interventions [27]. The FHSQ has been subjected to a fairly comprehensive validation process and has already been used in patients with a range of conditions, generating a normative data set for this measure in the general Australian population [310].

The FHSQ scores HRQoL in four general health domains derived from the generic HRQoL measure, the Medical Outcomes Survey, Short Form-36 (SF-36), and in four foot-specific domains: foot pain, foot function, footwear and general foot health. The FHSQ is scored such that such that each of the domains yields a value between 0 and 100, with a high score representing good foot health and a low score, poor foot health. The FHSQ has been directly compared to the FFI in one comparative study and was found to be more sensitive to change [308].

## The Manchester Foot Pain and Disability Questionnaire (MFPDQ)

The most recent addition to the stable of foot specific HRQoL measures, the MFPDQ shows some promise in the evaluation of foot related health status. It comprises 19 short statements with trichotomous responses. It has been subjected by its authors to a validation process and is suitable for self- administration [311]. There have been no direct comparisons between the MFPDQ and any other foot specific HRQoL measures, and as yet, there are no normative data against which to make comparisons.

The foot specific HRQoL measure chosen for inclusion in the Australian Charcot-Marie-Tooth Health Survey, 2001 was Bennett's FHSQ. This choice was based on the FHSQ best fitting the defined criteria i.e. evidence of validation, and the existence of Australian norms, coupled with its similarity to, and compatibility with the SF-36.

Having decided to include the SF-36 and FHSQ measures, the collection of descriptive data on CMT was considered. It was not deemed appropriate at this stage to design and validate a specific HRQoL measure for CMT, as there was no imperative to quantify change in HRQoL specific to CMT. A purely descriptive question-set was designed for this section of the survey.

## *3.3. METHODS*

### 3.3.1 Survey construction

The first stage was to make a preliminary identification of the common areas of secondary presentation occurring in CMT. This was achieved by combining a rigorous review of the literature (outlined in Chapter 2) with consultation with the CMT community, and health practitioners involved in CMT care. The consultation process was initially based on verbal interviews with representative health disciplines including two neurologists, two physiotherapists, one occupational therapist and three podiatrists, and an open consultation session at a CMTAA meeting.

The interviews with health care practitioners were simple and based on two open questions. Respondents were asked:

> *What secondary features of CMT are you aware of?*
>
> and
>
> *What treatments for the secondary features of CMT in the lower limb are you aware of?*

The respondents were also asked to indicate any other areas they would wish to see included in the survey. The questions formed the basis for an open dialogue with the responses recorded by the author. From the combination of literature review and initial interviews, 13 areas were identified as having sufficient relevance to warrant further consideration (Table 3.3)

**Table 3.3. Areas of interest identified during initial interviews.**

| | |
|---|---|
| 1. Demographic variables | 2. Family history – heritability |
| 3. Diagnosis | 4. Pregnancy |
| 5. Physical changes – Back | 6. Physical changes – Arms/hands |
| 7. Physical changes – Legs/feet | 8. Sensory changes |
| 9. Assistive aids and devices | 10. Footwear |
| 11. Balance | 12. Treatment – conservative |
| 13. Treatment- surgical | |

These were incorporated into a preliminary draft of the survey. Where possible the questions were designed to elicit closed responses, and where appropriate any closed response was combined with an option for a further open response to provide more detail. All questions relating to patients' perceptions and their rating of experience were based on the well recognised five-point Likert type scale [312-319]. As far as possible the scales were consistently ordered with no change, or the minimal change in perception acting as the left anchor, and the maximal change acting as the right anchor. Each of the five response options was labelled in each question for clarity.

### 3.3.2 Pilot study

The draft survey was piloted by the CMTAA at a local meeting. Pilot participants were asked to identify any problems with the survey, and to nominate areas of concern not covered by the draft survey forms.

Three further areas of interest were identified as a result of the pilot process

14. Genito-urinary manifestations
15. 'Restless legs'
16. Alternative therapies

A number of minor amendments were also made to the survey forms resulting in the final form detailed in Appendix D

The Australian Charcot-Marie-Tooth Health Survey, 2001 was a wide ranging survey that explored all the areas outlined in

Table 3.4. Only those items in bold typeface are reported in this chapter. For the results relating to the other features the reader is directed to the Australian Charcot-Marie-Tooth Health Survey, 2001 - Results and Final Report.

**Table 3.4. Areas explored in the full survey**

| *AREAS INCLUDED IN THE SURVEY* | *COMMENTS ON REASONS FOR INCLUSION AND TYPE OF DATA REQUIRED* |
|---|---|
| **Gender** | ***Identification of gender specific variation in presentation and impact was considered valuable. Gender based differences have been noted in other health measures such as the SF-36.*** |
| **Marital status** | ***Included to investigate the effect of presence of a partner or significant other on local support mechanisms. The classifications used were those used by the Australian Bureau of Statistics.*** |
| **Age at last birthday** | ***Age related variations in health status are widely reported, and it was desirable to stratify analyses by age. It is also appropriate to treat some juvenile data differently to the adult data.*** |
| **Age at diagnosis/ Age at onset of symptoms** | ***An indicator of the duration of disease was desirable although problems with recall are a concern. The two can be combined into a broad indication of the gap between onset of symptoms and diagnosis.*** |
| Initial diagnosis | *Many CMT patients complain that lack of medical awareness leads to delayed diagnosis and misdiagnosis at initial presentation.* |
| **Type of CMT** | ***To obtain some indication of the proportion of CMT population affected by the various types of CMT. The potential problems with relying on patient recall /understanding were considered but it was considered necessary to attempt to differentiate CMT types. In the absence of physician confirmation, these responses are to be interpreted with caution.*** |
| Family history | *A series of questions was formulated concerning the inheritance of CMT.* |
| Pregnancy | *It has been reported previously that some women experience a worsening of their neuropathy during pregnancy.* |
| Scoliosis | *The prevalence of scoliosis reported in the literature is variable and dependent on the diagnostic criteria used. Obtaining the patients' own perspective was considered worthwhile.* |
| **Changes in** arms/hands/ **legs/feet** | ***A number of peripheral changes are reported by patients with CMT. These include weakness, muscle wasting, tremor, hyper-sensitivity to cold and changes in foot structure.*** |
| **Sensation** | ***The subsections evaluated under the heading of sections included cranial nerve functions (vision and hearing) which are usually only minimally affected, and peripheral sensation.*** |
| Bladder and sexual function | *Genito-urinary dysfunction supposedly affects only a small proportion of CMT sufferers but is highly significant to those affected.* |
| **Loss of protective sensation** | ***This leads to increased risk of injury or slowed reaction to pain. The loss of sensory perception associated with CMT is usually small, but when severe can be significant.*** |
| **Positive neuraesthesia** | ***Anecdotal reports of shooting or tingling sensations in the limbs are common but unquantified.*** |
| **'Restless legs'** | ***Reported by a small number of CMT patients in the clinical setting. This is not disabling but is a noted feature.*** |
| **Aids and devices** | ***The requirements for these is varied, but dependency on aids is of great concern to CMT patients. In particular, information regarding the proportion of CMT sufferers becoming wheelchair bound was a priority.*** |

| | |
|---|---|
| **Footwear solutions** | ***The impact of CMT on finding suitable footwear is covered in the FHSQ and was not therefore duplicated in the descriptive survey. However, the CMTAA requested an option for people with CMT who had identified solutions for their footwear problems, to share their information. A box was provided which was not for inclusion in the statistical analysis.*** |
| *Balance* | Patients report a range of balance problems and coping strategies. |
| **Conservative treatments** | ***Many conservative treatment options are employed in people with CMT, including stretching/strengthening regimes, day splints, night splints, shoe orthoses and plaster casts. Respondents related their experiences with these approaches and provided information about their perceptions of the relative merits of the approaches.*** |
| Alternative therapies | *In the absence of a cure for CMT and an arguably ad hoc approach to the medical management of many of the sequelae, many patients with CMT have tried alternative therapies in attempt to palliate symptoms. We know little of these self-help habits nor their efficacy, and it was considered a valuable section to add.* |
| Surgical therapies | *A valuable but problematic area to survey. Patients are often ill-informed about the type of surgeries they may have undergone, and there is great potential for confusion over terminology. Furthermore surgical techniques vary by surgeon, and changes in techniques over time preclude provision of a comprehensive list for closed responses. Classes of surgeries were presented therefore, and patients were requested to report their experience with the various classes of surgery.* |

### 3.3.3 Survey delivery

Eight months prior to the commencement of the survey, to maximise participation, a publicity campaign was started by the CMTAA. This included a personal letter from the CMTAA president, and multiple publicity pieces in association newsletters. The survey was delivered by post to all members of the CMTAA in August 2001, together with a detailed cover letter explaining again the purpose of the survey and encouraging participation.

The CMTAA mailing list database contained contact information for 375 members including 57 members who are health professionals, or non-CMT sufferers with a secondary interest. The active sample was therefore 318 members who each received by mail, a copy of the form, with a deadline for completion and return eight weeks later.

Survey forms were anonymised so that members could provide full feedback without fear of repercussion. There had been some concern noted at the initial survey development meetings, that patients' long-term relationships with the medical staff involved in their care would be problematic unless responses were completely anonymised. Follow-up to the initial mail-out was therefore aimed at the CMT community at large (newsletter, local state events and at the CMTAA Annual General Meeting), rather than by direct contact.

The CMTAA contact details were documented on the survey and the covering letter, and members were encouraged to contact the CMTAA for clarification or assistance if help was needed to complete the survey forms. Respondents too young to complete the form themselves were permitted to do so with the help of parent/guardian.

During the period immediately after the mail-out, the CMTAA offices and telephone lines were continuously manned during office hours on Monday, Wednesday and Friday. Individual contacts were not itemised but office staff indicated that some 10-15 people contacted the offices for such assistance. After one extension to the initially advertised return deadline, the response set was finalised five months after the mail out.

### 3.3.4 Data management

On arrival in the office the responses were codified, and data were entered into one of two systems by CMTAA office staff. Part A (CMT responses) and B (SF-36 responses) were entered into a bespoke database authored in Microsoft Access. Missing data for the SF-36 were treated according to the SF-36 authors' protocols, with imputation of items if fewer than 50% of items in a domain were missing, or omission of the case's SF-36 score if more than this were missing. Part C (the FHSQ) was entered into the proprietary FHSQ software, and scoring was undertaken within this software.

Data for Parts A and B were exported from the database into SPSS v11.1 for full analysis. SF-36 data were exported into a pre-defined template, and processed according to an SPSS script developed at the Clinical Health Outcomes Centre, Department of Health and Community Care, Canberra, ACT (used courtesy of Dr B. Shadbolt) and validated against the MOS standardised data set.

### 3.3.5 Strategy for data analysis

All data are first presented descriptively, along with exploratory analyses where appropriate, to identify factors potentially influencing the various variables. Where a predictive relationship may exist, the data are modelled using an appropriate regression technique. The data for the health related quality of life measures are presented in two discrete sections. The data are represented descriptively in the first section and at the end of the chapter, a series of regression models are constructed in which the interactions between factors that might predict quality of life in patients with CMT, are brought together to provide some indication of the real impact on the lives of CMT sufferers.

## *3.4. RESULTS*

A total of 330 people with CMT were mailed survey forms, the sample comprised of the 318 people on the CMTAA database and a further 12 who requested copies of forms after hearing of the survey from relatives or from the CMT press. 324 completed surveys were received, an empirical response rate of 98.2%. This is exaggerated however, because 74 responses were received as multiple returns coordinated by CMTAA members representing a family or group (250 single returns, 25 x double returns and eight triple returns). Thus the response rate adjusted for multiple respondents per CMTAA member was 85.8%.

Prior to analysis, the data were subjected to a rigorous error checking protocol, including re-entry of a random sub-sample of data, checking for mutually exclusive responses (such as male gender and pregnancy). In total, 3240 items were subject to checking and four errors were detected (0.12%). There was no evidence of systematic error or mismatch of cases in data entry.

### 3.4.1 Respondent demographics

The sample consisted of 132 males (40.7%) and 192 females (59.3%). 85 (26%) had never married, 198 (61.1%) were currently married or living in a de facto relationship, 27 (8.3%) separated or divorced and currently single, and 14(4.3%) reported their marital status as widowed.

The mean reported age of the sample (N=320) was 46.2 years (46.2 years for males and 46.7 for females), with a range of 2 to 87 years.

There were 18 (5.6%) respondents aged less than 16 years, and 61 (16.9%) aged 65 years or older.

As might be expected, the technical definitions required for the classification of CMT types led to some difficulties for patients, and the type of CMT was not well reported. 145 (44.9%) were not sure of their CMT type, 106 (32.8%) reported CMT1A, 6 (1.9%) CMT1-other demyelinating form, 23 (7.1%) CMT2 axonal form, 5 (1.5%) CMT 3 (Dejerine-Sottas Disease), 27 (8.3%) CMT X linked, and 11 (3.4%) 'other' forms. Despite confusion over their precise disease classification, 222 (68.5%) of respondents reported having had genetic testing to check the diagnosis, with genetic confirmation of peripheral neuropathy in 178 (54.9%). A binary logistic regression model indicated that younger people were more likely to have had genetic testing (OR=0.982 (95%CI 0.970 to 0.995), P=0.007).

### 3.4.2 Indicators of health related quality of life in the sample (Questionnaire parts B and C.)

**(The MOS Short-form 36 (SF-36), and Foot Health Status Questionnaire (FHSQ))**

Both the MOS SF-36 and FHSQ have been validated in adult populations, but the validity of these measures in paediatric populations is unclear. The SF-36 and FHSQ data presented in this analysis are based therefore, only on the responses of those returns from adults, i.e., only those over the age of 18 years (N=302). The mean age of this group was 48.66 years, with a gender distribution of 127 (42.1%) male and 175 (57.9%) female.

The overall SF-36 and FHSQ data will be supplemented where possible in this analysis, by age and gender matched normative data. The SF-36 normative data are derived from the 1995 ABS Australian Population Norms [292] and the FHSQ norms are derived from data published by the original author [27 310].

The CMT sample demonstrated a slightly different age and gender profile to the normal population. The overall scores for the CMT population are thus presented for the CMT sample overall, and for the sample, age-adjusted to the Australian normal population using the direct standardisation formula recommended by the ABS [292].

$$\frac{\underline{\Sigma_i \text{ mi x pi}}}{\text{P}}$$

*Where mi = the unstandardised mean score for each age strata, pi = the population count for the standard population in each age strata, and P = the total standard population.*

The significance of any differences between age standardised scores for the CMT sample and the normal population are tested using one-sample T-Tests with the relevant population normal value as the test value.

### 3.4.2.1 Overall effect of CMT on SF-36 and FHSQ scores

**Table 3.5. Age-standardised SF-36 scores for the CMT sample and comparative Australian norms (Scored 0-100 in each dimension, where 100 = perfect health)**

| Sample (N) | Physical function | Role physical | Bodily pain | General health | Vitality | Social function | Emotional role | Mental health |
|---|---|---|---|---|---|---|---|---|
| **Age standardised Australian norms** | 82.5 | 79.8 | 76.8 | 71.6 | 64.5 | 84.9 | 82.3 | 75.9 |
| **Age standardised CMT sample (N=295)** | 57.35 | 65.24 | 65.38 | 61.91 | 51.09 | 77.02 | 76.83 | 72.20 |
| **Gender** | | | | | | | | |
| **Male (N=124)** | 55.04 | 59.07 | 65.72 | 60.9 | 51.98 | 76.31 | 75.54 | 72.83 |
| **Female (N=171)** | 55.4 | 63.3 | 65.67 | 63.01 | 50.32 | 77.92 | 78.17 | 73.14 |

Significance of differences between the CMT sample and norms.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mean diff (95%CI)** | -27.4 (-30.7 to-24.2) | -18.4 (-23.1 to –13.7) | -11.4 (-14.3 to –8.6) | -9.7 (-1.4 to – 7.0) | -13.7 (-16.2 to –11.2) | -7.6 (-10.5 to –4.7) | -6.3 (-10.5 to -2.1) | -3.3 (-5.3 to – 1.2) |
| **Significance** | P<0.001 | P<0.001 | P<0.001 | P<0.001 | P<0.001 | P<0.001 | P=0.003 | P=0.002 |

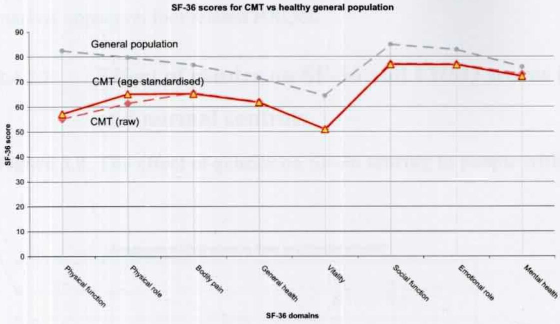
**Table 3.6. Foot Health Status Questionnaire Scores for the CMT sample and comparative Australian norms (Scored 0-100 in each dimension, where 100 =perfect health)**

| Sample (N) | Foot pain | Foot function | Shoe | General foot health |
|---|---|---|---|---|
| **Australian norms** | 85.0 | 89.0 | 40.0 | 62.0 |
| **Age standardised CMT sample (N=291)** | 68.69 | 58.01 | 24.73 | 38.88 |
| **Gender** | | | | |
| **Male (N=124)** | 69.65 | 54.73 | 32.99 | 32.80 |
| **Female (N=171)** | 69.69 | 54.0 | 19.94 | 36.74 |

Significance of differences between the CMT sample and norms.

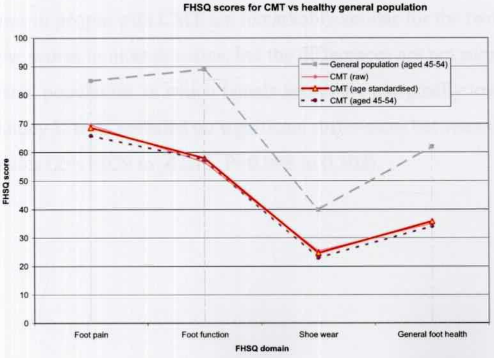
| | | | | |
|---|---|---|---|---|
| **Mean diff (95%CI)** | -15.0 (-17.9 to -12.1) | -32.1 (-35.5 to –28.7) | -14.3 (-17.3 to –11.4) | -26.5 (-29.7 to –23.4) |
| **Significance** | P<0.001 | P<0.001 | P<0.001 | P<0.001 |

**Figure 3.6. Comparison of SF-36 scores in CMT with the general Australian population (ABS 1995).**



People with CMT demonstrate significantly lower SF-36 scores than the general population in all SF-36 domains. The disparity between people with CMT and the normal population is greater for the physical domains than for the mental health domains. The effect of age standardisation is more apparent in the physical domains as the slightly increased age in the CMT sample further deflates the physical domain scores.

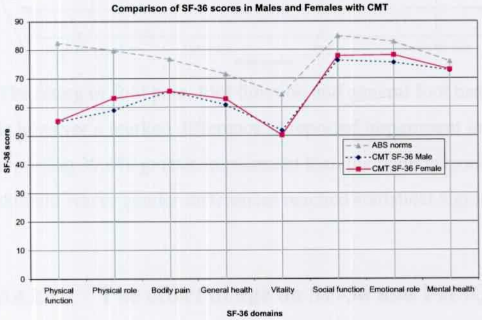
**Figure 3.7. Comparison of FHSQ scores in CMT with the general Australian population**



There is a highly significant difference between the FHSQ scores of the CMT sample compared to the normal population in all domains. In proportional terms, the differences range from 19.1% for foot pain, to 38.2% for shoe wear. The data suggest that CMT has a marked impact on foot related HRQoL

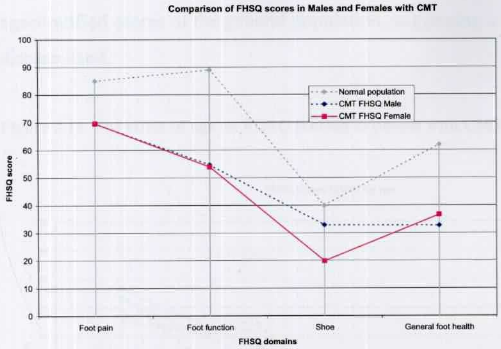
#### 3.4.2.2 Effect of gender on SF-36 and FHSQ scores in people with CMT and normal controls

**Figure 3.8. The effect of gender on SF-36 scoring in people with CMT.**



Gender related differences in SF-36 scores have been reported previously, with a trend toward marginally higher scores in males in the general population. The gender profiles for SF-36 scores in people with CMT are remarkably similar for the two genders. Males report slightly lower scores in most domains, but the differences are not substantial. This contrasts with the general population, in which female scores are marginally lower. In the CMT sample Mann-Whitney U tests revealed no significant differences between the responses of males and females (Z=-1.029 to -0.015, P=0.998 to 0.303).

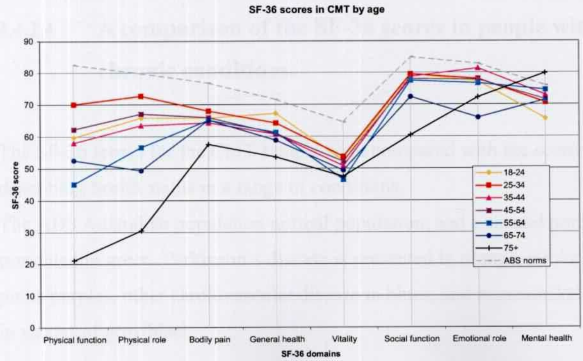
**Figure 3.9. The effect of gender on FHSQ scoring in people with CMT.**



The rating of foot pain, foot function and general foot health is similar for both genders. There is however a marked difference in reported impairment in the footwear domain, with females reporting 39.6% greater impairment than the male respondents. Footwear was the only FHSQ domain where gender differences reached statistical significance (Z=-4.56, P<0.001).

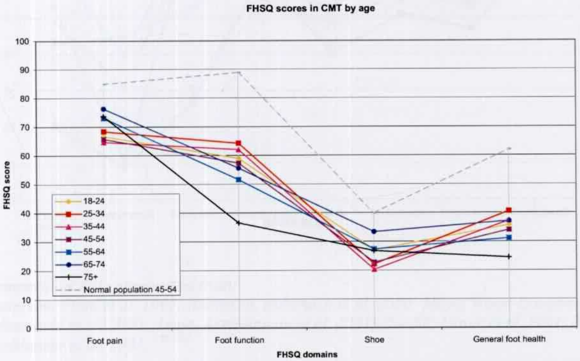
### 3.4.2.3 The effect of age on SF-36 and FHSQ scores in people with CMT and normal controls

**Figure 3.10. The effect of age on SF-36 scoring in people with CMT**



Age has a significant impact on SF-36 scores, with substantial lowering of scores in older patients. The trend in the CMT sample is less consistent than the trend for the general population suggesting some confounding effect according to disease severity or other CMT specific factors. The data for the younger six strata are more compressed than the comparable age stratified scores of the general population, suggesting a floor effect imposed by the disease itself.

**Figure 3.11. The effect of age on FHSQ scoring in people with CMT**



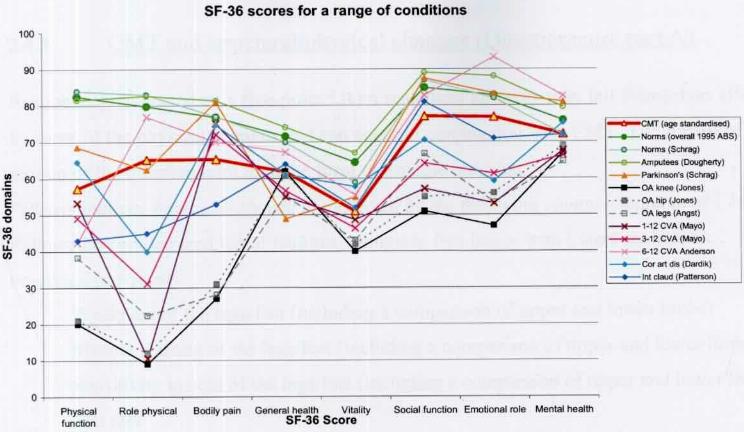
The age related trends in three of the FHSQ domains are small and generally are in line with expectations, indicating worse foot health with increasing age. It is interesting to note however, that respondents in the age ranges 25-45 report the worst impairment with footwear.

### 3.4.2.4 A comparison of the SF-36 scores in people with CMT and other chronic conditions.

The SF-36 scores for the CMT sample were compared with the scores from published studies describing health status in a range of conditions.

The ABS Australian population normal population, and a second normative group are presented in green. Parkinson's disease is presented in orange, stroke is presented in pinks/purples, other cardiovascular disease in blues, and musculoskeletal disease is presented in shades of grey/black.

**Figure 3.12. Comparison of SF-36 scores in the CMT sample with a range of chronic conditions**



*Comparative data are derived from:*
*Patterson, Pinto et al. 1997; Anderson, Rubenach et al. 2000; Mayo, Wood-Dauphinee et al. 2000; Schrag, Jahanshahi et al. 2000; Angst, Aeschlimann et al. 2001; Dardik, Minor et al. 2001; Dougherty 2001; Jones, Voaklander et al. 2001.* [320-327].

Overall, the CMT SF-36 scores lie in the middle of the range of scores for the conditions being compared. Parkinson's disease and CMT scores are similar for the two physical function domains although CMT patients report more pain and less impairment to their general health. The mental health component scores are lower in CMT than Parkinson's disease.

CMT patients appear to have better health than patients affected by osteoarthritis in the lower limbs. The CMT scores are higher than the scores for patients in the initial three months post-stroke, but the improvement in the stoke patients more than 6 months post CVA results in a set of scores broadly similar to the CMT patients, a feature noted in an unrelated study published after these data were collated [114].

### 3.4.3 CMT and structural/physical changes (Questionnaire part A)

Respondents indicated on a five-point Likert scale how severely they felt themselves affected by some of the physical changes that can occur in conjunction with CMT. The format of this section of the questionnaire took the form of a single question:

*"Please indicate how severely you are affected by the following common features of CMT."*

Followed by an itemised list of features, alongside five boxes with Likert anchors as described previously:

Weakness of the legs/feet (including a comparison of upper and lower limbs)
Muscle wasting of the legs/feet (including a comparison of upper and lower limbs)
Sensitivity to cold of the legs/feet (including a comparison of upper and lower limbs)
Flat feet
High arched feet

The full questionnaire is reproduced in Appendix D. This chapter reports only the data specific to the lower limb, and the reader is referred to the full report for comprehensive results including the complete range of systemic and upper limb factors.

The data are presented, based on a consistent protocol for each of the variables. For the sake of brevity, brief summaries only are presented for some of these analyses, particularly where findings are clearly not significant. The analyses performed were:

*An overall descriptive report* – outlining key findings, with graphical representation of total responses (reported for all variables) descriptive statistics, and a brief comparison of upper and lower limb responses. The proportion of responses is reported graphically using pie-charts.

*Sub group explorations* were then undertaken to investigate the effects of the factors gender and age on the reported structural/ physical changes. For the categorical factor gender, visual inspection was made using box-plots of the reported severity for each level of the two factors. For brevity, these are not presented. Similarly, scatterplots were constructed to explore the relationship between age and the reported severity of each of the structural/physical changes but are not presented here.

To evaluate the interactions between the factors, a regression model was calculated for each variable. Binary logistic regression modelling was considered a more robust approach than ordinal or linear regression modelling because of the potential problems with the large number of levels within the data set. To enable cross-tabulation and logistic regression modelling, variable recoding was undertaken as follows:

- Severity of weakness was dichotomized so that the most severe two categories were collapsed into a single category designated 'More severe'. The lower three levels of weakness response were collapsed into a single category designated 'Less severe'.
- Data from respondents with confirmed CMT1A were separated out for comparison with responses from the rest of the sample.
- The continuous variable 'age' was stratified into 20 year strata as recommended by the Australian Bureau of Statistics (0-20, 21-40, 41-60, 61-80, 81+).

The individual effects of the factors are presented for completeness, along with continuity corrected chi-square results with significance. For the full logistic regression model the odds ratio (OR), its 95% confidence interval and significance level are presented. Significant factors are highlighted in italics. A final summary paragraph is provided for each variable to aid in the interpretation of the tabular data.

### 3.4.3.1 Feet/legs - weakness

*Question form: Please indicate how severely you are affected by…weakness in the legs and feet*

More than 80% of the respondents reported moderate or worse weakness in the legs/feet. Indeed only 7% reported no leg/foot weakness, a figure in accordance with the many reports in the literature [45 86]. More than half of respondents considered the weakness in their legs/feet to affect them 'quite a lot' or 'severely'. There was more weakness reported in the lower limbs than the upper limbs, with more than half reporting 'quite a lot' or more weakness in the legs, compared with less than 30% in the arms (see full report for details).

**Figure 3.13. Pie chart of severity of weakness**

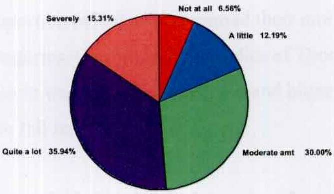


**Table 3.7. Factors influencing weakness - logistic regression modelling**

Examining the effect of CMT type, 46.8% of respondents with confirmed CMT1A reported severe weakness compared to 52.3% of all other types (chi square=0.818, P=0.366). More males (61.2%) than females (44.2%) reported severe weakness (chi square=9.124, P=0.003). The effect of age was not linear but the chi-square model revealed a possible age related effect (chi square=11.556, P=0.021).

A binary logistic regression model was constructed to test for main effects, including interactions.

| | OR (95%CI) | P Value |
|---|---|---|
| CMT type (other) | 1.17 (0.69 to 1.98) | 0.560 |
| *Gender* | *2.05 (1.29 to 3.27)* | *0.002* |
| *Age* | *1.02 (1.01 to 1.03)* | *0.001* |

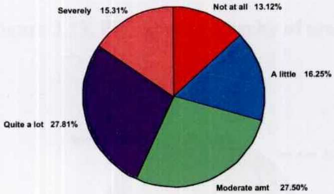
The regression model confirms the effect of gender, with male respondents more likely than females to report more severe weakness with an odds ratio of approximately two. The effect of age is statistically significant but small in the adjusted model, with the risk of reporting more severe weakness increasing x1.02 per 20 years. The model confirmed that respondents with CMT1A did not report any more or less severe weakness compared to other groups.

### 3.4.3.2 Feet/legs - muscle wasting

*Question form: Please indicate how severely you are affected by...muscle wasting in your legs/feet.*

Apart from negative reports from a small group (13%), muscle wasting in the legs and feet was reported by most respondents, a finding almost identical to previous reports [86]. A high proportion (43%) again reported their muscle wasting as falling into the two most severe categories. Confirming the studies of Thomas et al [120], we found the prevalence of leg/foot muscle wasting to be very high, and higher than the prevalence of wasting in the arms/hands (see full report).

**Figure 3.14. Pie chart of severity of muscle wasting**



In common with the results from the exploration of weakness, more males (56%) than females (33.9%) reported severe wasting (chi square=14.621, P<0.001). Examining the effect of CMT type, 34.2% of respondents with confirmed CMT1A reported severe weakness compared to 46.1% of all other types (chi square=2.957, P=0.086). The effect of age was more linear than for muscle weakness and the chi-square model suggested an independent age related effect (chi square=13.197, P=0.001).

A binary logistic regression model was again constructed to test for main effects, including interactions.

**Table 3.8. Factors influencing muscle wasting - logistic regression modelling**

| | OR (95%CI) | P Value |
|---|---|---|
| CMT type (other) | 1.53 (0.88 to 2.65) | 0.131 |
| *Gender* | *2.52 (1.57 to 4.05)* | *<0.001* |
| *Age* | *1.02 (1.01 to 1.03)* | *<0.001* |

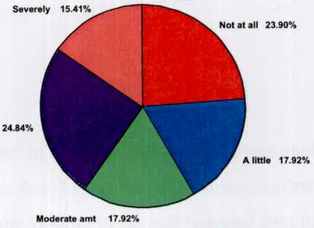
The regression model confirms the effect of gender, with male respondents more likely than females to report more severe wasting with an odds ratio of approximately 2.5. The effect of age is again statistically significant but small in the adjusted model, with the risk of more severe muscle wasting increasing x1.02 per 20 years. The model confirmed that respondents with CMT1A did not report any more or less severe wasting compared to other groups.

### 3.4.3.3 Feet /legs - sensitivity to cold

*Question form: Please indicate how severely you are affected by… sensitivity to cold in your legs/feet*

Fewer than one-quarter reported not being sensitive to cold, and 58% rated their sensitivity to cold as being 'moderate' or worse.

**Figure 3.15. Pie chart of severity of sensitivity to cold**



When rating sensitivity to cold, more females (61%) than males (54%) reported severe sensitivity, although the difference was not statistically significant (chi square=1.262, P=0.261). The CMT type appeared to have little effect either, with both confirmed CMT1A cases (61%) and all other groups (58%) reporting similar rates of the more severe category of response (chi square=0.164, P=0.685). There appeared to be an age-related effect, with a low proportion of the 0-21 age strata reporting severe sensitivity to cold (35%), a similar higher proportion of respondents in each of the three age strata between 21 and 81 years (58% to 64%), and a higher proportion again in those over 81 years (83%) . The effect of age independently was significant (chi square=11.128, P=0.025).

A binary logistic regression model was again constructed to test for main effects, including interactions.

**Table 3.9. Factors influencing sensitivity to cold - logistic regression modelling**

| | OR (95%CI) | P Value |
|---|---|---|
| CMT type (other) | 0.88 (0.52 to 1.49) | 0.630 |
| Gender | 1.33 (0.85 to 2.12) | 0.214 |
| *Age* | *1.02 (1.00 to 1.03)* | *0.010* |

The regression model confirms the absence of effect of either gender or CMT type in reported severity of sensitivity to cold. The effect of age was again statistically significant but small. These data appear to confirm anecdotal reports of increased sensitivity to cold in people with CMT. It has been demonstrated that some 85% of people with CMT disease have an abnormal plethysmographic response to cold stress, although the underlying mechanism is not understood, and CMT related autonomic dysfunction does not appear strongly related to cold intolerance [130].

### 3.4.3.4 Foot structure

The effect of CMT on foot structure was explored using a similar approach to that used for the previous data. Firstly however, some confirmatory exploration of the data was undertaken to ensure the validity of the self reported data for such a clinically defined variable. One consideration was to ensure that the two mutually exclusive extremes of these responses had not been misunderstood by the respondents. Respondents were deemed therefore to have misclassified their foot type if they scored >4 on both questions i.e. had reported both

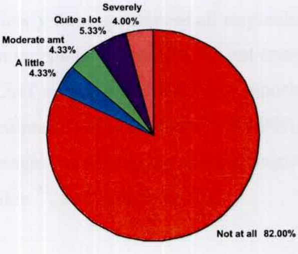
severely flattened and high arched feet. Fifteen such response sets were noted and responses from these individuals were therefore excluded from this part of the analysis.
Variables were recoded as described previously, with the exception that the foot type characterisation was dichotomised by collapsing the two most severe categories and the three least severe categories respectively, rather than recoding based on the 50th centile. This change was introduced because of the skewness in these responses (see Figure 3.12). For this and subsequent analyses, a fourth factor was also introduced into the sub group analyses and logistic regression modelling – leg/foot weakness. This variable was introduced to test the hypothesis that those with severe weakness may be more prone to the secondary effects of CMT [88]. The leg weakness was introduced as a dichotomous factor recoded from original responses as outlined in Section 3.4.3.

#### 3.4.3.4.1 *Foot Structure - Flat feet*

*Question form: Please indicate how severely you are affected by…flat feet*

Very few respondents reported their foot type as significantly flattened. There are no data available for the general population against which to compare these responses.

**Figure 3.16. Pie chart of reported severity of flat foot**



CMT type appeared to be more important in reported flat foot than it was for the variables explored in the previous section. Only 3% of respondents with confirmed CMT1A describing their foot type as severely flattened, compared with 11% of respondents with other forms of CMT (chi square=4.075, P=0.044). Gender was not a factor (males 10%, females 8%, chi square=0.106, P=0.755), nor was age (chi square=2.737, P=0.603), or self-reported severity of weakness (chi square=1.172, P=0.279). A binary logistic regression model was constructed as in the previous section to test for main effects, including interactions.

**Table 3.10. Factors influencing reporting of flat footedness - logistic regression modelling**

| | OR (95%CI) | P Value |
|---|---|---|
| *CMT type (other)* | *4.45 (1.03 to 19.28)* | *0.046* |
| Gender | 1.073 (0.47 to 2.43) | 0.864 |
| Age | 1.14 (0.76 to 1.71) | 0.524 |
| Leg/foot weakness | 0.59 (0.25 to 1.39) | 0.227 |

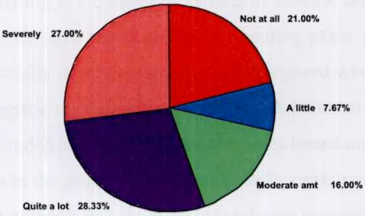
Almost all of the explanatory weighting for the relationship between CMT type and flat foot appeared to load onto CMT type. Those respondents with forms of CMT other than CMT1A were approximately four times more likely to report flat feet than those with confirmed CMT1A.

### 3.4.3.4.2 *Foot structure - High arched (cavus) feet*

*Question form: Please indicate how severely you are affected by…high arched feet*

Nearly three-quarters of all respondents reported their feet as being moderately highly arched or worse, although 21% did not consider themselves to have high arches. The prevalence of CMT related cavus deformity reported in the literature varies considerably. While the higher estimates are in the range of 80-90% [2] [141], our data are in close agreement with the lower ranges reported in the epidemiological and detailed clinical studies of Hoogendijk et al [119], Skre [42], and Holmberg [45].

**Figure 3.17. Pie chart of severity of high arched feet**



As would be expected if the data are valid, CMT type also appeared to be influential in reporting of cavus foot high arched foot types, demonstrating an inverse trend to the reporting of flat feet. While 49% of all other CMT respondents reported a severely high arched foot type, 68% of those with confirmed CMT1A reported a severely high arched foot type (chi square=7.262, P=0.007). Gender was again not found to be a factor (males 57%, females 52%, chi square=0.732, P=0.392), and again age did not appear related to severe pes cavus (chi square=5.406, P=0.248). Self-reported severity of leg/foot weakness was significant, with 64% of those reporting severe weakness also reporting a pes cavus foot type compared to only 45% of those with less severe weakness. (chi square=1.172, P=0.279).

**Table 3.11. Factors influencing reporting of high arched feet - logistic regression modelling**

| | OR (95%CI) | P Value |
|---|---|---|
| *CMT type* | *2.47 (0.14 to 4.40)* | *0.002* |
| Gender | 1.16 (0.71 to 1.88) | 0.564 |
| Age | 0.99 (0.98 to 1.01) | 0.452 |
| *Leg/foot weakness* | *2.36 (1.44 to 3.86)* | *0.001* |

Severity of cavus foot change was linked to both CMT type and severity of leg/foot weakness. Presence of confirmed CMT1A and severe leg foot weakness each increase results in an increase in the odds ratio of greater than two.

### 3.4.4 CMT - sensory impairment

In this section respondents were asked do indicate how often they noticed impairments relating to a number of aspects of somatic sensation (i.e. loss of sensation, susceptibility to burns, slow reaction to pain, shooting pains, paraesthesia, cramps and restless legs). These are initially described simply, and compared where relevant to the existing literature. Binary logistic regressions explore the link between frequency of each of the sensory manifestations, recoded as a dichotomous variables based on the 50th centile, and age, gender and CMT type as in the previous sections. Muscle weakness is retained in the analysis, based on a previous hypothesis that the muscle weakness reported in the previous section may be a general marker for disease severity [88].

#### 3.4.4.1 Shooting pains in legs/feet

*Question form: Do you experience shooting pains in your legs/feet?*

More people reported shooting pains in the legs/feet (59% ) than in the arms/hands (38%) (Wilcoxon's test, Z=-7.569, P<0.001, N=311). The proportion of people reporting lower limb shooting pains 'often' or more frequently in the legs/feet was 21.9%, compared with 10% in the upper limbs.

**Figure 3.18. Pie chart of frequency of shooting pains in legs/feet**

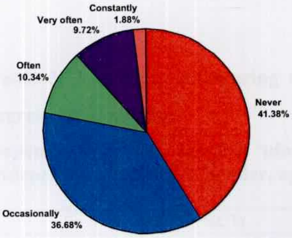


**Table 3.12. Factors influencing shooting pains - logistic regression modelling**

**Dependent variable: Leg/foot shooting pains**
**Independent variables: Gender, age, leg weakness, CMT type**

| | OR (95%CI) | P Value |
|---|---|---|
| CMT type | 1.39 (0.82 to 2.37) | 0.227 |
| Gender | 0.76 (0.48 to 1.22) | 0.255 |
| Age | 1.0 (0.98 to 1.01) | 0.531 |
| Leg/foot weakness | 1.52 (0.95 to 2.44) | 0.082 |

Frequency of shooting pains was not associated significantly with any of the factors either individually or in the adjusted model.

### 3.4.4.2 ‘Pins and needles’ in legs/feet

*Question form: Do you experience ‘pins and needles’ in your legs/feet?*
A significant majority (72.3%) of CMT sufferers report pins and needles in the legs/feet. For more than one-in-eight CMT sufferers (16.7%) these occur ‘very often’ or are ‘constant’.

**Figure 3.19. Pie chart of frequency of ‘pins and needles’**

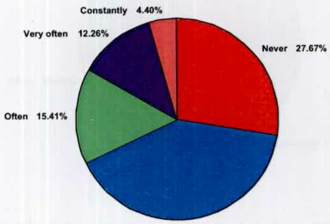


**Table 3.13. Factors influencing reporting of ‘pins and needles’ experience - ordinal regression modelling**

**Dependent variable: Leg/foot ‘pins and needles’**
**Independent variables: Gender, age, leg weakness, CMT type**

| | OR (95%CI) | P Value |
|---|---|---|
| CMT type | 1.23 (0.71 to 2.14) | 0.460 |
| Gender | 0.88 (0.53 to 1.45) | 0.624 |
| Age | 0.99 (0.98 to 1.00) | 0.266 |
| *Leg/foot weakness* | *2.05 (1.23 to 3.40)* | *0.006* |

This model determined that severity of foot and leg weakness was the only significant predictor of the frequency of lower limb pins and needles with those reporting more severe weakness also reporting more frequent pins and needles with an odds ratio of approximately two.

### 3.4.4.3 Cramps in the legs

*Question form: Do you experience cramps in your legs/feet? (cramps = <u>painful</u> spasms in the muscles)*

Leg cramps are widely reported in the literature [114 120 133], a finding confirmed by this study. Fewer than one-quarter of the sample reported being unaffected by leg cramps. For 20.3% of CMT sufferers the cramps occur very often or constantly.

**Figure 3.20. Pie chart of frequency of cramps in legs/feet**

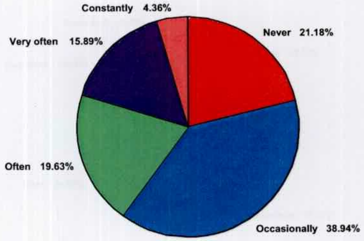


**Table 3.14. Factors influencing leg cramps - logistic regression modelling**

All the factors were entered into the ordinal regression model.

**Dependent variable: Severity of leg cramps**
**Independent variables: Gender, age, leg weakness, CMT type**

| | OR (95%CI) | P Value |
|---|---|---|
| *CMT type* | *2.29 (1.36 to 3.88)* | *0.002* |
| Gender | 0.78 (0.48 to 1.25) | 0.296 |
| Age | 1.00 (0.99 to 1.02) | 0.676 |
| Leg/foot weakness | 1.42 (0.88 to 2.29) | 0.156 |

Gender was not a significant parameter in the combined model, and age as expected, did not contribute significantly. Leg/foot weakness was not a predictor of the frequency of cramps.

There was a statistically significant effect of CMT type in the regression model, with respondents with confirmed CMT1A reporting more frequent leg cramps with an odds ration of greater than two.

### 3.4.4.4 'Restless legs'

*Question form: Do you experience 'restless' legs at night or when sitting?*

Restless legs were not a significant problem for most people with CMT, although some 21.2% report restlessness in the legs 'very often' or 'constantly', with a further 24.9% reporting restlessness 'often'.

**Figure 3.21. Pie chart of severity of 'restless legs'**

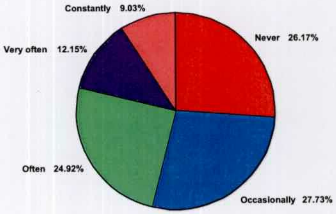


**Table 3.15. Factors influencing restless legs - ordinal regression modelling**

**Dependent variable: Restlessness of legs**
**Independent variables: Gender, age, leg weakness, CMT type**

| | OR (95%CI) | P Value |
|---|---|---|
| CMT type | 1.08 (0.65 to 1.81) | 0.766 |
| Gender | 0.81 (0.51 to 1.28) | 0.360 |
| Age | 1.00 (0.99 to 1.01) | 0.777 |
| *Leg/foot weakness* | *1.61 (1.01 to 2.57)* | *0.043* |

Leg/foot weakness is again a significant explanatory variable, with the odds ratio of more frequent restless legs raised in those with more severe leg/foot weakness. Other parameters are not significant, with the frequency of restlessness in the legs independent of gender, CMT type or age. Gemigiani et al have reported previously that restless legs are not seen in patients with CMT type 1 but in more than one third of patients with axonal CMT [328]. Our data do not support these findings, with evidence of heterogeneity in the prevalence of reported restless legs in people with the demyelinating and axonal forms of CMT. The Gemigiani study used stringent criteria for the diagnosis of restless legs syndrome, and is likely to have been more conservative estimate than our patients' self-reported estimation.

### 3.4.5 CMT – impacts on daily function

*The first section took the form: 'Do you use any of the following aids or devices? (please tick all that apply)':* followed by a list including all of the aids and devices detailed in this section.

#### 3.4.5.1 CMT and use of aids and devices

It is known that people with CMT often require assistance, although the proportion of people affected, and the possible predictive markers are not known. Again these data are presented starting with an overall summary of responses, followed by analysis of the contribution of various factors to an explanatory regression model. The factors of interest are:

*Age*

*CMT type*

*Leg/foot weakness* as a marker for disease severity.

*Marital status,* which was also included in this section to determine whether the availability of a partner may influence dependency on aids and devices. As the hypothesis was dependent solely on the availability of a partner, the three singles states (single, divorced/separated and widowed were aggregated into one category) for comparison with the couples (married/de facto).

### 3.4.5.2 Aids and devices, wheelchair

Fewer than 6% of 302 eligible* respondents in this sample reported using a wheelchair. This represents a lower proportion than the 10% often quoted in the literature but a slightly higher proportion than the 1/119 reported in a previous study of disability in CMT [86].

**Note:* *to ensure that the concept of use of a 'wheelchair' had not been confused by respondents, with the use of a 'pushchair' or 'stroller' for young children, responses for those aged <=5 years were not included in the questions relating to wheelchair use.*

**Figure 3.22. Pie chart of the proportion of respondents using a wheelchair**

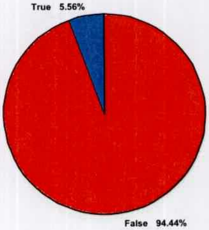


**Table 3.16. Factors influencing wheelchair dependence - Logistic regression modelling**

**Dependent variable: Wheelchair dependence**
**Independent variables: Age, CMT type, leg weakness, marital status**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.05 (1.02 to 1.08)* | *0.001* |
| CMT type | 4.86 (0.61 to 39.14) | 0.137 |
| Leg/foot weakness | 3.102 (0.94 to 10.28) | 0.064 |
| *Marital status* | *5.52 (1.88 to 16.21)* | *0.002* |

The mean age of non-wheelchair users was 45.6 years, significantly lower than the mean of 60.72 in the wheelchair using group. Age was a strong predictor with the risk of wheelchair dependency increasing x1.05 per 20 years. Leg/foot weakness was weakly associated with increased risk of wheelchair dependence but did not reach significance. There was a significant relationship between marital status and wheelchair use. Single people (including those separated, divorced or widowed), had nearly a six-fold risk of wheel chair dependence compared with those in a married/de facto relationship. The risk of wheel chair dependence was not related to type of CMT despite only 1% of respondents with confirmed CMT1A being wheelchair dependent compared with 7% of respondents with other forms of CMT.

### 3.4.5.3 Aids and devices, motor scooter

Only 2% of this sample of 324 respondents uses a motor scooter.

**Figure 3.23. Pie chart of the proportion of respondents using a motor scooter**

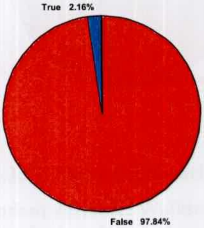


**Table 3.17. Factors influencing motor scooter dependence - logistic regression modelling**
**Dependent variable: Motor scooter dependence**
**Independent variables: Age, CMT type, leg weakness, marital status**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.06 (1.01 to 1.11)* | *0.027* |
| CMT type | 0.55 (0.10 to 3.16) | 0.502 |
| Leg/foot weakness | 4.51 (0.52to 39.22) | 0.172 |
| Marital status | 3.24 (0.68 to 15.40 | 0.139 |

The mean age of non-motor scooter users was 46.04 years, significantly lower than the mean of 63.71 in the scooter-using group. Age was again the most significant predictor as it might be in the general population, with the risk increasing x1.06 per 20 years of life. No other factors were significant predictors of reliance on a motor scooter.

### 3.4.5.4 Aids and devices, walking stick

All 324 respondents answered this question. Nearly 20% of this sample reported using a walking stick.

**Figure 3.24. Pie chart of the proportion of respondents using a walking stick**

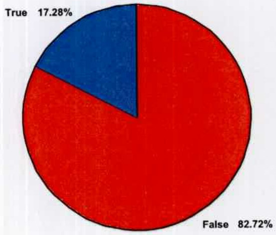


**Table 3.18. Factors influencing walking stick dependence - logistic regression modelling**

**Dependent variable: Walking stick dependence**
**Independent variables: Age, CMT type, leg weakness, marital status**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.07 (1.04 to 1.09)* | *<0.001* |
| CMT type | 0.91 (0.41 to 2.02) | 0.812 |
| *Leg/foot weakness* | *5.55 (2.50 to 13.32)* | *<0.001* |
| Marital status | 1.05 (0.50 to 2.18) | 0.902 |

The proportion of respondents in this sample using a walking stick to aid ambulation is several times higher than the <5% reported previously in French patients with confirmed CMT1 [86]. It is not clear why this should be the case, although age related differences might be significant. Data on the prevalence of walking stick use in the general population were sought but could not be found. The mean age of non-walking stick users was 43.1 years, significantly lower than the mean of 62.13 in the walking stick using group, hence age was a significant predictor in the model with the risk of stick use increasing x1.07 per 20 years of life. Leg/foot weakness was also strongly associated with increased risk of walking stick dependence, with the risk increased to more than five-fold in those with more severe leg/foot weakness. Marital status and CMT type did not predict walking stick reliance.

### 3.4.5.5 Aids and devices, walking frame

All 324 respondents answered this question. Fewer than 6% of this sample uses a walking frame.

**Figure 3.25. Pie chart of the proportion of respondents using a walking frame**

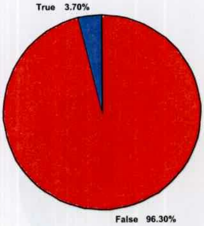


**Table 3.19. Factors influencing walking frame dependence - logistic regression modelling**

**Dependent variable: Walking frame dependence**
**Independent variables: Age, CMT type, leg weakness, marital status**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.12 (1.05 to 1.18)* | *<0.001* |
| CMT type | 2.28 (0.26 to 19.87) | 0.454 |
| Leg/foot weakness | 3.33 (0.66 to 16.91) | 0.147 |
| Marital status | 1.44 (0.38 to 5.46) | 0.590 |

The mean age of non- walking frame users was 45.45 years, significantly lower than the mean of 71.58 in the walking frame using group. Once more, age was a moderate predictor with the risk increasing x1.113 per year of life. Leg/foot weakness was also associated with increased risk of walking frame dependence, with the risk more than doubling with each point of reported increased severity. Marital status and CMT type were not related to walking frame dependence.

### 3.4.5.6 Aids and devices, in-shoe orthoses

All 324 respondents answered this question. A significant proportion of this sample currently uses in-shoe orthoses.

**Figure 3.26. Pie chart of the proportion of respondents currently using in-shoe orthoses**

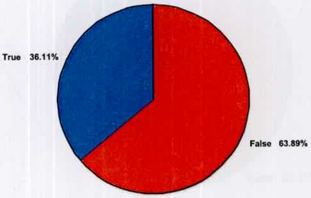


**Table 3.20. Factors influencing current in-shoe orthosis use - logistic regression modelling**

**Dependent variable: In-shoe orthoses current use**
**Independent variables: Age, CMT type, leg weakness, marital status**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *0.98 (0.97 to 1.00)* | *0.009* |
| *CMT type* | *2.161 (1.272 to 3.61)* | *0.004* |
| Leg/foot weakness | 0.91 (0.57 to 1.47) | 0.705 |
| Marital status | 0.98 (0.58 to 1.66) | 0.937 |

The mean age of non-users of in-shoe orthoses was 48.9 years, higher than the mean of 40.3 in the in-shoe orthosis wearing group. Age was a weak predictor with the use of orthoses decreasing slightly per year of life. Neither leg/foot weakness or marital status were associated with increased in-shoe orthosis use. The risk for in-shoe orthosis use was related to type of CMT however, with respondents with CMT1A twice as likely to use in-shoe orthoses, as the other groups.

### *Aids and devices, ankle-foot orthoses*

All 324 respondents answered this question. Fewer people in this sample use AFOs than in-shoe orthoses.

**Figure 3.27. Pie chart of the proportion of respondents using ankle-foot orthoses**

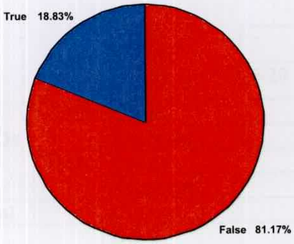


**Table 3.21. Factors influencing AFO use - logistic regression modelling**
**Dependent variable: AFO current use**
**Independent variables: Age, CMT type, leg weakness, marital status**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.00 (0.99 to 1.02) | 0.790 |
| *CMT type* | *3.07 (1.31 to 7.22)* | *0.010* |
| *Leg/foot weakness* | *3.91 (2.02 to 7.57)* | *<0.001* |
| Marital status | 0.70 (0.36 to 1.36) | 0.293 |

The mean age of non AFO orthoses wearers was 45.61 years, higher than the mean of 49.92 in the AFO orthoses using group. Age was not a significant factor overall, but the graphical output (not presented here) suggested some non-linear relationship which is developed below. AFO dependence was related to type of CMT, and people in the group with forms of CMT other than CMT1A were more likely to use AFOs than the CMT1A group with an OR of more than 3.0. As might be expected, leg/foot weakness was a significant predictor of AFO use, with the risk of AFO dependence nearly four times greater in those with more severe leg weakness. Marital status was not associated with altered risk for AFO orthoses use.

The non-linear relationship with age was developed further as it appeared from the graphical output that there may be a watershed around the age of 20 years which may be influential. The stratified age data were thus cross-tabulated with AFO use to identify significant non-linear interactions.

**Table 3.22. Cross tabulation of stratified age with AFO use.**

| | | | Age stratified | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **0-20** | **21-40** | **41-60** | **61-80** | **81+** | TOTAL |
| **Use AFOs** | **False** | **Count** | 27 | 82 | 88 | 57 | 5 | 259 |
| | | **Expected** | *29.9* | *72* | *87.4* | *64.8* | *4.9* | *259* |
| | **True** | **Count** | 10 | 7 | 20 | 23 | 1 | 61 |
| | | **Expected** | *7.1* | *17* | *20.6* | *15.3* | *1.1* | *61* |
| **Total** | | **Count** | 37 | 89 | 108 | 80 | 6 | 320 |
| | | **Odds ratio(95%CI)** | NS | 0.267 (0.117-0.611) | NS | 2.004 (1.109-3.622) | NS | |

*Chi square=13.668, P=0.008*

The 21-40 age group demonstrate a reduced odds ratio of 0.26 indicating reduced odds ratios for AFO use compared with other age groups, while CMT sufferers in the 61-80 age group are approximately twice as likely to use AFOs. Possible reasons for this are developed in the discussion.

### 3.4.6 CMT – non surgical treatments

In this section of the survey respondents were asked to indicate their experiences with the conservative treatments itemised. The overall usage figures are reported, along with overall data on reported ease of use for each of the therapies. The effectiveness is also reported overall and then explored further in an attempt to determine whether treatments may be better targeted at specific patient groups.

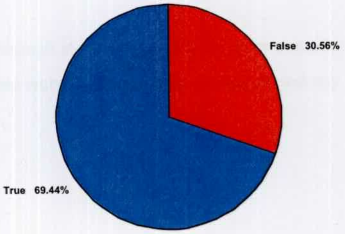
The sub-groups investigated were again, age, CMT type, with leg/foot weakness included as a surrogate for disease severity. The data are reported graphically and again, following recoding of the dependent variable into a dichotomous variable based on response about the 50th centile, are entered into a logistic regression model in an attempt to establish predictors for the likely effectiveness of an intervention.

### 3.4.6.1 Stretching exercises

*Stretching exercises – usage*

Nearly 70% of the respondents had tried stretching exercises at some point.

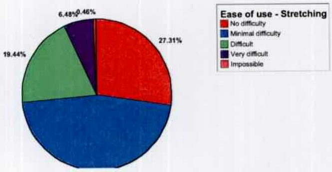
**Figure 3.28. Pie chart of the proportion of respondents having tried stretching**



*Stretching exercises – ease of use*

Stretching exercises were generally considered easy to use as a modality. Only one respondent found stretching exercise regimes impossible to comply with, while nearly three-quarter reported 'no' or only 'minimal' difficulty in complying with stretching therapy.

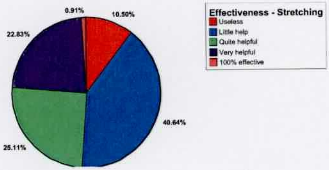
**Figure 3.29. Pie chart of the reported 'ease of use' of stretching exercises**



*Stretching exercises – effectiveness*

For all its ease of use, less than half the respondents reported that stretching regimes were, in their opinion, 'quite' or more effective. For just less than one quarter however the degree of effectiveness was high ('very helpful' or '100% effective').

**Figure 3.30. Pie chart of the reported effectiveness of stretching exercises**



None of the three factors explored appeared strongly related to the perceived effectiveness of stretching. Leg/foot weakness showed a weak inverse relationship, suggesting that those with least severe weakness tended to find stretching more helpful.

**Table 3.23. Factors influencing stretching effectiveness - logistic regression modelling**

**Dependent variable: Effectiveness of stretching**
**Independent variables: Age, leg weakness, CMT type**

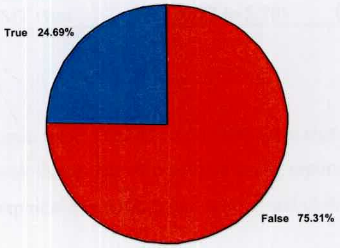
| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.01 (0.99 to 1.02) | 0.443 |
| Leg/foot weakness | 0.85 (0.50 to 1.48) | 0.583 |
| CMT type | 0.78 (0.43 to 1.40) | 0.400 |

Although stretching exercises were considered effective by nearly half of all respondents there were no factors that demonstrated any significance within the model.

### 3.4.6.2 Ankle/foot splints/orthoses (AFOs) - (daytime use)

AFOs are reportedly often used for functional daytime use in people with anterior leg weakness leading to dropfoot. Only one-quarter of the respondents (N=80) reported having used AFOs for daytime wear.

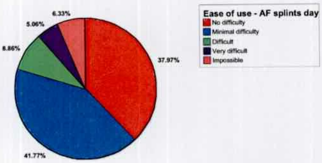
**Figure 3.31. Pie chart of the proportion of respondents having tried AFOs**



*AFOs (daytime) – ease of use*

Of the 80 people who reported having used daytime ankle/foot splints, nearly 80% found them easy to use.

**Figure 3.32. Pie chart of the reported 'ease of use' of AFOs**



*AFOs (daytime) – effectiveness*

Those that use daytime ankle/foot orthoses find them useful. Fewer than one-in-five respondents considered them to be of only 'little help' or 'useless'. Nearly 70% of respondents who had tried AFOs found this treatment approach 'very helpful' or '100% effective'. No data exist in the literature for comparison.

**Figure 3.33. Pie chart of the reported effectiveness of AFOs**

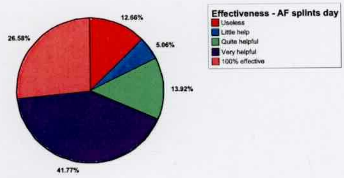


**Table 3.24. Factors influencing perceived effectiveness of AFO use - ordinal regression modelling**

**Dependent variable: Effectiveness of daytime AFO use**
**Independent variables: Age, leg weakness, CMT type**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.02 (0.99 to 1.04) | 0.181 |
| Leg/foot weakness | 1.16 (0.38 to 3.59) | 0.796 |
| CMT type | 1.74 (0.53 to 5.70) | 0.359 |

Again there were no factors that were significant to the model, there was a suggestion of a weak linear trend toward increasing reported effectiveness with age in the preliminary graphical evaluations, but adults' and children's responses appeared to differ.

### 3.4.6.3 AFOs/splints (night time)

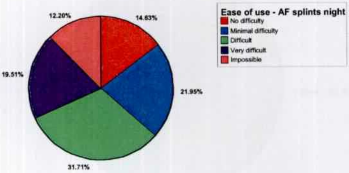
AFOs/ankle splints are sometimes used at night to provide a sustained stretch to the calf musculature. Only 13% of the respondents in this survey reported having tried night splint stretching.

**Figure 3.34. Pie chart of the proportion of respondents having tried night splinting**

*AFOs/splints (night time) – ease of use*

Nearly one-third of the 42 respondents who had tried night splints found them very difficult or impossible to comply with. Only one in eight respondents reported no difficulty with using this therapy.

**Figure 3.35. Pie chart of the reported 'ease of use' of night splints**



*AFOs/splints (night time) – effectiveness*

The wearing of night splints was not considered particularly helpful by more than 60% of respondents. A little over one in ten did however report that night splints were 'very helpful' or '100% effective'.

**Figure 3.36. Pie chart of the reported effectiveness of night splints**

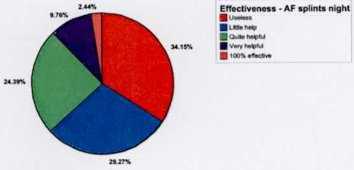


**Table 3.25. Factors influencing perceived effectiveness of night splinting - ordinal regression modelling**

**Dependent variable: Effectiveness of night splinting**
**Independent variables: Age, leg weakness, CMT type**

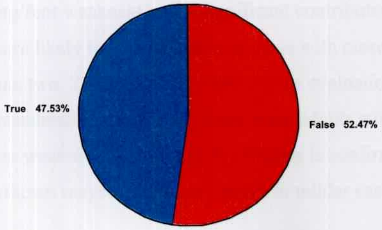
| | OR (95%CI) | P Value |
|---|---|---|
| Age | 0.99 (0.96 to 1.02) | 0.501 |
| Leg/foot weakness | 1.53 (0.35 to 6.73) | 0.576 |
| CMT type | 4.14 (0.80 to 21.59) | 0.091 |

No factors were significant in the adjusted model although CMT type, before adjustment for age and superimposed weakness had appeared individually significant. Some 63% of respondents from the confirmed CMT1A sample reporting night splinting to be effective compared with 30% of the other CMT types but despite being moderately close to statistical significance the difference was not supported in the adjusted model.

### 3.4.6.4 Shoe inserts (experience of use at any time previously)

Shoe inserts or in-shoe orthoses may be used by people with CMT to improve the mechanical function of the foot or to redistribute excessive pressure around the foot. As would be expected, more people reported in response to this question that they had tried shoe inserts 'at some point', than had reported 'currently' using them in the previous question on page 89. Just less than half of the respondents had tried in-shoe orthoses at some point.

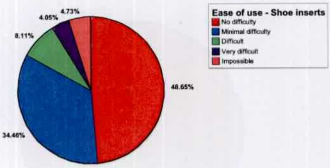
**Figure 3.37. Pie chart of the proportion of respondents having tried shoe inserts**



*Shoe inserts – ease of use*

In-shoe orthoses are generally considered by the CMT community to be easy to use. Only 17% of the respondents who had worn them (N=154) considered them difficult to use.

**Figure 3.38. Pie chart of the reported 'ease of use' of shoe inserts**



*Shoe inserts – effectiveness*

Seventy percent of the respondents who had used in-shoe orthoses reported that they were 'quite helpful' or better.

**Figure 3.39. Pie chart of the reported effectiveness of shoe inserts**

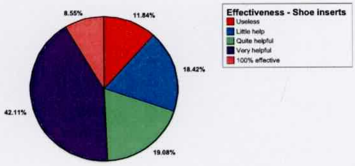


**Table 3.26. Factors influencing perceived effectiveness of shoe inserts - ordinal regression modelling**

**Dependent variable: Effectiveness of shoe inserts**
**Independent variables: Age, leg weakness, CMT type**

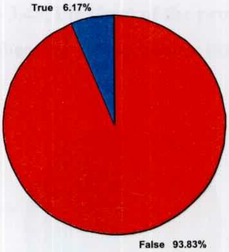
| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.01 (0.99 to 1.03) | 0.559 |
| *Leg/foot weakness* | *2.25 (1.15 to 4.39)* | *0.017* |
| CMT type | 1.412 (0.70 to 2.85) | 0.337 |

Leg/foot weakness was a significant contributor to the model indicating that shoe inserts were more likely to be ineffective in those with more severe weakness with an odds ratio of more than two. The preliminary descriptive evaluations had revealed that shoe inserts were considered ineffective by more respondents with more severe weakness (60%) than those with less weakness (42%), and this finding is confirmed in the adjusted model suggesting that orthoses maybe of greater benefit in milder cases.

### 3.4.6.5 Plaster casts

The application of plaster casts to provide a prolonged stretch is used in cases where tight calf musculature has proven resistant to less invasive treatments. In this regime, casts are applied serially, and worn constantly over a period of 2-6 weeks. Only a small number of respondents (N=20) had tried plaster casts. The small sample precludes the construction of meaningful regression models and these data are therefore presented descriptively only.

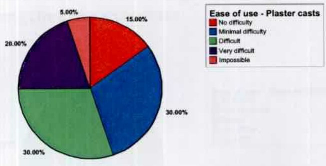
**Figure 3.40. Pie chart of the proportion of respondents having tried plaster casts**



*Plaster casts – ease of use*

Stretching exercises were considered easier to use as a modality than might have been expected for a modality with a significant impact on daily function. Nearly half the respondents reported the therapy as presenting no difficulty or only minimal difficulty.

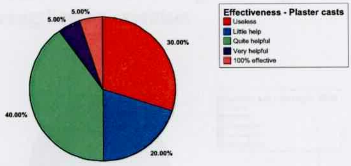
**Figure 3.41. Pie chart of the reported 'ease of use' of plaster casts**



*Plaster casts – effectiveness*

The respondents were equally divided on the benefit of plaster casting. One half felt casting to have no effect or only minimal effect, while for half it was considered 'quite helpful' or better. For only 10% was casting considered 'very effective' or better.

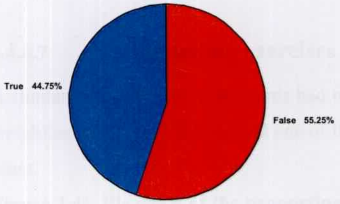
**Figure 3.42. Pie chart of the reported effectiveness of plaster casts**



### 3.4.6.6 Strengthening exercises (non-weightbearing or 'NWB')

Strengthening programs to address the progressive muscle weakness are commonly prescribed to people with CMT. The effectiveness of these in improving distal muscle power has not been evaluated in clinical trials however. Strengthening programs for the legs may involve exercises undertaken sitting or lying (non-weightbearing) and using free weights, or may be done weightbearing using the body mass for resistance, and replicating movements used in daily function. Just less than one half of the sample reported having tried non-weightbearing exercise regimes to improve strength.

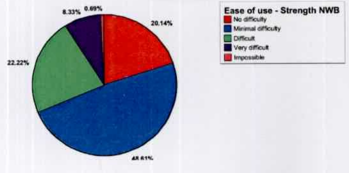
**Figure 3.43. Pie chart of the proportion of respondents reporting having tried non-weightbearing strengthening exercises**



*Strengthening (NWB) – ease of use*

Non-weightbearing strengthening exercises were generally considered easy to comply with. Only 31% of the sample reported significant difficulty with compliance.

**Figure 3.44. Pie chart of the reported 'ease of use' of non-weightbearing strengthening exercises**



*Strengthening (NWB) – effectiveness*

Fewer than half the respondents reported that the non-weightbearing strengthening regimes were, in their opinion, 'quite' or more helpful. Non-weightbearing strengthening regimes were perceived as less effective than stretching regimes.

**Figure 3.45. Pie chart of the reported effectiveness of non-weightbearing strengthening exercises**

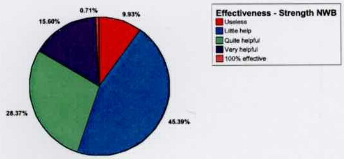


**Table 3.27. Factors influencing NWB strengthening effectiveness - ordinal regression modelling**

**Dependent variable: Effectiveness of NWB strengthening**
**Independent variables: Age, leg weakness, CMT type**

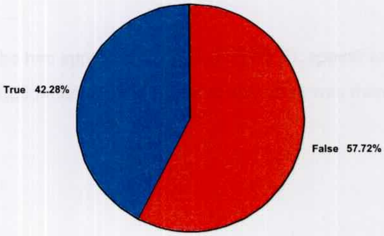
| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.01 (0.99 to 1.03) | 0.385 |
| Leg/foot weakness | 1.01 (0.51 to 2.00) | 0.583 |
| CMT type | 1.33 (0.62 to 2.84) | 0.464 |

There were no significant factors in the model.

### 3.4.6.7 Strengthening exercises (weightbearing (WB))

A similar proportion of respondents had tried strengthening regimes weight bearing and non-weightbearing. Only 30 had tried one of the regimes of strengthening exercise without the other.

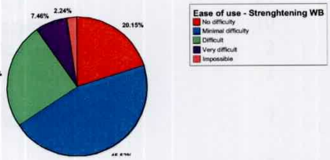
**Figure 3.46. Pie chart of the proportion of respondents reporting having tried weightbearing strengthening exercises**



*Strengthening WB – ease of use*

The responses for ease of use of weightbearing strengthening regimes appeared to mirror those for the non-weightbearing strengthening regimes.

**Figure 3.47. Pie chart of the reported 'ease of use' of weightbearing strengthening exercises**



*Strengthening WB – effectiveness*

The responses for effectiveness of use of weightbearing strengthening were again similar to those for the non-weightbearing strengthening regimes, although weightbearing exercises were perceived as being marginally more effective.

**Figure 3.48. Pie chart of the reported effectiveness of weightbearing strengthening exercises**

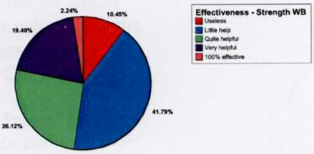


**Table 3.28. Factors influencing effectiveness of weightbearing exercises - ordinal regression modelling**

**Dependent variable: Effectiveness of WB strengthening**
**Independent variables: Age, leg weakness, CMT type**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.00 (0.99 to 1.02) | 0.726 |
| Leg/foot weakness | 1.24 (0.63 to 2.44) | 0.535 |
| CMT type | 1.06 (0.49 to 2.25) | 0.891 |

The two approaches (WB and NWB), appear to carry a similar perception of ease of use and effectiveness although in neither case was there a significant factor in the models.

### 3.4.7 CMT - alternative therapies

Seventy-four respondents gave 111 responses on their use of alternative treatments. In all, 26 alternative therapies were identified.

**Table 3.29. Use of alternative therapies**

| Therapy | Number tried | Therapy | Number tried |
|---|---|---|---|
| Homeopathy | 3 | Vitamin therapy | 4 |
| Naturopathy | 8 | Cell therapy (Niehans) | 1 |
| Massage | 15 | Mannatech tablets | 1 |
| Chiropractic | 10 | Alexander technique | 1 |
| Muscle stripping | 2 | Reflexology | 4 |
| Electromagnetic therapy | 1 | Tai Chi | 1 |
| Hydrotherapy | 7 | Traditional Chinese Medicine | 1 |
| Yoga | 5 | Maharishi Ayur Vedi | 1 |
| Gym exercises | 5 | Deep tissue | 4 |
| Acupuncture | 23 | Herbal tonics | 1 |
| Bowen technique | 4 | Diet Candida | 1 |
| Pilates | 2 | Hatchard's Way | 1 |
| Reiki | 2 | Myra Therapy. | 3 |

Twenty-four respondents had used multiple alternative therapies (two or more).
Women were nearly twice as likely as men to use alternative therapies (odds ratio =1.789 (95%CI 1.046-3.06), $X^2$=4.577, P=0.022). A full analysis of the use of alternative therapies is given in the CMTAA survey report.

### 3.4.8 CMT – surgery

In response to the question on surgeries, 101 respondents returned data on 209 foot surgeries. Sixty-two people had undergone multiple surgeries (more than two episodes of surgery). The average age of first surgery was 24.4 years, second surgery 29.3 years, third surgery 33.2 and fourth surgery 32.2 (this apparent anomaly results from 3 of the 11 people who had undergone four surgeries having had multiple surgeries in early life). Again, for brevity the full analysis of this complex area of the survey is not included here, as the subsequent work in this thesis relates primarily to evaluation of conservative therapy. The interested reader is again directed to the full CMTAA survey report for details.

### 3.4.9 Predictors of overall health outcome

The final analysis of the survey dataset involved the construction of a series of multiple logistic regression models in an attempt to quantify the factors contributing to the patients' reported health related quality of life. On the basis of the previous analyses in the chapter and an empiric assessment of clinical importance, the relevance of all the factors to overall quality of life scores was considered. For the reasons outlined in the table, the following factors were determined to be of greatest interest and were further explored for suitability for inclusion in the regression modelling.

**Table 3.30. Factors included in regression modelling of predictors of health outcome.**

| Variable | Reasons for inclusion |
|---|---|
| Gender | *A factor independent of CMT disease but potentially influential over HRQoL* |
| Age | *A factor independent of CMT disease but potentially influential over HRQoL* |
| Marital status (couple or single status only) | *A factor independent of CMT disease but potentially influential over HRQoL* |
| CMT type | *To evaluate comparability of the different forms of CMT and their effect on HRQoL* |
| Leg/foot weakness | *As a marker of disease severity* |
| Severity of pes cavus | *To determine whether the most common foot deformity contributes to HRQoL scores* |
| Shooting pains in the legs/feet | *To determine whether the day-to-day presence of positive neurogenic features impacts on HRQoL.* |
| Pins and Needles in the legs/feet | *To determine whether the day-to-day presence of positive neurogenic features impacts on HRQoL.* |
| Cramps in the legs | *To determine whether the day-to-day presence of positive neurogenic features impacts on QoL.* |

It is not appropriate to include in regression modelling factors that are largely co-dependent, and the score and ordinal variables were first re-assessed therefore for co-linearity. As noted previously, leg and foot weakness was significantly correlated with several of the intended factors. Shooting pains, leg cramps and pins and needles were highly correlated. Exclusion of co-dependent variables reduced the factors to be included to :

Age
Gender
Marital status
CMT type
Leg/foot weakness
Leg cramps

Logistic regression models were again constructed after first dichotomising each of the SF-36 dimension response sets to scores either side of the 50th centile. Those responses below the 50th centile were categorised as 'poor health' and those above, 'good health'.

A table of regression summary statistics is provided for each HRQoL dimension with a significant factors highlighted with italics. A brief summary is provided at the end of the four physical health dimensions, at the end of the mental health dimensions of the SF-36 scores, and again and for the four foot-specific dimensions of the FHSQ.

## Logistic regression modelling –SF-36 dimensions

*SF-36 Physical Function*

**Dependent variable: SF-36 Physical function dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.82 (1.37 to 2.43)* | *<0.001* |
| Gender | 1.56 (0.91 to 2.68) | 0.109 |
| Marital status | 0.57 (0.31 to 1.01) | 0.056 |
| CMT type | 1.15 (0.63 to 2.12) | 0.655 |
| *Leg/foot weakness* | *6.68 (3.91 to 11.43)* | *<0.001* |
| *Cramps* | *2.02 (1.18 to 3.45)* | *0.011* |

*SF-36 Role Physical*

**Dependent variable: SF-36 Role Physical dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.38 (1.07 to 1.79)* | *0.013* |
| Gender | 0.87 (0.53 to 1.41) | 0.573 |
| Marital status | 0.76 (0.45 to 1.29) | 0.307 |
| CMT type | 0.94 (0.54 to 1.64) | 0.840 |
| *Leg/foot weakness* | *2.40 (1.49 to 3.88)* | *<0.001* |
| *Cramps* | *1.94 (1.18 to 3.18)* | *0.009* |

*SF-36 Bodily pain*

**Dependent variable: SF-36 Bodily pain dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 0.89 (0.69 to 1.14) | 0.349 |
| Gender | 0.94 (0.57 to 1.53) | 0.795 |
| Marital status | 1.05 (0.62 to 1.77) | 0.851 |
| CMT type | 1.35 (0.77 to 2.38) | 0.297 |
| Leg/foot weakness | 1.58 (0.98 to 2.58) | 0.062 |
| *Cramps* | *3.65 (2.21 to 6.01)* | *<0.001* |

*SF-36 General Health*

**Dependent variable: SF-36 General health dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 0.87 (0.68 to 1.12) | 0.280 |
| Gender | 0.97 (0.60 to 1.57) | 0.901 |
| Marital status | 1.12 (0.67 to 1.88) | 0.658 |
| CMT type | 1.12 (0.65 to 1.95) | 0.683 |
| *Leg/foot weakness* | *2.69 (1.66 to 4.31)* | *<0.001* |
| *Cramps* | *2.02 (1.24 to 3.30)* | *0.005* |

### Summary for SF-36 Physical Component Scores

Leg/foot weakness and cramps were both related to physical HRQoL as measured by the SF-36. In the physical function dimension leg/foot weakness was highly significant with a greatly enhanced risk for those with more severe weakness reporting worse Physical Functioning (OR>6.0). Leg/foot weakness was significant in all of the physical dimensions except Bodily Pain where leg cramps were highly significant. The risk of those with more frequent leg cramps reporting Bodily Pain scores below the 50th centile (more pain) was increased approximately 3½ fold. Age was a significant factor in tow of the physical dimensions as might be expected, with increasing age increasing the risk of reporting physical impairment worse than the median response (OR 1.38-1.82 per 20 years of life). Gender, marital status and CMT type did not appear to affect significantly the scores in the physical dimensions of the SF-36.

### *SF-36 Vitality*

**Dependent variable: SF-36 Vitality dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.28 (0.99 to 1.64) | 0.056 |
| Gender | 1.22 (0.76 to 1.99) | 0.412 |
| Marital status | 0.97 (0.58 to 1.62) | 0.916 |
| CMT type | 1.35 (0.77 to 2.34) | 0.296 |
| *Leg/foot weakness* | *1.98 (1.23 to 3.20)* | *0.005* |
| *Cramps* | *2.00 (1.23 to 3.26)* | *0.005* |

### *SF-36 Social Function*

**Dependent variable: SF-36 Social function dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.24 (0.96 to 1.59) | 0.096 |
| Gender | 1.31 (0.81 to 2.12) | 0.275 |
| *Marital status* | *2.04 (1.21 to 3.34)* | *0.007* |
| CMT type | 0.93 (0.53 to 1.60) | 0.781 |
| *Leg/foot weakness* | *2.05 (1.27 to 3.32)* | *0.003* |
| *Cramps* | *1.76 (1.08 to 2.85)* | *0.023* |

### *SF-36 Emotional role*

**Dependent variable: SF-36 Emotional role dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.23 (0.96 to 1.60) | 0.093 |
| Gender | 0.96 (0.59 to 1.56) | 0.861 |
| *Marital status* | *0.59 (0.35 to 1.00)* | *0.048* |
| CMT type | 1.01 (0.57 to 1.77) | 0.983 |
| Leg/foot weakness | 1.11 (0.68 to 1.81) | 0.667 |
| *Cramps* | *1.86 (1.14 to 3.05)* | *0.013* |

*SF-36 Mental health*

**Dependent variable: SF-36 General health dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age * | 0.78 (0.61 to 1.01) | 0.051 |
| Gender | 1.42 (0.88 to 2.29) | 0.148 |
| Marital status | 0.99 (0.60 to 1.64) | 0.971 |
| CMT type | 2.23 (1.38 to 3.59) | 0.858 |
| *Leg/foot weakness* | *6.68 (3.91 to 11.43)* | *0.001* |
| Cramps | 1.50 (0.93 to 2.42) | 0.096 |

* Note: Younger people reported **worse** mental health scores

**Summary for SF-36 Mental Component Scores**

Leg/foot weakness and cramps were linked to the SF-36 mental component scores in a number of dimensions. Both were significant in three models and cramps were borderline for significance in the fourth. More severe leg/foot weakness was associated with a substantial increase in risk of a score in the Mental Health dimension (depression/anxiety), indicating that the disease related weakness may be mentally debilitating as well producing the more obvious physical effects. The presence of more frequent cramps was associated with an increased risk (OR=1.76 to 2.0) of scores below the 50th centile (i.e. scores indicating poorer mental health) in Vitality, Social Function and Emotional Role.

Age was not significant in any of the models although it was close to significance in all four. Of note is the trend towards increasing age increasing the risk of lower mental component scores in all dimensions except for Mental Health, where younger respondents were at marginally higher risk of worse scores. Marital status was only significant in the Emotional Role and Social Function dimensions and the responses were associated with opposite spectra of risk. In the Emotional Role dimension respondents without partners reported less risk of significant impairment of their role than those with partners (OR 0.59), while singles were at greater risk of more severe impairment to their Social Function (OR 2.04).

**Logistic regression modelling –FHSQ dimensions**

*FHSQ Foot pain*

**Dependent variable: FHSQ Foot pain dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.26 (0.96 to 1.64) | 0.089 |
| Gender | 1.20 (0.73 to 1.99) | 0.473 |
| Marital status | 0.86 (0.50 to 1.48) | 0.589 |
| *CMT type* | *1.80 (1.01 to 3.20)* | *0.045* |
| *Leg/foot weakness* | *2.23 (1.34 to 3.71)* | *0.002* |
| *Cramps* | *4.00 (2.41 to 6.62)* | *<0.001* |

*FHSQ Foot function*

**Dependent variable: FHSQ Foot function dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| *Age* | *1.46 (1.11 to 1.91)* | *0.007* |
| Gender | 1.32 (0.79 to 2.22) | 0.291 |
| *Marital status* | *0.53 (0.30 to 0.94)* | *0.028* |
| CMT type | 1.63 (0.90 to 2.95) | 0.109 |
| *Leg/foot weakness* | *5.01 (3.00 to 8.38)* | *<0.001* |
| *Cramps* | *1.74 (1.04 to 2.92)* | *0.036* |

*FHSQ Shoes*

**Dependent variable: FHSQ Shoes dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.10 (0.85 to 1.42) | 0.454 |
| *Gender* | *3.23 (1.95 to 5.32)* | *<0.001* |
| Marital status | 1.373 (0.81 to 2.32) | 0.269 |
| *CMT type* | *1.86 (1.05 to 3.27)* | *0.033* |
| Leg/foot weakness | 1.38 (0.84 to 2.62) | 0.210 |
| *Cramps* | *2.09 (1.28 to 3.44)* | *0.003* |

*FHSQ General Foot Health*

**Dependent variable: FHSQ Foot pain dimension**
**Independent variables: Age, gender, marital status, CMT type, leg/foot weakness, leg cramps**

| | OR (95%CI) | P Value |
|---|---|---|
| Age | 1.26 (0.97 to 1.62) | 0.076 |
| Gender | 0.87 (0.54 to 1.41) | 0.582 |
| Marital status | 0.70 (0.41 to 1.17) | 0.169 |
| CMT type | 0.92 (053 to 1.58) | 0.754 |
| *Leg/foot weakness* | *2.13 (1.33 to 3.42)* | *0.002* |
| Cramps | 1.28 (0.79 to 2.08) | 0.315 |

## Summary for FHSQ Foot-specific Scores

Leg/foot weakness and cramps were both significant in three of the four models. Those with more frequent cramps had a greatly increased risk of reporting poorer HRQoL in the foot pain dimension (OR 4.0). Those reporting more severe weakness demonstrated substantially increased risk for reporting low (poor) scores in the Foot Function dimension (OR=5.01) and double the risk for scores below the 50th centile in Foot Pain and General Foot Health. Disease independent factors (gender and age) were less consistent, although females were at increased risk of severe impairment in the FHSQ Shoes dimension (OR=3.23), which is consistent with the gender specific influence noted in the descriptive evaluations at the beginning of the chapter. The risk of impairment in the FHSQ Shoes dimension was also dependent on CMT type with respondents in the confirmed CMT1A group nearly twice as likely to report FHSQ Shoes scores below the median. Age was significant only in the Foot Function domain, a finding consistent with its significance in the general Physical Function dimension of the SF-36 reported previously.

## 3.5 *DISCUSSION AND CONCLUSIONS.*

The broad intentions of the survey were to improve our understanding of what, to-date, has been an incomplete clinical picture, to provide better information for patients, and to compare the effects of CMT on health related quality of life (HRQoL), with the impacts of other diseases. It is a strength of this survey that the HRQoL data were derived from validated and widely used measures, providing quality data describing the place of CMT in the spectrum of other chronic diseases. The additional HRQoL data derived from the FHSQ survey has greater limitations but is still useful and significant. The lack of validation of the CMT specific question-set must be acknowledged, particularly where respondents were required to provide information of a clinical nature. It was noted in the introduction that it was not considered necessary to construct a fully validated HRQoL measure for this one-off survey, but the limitations of the piloting program and the absence of a rigorous validation should be factored into any conclusions drawn from the survey.

The response rate of 86% was high for a postal survey, especially as there was no capacity for direct follow-up, and reflects the strong sense of community in the CMT Association. Male respondents are marginally under-represented compared with the general population [292] although the spread of ages and CMT types was good. Patient self-reporting of CMT type is problematic, even in this relatively well-informed community, and although some 45% were honest enough to report being unsure of the precise type of CMT, others will have erroneously reported their disease type. Data relating to CMT type must be viewed therefore as a broad indicator only.

People with CMT score lower than the general population on all dimensions of the SF-36 and FHSQ indicating significantly poorer HRQoL confirming the data from the SIP sccoring [114]. The trend was particularly marked for the physical dimensions of the SF-36 and for the FHSQ. Foot HRQoL in CMT was worst in the domains of foot function and footwear. The responses to the footwear items confirm anecdotal reports from the CMT community indicating significant problems with obtaining suitable footwear. The problem is, perhaps unsurprisingly, worse for female than for males, probably reflecting the greater conflict between fashion and function seen generally in female footwear.

The SF-36 scores for the CMT community showed much greater differentiation with age than is seen in the general population, possibly indicating some cumulative effect of the disease on

HRQoL over the lifespan. The FHSQ scores also demonstrated considerable worsening with age except for the domain exploring footwear related issues. Interestingly the lowest scores in this dimension were seen in the age strata spanning the years 25-45. It is not clear why this should be the case. This may be a period when disease severity accelerates, although laboratory data do not support this. An alternative hypothesis is that this age group is likely to be highly socially active, and perhaps more conscious of appearance. This may create conflict between the demands of style, and adaptation to footwear choice required by the progress of the disease.

The type of CMT did not appear to be highly influential of reported HRQoL, with the exception of the small group reporting CMT type 3 (Dejerine-Sottas Syndrome). This is arguably the most severe of the CMT types and resulted in significant reduction in reported HRQoL in the physical function and physical role dimensions of the SF-36. Those with DSS also reported less bodily pain and foot pain (i.e. higher scores) than those with other forms of CMT, although their foot function scores were low. Those with DSS reported fewer footwear problems than those with other CMT types, perhaps due to less foot deformity, reduced activity, or maybe better access to prescribed footwear because of greater general disability. This anomaly warrants further investigation in future.

Examination of the SF-36 scores for CMT and a range of other chronic conditions reveals useful information about the impact of the disease on sufferers. CMT does not impact substantially on lifespan and its impact is often trivialised as a consequence. Clearly, as a long term degenerative condition, CMT does not have as severe an impact on HRQoL as the pain associated with advanced arthritis, or the significant impact on function seen immediately post-stroke, but it is comparable to other chronic conditions such as Parkinson's disease, and to stroke patients six-months after the cerebrovascular event, as noted previously [114]. These data suggest that in the absence of quantification, the impact of CMT on the HRQoL of sufferers has been underestimated previously.

The patient's own estimate of the severity of disability has been suggested previously to be a good marker of disease severity [88] and was thus of great interest in this study. Self-reported muscle weakness was much more profound in the lower limbs than the upper limbs, a finding in agreement with previous reports. Weakness was also implicated in the severity of muscle wasting in both upper and lower limbs, although age also factored in the severity of muscle wasting. It was interesting to note that muscle wasting was reported as more significant by the male respondents. It cannot be determined from this study the extent to which this reflects any genuine gender-related difference in muscle atrophy, whether loss of muscle strength is genuinely more important to the work and leisure activities of men, or whether psychosocial definitions of masculinity influence their reporting of the impact of reduced muscle strength. Sensitivity to cold is often mentioned by patients with CMT and increased sensitivity to cold in the legs and feet was a reported by three-quarters of respondents. Sensitivity to cold was perceived to be worse in the lower limbs than the upper limbs, in agreement with anecdotal reports and in common with most 'vascular-type' presentations.

Estimates of prevalence of CMT-related foot deformity vary widely. It is remarkable that many papers refer only to generic foot deformity, often commenting on the preponderance of foot deformity, but failing to provide specific data on the proportion of cavus/planus presentations. This may well be due to the recognised difficulties in defining foot type in CMT [87] and as already addressed in the review of the literature. The problems described previously must therefore be considered to apply even more profoundly to patient self-reported data. Nonetheless the patients' own reports are broadly in agreement with the clinical literature. Flat feet were reported to be a relatively uncommon presentation in CMT, with fewer than 15% of respondents rating flatfootedness in the worse three classifications. Indeed, more than 80% reported their feet as not being flattened 'at all' -a figure entirely in agreement with previous studies [2]. There was less reporting of flatfootedness in the younger age groups, although it cannot be confirmed whether the prevalence is really lower or whether other factors, such as a perception that some flatfootedness is more normal in children, also comes into play in these responses. It must also be considered that for many of the adult responses surgical interventions will have artificially altered the foot structure, perhaps creating a flat foot type from a previously cavus foot. The high prevalence of a cavus foot type was in agreement with the previous literature.

Shooting pains in the limbs were problematic for more than half of the respondents in this sample. The prevalence of the milder positive neurogenic presentation of 'pins and needles' is higher again, affecting more than three-quarters of the people with CMT represented by this sample. For both of these presentations the lower limb is affected more than the upper limb, probably reflecting the more advanced disease progression in the lower limbs.
The other positive physical signs explored in the survey were cramps and restless legs. It is not known whether these manifestations relate to neurogenic or other mechanisms but anecdotal reports of these features in CMT are common. This survey confirmed a high

prevalence of leg cramps in people with CMT. While the mechanism underpinning the cramps is not known, in this sample, the relationship between weakness and prevalence of cramps is again of note. Cramping may result directly from the primary neurogenic factors also causing the progressive weakness, or the cramps may be secondary features, perhaps reflecting underlying histological or functional changes in the muscle. This warrants further research, as the presence and severity of leg cramps proved a significant factor in the models predicting HRQoL. There is a suggestion that addressing cramping in the CMT population may improve quality of life for these patients.

Three-quarters of the sample reported restless legs, a higher proportion than reported in studies employing physician definition/diagnosis of the problem. Again there was a relationship between restlessness of the legs and muscle weakness.

The survey explored the use of aids and assistive devices, ranging from those required only by the most impaired people, to those potentially of benefit to many people with peripheral neuropathy. The devices likely to be required by more impaired people (wheelchairs, electric scooters, walking frames) were not used by a high proportion of respondents, and the proportion of our sample using a wheelchair to aid mobility was actually slightly less than suggested in the anecdotal literature. Single people were more dependent on a wheelchair for mobility, but electric scooter use was not related to marital status. Dependence on these 'high-end' aids was highly age-related, and CMT-related weakness, while marginal for significance as a factor predicting wheelchair use, was not a significant factor in the model predicting use of an electric scooter. Walking stick and walking frame use was again highly age dependent, although in the case of these aids, leg/foot weakness also appeared more relevant to the models. This suggests that disease related weakness may be additive to the increased dependence on such aids normally associated with ageing in the general population. Age normalised data for the use of such aids in the general population could not be found, but would doubtless be helpful in interpreting the disease specific effects in the CMT population.

A significant proportion of respondents reported current use of in-shoe orthoses, and the subsequent exploration of all those who had used these devices found that more than 70% reported them to 'quite helpful' or better. The positive effects of in-shoe orthoses appeared to be greater in people with less weakness, with the perceived effectiveness reduced in more severe cases.

Ankle-foot orthoses (AFOs) have been suggested to be helpful in restoring function [172] although there are no scientific data to support this. AFOs were used by fewer people than reported using in-shoe orthoses. The risk for AFO use loaded heavily on severity of leg/foot weakness, although the effect of age was illuminating. In the age group representing those aged less than 20 years, the prevalence of AFO use was largely in line with the figure predicted by cross tabulation, but in the age group 21-40 years the use of AFOs was only one-quarter of that predicted. Conversely in the 61-80 age strata the prevalence of AFO use was increased to double that which might be expected. It is unlikely that the inexorable progress of the disease process itself would have produced such age-related variation alone, so other factors are also implicated. The FHSQ data suggested that this age group also find footwear issues particularly profound, and it is possible that similar factors may be implicated, namely a trade-off between social acceptability or cosmesis, against the burden of disability imposed by the CMT. Older people may be more prepared to accept the reduced cosmetic appeal, or may succumb to progressing weakness, while the very youngest age strata are more likely to be wearing AFOs primarily at the behest of parents. These hypotheses cannot of course be tested within the context of this study, but are worthy of consideration. In the subsequent evaluation of the effectiveness of AFOs, more than 70% of people who had used them did consider the approach effective. The overall model predicted a creditable one-quarter of the variance in improved effectiveness, but this did not load onto any specific factors. The adults and children exhibited quite different response patterns. This perhaps reflects the mainly fashion/cosmetic considerations, but the many factors likely to influence success with this treatment should be considered carefully by the prescribing physician when AFOs are being contemplated.

Of the more aggressive non-surgical therapies, night splinting was generally considered unhelpful and difficulties were reported in relation to compliance. Again, the best results were reported by patients with less weakness, but night-splinting did not appear to be a popular modality overall. This conflicts with the anecdotal literature [1 163] but in the absence of clinical trial data, firm conclusions are not appropriate.

Unsurprisingly, plaster casting was considered more difficult to comply with than removable night splints, but conversely, was also considered marginally more effective. Whether this trade-off is ultimately worthwhile is unknown. Strengthening of weakened muscles, either weightbearing or non-weightbearing, was considered effective by the majority. Strengthening regimens were reported to be easy to use, but studies of compliance in other areas have suggested that long-term compliance in such self-directed regimes tends to be poor. There is little to separate weightbearing and non-weightbearing approaches, although the weightbearing approach was considered marginally more effective, perhaps reflecting its improved relevance to real-life activities.

Stretching is widely advocated, even in the absence of any trial data [1 162], and had been tried by 70% of the respondents. Stretching exercises are considered easy to use, although as noted previously, actual compliance is often poor in practice. Stretching is considered effective by half the respondents.

Alternative therapies were widely used, with a wide variety of approaches reported. Many respondents who had tried one alternative approach also tried other alternative therapies.

Surgery for CMT is an area of great concern for physicians involved in the care of these patients. As noted in the literature review, there are no established standards of surgical care in this field, and any surgical approach employed in an individual case cannot be well substantiated in the literature. Many respondents had undergone surgery although there was little variation in reported outcome regardless of whether patients had been subjected to more or less aggressive surgeries.

The overall predictors of HRQoL in people with CMT were interesting. Of the general physical health dimensions, leg/foot weakness was the single most influential factor in the analysis, appearing as a significant factor in three of the four SF-36 physical dimensions. Age was also implicated in reducing the reported physical health related quality of life, as it is in the general population [292], although age standardised figures point to a significant disease specific effect. The pain dimension appeared to be affected more by the presence of cramps than features secondary to other physical factors such as foot deformity.

In the general mental health dimensions, the merit of leg/foot weakness as a marker for overall disease severity is again substantiated. Leg/foot weakness and cramps were both , perhaps surprisingly, significant factors in the predictive model for three of the four mental health dimensions. Other, less influential factors included age and marital status.

As was seen in relation to the general health scores, foot health status was dependent on a range of disease-specific and disease-independent factors. Foot pain scores were influenced by increased frequency of cramps and by leg/foot weakness. Foot function was strongly related to leg/foot weakness and age, with the frequency of cramps again acting as a minor factor. The reported impairment with footwear was related only weakly to frequency of cramps, and this factor was overwhelmed by the influence of gender. It is difficult to discuss why females should report greater difficulty with footwear without engaging in broad, anthropologic speculation. It is widely believed however that female fashion footwear is less accommodating to the foot than the equivalent male footwear. It is likely therefore, that the mismatch between the female foot and shoe recognised in the general population is exacerbated in people with a foot pathology related to CMT. Also to be factored into this aspect of the discussion is the potential for women with a foot type altered by CMT, to experience difficulties in finding and buying suitable footwear from high street outlets. In this context, greater footwear-related difficulties will be reported by women, not just because of physical shortcomings in shoe shape or structure, but also because of social/cultural issues such as cost and physical accessibility, which will influence the availability of more accommodating shoes.

Finally, the importance of leg/foot weakness in predicting the impact of CMT disease on the lower limb is illustrated by the domain in the FHSQ of general foot health, variation of which loaded entirely on leg/foot weakness.

## Conclusions

The conclusions drawn from this study must be considered in light of the methodological limitations of the survey technique, and clinical trials are clearly required in this area of study. Nonetheless, this is a large sample, and the study clearly addressed the main aims. The survey is the first to examine the effects of CMT on HRQoL and has yielded invaluable data in this regard. In terms of the impact on sufferers, CMT lies in the mid range of chronic conditions, and the effects have probably been underestimated previously. The specific type of CMT did not, in this sample, appear to be of great importance, but this should be explored further in a sample in which the CMT type is confirmed by physician assessment before such an assertion can be made with any confidence. Health related quality of life in these patients is predicted strongly in many dimensions by leg/foot weakness, and it could be argued that a thorough evaluation of weakness should be emphasised in all evaluations of patients with CMT. Even diligent recording of self-reported assessment of weakness is likely to yield information useful to the clinician. Lower limb problems are highly prevalent in people with CMT, along with many other secondary features. Few people with CMT rely on aids to any great extent. Milder cases appear to respond reasonably well to more conservative therapies, with stretching and strengthening regimes evaluating relatively strongly. Splints and casts are not favoured by the CMT community. AFOs improve function in a proportion of people with more profound weakness, but the complex social factors must be considered by the prescribing clinician. In-shoe orthoses are also considered helpful by many people who have tried them. These are a non-invasive approach with fewer social/cosmetic implications than

AFOs, and warrant further evaluation in clinical trials. 'Alternative' therapies did not evaluate well generally, although massage and chiropractic may be of benefit. The choice of surgical intervention remains unclear.

In summary, this survey met the aims outlined at the beginning of the study and has yielded data which should impact on the understanding and care of people with CMT. The impact of CMT on quality of life has been quantified and the prevalence of a range of features, hitherto recognised only anecdotally, has been described. Weakness has transpired as a useful predictive marker, and its evaluation and documentation should receive greater emphasis. Similarly cramps are widely recognised, but their influence on HRQoL responses has not been considered previously. Further directions for future research have been identified, and clinical trials in a number of areas would be advantageous.

It is clear from the review presented in Chapter Two, and from the foot-related data presented here, that further work on the manifestations of CMT in the foot is a priority for this community. Given that the barriers to such work imposed by the absence of suitable clinical measures of foot type have already been established, the next three chapters will focus on an attempt to produce and validate an appropriate instrument, before returning to a more CMT-specific focus in Chapter Seven.

# CHAPTER FOUR. CONSTRUCTION OF A NOVEL RATING SYSTEM FOR EVALUATING FOOT POSTURE, THE FOOT POSTURE INDEX (FPI).

---

***Chapter overview***

*Chapter Two presented a discussion of the shortcomings of existing clinical measures for assessing the foot, and suggestions for improvements found in the literature. Chapter three describes an attempt to measure the impact of CMT in general on the lower limb, and in this chapter the process is described by which a new measure, the Foot Posture Index, was built from basic principles, in an attempt to address the shortcomings of current measures of foot posture.*

*The construction of the FPI is, throughout, grounded in the literature and so this chapter starts with a justification for the factors that were considered appropriate to the new measure. The derivation of the new measure from existing literature is then described, along with the preliminary attempts to assess the general feasibility of the approach, and the evolution of early iterations of the index. The chapter concludes by presenting the draft of the FPI to this point, the version that was investigated further in the validation processes described in Chapters 5 to 7.*

---

## *4.1* *AIMS*

The aims of the stages presented in this chapter were:

- To identify the desirable characteristics of a new measure of foot posture.
- To identify in the literature, a number of component measures that together, would provide for an enhanced evaluation of foot posture.
- To assess the feasibility of using this approach in the clinical setting.
- To generate structured feedback from clinicians, on the merits of using the new measure, and if appropriate, to refine the measure prior to validation studies.

## *4.2* *FACTORS DEFINING THE NEW MEASURE*

Many of the guiding principles for the derivation of the measure were provided by either the 2001 consensus statement of the Foot and Ankle Special Interest Group of the American Physical Therapy Association (detailed in Chapter 2)[9] and the recommendations of Kitaoka et al [17], both discussed previously.

These guiding principles warrant further discussion, and are discussed sequentially in points 4.2.1 to 4.2.7.

1. *Both dynamic and static methods have identifiable strengths and weaknesses.*
2. *Measures should be taken weightbearing.*
3. *A measure should include graded subjective and objective clinical factors.*

4. *Where possible, the measure should use continuous measures.*
5. *Measures need to reflect the complexity of the interrelationships occurring within the leg and foot.*
6. *The scale should be validated.*
7. *Measures should be quick to use and should not require sophisticated equipment such as a gait laboratory.*

## 4.2.1 Dynamic and static evaluation of foot function.

In an ideal world, all clinical decision making relating to the lower limb would be based only on validated, non-invasive and objective measures of dynamic function. Technology has not yet evolved to the point where this is possible however, even in the best equipped facilities. Dynamic evaluations of gait are costly and time consuming [23 189], and once objective data have been obtained, agreement on its interpretation can still be low [329]. In the clinical setting the ideals of objectivity and accuracy are sacrificed to save clinician time, and to preclude the need for expensive equipment [189]. Gait may be observed empirically, but so-called observational gait analysis is known to be unreliable [330] except for detecting substantial variations from normal [331], and quantification of the more subtle variations in gait is simply not possible without the time consuming and expensive approaches alluded to above. In practice, the most commonly applied compromise is to take static measurements with the intention of inferring dynamic function from the static data, based on the widely held assumption among clinicians that the static foot posture gives the clinician a useful indicator of the likely function of that foot [15 24 6]. There is though, evidence that there are measurable differences between static and dynamic measures, with static measures seeming to underestimate the extreme positions encountered during gait [332 333]. Any use of static measures should include therefore, at least some consideration of the degree to which the static measure may predict the true motions occurring during walking. A range of static measures have been employed previously with the aim of estimating dynamic function. These are discussed below.

### 4.2.1.1 Arch Index

Atkinson-Smith and Betts (1992) employed the arch index, followed up with video gait assessment. The arch index is an objective measure of an inked foot print, in which the area of the midfoot is divided by the sum of the hindfoot, midfoot and forefoot areas [249]. The Atkinson-Smith study employed only nine subjects however, and all of the subjects were selected on the criterion of having either a normal to high arched foot type. The authors of the paper report concerns over the reliability of the measures used to determine the rearfoot measures during gait, which relied on an *ad hoc* manual measure rather than the more sophisticated computer tracking regarded as optimal in gait studies. The small number of subjects, the lack of a range of foot types employed combined with dubious validity of both the static and dynamic measures and suggest that the authors overstate their conclusion that static foot prints are unreliable indicators of foot function.

#### 4.2.1.2 Radiography

The relationship between foot morphology and the resulting pressures underneath the weightbearing foot have been investigated by Cavanagh and others [144 258 334]. Cavanagh et al investigated the relationship between a complex set of static radiographic measures, and dynamic plantar pressures under the heel and first metatarsophalangeal joint. In this study some 35% of the variation in pressures was explained by variation in combinations of radiographic measures, although to attain this degree of prediction a combination of four radiographic angles were required. Individual radiographic measures in isolation explained no more than 13% of the dynamic variance. This association between the morphology and pressures remains the best reported to date. Even though radiographic measures are supposedly the 'gold standard' among static evaluations however, the authors report some problems with reliability. For six of the 27 measures the ICC was less than 0.75, reflecting problems also encountered by Anderson et al [236]. An exploration of the relationship between static structure and plantar pressures at specific sites in the foot was provided by Walker and Fan [334], who conclude that the site of peak pressure was not well predicted by their measures of standing foot posture. These data are not supported however by the subsequent report of Arangio and co-workers [144], in which a medial shift in load was associated with systematic pronation of the foot and a lateral shift in load occurred with supination. A five degree shift was associated with approximately 50% increase in the moment about the navicular-medial cuneiform and calcaneal-cuboid joints respectively, during pronation or supination movements.

### 4.2.1.3 Foot prints

In one novel variation, Freychat derived foot prints from both static and dynamic passes over a specially designed apparatus [250]. A variety of angles were obtained from the relationships of the anatomical segments identified on the footprint. The coefficient of determination of the dynamic footprint data and its capacity to predict several measures of force under the foot was 35-40%, again a figure similar to that of Cavanagh et al. This however, was based on the relationship between two dynamic measures. The relationship between the static foot print and the dynamic force data were not reported, but the correlation between the static and dynamically derived foot print angles were low (R=0.37), suggesting a still weaker relationship with the force data.

### 4.2.1.4 Two and three dimensional motion analysis

The strength of the relationship between static posture and dynamic function has been supported by more recent work by Donatelli et al [335] and Cornwall and McPoil [336]. In the Donatelli study agreement between the static and dynamic measures was good although the study was methodologically weak, relying on clinical static evaluation and only a two-dimensional dynamic assessment. In the Cornwall and McPoil study, simple repeat measurements of navicular bone height in static stance and dynamic movement during gait using an electromagnetic motion tracking system demonstrated close agreement between the static and dynamic measures. These findings contrast with the findings of Cashmere et al who demonstrated only a weak relationship between standing medial arch height, and the arch compression during gait (R=0.089) [337], and those of Hunt et al who, as part of the same group of researchers, also investigated the relationship between static measures of medial arch height and heel eversion with their dynamic equivalents. Hunt et al, concluded that individual static measures are poorly predictive of dynamic motions [338].

It is possible that the conflicting conclusions from these data reflect the findings of McPoil and Cornwall in a previous 1996 study, in which the coefficient of determination between **independent** foot static and dynamic measures (for example arch height vs calcaneal angle) was found to be particularly low. ($R^2=0.17$) [24]. It is also possible however, that the relationship between static and dynamic measures varies according to site. Nawoczenski et al [339] reported a high correlation between the static and dynamic measures of hallux dorsiflexion using an electromagnetic motion tracking system. It is likely that this finding reflects the larger ranges of motion seen at the first metatarsophalangeal joint, and the relative stability of markers attached to the segments proximal and distal to the joint under investigation.

Clearly, the extent of the relationship between static measures and subsequent dynamic function will continue to be limited even with improved static measures [6], as the dynamic component is substantially more complex. A number of other factors including structural factors such as leg rotation (foot placement angle) [253], the physical rigidity of the foot and leg [276 340], active and passive muscle control [341 342], point of application of input force [285] and subtle neuromuscular mechanisms as proposed by Nigg [343] may come into play, along with the structural and morphological characteristics of the foot.

There can be no doubt that dynamic measures remain the ideal but, given the ready availability of static measures and the limited application of dynamic measures in routine clinical practice, static measures may continue to play a part in the assessment of the human foot for some time.

### 4.2.2 Weightbearing and non-weightbearing measures

An open kinetic chain exists where an anatomical segment moves relative to one fixed point but where the remainder of the segment is free to move in space i.e. in a non-weightbearing state such as seen in the arm and hand. The foot and leg more usually function weightbearing however, in a closed kinetic chain where the limb is constrained at both ends. In the case of the many, interdependent relationships occurring in the small joints of the feet, this closed chain activity becomes particularly important. Many of the early attempts to objectify assessment of foot and leg function were based on open kinetic chain measures [213 344], and have thus been criticised by clinicians as lacking clinical applicability and validity [270]. The effects of varying degrees of loading were investigated by Kitaoka et al in 1995 who determined differences between loaded and unloaded measures of up to 9.4° at the TNJ and 4.4° at the subtalar joint, equivalent to 20-30% of the joints' total range of motion [221]. In practical terms this underpins a systematic underestimate of weightbearing function when non-weightbearing measures are employed [345 188]. Despite the theoretical superiority of weightbearing measures, proponents of high quality, objective measures note that the difficulties associated with accurate in vivo measurement in the closed chain remain insurmountable, resulting in measures of generally poor reliability [346 347]. More general qualitative assessments are widely used in the clinical field, but are themselves of limited use where they do not adequately quantify the function of the parts. Most now agree that weightbearing assessment is preferable, with supplementary measures from non-weightbearing assessments also incorporated if necessary [188 221 272 345 347].

### 4.2.3 Subjective and objective clinical factors

Due in no small part to the seemingly intractable problems associated with pseudo-objective measurements derived from angles measured directly from the joints, or from lines drawn on the skin, Keenan, in 1997 was moved to comment:

*'Rather than attempting to quantify the position and range of motion of the foot in terms of degrees, there is some evidence to suggest that a more qualitative or positional assessment would be more appropriate'* [16].

This is substantiated by the data of Pearce and Buckley [214] who identify significant overestimation of angular rotation by clinical measures. They also conclude that empiric clinical measurements may be more valid than spurious clinical measurements in degrees. This concept is developed further in the following sections.

### 4.2.4 Continuous scales and categorisation of foot type

One long-standing difficulty with foot type assessment is associated with defining an appropriate reference point or 'neutral position'. This is highlighted by the range of examples whereby definitions of neutral are based on anatomical convenience rather than functionally meaningful positions. [188 348 349]. Thus, irrespective of the technological efforts directed toward establishing accurate measures of foot function, this area of study remains handicapped by the continued inability to define the starting point for all such measures [14 140 344]. Even if a compromise definition is accepted, and the neutral position is defined, for instance, as the position of maximal congruence in the talo-navicular joint, then the problem remains that an inherently subjective measure acts as the starting point for all subsequent objective measures [212]. This fact alone may indicate hopelessness of attempting to rely solely on objective quantification of foot function. Experienced practitioners have been shown to achieve some consensus when required to place the foot into a 'neutral' position, but only after as many as six measures on the same subject [10] and more reliable or useful bases have been sought. Astrom and Arvidson propose that the entire paradigm of an 'ideal' foot is based on an invalid theoretical concept, arguing that a proper reference should be based on clinical observations, rather than on unreliable and theoretically driven but unsubstantiated considerations [347]. It has been proposed that the theoretically 'normal' foot i.e. the subtalar 'neutral' foot is a rarity [347 231]. It is argued that the range of theoretical definitions of pathology which in truth also encompass subtle variations from normal is quite large, and Cornwall and McPoil in 1999 advocate using the term 'typical' to ameliorate the dispute over the definition of the theoretical term 'normal' [350].

Despite the difficulty in defining 'normality' it is possible to identify characteristics associated with various types of foot morphology [135]. These are so well documented as to be taken for granted, indeed Anderson [236] makes the tongue in cheek observation that 'typically a clinician calls a foot flat when it appears flat.'

To date most such methods have focussed on only one aspect of foot function and there remains no single, easily performed method for quantitatively determining different foot types [351]. Kelly, as early as 1947, had recognised the inadequacy of relying on single measures. Kelly outlined a study in which five such measures derived from footprints, and a range of other indicators employed with the child standing, sitting or semi- weightbearing yielded data from a total of 32 empirical morphological and functional variables [222].

Menz has also questioned the validity of inferring complex foot function from discrete single plane measures[15] although his proposed solution incorporated techniques that involve multiple moderately complex, instrumented measures. While such measures are largely objective, the inconvenience associated with obtaining them has led to limited uptake of this approach. Where pragmatic clinical assessments are required, measurements using clinician generated criteria are common in medicine. In the evaluation of benign joint hypermobility syndrome for instance, hypermobility is almost universally defined according to a nine point scale known as the Beighton-Carter-Wilkinson (BCW) scale [352]. In using the BCW scale, the presence or absence of a range of specific criteria are simply noted and scored by the clinician. The combination of the criteria thus enables a composite score giving an indication of the overall mobility of the individual. The BCW scale has been criticised for its simplicity, its subjectivity, and its non-linearity, all criticisms which could equally be levelled at a criterion based measure of foot posture. In practice however, because there is no definitive laboratory or biochemical assay which can provide a definitive quantification of joint mobility, the BCW scale remains the almost unanimous choice of clinicians wishing to quantify quickly, the joint mobility in the clinical setting[353]. Modifications to increase objectivity have been suggested over the years, [354 355] but without exception have fallen rapidly into disuse, as the simplicity and clinical utility of the existing measure remain its most compelling features [353].

### 4.2.5 Multifactorial variations in structure and function

Foot function is a product of the combined motions occurring at the STJ/ MTJ and at distal joint complexes. The interrelationships of the joints of the foot have been discussed at a theoretical level in a number of papers [220 221 356-359] and some of the theory has been

substantiated by the *in vivo* studies of Cornwall & McPoil [350], Ouzonian & Shereff [360], Lundberg et al [358] and Winson et al [361], and by the intervention studies of Astion et al [362]. In these studies the combined function of the segmental components (often the rearfoot, mid foot and the metatarsals) are thoroughly investigated. The importance of the midfoot is highlighted in the magnitude of motions observed in the midtarsal segment [358 360 361], and the interrelationships between the segments have been described in some detail. Astion et al employed the clever design of selective arthrodesis of cadaverous foot /ankle complexes. In this study of ten specimens the effects of the complex interrelationships between the joints in the rearfoot and midfoot were explored in detail [362]. In agreement with the work of other authors [221 350 357 358 360], large excursions were found in the mid foot joints, and in the talo-navicular joint in particular. Importantly however, Astion et al were able to demonstrate the importance of this joint to consequent motions in other joints in the foot. In any of the combinations of arthrodesis that involved the TNJ, motion in the other joints was restricted to approximately two degrees.
Central to the concept of the new measure is the recognition that movement in the joints of the foot is tri-planar and will therefore result in observable changes in all three body planes [216 342 344]. *In vitro* studies have long suggested that single plane measures, in particular frontal plane rearfoot motion is an inadequate basis for predicting subtalar motion [363]. Similarly the ink footprint derived arch index has been shown to be only moderately correlated (R=0.71) with normalised navicular height (note: this equates to $R^2$=0.50, although the $R^2$ was not modelled or reported explicitly)[262]. Mueller reports 27-33% coefficients of determination for navicular drop to rearfoot / forefoot position [271]. Freychat again reports a similar figure (36%) from a composite rearfoot to forefoot angle derived from an inked footprint, but these represent only the relationships between static motions in various segments and body planes.

Foot pronation/supination involves a complex triad of motions comprising eversion of the rearfoot and adduction and plantarflexion of the talus on the calcaneus, however, and there is considerable between-subject variability in the degree of coupling of each of these component motions [14 15 217 220 278 342]. This variability was noted early in the clinical tomographic studies of the rearfoot joint ranges of motion [364] and has since been confirmed in many studies. Despite the acknowledged complexity of the foot joints, much of the clinical examination used today relies on inadequate single plane measures such as inversion /eversion of the rearfoot [363] or arch height [185 224].

The contribution to the composite motion of the foot, of specific motion in each of the component planes varies between individuals according to the orientation of the joint axes, the rigidity of the structures and the point of application of forces about the joints [365]. In one *in vitro* kinematic study of composite talo-crural and talo-calcaneal motions, incorporating multi-planar observations has been shown to be superior [363]. The implication is thus that measures involving more than one planar component would offer benefits in the quantification of foot posture.

This concept is described and developed by Smith in his 1997 treatise on the surgical management of flat feet [264]. In this paper, different types of foot are identified, each associated with dominant motions in one of the three cardinal body planes. This of course represents an oversimplification of the problem but serves to highlight the main issue. Song et al similarly conclude that existing systems of classification are deficient where they do not differentiate variations in foot posture/function caused by 1st ray position, transverse plane deformity, and forefoot/rearfoot sagittal plane deformities [273]. The incomplete relationship between pairs of discrete single measures is well documented [255 271] and was discussed in the review in Chapter Two.

### 4.2.6 Repeatability and validation

It is widely recognised that measurement of the small joints of the foot is less reliable than measurement of large joints such as the knee and hip [268]. The issues of reliability have been discussed in Chapters One and Two and will not be developed again here. One point to note however, relates to the issue of drawn segment bisections, lines drawn on to the skin against which supposedly objective clinical measures can be derived. Significant error has been shown to exist even in the preliminary marking of segment bisection lines [366], introducing error before the act of manual measurement.

Recent attempts have been made to attempt to refine the marking of bisection lines through calliper-derived markings [11], but while this approach appears to improve the technical reliability of measurements, such techniques are time consuming and technically awkward, and have not been adopted in routine practice. Any new measure must be better evaluated for reliability and validity prior to its adoption in practice, to prevent a repeat of the existing state of affairs.

### 4.2.7 Time to complete the assessment and requirement for specialised equipment

It has been noted previously that the time taken to undertake objective evaluations and requirement for specialised equipment can be a barrier to their use in clinic [189]. Further detailed discussion of this point is therefore unnecessary, other than to make the point that it was considered desirable therefore, for a clinical measure such as the FPI to be quick to conduct and not to require specialist equipment.

## *4.3 CONSTRUCTION OF A DRAFT FOOT POSTURE INDEX*

### 4.3.1 Identification of potentially suitable components

In a comprehensive review of the literature, 119 papers were identified as describing in adequate detail, the clinical evaluation of foot posture. Descriptions ranged from incidental outlines of the methods used to evaluate interventions, through to comprehensive studies of the validity or reproducibility of specific measures. It is recognised that even a large search such as this may not include all such literature but the degree of duplication encountered toward the end of this stage of compilation, indicated that the majority of the concepts reported in the literature had been covered.

From the 119 papers reviewed, a range of 36 clinical indicators was identified, many of which are in current general use as outlined in the table overleaf (Table 4.31).

## Table 4.31. Clinical indicators of foot posture.

| Clinical indicators | Comment |
|---|---|
| 1. Frontal plane position of the calcaneus [11,14,195,209,219,220,276,278-280,283,284,333,335,347,367-378] | The frontal plane position of the heel is reported in a variety of forms. Most obviously it may be estimated or measured, with or without a guide bisection. This was the most frequently reported measure by some margin. |
| 2. Subtalar joint total range of motion non-weightbearing [140,333,347,374] | This was widely reported, but is based on a non-weight bearing measure and so failed to meet the empirical criteria for inclusion.<br>*Note: this citation list has been truncated for brevity as this measure was not to be considered further.* |
| 3. Palpation of the head of talus to determine talo-navicular congruence [10,219,275,276,278,281,333,347,348,367,368,379] | Palpation of the head of the talus is used widely in defining the 'neutral' reference position for further study. Reports relate to both weightbearing and non-weightbearing assessment. |
| 4. Arch height [14,185,193,195,209,219,220,224,278,279,284,342,370,372,373,378,380,381] | Various interpretations of measures of arch height were reported Arch height measures may reported raw, or normalised to other measures such as foot length. |
| 5. Visible lack of congruence or 'bulging' of the talo-navicular joint [195,219,241,369,373,380,382,383] | This is a subjective measure but was considered further as the talonavicular joint is known to be important to midfoot stability, and few other measures exist. |
| 6. Transverse plane deviation of the foot at the mid-foot [195,219,220,257,258,283,284,342,370,372,373,375,377,380,381,383-385] | Variations on this feature (including Johnson's widely known 'too-many-toes' sign) are commonly reported. |
| 7. Arch index [140,256,272,371] | The ratio of the area of the middle 33% of a truncated foot print to the area of the total print. Objective and widely reported but criticised for having a weak relationship with foot function |
| 8. Valgus index [14,386,387] | A measure of the shift of the malleoli over the hindfoot. As with arch index it is objective, but not correlated well with other measures of foot function. Requires time consuming measurement and is enhanced by the use of special instrumentation. |
| 9. Footprint 'width'[187] | An empiric measure of the width of the footprint at defined anatomical landmarks. Objective but not well related to foot function. |
| 10. Chippaux-Smirak index[272] | Uses a foot print as the basis for deriving a number of lines describing the geometric relationships of the segments making up the print. Objective, but time consuming and complex. |
| 11. Photopodogram[272] | A further variation on the philosophy of the arch index and Chippaux-Smirak index, photopodogram uses a camera to derive an image of the weightbearing surface of the foot during standing. |
| 12. Alpha angle [257] | A measure of the forefoot to rearfoot angular relationship in the transverse plane. Derived from footprints as above |
| 13. Footprint angle of Schwartz[272] | A further measure of the forefoot to rearfoot angular relationships derived from footprints as above. |
| 14. 'Podometrics' [388] | A complex multi-angled approach to foot classification. Represents an approach rather than a specific measurement technique. |
| 15. Contour of the lateral border of the foot [220,373,375] | This observation is employed by clinicians but its low rate of occurrence in the literature reflects the lack of acceptance of such subjective measures in the research community. |
| 16. Convexity of the medial border of the foot[220,389] | This observation is noted by clinicians, but is not a common finding. Convexity of the medial border of the foot occurs in severe pes valgus pathology with significant MTJ deformity. |
| 17. 'Peek-a-boo' heel sign [390] | A sign noted when the medial border of calcaneus is visible medially when the foot is viewed anteriorly along it longitudinal axis. Reported to indicate a cavo-varus attitude of the foot. |
| 18. Congruency of the curves above and below the lateral malleolus[223,367] | Often used in clinical practice as a general observation but not quantified. Has not been validated, and in general use is subjective. |
| 19. Puckering of the skin overlying the sinus tarsi[223] | A subjective measure, rarely used in clinical practice, and not adopted by the research community. |
| 20. 'Arch angle' [195] | The angle formed by two lines connecting the medial malleolus, the navicular tuberosity and the first mtp joint. Allows for quantification of foot posture and has been validated. |
| 21. Tibial rotation in the transverse plane[191,195,219,220,278,280,391,392] | McPoil and Cornwall used a device (LERMED) to facilitate easier measurement and Nester quantified the shank rotation precisely using a video based analysis system. The linearity of any relationship between foot and tibia was criticised by Reischl et al [18], and Nester also notes shortcomings in this technique. |
| 22. Hallux rotation in the frontal plane [393,369] | This appears to be a valid measure and is consistent with the findings of Benink and Lundberg, it is not possible to accurately measure in the clinical setting however, and is discounted from subsequent consideration. |
| 23. Navicular drop[15,276-278,394] | This is a pseudo-dynamic test, rather than a simple observation. Navicular drop quantifies the change in navicular height as the foot assumes a relaxed posture from a 'neutral' starting position. Some evidence for its validity but relies heavily on the reliability of the 'neutral' position. |
| 24. Relative arch deformation [282] | This pseudo dynamic test provides a measure of the 'stiffness' of the arch. It is based on the difference in arch height between loaded and unloaded states, |

| | |
|---|---|
| | after factoring resistance to deformation and body weight. Requires calculation. |
| 25. Navicular drift[15] | A measure of translational change in the medio-lateral position of the navicular tuberosity parallel to the floor. Similar in concept to the widely used navicular drop but based on the premise that motion is occurring in 3 planes and that talar head plantarflexion is accompanied by adduction. |
| 26. Arch shape[373] | The congruence of the curve of the medial arch. This is a widely used clinical observation, which has proven difficult to quantitate. It is used in conjunction with observation of arch height to estimate medial stability. |
| 27. Helbing's sign[143 219 373 378 395] (also quantified by Grumbine) [381 396] | An observation of deviation of the tendo-Achilles at its insertion to the superior border of the calcaneus. Not quantified or validated but a widely reported clinical sign. |
| 28. Subtalar joint axis orientation[283 285] | Estimation of STJ axis orientation is not strictly an estimation of foot posture. Proponents contend that estimating STJ axis orientation in addition to other estimates of foot posture enhances assessment. Not validated. |
| 29. Medial vs lateral malleolar prominence[283 378] | An indication of the medial displacement of the hindfoot thought to occur with hindfoot pronation. Analogous to Rose's Valgus index (above) with out quantification. |
| 30. Passive hallux dorsiflexion in relaxed standing[339 397-399] | Widely known as 'Jack's test' or the Huebschner 'manoeuvre' , this is a pseudo-dynamic evaluation of medial column flexibility. Despite being in widespread clinical use, it is not a direct measure of foot posture and will not be considered further. |
| 31. Lateral arch contour (sagittal plane) [375] | This measure of the relative positions of the anatomical components of the lateral border of the foot is primarily associated with non-weightbearing patient assessment. |
| 32. Rearfoot, midfoot and forefoot classification matrix[225] | A complex system defining a matrix of a range of features apparent in the foot . Foot types are classified according to observations and placed into a matrix , which then predicts likely function. Not validated and has not been widely adopted. |
| 33. Malleolar valgus index[279] | A subtle variation on Rose's valgus index (See above) |
| 34. "Feiss line" [143 280 281] | The relationship of the navicular tuberosity to a line drawn between the medial malleolus and the 1st mtpj.(see Arch angle) |
| 35. Navicular height [14 185 193 224] | Variously reported either as a raw measure, or as a value normalised against foot length. |
| 36. Block test[137] | A test is performed on feet which appear to be cavus in order to determine whether the deformity is fixed or flexible. A non-weightbearing variant, based on the same principles was also proposed by Price and Price[400].The block test does not attempt to quantify foot posture directly but provides a measure of the degree of flexibility of a foot position. |

It is evident that a wide range of approaches can be applied to evaluating the function of the weightbearing foot, and there is evidence of overlap between some measures. The measures outlined in the table were next classified according to how each represented the foot. Five categories were identified: 1) Direct measures of foot posture, 2) Indirect measures of foot posture, 3) Philosophies or approaches to foot classification, 4) Pseudo dynamic tests, 5)Supplementary tests aimed at predicting how a given posture might function (rather than measurement of the foot posture *per se*.)

A single measure incorporating all of the above features was felt to be impractical, as it was impossible to assert that such a complex combination of factors could be distilled into a single quantitative measure. Mindful that the primary purpose of the new instrument was to quantify foot posture according the guidelines outlined in the APTA Foot and Ankle Special Interest Group consensus statement, emphasis was placed on direct measures that may contribute to fulfilling this specific aim. Direct and indirect measures of foot posture were placed into the matrix outlined in the table overleaf (Table 4. 32), to identify duplicate measures.

**Table 4. 32. Matrix detailing the coverage by existing clinical measures, of the three planes and anatomical foot components.**

| | Rearfoot | Midfoot | Forefoot | Composite (direct) | Composite (indirect) |
|---|---|---|---|---|---|
| Frontal plane | • Frontal plane position of the calcaneus<br>• 'Peek-a-boo' heel sign<br>• Congruency of the curves above and below the lateral malleolus<br>• Helbing's sign<br>• Medial vs lateral malleolar prominence | N/A | • Hallux rotation in the frontal plane | | • Valgus index |
| Sagittal plane | N/A | • Arch height /normalised arch indices<br>• Visible lack of congruence or 'bulging' of the talo-navicular joint<br>• 'Arch angle'<br>• Arch 'deformation'<br>• Arch shape<br>• Navicular drop Lateral arch contour (sagittal plane)<br>• Navicular height<br>• Feiss line | N/A | | • Arch index |
| Transverse plane | • Tibial rotation in the transverse plane | • Palpation of the head of the talus to determine talo-navicular congruence<br>• Visible lack of congruence or 'bulging' of the talo-navicular joint<br>• Transverse plane deviation of the foot at the mid-foot (inc too-many-toes)<br>• Straightness of the lateral border of the foot<br>• Navicular drift<br>• Alpha angle (after Freychat) | N/A | | • Alpha angle<br>• Freychat's angle |
| Triplanar (all 3 planes) | N/A | N/A | N/A | • Stretching or puckering of the skin overlying the sinus tarsi<br>• Rearfoot, midfoot and forefoot classification matrix | • Valgus index<br>• Footprint 'width'<br>• Malleolar valgus index<br>• |

#### 4.2.1.1 Component selection

Of the measures identified in the above matrix, all those requiring either a formal measurement or special equipment were excluded, due to potential problems with learning techniques, or where a requirement for equipment may present a barrier to their use in clinical practice. Any measures requiring the drawing of bisections based on anatomical features, or necessitating time-consuming measurements were similarly excluded.

After these exclusions, sixteen measures were selected from the matrix, providing in combination, adequate coverage of the position of the component parts of the foot.

1) Frontal plane position of the calcaneus
2) 'Peek-a-boo' heel sign
3) Congruency of the curves above and below the lateral malleolus
4) Helbing's sign
5) Medial vs lateral malleolar prominence
6) Arch height /normalised arch indices
7) Visible lack of congruence or 'bulging' of the talo-navicular joint
8) Arch shape
9) Lateral arch contour (sagittal plane)
10) Palpation of the head of the talus to determine talo-navicular congruence
11) Visible lack of congruence or 'bulging' of the talo-navicular joint
12) Transverse plane deviation of the foot at the mid-foot (inc too-many-toes)
13) Straightness of the lateral border of the foot
14) Navicular drift
15) Stretching or puckering of the skin overlying the sinus tarsi
16) Hallux rotation in the frontal plane

These 16 measures were considered further against the desirable characteristics of the FPI components outlined earlier. Composite measures covering multiple planes or segments were excluded, as it would be inappropriate to include composite sub-components in an index such as the FPI, itself a composite measure. Some measures, such as 'stretching or puckering of the skin over the sinus tarsi' were considered too difficult to assess according to specific criteria. Finally, where there was overlap, with multiple measures assessing similar positions in similar parts of the foot, those identified as being the most commonly employed were adopted ahead of those less widely used.

At this stage it was not yet clear whether a novel measure as was being proposed would a) be feasible and b) be acceptable to the clinical community. Early, informal but wide-ranging consultation was undertaken over several months with some 20 practitioners experienced in the assessment of feet and foot types. Along with the theoretical considerations outlined above, the input of these clinicians led via an iterative process, to the selection of eight criteria for a draft version.

During the consultation period it also became clear that precise differentiation of forefoot and midfoot segments had the potential to be problematic. The consultation versions of the FPI incorporated measures scoring three anatomical segments, but early feedback suggested that philosophically, there may be better balance in an index describing only two anatomical segments, based on an instrument comprising four hindfoot components and four forefoot/midfoot components.

The position in which the patient would be placed for recording the scores was also considered. The requirement for the measure to be taken weightbearing has been discussed previously. The relaxed stance position has been previously shown to be repeatable and was a natural candidate, although consideration was also given to the assertion that single limb standing may be a better indicator of dynamic function than the classic double limb quiet stance[333]. It was ultimately decided to take all measures in double limb standing because: a) this position is better known to practitioners and b) the populations in which the new measure will be used includes patients with balance and postural control limitations.

#### 4.2.1.2 Selection of the scoring system

Once the eight measures were collated into a draft composite index, the scoring system was developed. A number of options were considered based on the requirement of the new measure to be simple to score yet to yield valid quantitative data.

Analogue scales are used widely in similar applications but require the clinician to measure them after the patient encounter, and they can be less reliable than other forms of measure. Likert type scales are widely used where rapid and consistent data collection is important [312].

While Likert–type scoring scales exist in many forms, the common features are of defined positions on a constant scale, and a limited number of response options [315 316] This format matched the remaining key principles and was considered further.

Likert-type scales may have from three to twenty or more graduations but although increasing the number of graduations increases the sensitivity of the scale it also decreases the reliability.

It was also clear that for a clinical tool such as the FPI, where it is desirable to have specific criteria matching each point on the scale, a smaller number of intervals is preferable [315 316]. Likert scales may be presented with an odd or even number of intervals [315 317]. For surveys it is common to construct scales with an even number of potential responses to avoid non-committal responses. For the purposes of the FPI however, it was immediately apparent that were the scale to have a central value variations toward each of the two postural directions of pronation and supination could be described symmetrically.

Seven and nine point scales were considered but discarded due to difficulties with defining multiple criteria, and potential problems for clinicians in learning the many graduations. A three point Likert scale would be expected to improve reliability but was felt during the consultation period to be lacking in discrimination. A five point, Likert-type scale with symmetrical scalar responses either side of a normal neutral position has been suggested previously to provide the best compromise between sensitivity, reliability and ease of use [315 317], and so this format was considered further for the FPI. Pronation and supination are motions either side of a central, idealised 'normal' position so instead of scoring the left anchor at '0' or '1' the central 'normal' response was valued at 0, with the sign of the scalar deviation from this central response indicating the direction of postural change. Foot postures tending towards a more supinated position are denoted by a negative score, with a positive score indicating a feature associated with pronation of the foot.

| **Features associated with marked supination** | **Features associated with moderate supination** | **Features associated with a 'normal' foot posture.** | **Features associated with moderate pronation** | **Features associated with marked pronation** |
|---|---|---|---|---|
| -2 | -1 | 0 | +1 | +2 |

With eight component measures, each scored on a symmetrical five point scale, the composite scores for the eight-item FPI as a whole range from –16 to +16. Including the zero, this makes a composite scale of 33 points requiring no calculation other than a simple tally of the eight components. The eight components can also be considered in total, or in various combinations according to a part of the foot or plane of positional change of particular interest.

***Note***: in the course of the validation process (detailed subsequently throughout Chapters 4 to 7) the scoring criteria for each component measure were refined continuously. The definitions provided below represent the first iteration, the latest definitions are provided subsequently.

### 4.3.2 Selected component measures

The eight clinical observations included in the early draft of the FPI (FPI-8) were:

1. Talar head palpation
2. Supra and infra lateral malleolar curvature.
3. Helbing's sign
4. Prominence of the sustentaculum tali
5. Congruence of the medial longitudinal arch
6. Congruence of the lateral border of the foot
7. Abduction/adduction of the forefoot on the rearfoot.
8. Calcaneal frontal plane position

#### 4.3.2.1 Talar Head Palpation

*Clinical observation*

*The head of the talus is palpated on the medial and lateral side of the anterior aspect of the ankle. Using either the thumb and forefinger of one hand or the forefinger of both hands the prominence of the head of the talus is palpated immediately anterior to the most distal portion of the tibial and fibular malleoli. The relative prominence on the medial and lateral side of the ankle joint is determined, as an estimate of the congruence of the talo-navicular joint.*

This assessment measures the congruence of the talo-navicular joint (TNJ), and represents the relationship between the rearfoot and mid foot predominantly in the transverse plane. It was first described by Inman in 1969 and has since been described extensively in the literature [212 213 269 344 347]. Talar head palpation appeared in nearly half of the papers informing this section of the study. The reliability of this test has been questioned, [212 213 269 344] because of the experience required on the part of the examiner, and the difficulty in accurately determining congruence of the talo-navicular joint (TNJ) by manual palpation alone. However, the TNJ has been shown to vary its position significantly with changes in foot posture, and it represents a useful clinical indicator if taken in the context of other clinical observations.

Criteria for Talar Head Palpation scores were originally defined as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Head palpable on lateral side/not on medial side | Head palpable on lateral side/slightly palpable on medial side | Head equally palpable on lateral and medial side | Head slightly palpable on lateral side/ palpable on medial side | Head not palpable on lateral side/ palpable on medial side |

#### 4.3.2.2 Supra and infra lateral malleolar curvature

*Clinical observation*

*With the patient standing in the relaxed calcaneal stance position, the profile of lateral ankle is visualised from behind with the observer placing himself or herself in line with a bisection of the long axis of the foot. The concavity of the curves above and below the lateral malleolus is observed. In the neutral foot, the curves should be approximately symmetrical above and below the malleolus.* [223]*. Frontal plane eversion of the rearfoot associated with pronation will increase the concavity of the curve below the malleolus, while the reverse will occur with supination.*

The reliability of this method has not been rigorously evaluated, although it has been reported by Cook et al [223] to have a similar degree of reliability to the widely employed calcaneal frontal plane measure described previously.

The supra and infra lateral malleolar curvature was scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Infra – malleolar curve markedly straighter than supra | Infra – malleolar curve slightly straighter than supra | Both infra and supra malleolar curves roughly equal | Infra – malleolar curve slightly more curved than supra | Infra – malleolar curve markedly more curved than supra |

#### 4.3.2.3 Helbing's sign

*Clinical observation*

*With the patient still standing in the relaxed calcaneal stance position, the ankle is again visualised from behind with the observer placing himself or herself in line with a bisection of the longitudinal axis of the foot. The frontal plane orientation of the tendo-achilles (TA) is noted at the insertion into the calcaneus. This indicates the frontal plane position of the rearfoot, as lateral deviation of the TA is associated with eversion of the calcaneus.*

Bowing of the tendo-Achilles was first described in a study by Kelly [222] and has since been described by Franco [143] and others [369 373 396]. Helbing's sign is almost universal in its use in the clinical assessment of foot type and function.

Helbing's sign was scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Tendo-Achilles markedly bowed into inversion | Tendo-Achilles slightly bowed into inversion | Insertion of Tendo-Achilles straight | Tendo-Achilles slightly bowed into eversion | Tendo-Achilles markedly bowed into eversion |

### 4.3.2.4 Bulging of the talo-navicular joint in the region of the sustentaculum tali

*Clinical observation*

*In this observation the patient is again observed from behind while standing in their relaxed stance position. The area of the medial side of the foot immediately posterior to the tuberosity of the navicular is observed. Where the TNJ is significantly incongruent in pronation, the soft tissues overlying the TNJ will be distended*[143 369 373 234].

This measure was described in more detail by Dahle et al who found it to contribute to a reliable overall indication of foot posture[195]. It has also been shown to be a significant predictor of MRI quantified foot posture in people with rheumatoid arthritis [234]. The reliability of this technique in isolation has not been established although Dahle reports satisfactory agreement with other measures.

This is a measure of the relationship between the rearfoot and midfoot in the transverse plane. The amounts of motion occurring in the midtarsal joints have been suggested to exceed motions occurring in the rearfoot [350]. The midtarsal joint is co-dependent with the rearfoot for tarsal stability, and changes in talo-navicular joint position are a useful indicator of foot posture.

Bulging of the area overlying the talo-navicular joint was scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Area of TNJ markedly indented | Area of TNJ slightly, but definitely indented | Area of TNJ flat | Area of TNJ bulging slightly | Area of TNJ bulging markedly |

### 4.3.2.5 Congruence of the medial longitudinal arch (MLA)

*Clinical observation*
*With the patient standing, the arch height and the congruence of the curvature of the arch is observed obliquely from the medial aspect. In a neutral foot the curvature of the arch is expected to be relatively uniform, similar to a segment of the circumference of a circle. As the foot supinates the arch height increases and the curve of the MLA becomes more acute at the proximal end of the arch. In the more pronated foot the arch height decreases and the MLA becomes flattened in its central portion, as the midtarsal and Lisfranc's joints sublux in the sagittal plane.*

The changes in arch height and congruence associated with changes in foot posture are well documented. The height of the arch has long been recognised as an indicator of foot function [143 220 276] with references to flat foot posture documented as early as the 16th century. The congruence of the arch has been described in the recent literature [373 389] but while widely reported, it is not as universal an indicator as arch height [191]. The reliability of the clinical observations has not been well documented. Some authors have questioned the reliability and validity of measuring arch height accurately [15 249 255]. Cowan in 1994 [401] found that the inter-rater reliability of clinicians in evaluating the arch height from photographs was variable at best, although Saltzmann reported the measurement of arch height to represent a valid and reliable first order approximation of the MLA structure [185], a finding which was supported by Sell et al [272] and later by Weiner-Ogilvie. [14].

The arch height and congruence are scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Arch high and acutely angled | Arch moderately high and slightly acute angle | Arch height normal and concentrically curved | Arch lowered with some flattening | Arch very low with severe flattening |

### 4.3.2.6 Congruence of the lateral border of the foot

*Clinical observation*

*With the patient again standing in the relaxed calcaneal stance position, the lateral border of the foot is visualised from behind with the observer placing himself or herself in line with the longitudinal axis of the rearfoot. The observation of lateral border congruence relates to the congruence of the joints of the midfoot in the transverse plane [220 373].This measure is not* *appropriate where there is a fixed adduction deformity of the forefoot on the rearfoot in the non-weightbearing state.*

Lateral border profile has been described by Dahle et al [195], who found that this measure contributed with satisfactory reliability to the determination of foot type when used in conjunction with other measures. Freychat et al [250] suggest that the amount of abduction or adduction of the forefoot on the rearfoot is a good indicator of foot function.

Lateral border congruence is scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Lateral border markedly convex | Lateral border slightly convex | Lateral border straight | Lateral border slightly concave | Lateral border markedly concave |

#### 4.3.2.7 Abduction/ adduction of the forefoot on the rearfoot

*Clinical observation*

*The measure is based on the premise that when viewed from directly behind the heel the neutral foot will allow the observer to see equal amounts of the forefoot on the medial and lateral sides. It is important in making this observation for the observer to place himself or herself carefully in line with the longitudinal axis of the rearfoot. Transverse plane motions occurring between the rearfoot and the forefoot will allow the visualisation of more of the forefoot on either the medial or lateral side. In the supinated foot the forefoot will adduct on the rearfoot resulting in more of the forefoot being visible on the medial side. Conversely pronation of the foot causes the forefoot to abduct resulting in more of the forefoot being visible on the lateral side.*

Observation of abduction/ adduction of the forefoot on the rearfoot has been described repeatedly in the literature by Duckworth [389] and others [220 250 373] but this clinical sign has not been documented for reliability. This observation is a variation of the 'too many toes sign' [384], although other variants such as the 'peek-a-boo' heel [390] have been described and rely on the same theoretical base. This measure is again potentially inappropriate where there is a fixed adduction deformity of the forefoot on the rearfoot in the non-weightbearing state.

Abduction/adduction of the forefoot on the rearfoot is scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | 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 |

#### 4.3.2.8 Calcaneal frontal plane position (Inversion / eversion)

*Clinical observation*

*The frontal plane orientation of the calcaneus relative to the weightbearing surface is assessed from behind, with the patient standing. The measurement can be made either with or without a bisection line drawn on the calcaneus and the reliability of bisection lines have been discussed previously. In the FPI study the position was visualised without bisection lines.*

This is one of the more commonly used clinical measures of foot posture, and has been described extensively in the literature [195 274 368 369 373 389]. The reliability of measuring calcaneal position has been criticised by many authors, [188 212 213 347] although it has been reported as being adequately reliable if the same rater takes the measure [368]. It has been reported to be more reliable when measured weight bearing [272] a position that is also considered better representative of the function during gait [345].
Goniometric measurement of calcaneal position is probably not valid as a single measure of foot posture, however it remains a useful observation, and is thought to serve clinically as a valid indicator of the degree of maximum rearfoot eversion during gait [333].

This is an observational equivalent of the measurements often employed to quantify the relaxed and neutral calcaneal stance positions. It is scored as follows:

| **Score** | **-2** | **-1** | **0** | **1** | **2** |
|---|---|---|---|---|---|
| **Description** | Markedly inverted | Slightly inverted | Vertical | Slightly everted | Markedly everted |

## 4.4 *ASSESSING THE FEASIBILITY OF REPORTING FOOT POSTURE BASED ON A COMPOSITE INDEX OF EIGHT CLINICAL INDICATORS*

### 4.4.1 Introduction

The first stage of the evaluation was to conduct a small pilot study evaluating the feasibility of the FPI concept prior to expending energy and resources on a more comprehensive validation process. This stage can be considered a precursor to any formal evaluations and was a single session undertaken purely to determine whether the entire concept was unfeasible, or whether there was merit in establishing the formal program of evaluation. The characteristics of interest at this stage were simple face validity, ease of use and the time taken to perform the assessments.

### 4.4.2 Method

Eight podiatrists with clinical experience ranging from 2 to 18 years were recruited from the staff of the podiatry program at the University of Western Sydney, to perform a series of evaluations of foot posture using the FPI eight component version (FPI-8). No training was given, as first impressions were important, although each component and its associated criteria were outlined at the start of the session. Raters were provided with written instructions on scoring each component according to set criteria, and data sheets upon which they could score their ratings confidentially.

Each of the eight removed their shoes and socks in turn and stood in a relaxed standing position while the other seven clinicians rated independently, the eight FPI components on the standing participant's right limb. Group members rated the foot posture without conferring, and without knowledge of the others' scoring. The author provided no input to the rating process at this point.

In a debriefing session the criteria were discussed and the members of the group critiqued each of the eight sets of criteria. Finally a short questionnaire was administered in which the participants were invited to provide, on a five point Likert scale, their ratings of "Ease of use', Ease of understanding' and 'Usefulness' of the overall draft FPI-8 measure, and each of its components.

### 4.4.3 Analysis

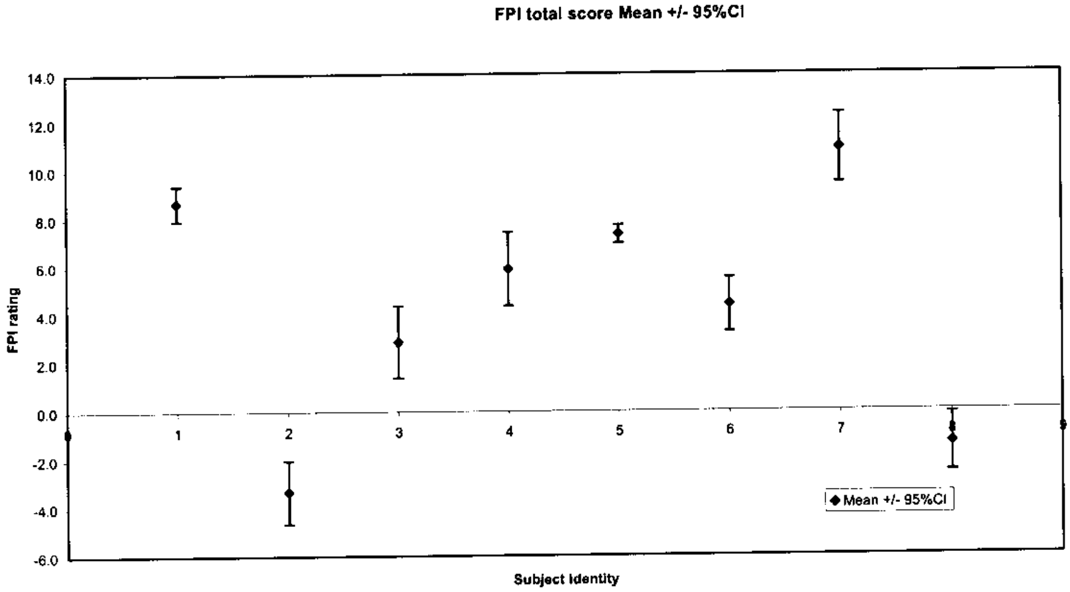
Inferential reliability statistics are inappropriate in a group of this small size. The agreement between the group members is therefore presented descriptively. Similarly the data for the group's perceptions of the ease of use and utility of the FPI-8 and its components are presented descriptively only, as appropriate to this preliminary evaluation. Full inferential analyses of aspects of the reliability and validity are undertaken in subsequent chapters.

### 4.4.3.1 Agreement between raters

*FPI total score*

A graphical representation of the agreement between raters is shown below. The graph demonstrates the mean (+/-95% confidence intervals) of seven ratings of the FPI-8 total score for each of the subjects 1 through 8.

**Figure 4.49 . The mean and 95% confidence intervals for the seven ratings of each of the eight subjects' FPI-8 total scores.**



The agreement between the ratings was adequate for this stage of the study. The group received minimal training in the use of the FPI, had no chance to develop any experience in rating feet using the index prior to their participation in the study, and had no access to manuals or other training materials. The criteria for each of the FPI components were also at their least refined.

### 4.4.3.2 Instrument utility

The survey results for the ease of use, ease of understanding and the utility of the FPI-8 are shown in Table 4.33. For all three items 1 = a low level of satisfaction and 5 = a high level of satisfaction.

**Table 4.33. Consumer satisfaction with the FPI-8 overall**

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 4.7 | 4.6 | 5.0 |
| Minimum | 4 | 4 | 5 |
| Maximum | 5 | 5 | 5 |

### 4.4.3.3 FPI components

FPI component measures were also evaluated individually and are presented on the subsequent pages. A figure plotting the mean and the 95% CI of the observations within the group is presented for each component and the 'consumer satisfaction' results are presented.

*FPI component 1. Talar head palpation*

Figure 4.50. Mean scores and 95%CI

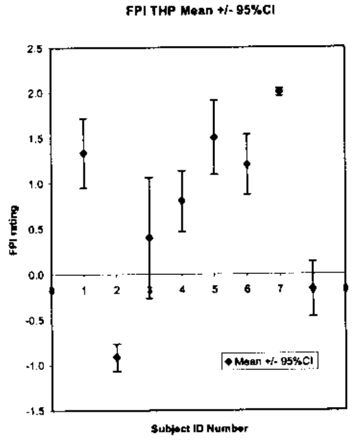


Table 4.34. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 4.9 | 5.0 | 5.0 |
| Min | 4 | 5 | 5 |
| Max | 5 | 5 | 5 |

*FPI component 2. Malleolar curves*

Figure 4.51. Mean scores and 95%CI

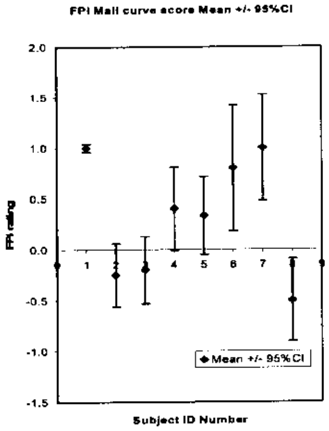


Table 4.35. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 4.7 | 4.9 | 5.0 |
| Min | 4 | 4 | 5 |
| Max | 5 | 5 | 5 |

*FPI component 3. Helbing's sign*

Figure 4.52. Mean scores and 95%CI

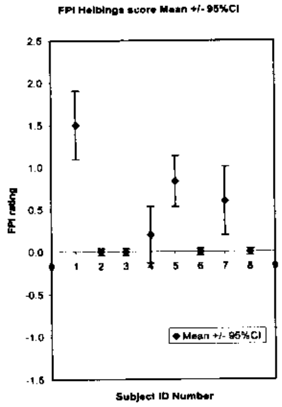


Table 4.36. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 5.0 | 5.0 | 4.7 |
| Min | 5 | 5 | 4 |
| Max | 5 | 5 | 5 |

*FPI component 4. Calcaneal position*

Figure 4.53. Mean scores and 95%CI

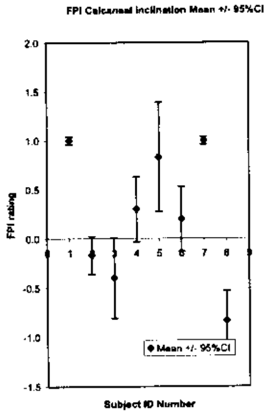


Table 4.37. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 4.6 | 5.0 | 5.0 |
| Min | 4 | 5 | 5 |
| Max | 5 | 5 | 5 |

*FPI component 5 Talonavicular congruence.*

Figure 4.54. Mean scores and 95%CI

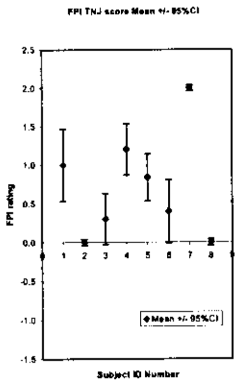


Table 4.38. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 4.6 | 4.4 | 4.4 |
| Min | 3 | 4 | 4 |
| Max | 5 | 5 | 5 |

*FPI component 6 MLA congruence.*

Figure 4.55. Mean scores and 95%CI

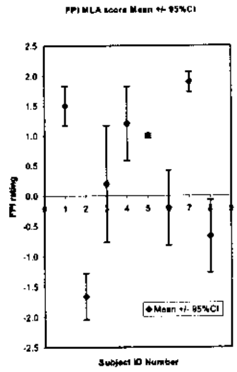


Table 4.39. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 5.0 | 5.0 | 5.0 |
| Min | 5 | 5 | 5 |
| Max | 5 | 5 | 5 |

*FPI component 7 Abd-adduction forefoot.*

Figure 4.56. Mean scores and 95%CI

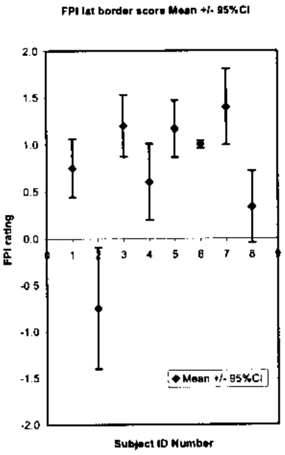


Table 4.40. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 4.9 | 4.7 | 4.6 |
| Min | 4 | 4 | 3 |
| Max | 5 | 5 | 5 |

*FPI component 8. Lateral border congruence*

Figure 4.57. Mean scores and 95%CI

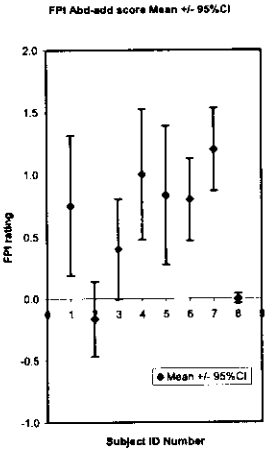


Table 4.41. Consumer satisfaction

| | Ease of use | Ease of understanding | Usefulness |
|---|---|---|---|
| Mean | 5.0 | 5.0 | 5.0 |
| Min | 5 | 5 | 5 |
| Max | 5 | 5 | 5 |

#### 4.4.3.4 Focus group feedback

The face validity was explored with the group, who compared the clinical description of foot types and with the relevant FPI scores.

**Table 4.42. Group foot type descriptions**

| Participant ID | Group description of overall foot type | Mean FPI overall score |
|---|---|---|
| 1 | Pronated – very flat footed. Almost no arch | 8.7 |
| 2 | Mild cavoid | -3.3 |
| 3 | Unusual. Heel looks like it should be supinated but the forefoot is abducted. | 2.9 |
| 4 | A bit pronated. Nothing remarkable | 5.9 |
| 5 | Definitely pronated | 7.3 |
| 6 | Quite normal | 4.4 |
| 7 | Very pronated | 10.9 |
| 8 | Rigid, slightly inverted | -1.3 |

*Note that the descriptors in the table are those provided by the group.*

There was a good degree of agreement evident between the terminology used in the clinical descriptions and the composite FPI scores.

The two foot types highlighted as the most pronated and supinated have the highest and lowest FPI scores respectively. No feet described by the group as 'pronated' had a score of less than +5 and neither of the 'high arched/ cavoid feet' had a positive FPI score.

The group also defined descriptors for the two functional segments nominated simply as the 'hindfoot' and 'forefoot', and these are compared with the relevant component scores in Table 4.43.

**Table 4.43. FPI scores for separate rearfoot and forefoot anatomical segments, along with group derived descriptors.**

| **Participant ID** | **Group defined rearfoot characteristics** | **Mean FPI rearfoot score** | **Group defined forefoot characteristics** | **Mean FPI forefoot score** |
|---|---|---|---|---|
| 1 | Quite perpendicular heel for the overall foot type | 4.4 | Very low arch. Almost touching floor. | 4.3 |
| 2 | Vertical, even a bit inverted | -1.2 | High arch and some clawing of the toes. | -2.1 |
| 3 | Vertical, slightly inverted even | 0.8 | Normal looking arch but forefoot abducted. A prominent lateral arch. | 2.1 |
| 4 | Quite everted | 2.7 | Just pronated | 3.2 |
| 5 | Everted | 3.4 | Quite a low arch. | 3.9 |
| 6 | Normal | 2.2 | Normal | 2.2 |
| 7 | Everted | 4.6 | Really flat footed | 6.3 |
| 8 | Neutral | -1.5 | Quite neutral | 0.2 |

The FPI forefoot/rearfoot scores were consistent with the clinical description in seven of the eight cases, and was sensitive to the two anomalous feet in the group (subjects three and eight), who had slightly atypical forefoot to rearfoot presentations.

In summary, the debriefing session provided useful feedback which was used to evaluate the face validity of the new instrument.

## 4.5 *DISCUSSION AND CONCLUSIONS*

The phases outlined in the second part of this chapter represent no more than the first stage in evaluating the feasibility of developing a new measure along the lines proposed, and a more detailed series of validation experiments are presented in the subsequent chapters. The initial feasibility investigation did however identify a range of issues worthy of further discussion. Starting with the context for the new FPI, it must be recognised immediately that the new measure is by intent a compromise rather than an absolute advance in its own right. More objective measures, limited though they may be in technical terms and in their availability to the clinician, do exist already. In support of the new approach however, it has to be recognised that the clinical methods commonly used in day-to-day practice demonstrate more shortcomings than is acceptable for their continued use, and a useful and validated compromise solution may still represent a genuine advance. The limitations of existing measures are recognised in some quarters but largely ignored by clinicians, although one recent large survey of physiotherapists demonstrated that demand for a valid new measure was high [189]. It was considered important therefore that the evaluations of the FPI-8 in subsequent chapters included quantification of the degree of compromise associated with a clinical measure such as this.

In any composite measure such as the FPI, there exists the potential for variability in the relative contributions of the components to produce the same total score despite internal variability between components (sometimes referred to as a lack of uni-dimensionality). This is true for any number of measures, including for example, the Beighton-Carter-Wilkinson scale for hypermobility, and for the majority of health related quality of life measures using multiple questions, such as in the extensively used MOS SF-36. This potential for internal inconsistency can be regarded as an undesirable feature, although this perceived deficiency can also be turned into a positive when it is made possible to break down the total score into sub-domains, as is the case with the SF-36. The careful composition of the FPI-8 such that scores can be so divided into sub-domains, (representing either the three body planes or the hindfoot or forefoot segments), may lead to the FPI having some advantage over existing single plane/segment measures.

In identifying suitable component measures it is important that the included components were all derived from existing literature. Firstly this provides a context for the historical evolution of a new measure, addressing some of the shortcomings of existing techniques, but also it ensures that for the most part no new techniques need to be presented or learned. It could be argued by contrast, that the limitations of existing measures persist in the FPI-8, and while the cross referencing of multiple components will go some way towards ameliorating this problem, this inherent shortcoming must be recognised.

Construction of a matrix based on the characteristics of the existing measures did allow for identification of a range of FPI components covering all the relevant planes of motion and, ultimately, two anatomical segments. The debriefing sessions with the eight clinicians involved in the first evaluations were highly informative in this regard, with the discussions highlighting differences in the clinical interpretation of the component observations by different observers. Ultimately the aggregation of the midfoot segment into the forefoot segment proved an appropriate solution, as most of the difficulty arose in the overlap of features between these two segments. The interposition of the tibia/ ankle joint between the hindfoot and the forefoot (with midfoot combined), did in the mind of the group allow for a clearer demarcation between these two segments, and this was the model that is taken forward. The discussions also highlighted areas where the scoring criteria could be made more explicit, and where formatting of the datasheets could be clarified. Although the development of the draft of the instrument was grounded firmly in the literature it is recognised that this early stage of the initial evaluative process was informal, and as such should be interpreted as no more than a preliminary phase where the basic concept was discussed and refined, informing but not pre-empting the subsequent validation process.

The protocol for using the FPI in quiet standing received positive feedback, as it was felt that the weightbearing examination was more reflective of dynamic function, than evaluations undertaken non-weightbearing. Quiet standing in double support has been shown to be broadly representative of function, and importantly for populations with systemic pathology such as CMT, is an adequately stable position for patients to stand still for the duration of the assessment.

The FPI is a score of the foot posture, as observed in quiet standing but it must be recognised that a range of supplementary clinical evaluations will still be required to obtain a complete clinical picture. The FPI is not intended to be a replacement for all clinical assessments, merely to provide, for one aspect of the standing foot posture- a more comprehensive evaluation than is provided by existing measures.

The application of a common scoring scale to a range of components has allowed for the derivation of a composite score from measures that otherwise might be expressed in a variety of units. A five point Likert scale provides for differentiation of responses without impacting unduly on reliability. Scoring the Likert scale around zero allows for the scores to reflect both magnitude and direction of postural variation. In preliminary testing, the reliability of repeat measures and the face validity of the new measure proved acceptable, as did ease of use, although it is recognised of course, that the test-retest evaluation was at this stage highly empirical, and that face validity and ease of use are largely subjective assessments.

Of the individual component measures, assessment of malleolar curves, lateral border congruence and forefoot, and calcaneal position demonstrated lower agreement than other measures. Talar head palpation was perceived as the most difficult measure to perform, and Helbing's sign showed less capacity for differentiating foot types than the other measures. No components performed particularly poorly however, and all were deemed suitable for retention in future drafts. The preliminary draft of the FPI-8, the first working version, and the final draft, the FPI-6 are presented in Appendices A,B and C at the end of the thesis.

## Conclusions

In this chapter the four aims were met. The review of the literature identified both the characteristics desirable in the new measure, and a range of potential component measures. Plotting the measures into a matrix, combined with an extensive period of consultation allowed for the most appropriate mix of components to be incorporated into the FPI draft. The measure proved easy to use in the clinical setting and received a positive response from clinicians. The structured feedback was highly positive, suggesting that the users considered the FPI-8 to be easy to understand and use. As anticipated, the feedback from this preliminary stage fed into some revisions of the formatting of the datasheets and wording of the scoring criteria. The FPI-8 demonstrated acceptable face validity both in terms of the total score, and in the segmental scores.

On the basis of its performance in the evaluations presented in this chapter, the draft FPI was considered suitable for more formal investigations of its reliability in a range of age groups.

# CHAPTER FIVE. PRELIMINARY FIELD TRIALS OF THE NEW INSTRUMENT.

---

***Chapter overview***

*This chapter outlines two separate preliminary field trials, and is thus presented in two parts.*
*In Chapter Five, Section one, the reliability of the FPI-8 is investigated, while Chapter Five , Section two details a preliminary round of validation, comparing the new FPI-8 with an extant clinical measure, Rose's 'Valgus Index'. The aim of the field trials was to provide an early indicator of whether the FPI-8 had merit enough, in terms of its reliability and validity to warrant the extensive and evaluations detailed in Chapter Six.*
*The reliability of the FPI-8 was investigated in three age groups representing the range of applications for which the measures is intended. This reliability evaluation was undertaken to establish the technical parameters within which the measure might be expected to operate, although the reliability of the measure in individual clinical populations will need to be quantified for studies involving specific foot pathologies.*
*In Section two the FPI was validated against an existing objective clinical tool. This evaluation was limited in that it reflected only the degree of agreement between two static measures of global foot posture, but it represented a level of investment appropriate to this stage of the process. Notwithstanding the limitations of the twin static assessments, this study allowed for a detailed analysis of some aspects of the validity of the eight components, and the finding that a large proportion of the variance in the objective measure was predicted by the FPI represented an important step leading to the detailed validation studies described in Chapter Six.*

---

## 5.1 CHAPTER FIVE, SECTION ONE – THE RELIABILITY OF THE FPI IN THREE AGE-STRATIFIED SAMPLES

### 5.1.1 Introduction

The reliability of the clinical application of the FPI was examined in three samples representing three distinct age groups from pre-school to adulthood. It was considered important to investigate the reliability of the measure independently in the three age groups, as the reliability of foot measurements have been reported previously to vary with age.

This aspect of the validation process required the input of several practitioners to perform the repeat measures, and was undertaken with the invaluable contribution of the co-workers, three experienced podiatrists from the University of South Australia. At the time this group was reviewing a range of existing clinical foot measures and agreed to collaborate with the evaluation of the reliability of the FPI. Thanks are due to Angela Evans, Rolf Scharfbillig and Alexander Copper for their contribution to this stage of the study.

Some of the data from this study subsequently contributed to a larger independent study conducted by Evans, Sharfbillig and Copper, evaluating a range of the available clinical foot measures. Some of the data has therefore been published recently as:

Evans A, Copper A, Scharfbillig R, Scutter S, Williams M. Reliability of the Foot Posture Index and traditional measures of foot position: *Journal of the American Podiatric Medical Association*, 2003, 93(3) 203-213 [402]

The analysis of the data presented in this chapter is however, entirely the product of the candidate's independent work, and relates specifically and in detail, to the FPI. No external assistance was received in analysing, compiling, or presenting the results herein.

The reliability studies were approved by the ethics review committees of the Universities of Sydney, Western Sydney, and South Australia. The boards of governors of the three schools at which data collection occurred also gave full permission. Individual written consent was obtained from the adult participants or from the parents of each participating child prior to their inclusion in the study.

## 5.1.2 Reliability study 1 – Adults aged 20-50 years

### 5.1.2.1 Introduction

The adult group was chosen for the first of the reliability studies, because the logistics of managing the clinical interaction were felt to be least problematic for this age group. It was decided at the outset to evaluate the two child groups later, once any unforeseen flaws in the study design had been rectified, and once the examiners had become more familiar with the data collection protocols.

The three independent examiners had not seen the FPI before their involvement with this study and the three raters had not used the FPI until the arrival of the candidate the day before the start of data collection.

A short training session was held immediately, but at the commencement of the reliability data collection session, each of the independent raters had only had the opportunity to use the FPI to score between six and eight foot postures. The effect of such inexperience is discussed in the summary of Chapter Five, Section one.

### 5.1.2.2 Method

A repeated measures approach was used, with both limbs of each participant measured independently using the FPI, by each of four assessors, on two occasions, over two days. The FPI manuals were available for reference regarding the specific scoring criteria, but the candidate, who at the time was the only member of the group familiar with the FPI, did not offer any advisory input once the data collection had commenced.

### 5.1.2.3 Sample

Thirty otherwise healthy normal adults were recruited from among the staff, students, patients and acquaintances of the School of Physiotherapy and Podiatry, University of South Australia. Prior to recruitment, potential participants were provided with written details of the requirements of their participation in the study and each potential participant gave full written consent.

All participants met the following criteria.

Aged between 20 and 50 years at the time of enrolment

No current injury or disease process affecting the lower limb

No history of significant trauma, disease or surgery with the potential for long term effects on the lower limb

Presence of ranges of motion in the lower limb sufficient to meet the requirements of the static assessment

Capacity to understand the information relating to the study and give informed consent.

### 5.1.2.4 Preparation of participants

At the measurement session the participants were given, in groups of four, appointments at 30 minute intervals. Participants were clerked-in and briefed by assistants independent of the study, and then changed into shorts to expose the lower limb from the knee down. All participants wore a surgical gown and a whole-face mask for the purposes of protecting their identity from the raters at the retest session. Once prepared for the measurement session, the participant stood on a large piece of paper in a relaxed angle and base of gait. A fifth podiatrist, not involved in the reliability ratings, drew an outline of the feet in the relaxed standing position onto the paper. This paper then accompanied the participant on all later measures to ensure consistency of foot placement. Each of the four participants in a group was directed to one of four low raised plinths placed in the four corners of the room. The participant stood on the paper and returned to the angle and base of gait recorded previously. Once the participant was standing comfortably, the FPI scores were rated independently by the four observers, with the left and right limbs rated in random order. The participant remained standing on the plinth in one corner of the room while the raters circulated individually between the four participants in a previously defined random order. Once each rater had completed a rating of a participant's foot the rating sheet was placed in a box so that the scoring was not visible to subsequent raters.

Each participant was known only by a code number to protect their identity from the raters at the retest session. The order of participants was again randomised at the retest session minimising the potential for recall of previous scores. Data were recorded to purpose-made collection sheets, and codified according to rater, prior to transcription onto electronic spreadsheets. Analyses were carried out using SPSS for Windows 11.1 (SPSS Inc, Chicago, IL) and Microsoft Excel (Microsoft Inc, Redmond, WA).

#### 5.1.2.5 Strategy for analysis

The intrarater and interrater reliability were initially investigated using intraclass correlation coefficients (ICCs) according to the method of Shrout and Fleiss. The appropriate ICC for the determination of the agreement between raters is Model 2, with the ICC based on a single measure from each observer. This application is commonly known as ICC (2,1). The calculation of the ICC model 2,1 in SPSS v 11.1 wasbased on a two-way ANOVA, with the observers entered as random effects and with the absolute agreement definition set.

Intra-rater, or 'test-retest' reliability was then investigated by deriving ICCs using the Shrout and Fleiss Model 3,1. In SPSS the ICC (3,1) was computed on a two-way ANOVA with the observers entered as mixed effects and with the consistency definition set.

In addition to the ICCs, the Measurement Error (ME) was computed for each of the raters, providing a result indicating the range in which the true value of a given measure might be expected to lie.

For two ratings ME is given by the formula

$$\mathrm{ME} = \frac{\mathrm{SD}_{\mathrm{differences}}}{\sqrt{2}}$$

and the result is expressed in the units of the original measurement. The ME and its 95%CI are reported individually, along with the mean value for the group of four raters.

Finally, mean-difference or 'Bland and Altman' plots were constructed to illustrate the stability of scoring for each of the four observers.

#### 5.1.2.6 Results – Adult group

***Investigation of agreement between raters – interrater reliability***

*ICC Two-way Random Effect Model (Absolute Agreement Definition):People and Measure Effect Random*

**Single Measure Intraclass Correlation (95%CI) = 0.57 (0.27-0.75)**

This inter-rater ICC of 0.57 lies on the border between 'fair' and 'moderate', according to the classification proposed by Landis and Koch [403].

***Investigation of test-retest agreement – intrarater reliability***

*ICC Two-Way Mixed Effect Model (Consistency Definition):*

*People Effect Random, Measure Effect Fixed*

**Table 5.44. Single Measure Intraclass Correlation**

| | ICC | 95% CI | F statistic | DF |
|---|---|---|---|---|
| Observer 1 | **0.73** | 0 .58 - 0.83 | 6.38 | 59 |
| Observer 2 | **0.79** | 0.67 - 0 .87 | 8.53 | 59 |
| Observer 3 | **0.87** | 0 .79 - 0.92 | 14.04 | 59 |
| Observer 4 | **0.85** | 0.76 - 0.91 | 12.11 | 59 |

The intra-rater retest reliability for the FPI scores ranged between 0.73 'good' and 0.87 'almost perfect'. This indicates a good deal of consistency for each rater between sessions. It would be expected that the intra-rater, retest reliability would be higher than the inter-rater reliability.

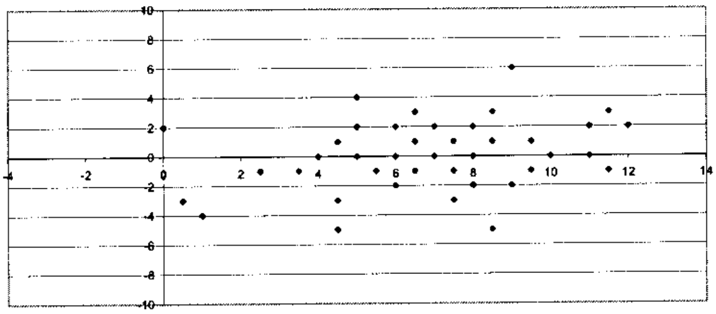
**Tests of relative and absolute agreement in FPI scores.**

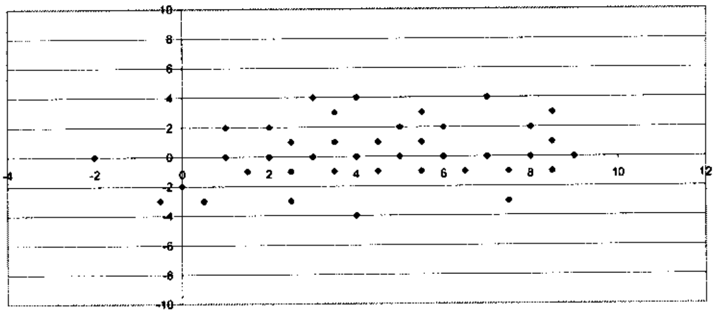
**Table 5.45. Measurement error and the 95%CI**

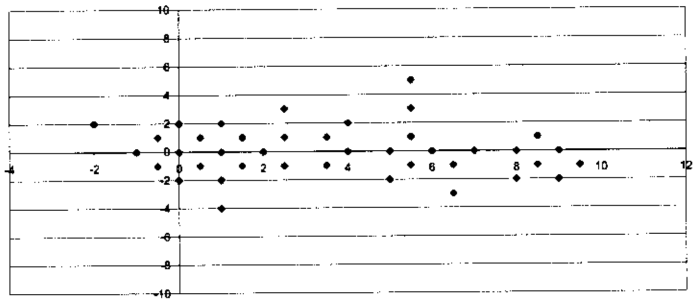
| | ME |
|---|---|
| Observer 1 | 1.48 (-1.42 to 4.38) |
| Observer 2 | 1.23 (-1.31 to 3.77) |
| Observer 3 | 1.14 (-1.09 to 3.37) |
| Observer 4 | 1.18 (-1.12 to 3.48) |
| **Mean** | **1.26 (-1.09 to 3.82)** |

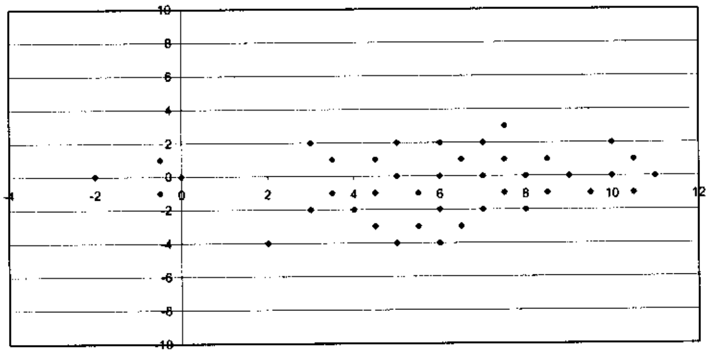
The ME values indicate that the FPI scores for repeat measures by each rater would be expected to lie within 1.2 to 1.5 FPI scale points of the raters' true quantification of that foot.

Mean-Difference plots of the scalar stability of the FPI scores.


Mean difference plot - Observer 1


Mean difference plot - Observer 2


Mean difference plot - Observer 3


Mean difference plot - Observer 4

The Mean - difference plots show good consistency between the rating habits of individual raters. In all cases the plots are grouped to an acceptable degree around the mean and there is no evidence of change in variation or difference as the mean score changes. This tends to indicate stability in the scalar responses, with clustering around the mean not varying greatly at the outer boundaries of the FPI scoring range.

## 5.1.3 Reliability study 2 – Children aged four to six years

### 5.1.3.1 Method

Again, a repeated measures approach was used, with both limbs of each participant measured independently according to the protocol described previously, on two occasions over two days. One of the raters involved in the adult evaluations was not available for this testing period, hence only three raters rated children in this subgroup.

### 5.1.3.2 Sample

Twenty-nine healthy normal children were recruited via their school. Letters were sent to the parents two weeks before the data collection sessions outlining the study, inviting the participation of the child, and providing a contact for further information if required. Parents indicating a willingness for their child to participate, completed and signed a consent form and returned it to the school. Only children for whom a completed, signed consent from was held were included in the data collection.

All participants met the following criteria.

- Aged four to six years at the time of enrolment
- No current injury or disease process affecting the lower limb
- No history of significant trauma, disease or surgery with the potential for long term effects on the lower limb
- Presence of ranges of motion in the lower limb sufficient to meet the requirements of the static assessment

Measurements of this sample were undertaken by three of the experienced raters mentioned previously.

### 5.1.3.3 Preparation of participants

Measurements were undertaken in a cleared area in the library of the school using the same protocol as was described previously for the adults study. Children attended in groups of four, for a set of measurements lasting approximately 30 minutes. The children stood on a raised plinth and the raters moved among them to perform the measures. Again the order of measurement of the raters and the rating of left and right limbs was randomised. Participants exposed the lower legs by rolling up trouser legs or skirts to knee height. As per the protocol for the adult group, participants stood in a representation of their angle and base of gait for all measures. Data were recorded to the same data collection sheets, and again codified according to rater.

### 5.1.3.4 Results – Children aged four to six years

*Intraclass correlation coefficients*

***Investigation of agreement between raters – interrater reliability***

*Two-way Random Effect Model (Absolute Agreement Definition):*

*People and Measure Effect Random*

**Single Measure Intraclass Correlation (95%CI) = 0.61 (0.34-0.78)**

*Investigation of test-retest agreement – intrarater reliability*

ICC Two-Way Mixed Effect Model (Consistency Definition):

People Effect Random, Measure Effect Fixed

**Table 5.46. Single Measure Intraclass Correlation**

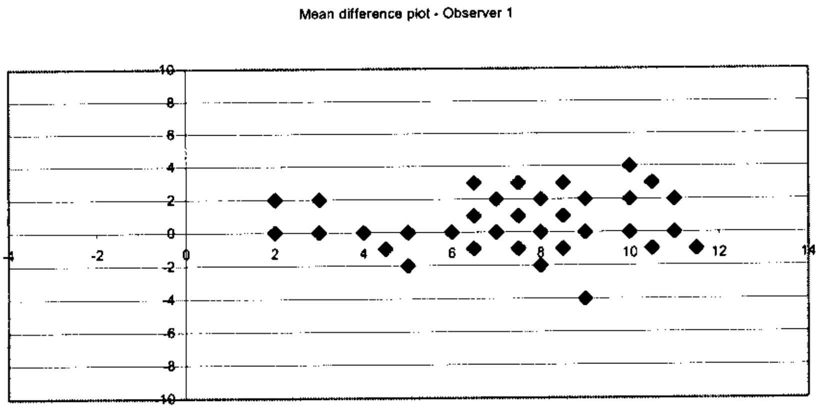
| | ICC | 95% CI | F statistic | DF |
|---|---|---|---|---|
| Observer 1 | **0.78** | 0 .65 - 0.86 | 7.99 | 57 |
| Observer 2 | **0.82** | 0.71 - 0 .89 | 9.86 | 57 |
| Observer 3 | **0.78** | 0 .66 - 0.86 | 8.13 | 57 |

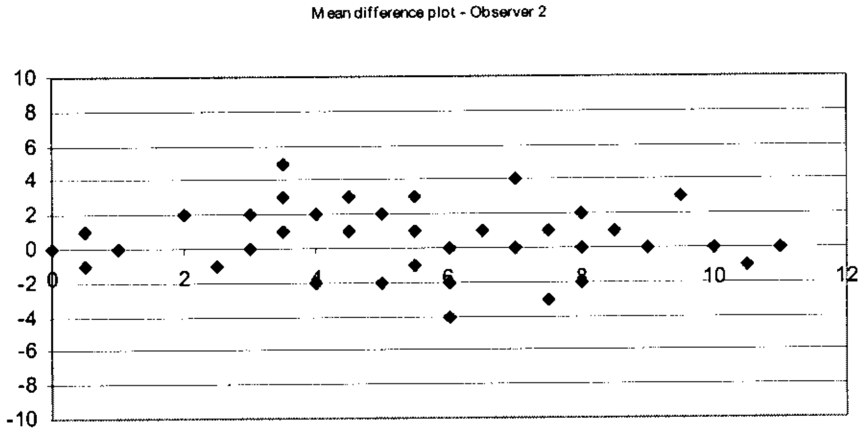
The intra-rater retest reliability for the FPI scores ranged between 0.78 'good', and 0.82 'almost perfect'. This indicates a good deal of consistency for each rater between sessions.

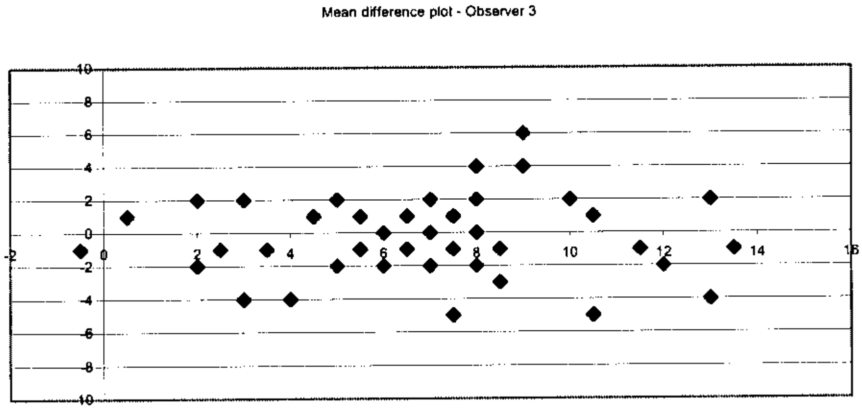
**Table 5.47. Measurement error and the 95% CI**

| | ME (95%CI) |
|---|---|
| Observer 1 | 1.13 (-1.09 to 3.37) |
| Observer 2 | 1.18 (-1.18 to 3.49) |
| Observer 3 | 1.14 (-1.55 to 4.59) |
| **Mean** | **1.15 (-1.29 to 3.77)** |

The scalar stability of the FPI scores for each rater is well represented graphically through the construction of Mean-Difference plots after Bland and Altman.







The Mean - difference plots again show a good linear relationship between the mean and the differences. There is some clustering evident in the plot for observer 1, but all the plots show a linear relationship between the mean score and the difference indicating scalar consistency in the younger age group similar to that seen in the adult sample.

### 5.1.4 Reliability study 3 – Children aged 8-15 years

#### 5.1.4.1 Method

This third part of the reliability evaluation employed the same protocol as for the four year old group. The rater missing from the second part of the study returned, and so four raters performed each pair of measures. Again, a repeated measures approach was used, with both limbs of each participant independently measured on two occasions over two days.

#### 5.1.4.2 Sample

The sample was again 30 normal, healthy children, this time aged 8-15 years. Recruitment criteria, invitation to participate, and consent procedures were as outlined in the previous section, with the only difference being the age of the target group.

#### 5.1.4.3 Results – Children aged 8-15 years

*1.1.1.1.*

*Intraclass correlation coefficients*

***Investigation of agreement between raters – interrater reliability***

*Two-way Random Effect Model (Absolute Agreement Definition):*

*People and Measure Effect Random*

**Single Measure Intraclass Correlation (95%CI) = 0.73 (0.62-0.82)**

*Investigation of test-retest agreement – intrarater reliability*

ICC Two-Way Mixed Effect Model (Consistency Definition):

People Effect Random, Measure Effect Fixed

**Table 5.48. Single Measure Intraclass Correlation**

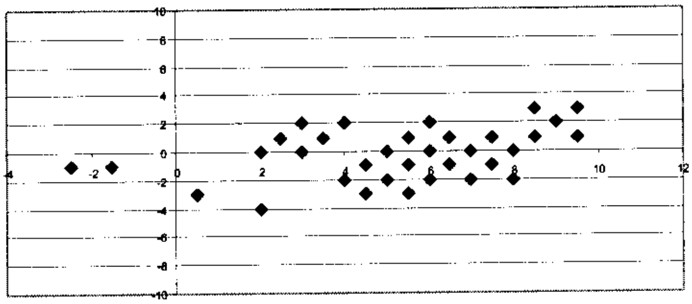
| | ICC | 95% CI | F statistic | DF |
|---|---|---|---|---|
| Observer 1 | **0.84** | 0.74 - 0.90 | 11.38 | 59 |
| Observer 2 | **0.83** | 0.74 - 0.90 | 11.10 | 59 |
| Observer 3 | **0.89** | 0.83 - 0.94 | 17.89 | 59 |
| Observer 4 | **0.79** | 0.68 - 0.87 | 8.75 | 59 |

The intra-rater retest reliability for the FPI scores ranged between 0.79 'good' and 0.89 'almost perfect'. This again, indicates a good deal of consistency for each rater between sessions.

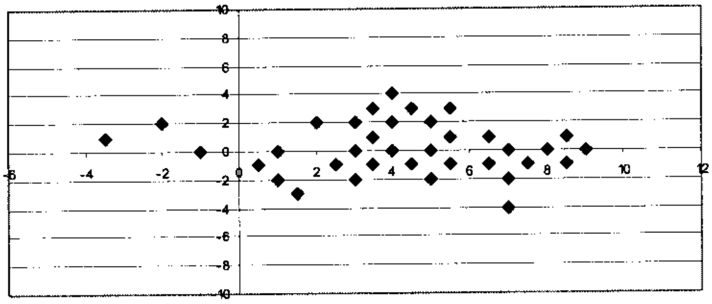
**Table 5.49. Measurement error and the 95% CI**

| | ME (95%CI) |
|---|---|
| Observer 1 | 1.13 (-1.08 to 3.34) |
| Observer 2 | 1.12 (-1.07 to 3.31) |
| Observer 3 | 1.01 (-0.97 to 3.01) |
| Observer 4 | 1.27 (-1.22 to 3.76) |
| **Mean** | **1.13 (-1.10 to 3.35)** |

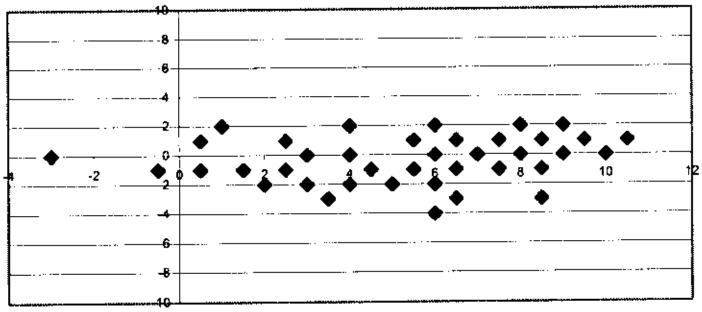
# Mean-Difference plots for the four observers



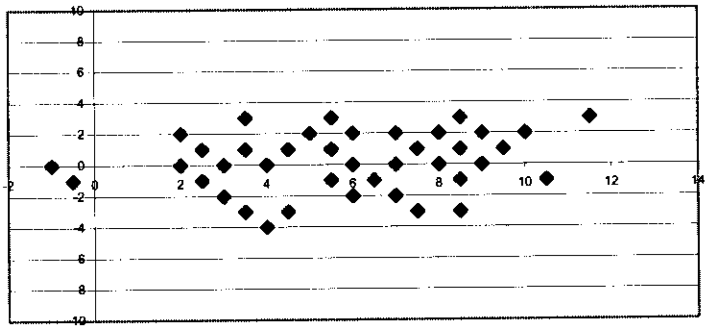
Mean difference plot - Observer 1



Mean difference plot - Observer 2



Mean difference plot - Observer 3



Mean difference plot - Observer 4

The mean - difference plots are stable and consistent for all four observers.

### 5.1.5 Summary

The FPI demonstrated moderate to good inter-rater ICCs, good to excellent intra-rater ICCs, measurement error of 1.13-1.26 points on the 33 point scale, and good scalar stability. Experience with the rating system appeared to improve reliability, with the interrater agreement better in the second two samples than in the adult group tested first. One rater in particular, (rater 3 in the first adult test group) while consistent on test-retest, was more conservative than the other three raters in the initial adult evaluations (see Table 5.50).

**Table 5.50. Median scores for the four observers in the initial adult group.**

| | Median score (range) |
|---|---|
| Observer 1 | 7 (-1 to 13) |
| Observer 2 | 5.5 (-2 to 11) |
| Observer 3 | 2 (-1 to 9) |
| Observer 4 | 5.5 (-2 to 11) |
| **Friedman $\chi 2$** | **95.43, N=30, p<0.001** |

Three of the four raters had no opportunity prior to the formal evaluations to familiarise themselves with the FPI. In discussion with rater 3, after testing with the adult group but prior to the testing sessions in the subsequent paediatric groups, this rater revealed that his interpretation of the manual may have put him in conflict with the other raters. Specifically, the working notes in the early drafts of FPI manual indicated 'where the observer is in doubt over whether a criterion is met in the presenting patient, they should score towards zero for that criterion'. Observer three expressed concern that he may have entered a zero score on many occasions when in fact he felt that there was a scorable criterion present but he 'could not be sure'.

From the interview it appeared possible that the isolated difference between observer three and the other raters was primarily due to difficulties associated with the interpretation and application of the criteria, coupled with inexperience in the use of the FPI. These difficulties were not as profound in the case of the other three raters and it is thus inferred that the ratings of observer three could, in the case of the adult group, be interpreted as genuine outliers.

Excluding the potentially erroneous measures obtained by rater three and recalculating the inter-rater ICC (2,1) yields an ICC (95%CI) = 0.69 (0.27-0.84)

Furthermore despite the reduction in observer degrees of freedom the confidence intervals are slightly reduced implying a more homogenous dataset.

On the basis of the analysis and discussions above, the wording of the preliminary working notes in the manual was amended to limit the potential for future misinterpretations yielding unduly conservative scoring responses, and the issue of experience has been addressed through the addition of a recommendation that new users cross-reference with a colleague, at least 20 ratings of foot posture using the FPI, before applying the measure in earnest in the clinical setting. Following revision of the manual and development of some experience by rater three, his ratings in the subsequent studies of paediatric groups fell into line with the other raters involved, and the overall inter-rater ICCs are consistent across the three age groups (0.69, 0.73, 0.61).

In summary the FPI scoring system yields good to excellent levels of reliability for test-retest measurements made by the same observer. For measurements made by different observers, reliability was good in the two paediatric groups, and the moderate reliability seen in the initial adult evaluation rose to good on removal of the outlying rater three. Valuable lessons were learned, informing refinement of the manual, and highlighting the need for new FPI users to allow some lead-in time to develop some experience in using the measure prior to its employment in practice.

## 5.2 *CHAPTER FIVE, SECTION TWO- PRELIMINARY CONCURRENT AND CONSTRUCT VALIDATION OF THE NEW MEASURE*

### 5.2.1 Introduction

This phase of the study evaluated the use of the FPI in the field, and explored the construct validity of the new instrument, as well as estimating its concurrent validity against a widely used objective measure of standing foot posture. The FPI-8 was included as a second measure in a large sample of triathletes participating in a study of injury patterns and risk factors, who were already undergoing objective evaluation of foot posture.

### 5.2.2 Aims

The aims of this study were

- To determine the concurrent validity of the FPI in comparison to an existing clinical 'industry-standard' of standing foot posture.
- To evaluate the construct validity of the FPI.
- To evaluate the internal reliability of the FPI.

### 5.2.3 Methods

The concurrent validity of the new FPI was examined using as a benchmark, simultaneous measures of foot type using Rose's "Valgus Index" (VI) [386]. The VI was chosen because it is widely used in clinical foot research and has been reported to be an adequate measure of foot posture [387]. The Limits of agreement (standard error+/- 95% CI) for a single measure VI scores is +/-3.0, improving to +/-2.0 for 3 repeat measures[387]. The VI is often used in clinical foot research because it is among the more objective clinical measures of foot posture, however it must be noted that the validity of the VI has been questioned by a number of authors [14 15 6]. There is particular concern that the VI, while possibly more objective than direct goniometric measures, still emphasises heavily, the frontal plane position of the rearfoot [6].

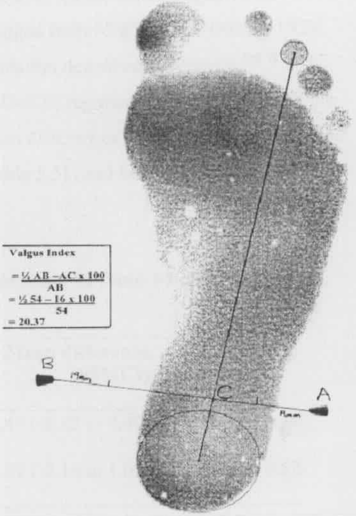
In the absence of a true "gold-standard" for measuring standing foot posture, the VI was employed as it is a clinical tool that has been widely employed in the clinical setting.

Ratings of the eight clinical indicators of the FPI were undertaken while the subject stood on a 'pedograph', ink and paper mat. Thus the foot posture at the time of scoring was preserved for subsequent derivation of the VI. The VI was later calculated from the inked footprint after the field data acquisition phase was complete, and the observer was blinded to the FPI score when calculating the VI score.

Valgus index is calculated from marking the medial/lateral position of the medial (B) and lateral (A) malleoli relative to an inked print of the foot in relaxed standing. The geometric centroid of the heel area of the print is defined using a pair of compasses and a long axis defined for the foot representing a line from the heel centroid to the 3rd toe. The point at which line A-B bisects the long axis is designated point C.

The formula for deriving the VI is given by

$$VI = \frac{\frac{1}{2} AB - AC \times 100}{AB}$$



The sample comprised club and elite level triathletes attending competitions in New South Wales, the Australian Capital Territory, and Victoria, Australia. All participants gave full written consent prior to enrolment.

Data were entered into SPSS for Windows version 11.1 (SPSS Inc, Chicago, IL.) and the analysis was undertaken in six stages, starting with a basic statistical description of the sample, and of the FPI and VI data sets. The concurrent validity was evaluated using an ordinal regression model to evaluate the capacity of the total FPI score to predict VI scores. The internal and construct validity were assessed via a comprehensive approach including examination of FPI inter-item reliability using Cronbach's alpha coefficient, and assessment of internal construct validity, in which elements of the FPI representing foot segments and body planes were entered into two multiple regression models. The internal validity was further explored via factor analysis of the eight sections of the FPI score to identify latent factors that could also explain the variance in the FPI scores, but were not apparent *a priori*.

## 5.2.4 Results

### 5.2.4.1 Sample demographics

The sample comprised 91 (69.5%) male and 40 (30.5%) female athletes aged 18-65 (Mean=33.7 years). The VI scores for the group ranged from –3.6 to 33.61 (Mean=10.28, SD=6.52), values close to those of the normal population described previously [386 387]. The FPI scores ranged from –7.0 to 15.0 (Mean=4.9, SD=3.9) representing a good range of the foot types likely to be encountered in practice. Mean differences between left and right limb data for both the FPI and VI scores were small (Table 5.51) and both the FPI and VI data sets were normally distributed.

**Table 5.51 Descriptive statistics for left and right limb, FPI and VI data**

| | Right or left side | N | Mean | Mean difference (95%CI) | T value | Sig. |
|---|---|---|---|---|---|---|
| **FPI total score** | *Right* | 131 | 4.7 | -0.47 (-1.42 to 0.49) | -0.96 | 0.34 |
| | *Left* | 131 | 5.1 | | | |
| **VI score** | *Right* | 125 | 10.0 | -0.97 (-2.16 to 1.09) | -0.65 | 0.52 |
| | *Left* | 125 | 10.5 | | | |

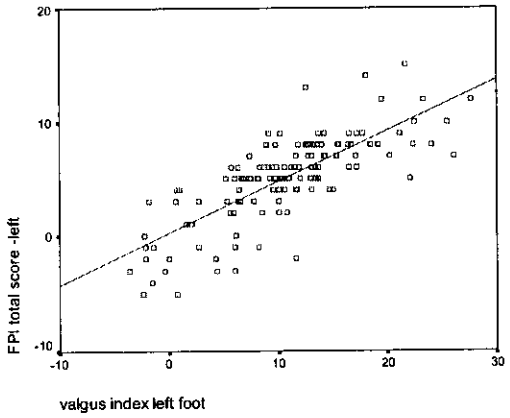
### 5.2.4.2 Concurrent validity

The clinical measures were obtained for both limbs of each participant, as these data were required for the parallel investigation of injury risk. To avoid paired limb observations leading to breaches of the assumption of independence in the data however, data from only one limb were included in the inferential analyses. In the absence of any clinically meaningful means for deciding on separation - such as formally established limb dominance, it was decided by coin toss to detail data from the left limb.

Regression models were constructed to assess the degree to which the FPI total score as the predictor variable, explained the variance in VI score, the dependent variable. The ordinal nature of the FPI scoring necessitated the use of ordinal regression modelling in the manner described in Chapter Three, where the ordinal regression model yields a goodness of fit statistic combined with a coefficient of determination along with the parameter estimate (B), its Standard Errors, the Wald statistic and significance.

The linearity of the relationships was assessed prior to undertaking the regressions.

**Figure 5.58. Scatter plot of FPI Score and Valgus Index Score ($\rho=0.776$, $P<0.001$, N=131)**



### 5.2.4.3 Ordinal regression modeling

***Dependent variable: VI left limb score***
***Independent variable: FPI-8, left limb score***

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =1457 (P=1.0 ) | 0.590 | 131 |

Where good model fit is characterised by high significance values (>0.05).

The Standard Errors, the Wald statistic and significance are tabulated as before.

| Covariate /Factor | Parameter Estimate | SE (B) | Wald | Sig | 95% CI (B) | |
|---|---|---|---|---|---|---|
| FPI score | .551 | .059 | .88.5 | .000 | .437 | .666 |

There was good agreement between the VI and FPI -8 scores, with FPI-8 total scores predicting 59% of the variance in VI values.

#### 5.2.4.4 Inter-item Reliability

The inter-item reliability was evaluated using Cronbach's α (Table 5.52). For the eight-item set, α was 0.834, indicating good inter-item reliability. The individual coefficients in column three of the table were high or very high for six of the eight FPI components. For the components based on lateral border congruence and observation of Helbing's sign (highlighted in bold for emphasis), reliability was lower, and this is discussed later.

**Table 5.52. Cronbach's α for the eight elements of the FPI.**

| | Scale Mean if Item Deleted | Scale Variance if Item Deleted | Corrected Item-Total Correlation | Alpha if Item Deleted |
|---|---|---|---|---|
| **Talar head palpation** | 4.1908 | 11.2633 | .6392 | .8042 |
| **Supra and infra lateral malleolar curvature** | 4.5573 | 12.1871 | .6353 | .8076 |
| **Helbing's sign** | 4.4809 | 12.0516 | **.3635** | .8524 |
| **Prominence of the TNJ** | 4.4046 | 12.1966 | .6518 | .8062 |
| **Congruence of the medial longitudinal arch** | 4.5573 | 10.6179 | .7184 | .7917 |
| **Congruence of the lateral border of the foot** | 4.8397 | 14.2280 | **.1987** | .8512 |
| **Abduction/adduction of the forefoot** | 4.5344 | 12.2661 | .6536 | .8066 |
| **Inversion/eversion of the calcaneus** | 4.3969 | 11.2412 | .7533 | .7895 |

**Reliability Coefficients**
N of Cases = 131 N of Items = 8 **Alpha = 0.834**

#### 5.2.4.5 Internal Construct Validity – FPI-8 segmental and planar components

The construct validity of the FPI was evaluated using further ordinal regression modelling, to assess the degree to which each of the individual component observations predicted the FPI total score. In the first model, components of the FPI representing a range of rearfoot and forefoot / midfoot segments were included. The six components were talar head palpation, lateral malleolar curvature, prominence of the talonavicular joint (TNJ), congruence of the medial longitudinal arch, abduction/adduction of the forefoot on the rearfoot, and congruence of the lateral border of the foot. In the second regression model, five components representing measures in each of the three anatomical planes were introduced. The model included two FPI measures for each of the frontal and transverse plane, and one for the sagittal plane. The five FPI components in this regression model were inversion/eversion of the calcaneus, Helbing's sign (curvature of the insertion of the tendo Achilles), talar head palpation, abduction/adduction of the forefoot and congruence of the medial longitudinal arch. All eight FPI components were included in at least one of the two regression models.

The six FPI components representing the foot segments were significant predictors of the FPI total score, predicting approximately 91% of variance in the FPI total score (see Table 5.53). This would be expected, as the FPI total score is of course, comprised of the six components in the model, plus the two others. More importantly, the individual regression coefficients indicate that all six components were significant predictors of the overall score. The Wald statistics indicate that the lateral border of the foot component was the weakest predictor, although even this component made a significant contribution to the FPI total score.

**Table 5.53 Ordinal regression summary table for the six FPI elements representing rear, mid and fore-foot segments.**

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2 = 304.009$ (P=1.0 ) | 0.914 | 131 |

| Covariate | Parameter Estimate | SE (B) | Wald | Sig | 95% CI (B) | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| **Talar head palpation** | 2.144 | .324 | 43.868 | .000 | 1.510 | 2.779 |
| **Supra and infra lateral malleolar curvature** | 2.722 | .403 | 45.724 | .000 | 1.933 | 3.511 |
| **Prominence of the TNJ** | 2.268 | .439 | 26.634 | .000 | 1.406 | 3.129 |
| **Congruence of the medial longitudinal arch** | 2.189 | .408 | 28.855 | .000 | 1.390 | 2.988 |
| **Congruence of the lateral border of the foot** | 1.480 | .347 | 18.152 | .000 | .799 | 2.161 |
| **Abduction/adduction of the forefoot** | 2.532 | .417 | 36.804 | .000 | 1.714 | 3.350 |

**Table 5.54 . Ordinal regression summary table for the five FPI elements representing each of the three body planes.**

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2 = 136.800$ (P=1.0 ) | 0.986 | 131 |

| Covariate | Parameter Estimate | SE (B) | Wald | Sig | 95% CI (B) | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Uppe |
| **Talar head palpation** | 3.021 | .376 | 64.716 | .000 | 2.285 | 3.75 |
| **Helbing's sign** | 2.321 | .277 | 70.276 | .000 | 1.778 | 2.86 |
| **Congruence of the medial longitudinal arch** | 3.399 | .446 | 58.017 | .000 | 2.524 | 4.27 |
| **Abduction/adduction of the forefoot** | 2.513 | .440 | 32.586 | .000 | 1.650 | 3.37 |
| **Inversion/eversion of the calcaneus** | 3.236 | .458 | 50.016 | .000 | 2.339 | 4.13 |

Table 5.54 shows that the five elements representing the three body planes predicted nearly 99% of the total FPI score. Again, this high value is to be expected, because the FPI total score is composed only of those five component measures plus the three excluded components. The data for each of the individual FPI elements are again more informative, and while the component estimating abduction/adduction of the forefoot on the rearfoot appeared relatively weak, all components were again significant predictors to this model.

### 5.2.4.6 Internal Construct Validity – Factor analysis

The ordinal regression models were based inherently on theoretical assumptions that may be questionable. To evaluate other factors that could predict the variance in FPI scores, but which could not be identified a priori, a factor analysis was performed. The model used was based on a principal components extraction of factors with Eigenvalues greater than 0.9, with varimax rotation. The first factor extracted explained 49% of the variance in the FPI score (see Table 5.55).

**Table 5.55. Summary statistics of the rotated factor matrix for the FPI item contributions to the total score.**

| Component (Factor) | Eigenvalue Total | % of Variance | Cumulative % |
|---|---|---|---|
| **1** | 3.95 | 49.4 | 49.4 |
| **2** | 0.978 | 12.2 | 61.6 |
| **3** | 0.740 | 9.3 | 70.9 |
| **4** | 0.635 | 7.9 | 78.8 |
| **5** | 0.571 | 7.1 | 85.9 |
| **6** | 0.488 | 6.1 | 92.0 |
| **7** | 0.322 | 4.0 | 96.0 |
| **8** | 0.317 | 4.0 | 100.0 |

*Extraction Method: Principal Component Analysis.*

This factor included seven of the FPI items (see Table 5.56).

The FPI elements with the greatest loading on Factor 1 were frontal plane position of the calcaneus, medial arch congruence and bulging in the area of the TNJ. Three other elements, talar head palpation, malleolar curvature and transverse position of the forefoot on the rearfoot also contributed significantly. The loading for Helbing's sign was lower than other items at 0.589 but was still significant.

**Table 5.56 Component factor matrix (varimax rotation) illustrating the individual FPI item loadings on the two factors.**

| Factor | Loading |
|---|---|
| **Factor 1** | |
| Talar head palpation | 0.712 |
| Supra and infra lateral malleolar curvature | 0.716 |
| Helbing's sign | 0.589 |
| Bulging in the area of the TNJ | 0.774 |
| Congruence of the medial longitudinal arch | 0.833 |
| Abduction/adduction of the forefoot on the rearfoot | 0.706 |
| Inversion/eversion of the calcaneus | 0.833 |
| **Factor 2** | |
| FPI - congruence of the lateral border of the foot | 0.910 |

The second factor, explaining a small but significant 12% of the variance, was primarily a function of the congruence of the lateral border of the foot (loading =0.91), suggesting that a separate subgroup with overall foot function independent of the lateral foot contour might be evident. The remaining factors explained only 4% to 9% of the variance.

When the data from two multiple regressions and the factor analysis are considered in combination, all eight elements of the FPI made valid contributions to the FPI total score. The congruence of the lateral border of the foot was a significant predictor in the regression model, but was also subsequently identified as a unique factor in the factor analysis. The role of this element is developed further in the discussion.

### 5.2.5 Discussion

It has been discussed previously that one significant shortcoming of existing clinical measures of foot posture is their reliance on using discrete aspects of foot morphology to define overall foot posture. Due to the complex inter-relationships of the components of the foot, these single plane measures may not always describe in adequate detail the range of foot presentations seen in practice [140 216 392]. The FPI-8 as a composite, triplanar, multisegmental measure seems to address some of these shortcomings and is thus able to predict as much as 59% of the variation in the VI score. This represents a significant improvement on previous reports in the literature, in which maximal values of prediction of the variance in one measure by another have been reported to range from only 1-17% [24 200 253 255 271 276 337 338].

The FPI does not though entirely overcome some of the limitations of the clinical measures of which it is comprised. It is recognised that the degree of agreement between the FPI and the VI, both static measures, is higher than would be expected if comparing the static FPI with a dynamic measure. This is further developed in the subsequent chapter.

The VI is, in common with all clinical measures, subject to many of the limitations outlined previously. The VI is a measure derived predominantly from frontal plane posture, and is therefore highly influenced by the proximity of the measured line to the axes of rotation in the rearfoot. As such the VI will not reflect adequately some important aspects of foot posture that are measured by the FPI, such as arch height and profile. The transverse plane relationships of the forefoot to rearfoot components will be reflected to some degree in the VI score, but due to the geometry of the VI, these transverse plane forefoot measures will be relatively under-represented compared to the frontal plane position of the rearfoot. It was acknowledged therefore that the VI was perhaps less than ideal as a benchmark measure, although this serves further to emphasise the need for better clinical measures of foot posture than exist currently. While any number of alternative clinical techniques might have been employed as an alternative to the VI, each would have been equally open to criticism.

In light of these issues, the ordinal regression modelling employed here has some shortcomings in determining concurrent validity in this study design. There is in this type of model a sometimes false assumption that the dependent variable, the 'gold-standard' measure is free of error. When the gold standard is entirely free of error, all of the unexplained variation in the dependent variable must arise as a consequence of error in the predictor. As 'benchmark' measures used in most *in vivo* gait and posture studies are clearly not free of error, it cannot be determined from the regression model, how much of the unexplained variance is due to error in the predictor, and how much is a consequence of unknown error in the dependent variable.

Despite these recognisable shortcomings, the VI was used for a number of reasons. Firstly, it is widely used for both routine clinical practice and for clinical research purposes, it is objective, and the print provides a permanent record. Secondly, the VI has been evaluated independently and despite some shortcomings, its error and reliability are well documented at least [387]. Finally, for the specific requirements of this study, the VI represented a clinical measure which could be performed quickly and concurrently with the FPI evaluations, and with the FPI observer blinded to VI score, minimising bias.

The triathletes forming the sample in this study demonstrated a wide range of foot postures according to both VI and FPI scores. All were fit and healthy members of the general population, and were relatively free of confounders. It is acknowledged that this group is not closely representative of patients with neuromuscular disease, but does provide for a larger sample than would be possible in the CMT population and was a homogenous sample well suited to a technical investigation of the validity of the method. Both the VI scores and FPI scores in this study suggested that the group-mean foot position inclined toward a slightly pronated position, a finding consistent with empiric observations at the time, and with previous studies [347].

Although all eight of the FPI components were found to make a valid contribution to the total score, two measures in particular, Helbing's sign, and lateral border transverse plane congruence warrant further discussion. Helbing's sign demonstrated only moderate validity, primarily due its limited reliability. Helbing's sign proved a valid component of the overall FPI score in the linear regression models, but while the reliability was adequate to justify its continued inclusion in the interim, its continued inclusion in later modifications of the FPI will be reviewed. The other component warranting further discussion is the congruence of the lateral border of the foot. In the case of this measure the reliability was good, but the significance values of this element in the regression models suggest that the shape of the lateral border may also have been influenced by factors other than functionally related variations in foot posture. The factor analysis confirmed the role of this element in a second factor, which appeared independent of functionally related foot posture. Such a finding would be commensurate with the presence of structural deformity causing variations in lateral border shape, independent of functional position. Subtle deformities such as the cavoid changes seen in CMT, Haglund's bump on the posterior aspect of the calcaneus, metatarsus adductus and hallux valgus are all encountered in the otherwise normal foot-types seen in the population at large, and require further consideration. The presence of minor structural deformity will impact only minimally on repeat measures on the same subject, but may affect the comparability of results between patients. In the factor analysis, the loading of the lateral border element of the FPI on the second factor probably reflects the presence, in some of the study sample, of latent structural deformity such as mild residual metatarsus adductus. The implication for clinical practice is that the examiner, in any given clinical situation, must be clear about the purpose of the assessment. Where repeat measures are to be performed on individual patients, the presence of a consistent structural deformity should have minimal impact, and indeed documenting such structural changes may prove useful in quantifying changes in disease related foot posture over time. If comparisons are to be made between otherwise normal patients however, where there is an assumption that the standing foot posture relates more closely to the foot function than to structural deformity, it may transpire that consideration should be given to removing a component from the FPI scoring if an individual demonstrates fixed deformity.

In conclusion, it appears that on the basis of this phase of the validation process, there appeared to be sufficient merit in the approach to warrant further detailed study of the concurrent validity. The FPI-8 total score predicted 59% of the VI score variation, which is a greater proportion than has been reported for previous pairs of foot measurements (such as between radiographic measures and arch index, $R=0.155$ ($R^2=0.02$) to $R=0.452$($R^2=0.20$)) that had been used to support conclusions of adequate concurrent validity for these other measures[255 404].

The construct validity of the FPI appears good overall, with high internal reliability and generally valid contributions of the component elements to the total score.

There were limitations in the VI as a gold standard measure however, and while the simplicity of the VI approach enabled the recruitment of a large sample, the VI cannot ultimately, be considered a genuine gold-standard. To address these limitations an attempt was made to enhance the gold-standard through the construction of a three-dimensional computer model of the lower limb using a sophisticated electromagnetic tracking system. The process leading to the development of a better benchmark model against which to evaluate the concurrent validity of the FPI is detailed in the next chapter.

# CHAPTER SIX. ELECTROMAGNETIC MOTION TRACKING STUDIES

---

***Chapter overview***

*As part of the validation process for the new measure it was desirable to establish the validity of component measures and of the aggregate scoring system in relation to a more substantive gold-standard. Evaluating the concurrent validity of individual component measures was appropriate so as to quantify the validity of individual measures, and to identify poorly performing or redundant measures for possible removal from the instrument. A second study of the revised instrument was required to quantify the extent to which the FPI composite scores reflect foot posture in static stance and are predictive of foot function during gait. In this chapter the process of establishing the best possible solution is outlined and two concurrent validity studies are described, one in static stance and one dynamic study of normal walking, with both employing electromagnetic motion tracking technology to provide a gold-standard model of the foot.*

*In section 6.1 a Polhemus Fastrak™ electromagnetic tracking system (Polhemus Inc., Colchester VT) was used to identify anatomical landmarks, which were then modelled in bespoke software to create a three-dimensional digital reconstruction of the leg and foot in static stance in each of three positions: resting, pronated and supinated. The EMT model was used to investigate the concurrent validity of the eight FPI components individually.*

*Following this part of the study, the continued inclusion of the individual components was evaluated, and two poorly performing components were deleted from the next draft of the instrument to create a truncated, six-item version of the FPI (FPI-6)*

*Section 6.2 details an experiment undertaken to build on the work done in 6.1, evaluating the predictive validity of the FPI-6 aggregate scores in relation to a static and dynamic EMT functional models.*

*Both experiments use similar hardware, but the experiment in section 6.1 employs a complex anatomical static model to identify the contribution of the eight original FPI component parts to the total score, whereas section 6.2 uses a simpler but well-validated dynamic model to estimate the proportion of variance in ankle joint complex (AJC) kinematics predicted by the FPI-6 aggregate scores*

*Finally in this chapter, the predictive validity of the FPI-6 is evaluated by assessing the sensitivity and specificity of the FPI-6 scores to predict the foot posture in the states artificially induced in the concurrent validation protocol.*

---

## *6.1 CHAPTER SIX, SECTION ONE – CONCURRENT VALIDITY OF THE FPI COMPONENTS, EVALUATED AGAINST A CUSTOMISED, THREE-DIMENSIONAL STATIC MODEL OF THE LOWER LIMB IN STATIC STANCE*

### 6.1.1 Introduction

The aim of this section of the thesis was to evaluate the performance of the FPI in relation to an objective measure of static foot posture. There is currently no true gold-standard however, with all clinical measures, and even the majority of laboratory based measures, subject to at least some of the shortcomings detailed in Chapter Two [15 188 212 213 229 248].

In an attempt to establish an adequate benchmark, a study was undertaken using hardware known to measure small joint segments with acceptable accuracy [240 336 339], combined with custom software written to model the resulting data. Cartesian coordinates of 17 critical anatomical landmarks on the lower leg were mapped digitally using an electromagnetic motion tracking system. Rigid models of the shank, hindfoot and forefoot in each of three postures were reconstructed in software as a comparator for concurrent FPI component evaluations. Foot postures were measured in a relaxed condition, and after manipulation into an induced pronated position or supinated position by the addition of medially or laterally oriented wedges under the heels of the subjects.

### 6.1.2 Aims

1. To develop a static 3D reconstruction of key joint segments of the foot and ankle, sufficient to model the standing foot posture accurately, and to quantify objectively, systematic changes in foot posture.

2. To determine the consistency between component scores derived from the foot posture index and the results derived from the objective model.

### 6.1.3 Method

#### 6.1.3.1 Overall method

Concurrent measurements of the foot posture of 20 individuals in each of three positions were undertaken using the FPI rating system and an objective, three-dimensional model created in software.

#### 6.1.3.2 Equipment

Electromagnetic motion tracking systems may be used to record either dynamic motions or static positions. For dynamic tracking, EMT systems must be configured with sensors applied directly to the skin. For static applications, the sensors may be mounted to the skin, or to a wand or stylus, which is then used to digitise points on the surface of the segment to be modelled.

A number of EMT systems exist, each varying slightly but using similar basic principles. The Fastrak™ system (Polhemus Inc., Colchester VT) used in this study consists of a three-axis magnetic dipole field transmitting antenna (transmitter), small sensors containing three mutually orthogonal coils, and a motion capture unit, integrating the sensor output into positional and orientation data. Three low frequency magnetic fields (12,019Hz) are generated in the hardware and passed via a transmitting antenna to generate a field 1to 305 cms from the source, with a field strength ranging from 1-30,000x10$^9$ Tesla (manufacturer's data). The system can be configured with either a short range or long range transmitter. The short range transmitter provides a spherical capture volume with the transmitter at its centre, and a useable volume in a space ranging from 1 to 76 cms separation from the source. The long range transmitter provides a spherical capture volume ranging from 90-305cms from the source (manufacturer's data). The three-axis coil antenna forming the sensor generates a signal based on flux in the generated electromagnetic field. The signal is pre-amplified, demodulated and passes through an analogue-digital converter in the motion capture unit (MCU) prior to processing in the hardware. Directional cosines and Cartesian coordinates (X,Y,Z), relative to the global reference frame defined by the fixed transmitter, are then passed to the interfacing software to yield motion data with six degrees of freedom.

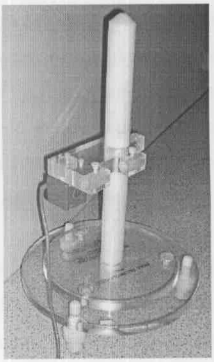


**Figure 6.59 The short range transmitter**

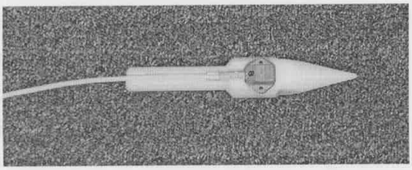


**Figure 6.60. A single Fastrak sensor mounted in a stylus**

The root mean square error for the Fastrak™ system is reported by the manufacturer to be 0.15° of rotation and <0.8mm in position in a highly optimised laboratory setup. Independent data for the set-up using a short-range transmitter confirm errors of less than 1° for sensor orientation [247 405], but suggest error of up to 1cm in position [247] in the clinical setting. These data are in accordance with those reported for the similar MotionStar® system (Ascension Inc, Burlington, USA) evaluated in the most recent published study [242]. Prior to data capture the error of the system was evaluated in detail for each of the two configurations used in this chapter. This experimental process is reported fully in Appendix F. In the short range transmitter configuration used in section 6.1, the EMT system was demonstrated to have a technical RMS error of between 0.87mm and 2.54mm for the measurement of the Cartesian coordinates of anatomical landmarks. Intraclass correlation coefficients were 0.999 for a subset of three landmarks evaluated in detail and reported in Appendix F.

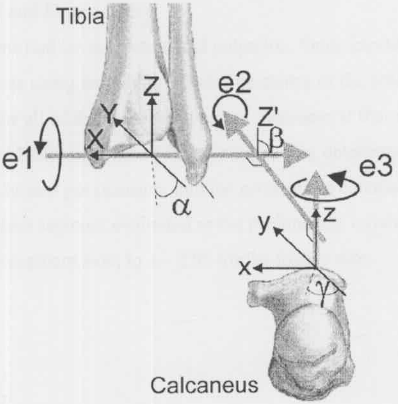
The field emitted by the EMT transmitters are sensitive to interference from ferro-metallic objects and electrical equipment generating electromagnetic interference. EMT systems therefore require a field relatively free of metallic objects and electrical equipment, and must be calibrated to their environment [405 406]. The protocols adopted to ensure freedom from metallic interference in this study are reported as appropriate in each of Sections 6.1 and 6.2.

For this experiment the Fastrak™ system, the short range transmitter configuration and two capture channels were used, feeding into a single MCU sampling at 60Hz. Channel one ($c_1$) collected data from a reference sensor fixed to the medial border of the tibia, while channel two ($c_2$) recorded the motion of a sensor attached to a stylus, which was used to digitise the position of the anatomical landmarks. Fastrak data were captured to a Pentium PC using custom written data capture and terminal control software (RealMotion v1 R.Lee, Polytechnic University of Hongkong.) Separate routines were written in TurboBasic v10.0 to identify the stylus tip at each landmark from the Cartesian coordinates and directional cosine values of the attached sensor, to define the segments from the precise coordinates of the anatomical landmarks, and to calculate the relative orientation of the segments in the three-dimensional limb reconstruction.

To ensure consistency of terminology throughout the reporting of these experiments, the joint coordinate system used to describe the motions and positions is that first described by Allard [407]. A slightly modified version of the AJC joint coordinate system has since been endorsed by an ISB working party [408] but was not available at the time of this experiment.

The maximum radius of the electromagnetic field for accurate data capture using the short-range transmitter is 75-80cm [247]. In this study, the maximum separation of any sensor from the transmitter was 50cms. All measurements were conducted on a 70cm raised wooden plinth, positioned in the centre of a room with at least 1.5m clearance to all sides and clear of sources of metallic interference.

**Figure 6.61. The ankle rearfoot joint coordinate system after Allard *et al* (1995) (Adapted from Woodburn *et al* (1999))**



This joint coordinate system defines a system whereby:
*X,Y and Z represents a body- fixed reference frame for the tibia. x,y and z are the body fixed reference frame for the calcaneus. The x,y and z frame is also used as a local reference frame to describe all the motions in the midfoot and forefoot. e1 is the axis fixed to the tibia/calcaneus and coincides with the X axis of the tibio-fibular frame. Rotation about this axis (α) consists of dorsiflexion (+ve) and plantarflexion (-ve).*
*e2 is the common perpendicular to e1 and e3, the floating axis. Rotation about this axis (β) is defined as inversion (+ve) and eversion (-ve).*
*e3 is the axis fixed to the calcaneus and coincides with the z axis of the calcaneal reference frame. Rotation about this axis (γ) corresponds to internal/medial rotation (+ve) and external /lateral rotation (-ve).*

### 6.1.3.3 Clinical protocol

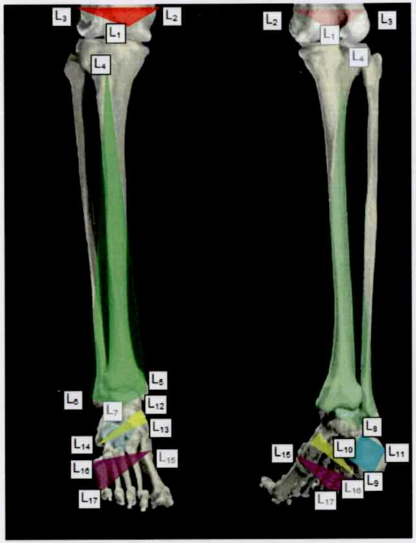
When employing the EMT system to model the coordinates of fixed anatomical landmarks, as in this experiment, a minimum of three non-contiguous sites are required to describe the position and orientation of each of the anatomic segments. A number of studies have described different protocols for direct or indirect static modelling the leg and foot [194 409], however none had described previously any protocol which will allow the separation of data from the hindfoot, mid foot and forefoot. Many previous studies have modelled the foot as a single segment [18], an inadequate model for this experiment, and it was decided therefore to define a complex landmark set using 17 landmarks ($L_{1-17}$) to allow foot segmentation as described in Table 6.57 and Figure 6.62.

Each landmark was identified by inspection and palpation. Once identified, the landmark was marked with a small cross using an indelible pen. The centre of the cross was used to orient the tip of the stylus $c_2$ for all of the subsequent repeat measures at that site.

As noted previously, the RMS error for stylus placement was determined for this protocol, to be between 0.87 and 2.54 mm per measure, and the error of the calculated segment orientations of the forefoot segment evaluated in the preliminary reliability study ranged from +/- 5.3° for the shortest segment side, to +/- 2.9° for the longer side.

**Table 6.57. and**
**Figure 6.62 Data collection protocol and landmark definition.**

| *Segment* | *Segment abbreviation* | *Landmark definition* | *Anatomical definition* |
|---|---|---|---|
| Femoral | fem 🟥 | $L_1$ | Base of patella |
| | | $L_2$ | Medial femoral condyle |
| | | $L_3$ | Lateral femoral condyle |
| Tibial | tib 🟩 | $L_4$ | Tibial tubercle |
| | | $L_5$ | Medial malleolus |
| | | $L_6$ | Lateral malleolus |
| | | $L_7$ | Mid-point Achilles tendon |
| Hindfoot (calcaneus) | hind 🟦 | $L_8$ | Insertion of TA into calc |
| | | $L_9$ | Lower calc |
| | | $L_{10}$ | Medial heel |
| | | $L_{11}$ | Lateral heel |
| Midfoot | mid 🟨 | $L_{12}$ | Navicular tuberosity |
| | | $L_{13}$ | Navicular /cuneiform joint line |
| | | $L_{14}$ | Cuboid notch |
| Forefoot | fore 🟪 | $L_{15}$ | 1st metatarsal head |
| | | $L_{16}$ | 5th metatarsal base |
| | | $L_{17}$ | 5th metatarsal head |



#### 6.1.3.4 Data acquisition

The sample for the concurrent validation study using the full model comprised 20 normal subjects, recruited from students and staff of the University of Western Sydney. All measures were undertaken on the right limb only with the participant in quiet standing on a 70cm raised wooden plinth with at least 1m clearance from any source of electromagnetic interference. The FPI ratings and the digitisation protocol were undertaken by an independent rater, who was otherwise independent of the study. At the start of the data collection session the rater carefully marked the 17 anatomical landmarks with a fine indelible pen. These marks then provided a consistent point for the reapplication of the stylus tip in the repeated measures.

To simulate the full range of variable foot postures that the FPI might be required to quantify, the subjects were manipulated, according to a pre-determined randomisation protocol, into each of three positions:

- A functionally neutral position corresponding to a ‘0’ score using the FPI
- Their maximally pronated stance position
- Their maximally supinated stance position

The functionally neutral FPI ‘0’ position was obtained by carefully manipulating the foot position so that the FPI total score rated at 0 or as near as was practicable. The maximally pronated position was achieved by having the subject internally rotate the leg and evert the foot until either the foot would move no further without discomfort, or until the lateral border of the foot started to rise from the weightbearing surface. The maximally supinated position was achieved by having the subject externally rotate their leg and actively invert their foot. The maximally supinated position was defined as where no further motion was possible or when the first metatarsal head started to raise from ground contact.

With the participant standing in the defined position, the independent rater recorded the eight FPI criterion scores for the foot posture, and while the participant maintained a fixed posture, the positions of each of the 17 anatomical landmarks were recorded by placing the stylus tip against the relevant landmark. Maintaining the stylus tip stationary over the landmark for 2 seconds enabled the software to identify presence of a landmark and determine its Cartesian coordinates. The process was repeated until the foot posture and the anatomical landmarks had been had been recorded using for each of the three standing positions. Data were stored to disk for subsequent processing and the FPI scoring sheets were returned to the author for analysis. The requirement for post processing of the EMT data ensured that all FPI ratings were completed with the rater blind to the results of the digitisation protocol.

#### 6.1.3.5 Data processing

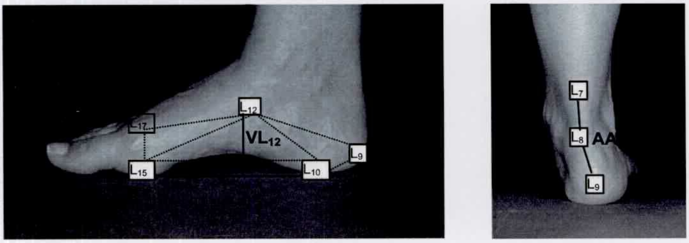
Following data acquisition and pre-processing in the MCU and terminal software, data were passed to the TurboBasic routines where the raw Cartesian coordinate and directional cosine data were processed into clinically meaningful segmental information, against which the FPI scores could be compared.

Postural variations in all three planes were calculated for the five joint complexes:

| | | |
|---|---|---|
| Tibia ($L_4$ - $L_7$) to calcaneus ($L_8$ - $L_{11}$) | designation | $TC_{\alpha,\beta,\gamma}$. |
| Tibia ($L_4$ - $L_7$) to forefoot ($L_{15}$ - $L_{17}$) | designation | $TF_{\alpha,\beta,\gamma}$. |
| Calcaneus ($L_8$ - $L_{11}$) to forefoot ($L_{15}$ - $L_{17}$) | designation | $CF_{\alpha,\beta,\gamma}$. |
| Calcaneus ($L_8$ - $L_{11}$) to midfoot ($L_{12}$ - $L_{14}$) | designation | $CM_{\alpha,\beta,\gamma}$. |
| Midfoot ($L_{12}$ - $L_{14}$) to forefoot ($L_{15}$ - $L_{17}$) | designation | $MF_{\alpha,\beta,\gamma}$. |

In addition, the frontal plane angulation between landmark markers $L_7$ (mid-point Achilles tendon), $L_8$ (insertion of Achilles tendon into calcaneus) and $L_9$ (lower calcaneus), was calculated to give an angle (AA) – the Achilles angle. Finally the true vertical height (V) of $L_{12}$ (the tuberosity of the navicular) was determined through triangulation from the positions and orientations of $L_9$, $L_{10}$, $L_{15}$ and $L_{17}$.

**Figure 6.63. Navicular height (VL12)and Achilles angle (AA) derivation**



### 6.1.3.6 Statistical analysis

The data analysis employed two stages. Firstly, the systematic differences in mean position in the three states were explored, and the significance of any differences calculated to establish the presence of a systematic effect. The systematic differences were explored using a repeated measures analysis of variance (ANOVA) model, and the significance of the individual differences between states (within-subject contrasts) was calculated using a comparison of main effects, with a Bonferroni adjustment for multiple comparisons.

Secondly, each of the FPI components was entered as the dependent variable into an ordinal regression model, and the contribution of the EMT measures to the explanation of variance in each FPI component score was established. As the output from the FPI scoring yields ordinal data with only five discrete levels it was appropriate to use ordinal regression modeling for the second stage of the analysis [410].

## 6.1.4 Results

### 6.1.4.1 Results 1. Descriptive statistics and significance of systematic differences.

In a study of foot posture such as this, it is predicted by anatomical theory that the values for each of the three foot positions should be associated systematic and predictable changes in the relevant measured segmental positions, with values for the neutral or FPI '0' position lying between those for the pronated and supinated positions. Throughout this section the results are presented therefore, in a standard order. The maximally pronated position is reported first, followed by the neutral position, with the maximally supinated position reported third.

**Table 6.58. Descriptive statistics and the significance of systematic differences in joint complex position between the three states.**

| | **Pronated state** | **'Neutral' state** | **Supinated state** | **Significance of contrasts** |
|---|---|---|---|---|
| **Joint complex** | **Mean angle ° (95%CI)** | **Mean angle ° (95%CI)** | **Mean angle ° (95%CI)** | **P='pronated', N='neutral', S='supinated'** |
| $TC_{\beta}^{a}$ | -5.9 (-9.2 to –2.6) | -1.1 (-4.7 to +2.6) | +8.4 (+5.1 to 11.7) | P-N, P=0.09; **P-S** and **N-S**, P<0.001 |
| $TC_{\gamma}^{b}$ | +4.1 (+1.4 to +6.7) | -0.3 (-2.9 to +2.4) | -1.4 (-3.6 to +0.8) | **P-N**, P=0.005; **P-S**, P<0.001; N-S, P=0.986 |
| $TF_{\alpha}^{c}$ | +71.4 (+68.7 to +74.1) | +80.9 (+79.3 to +82.4) | +80.5 (+78.8 to +82.2) | **P-N** and **P-S**, P<0.001; N-S, P=1.0 |
| $AA^{m}$ | +12.4 (+7.2 to –17.6) | +2.2 (-2.0 to +6.2) | -2.6 (-6.5 to +1.2) | **P-N**, P=0.005; **P-S**, P<0.001; N-S P=0.094 |
| $CM_{\alpha}^{g}$ | +83.3 (+78.7 to 87.7) | +89.5 (+86.0 to +93.0) | +91.2 (+84.7 to +97.8) | **P-N**, P=0.033; **P-S**, P=0.003; N-S, P=1.0 |
| $CM_{\beta}^{h}$ | +64.2 (+54.1 to +74.3) | +61.3 (+55.9 to +66.6) | +64.3 (+60.4 to +68.2) | P-N and P-S, p-1.0; N-S, P=0.46 |
| $CM_{\gamma}^{i}$ | +5.1 (+1.2 to +9.4) | +5.5 (+1.5 to +9.4) | +4.0 (0.0 to +8.1) | P-N, P=1.0; P-S, P=0.70; N-S, P=0.122 |
| $MF_{\alpha}^{j}$ | +40.4 (+34.8 to +46.0) | +39.8 (+34.4 to +45.2) | +37.8 (+32.2 to +43.5) | P-N, P=1.0; P-S, P=0.85; N-S, P=0.653 |
| $MF_{\beta}^{k}$ | -81.6 (-90.6 to –72.5) | -61.3 (-65.8 to –56.9) | -51.2 (-55.5 to –46.9) | **P-N,** P=0.002; **P-S** and **N-S,** P=<0.001 |
| $MF_{\gamma}^{l}$ | -35.1 (-41.6 to –28.5) | -35.6 (-42.0 to –29.1) | -37.8 (-44.1 to –31.5) | P-N, P=1.0; **P-S**, P=0.011; N-S, P=<0.061 |
| $CF_{\alpha}^{d}$ | +123.3 (+119.8 to +126.7) | +128.9 (+125.1 to +132.7) | +128.7 (+124.7 to +132.8) | **P-N**, P<0.001; P-S, P=0.054; N-S, P=1.0 |
| $CF_{\beta}^{e}$ | -0.3 (-3.7 to +3.2) | -1.4 (-3.5 to +0.7) | -2.6 (-5.4 to +0.3) | P-N and N-S, p-1.0; P-S, P=0.116 |
| $CF_{\gamma}^{f}$ | -29.9 (-34.8 to –25.0) | -30.0 (-34.6 to –25.4) | -33.7 (-38.5 to –29.0) | P-N, P=1.0; **P-S**, P=0.006; **N-S** P=0.004 |
| **Landmark** | **Mean height mm (95%CI)** | **Mean height mm (95%CI)** | **Mean height mm (95%CI)** | |
| $VL_{12}^{n}$ | +17.7 (+14.9 to +20.5) | +26.6 (+23.7 to +29.4) | +29.4 (+26.7 to +32.2) | **P-N** and **P-S,** P<0.001; **N-S,** P=0.015 |

[a] F= 30.3 (P<0.001), [b] F=13.6 (P=0.006) ,[c] F=42.7 (P<0.001), [d] F=6.72 (P=0.018), [e] F=1.69 (P=0.199), [f] F=5.58 (P=0.008), [g] F=5.97 (P=0.006), [h] F=0.293 (P=0.748), [i] F=1.41 (P=0.257), [j] F=1.067 (P=0.354), [k] F=28.3 (P<0.001), [l] F=4.7 (P=0.014) [m] F=17.68 (P<0.001), [n] F=89.39 (P<0.001) N=20

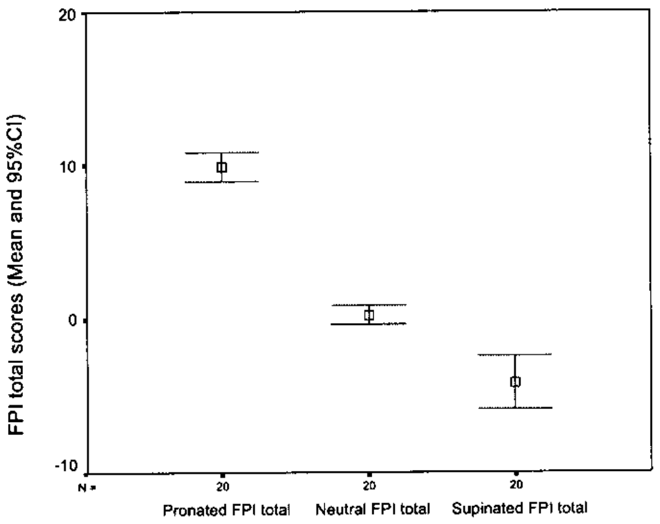
Significant relationships are highlighted in bold in column 5.

**Table 6.59. Descriptive statistics and the significance of systematic differences between Foot Posture Index scores in the three states.**

| FPI score | **Maximally pronated (95% CI)** | **'Neutral' (95% CI)** | **Maximally supinated (95% CI)** | **Significance of contrasts P='pronated', N='neutral', S='supinated'** |
|---|---|---|---|---|
| **FPI THP**[a] | 1.9 (1.8 to 2.0) | -0.2 (-0.4 to 0) | -1.3 (-1.5 to –1.0) | **All** P<0.001 |
| **FPI Mall**[b] | 1.3 (1.0 to 1.5) | 0.1 (-0.1 to 0.2) | -0.6 (-1.0 to -0.2) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.003 |
| **FPI Helbings**[c] | 1.1 (0.7 to 1.3) | 0 (0 to 0) | -0.4 (-0.7 to -0.1) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.05 |
| **FPI calc pos**[d] | 1.4 (1.1 to 1.6) | -0.1 (-0.2 to 0.1) | -0.6 (-0.9 to -0.3) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.002 |
| **FPI TNJ**[e] | 1.2 (1.0 to 1.4) | -0.1 (-0.2 to 0) | -0.9 (-1.1 to –0.6) | **All** P<0.001 |
| **FPI MLA**[f] | 1.3 (1.0 to 1.5) | 0.3 (0 to 0.6) | -0.3 (-0.8 to 0.2) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.003 |
| **FPI Lat border**[g] | 0.9 (0. to 1.0) | 0.3 (0.0 to 0.6) | 0 (0 to 0) | **P-N** and **P-S**, P<0.001, N-S, P=0.488 |
| **FPI ab/ad**[h] | 1 (1 to 1) | 0.2 (0 to 0.3) | -0.2 (-0.3 to 0) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.03 |
| **FPI Sagittal plane**[i] | 1.3 (1.0 to 1.5) | 0.3 (0 to 0.6) | -0.3 (-0.8 to 0.2) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.003 |
| **FPI Frontal plane**[j] | 3.6 (3.0 to 4.2) | 0 (-0.2 to 0.2) | -1.6 (-2.4 to –0.8) | **P-N** and **P-S**, P<0.001, **N-S**, P=0.002 |
| **FPI transverse plane**[k] | 6.2 (5.8 to 6.7) | 0 (-0.4 to 0.4) | -2.9 (-3.8 to –1.9) | **All** P<0.001 |
| **FPI rearfoot**[l] | 5.5 (4.8 to 6.1) | -0.2 (-0.4 to 0) | -2.9 (-3.9 to -1.8) | **All** P<0.001 |
| **FPI forefoot**[m] | 4.4 (4.0 to 4.7) | 0.5 (-0.1 to 1.0) | -1.3 (-2.1 to –0.5) | **All** P<0.001 |
| **FPI Total score**[n] | 9.9 (8.9 to 10.8) | 0.2 (-0.4 to 0.9) | -4.2 (-5.9 to -2.4) | **All** P<0.001 |

[a] F = 275.37 (P<0.001), [b] F = 82.64 (P<0.001), [c] F = 42.96 (P<0.001), [d] F = 161.44 (P<0.001), [e] F = 117.36 (P<0.001), [f] F = 61.35 (P<0.001), [g] F = 81.59 (P<0.001), [h] F = 87.24 (P<0.001), [i] F = 61.35 (P<0.001), [j] F = 111.69 (P<0.001), [k] F = 438.27 (P<0.001), [l] F = 184.24 (P<0.995), [m] F = 216.51 (P<0.001), [n] F = 253.16 (P<0.001) N=20
Significant relationships are highlighted in bold in column 5.

**Figure 6.64. Mean and 95% confidence interval for the FPI total scores in each of the three states.**



### 6.1.4.2 Results 2. Ordinal regression modelling for the eight FPI components

Each of the FPI components was examined in turn to determine which of the segmental angular relationships derived from the reconstructed 3D EMT model best predicted variance in each FPI component score. A first iteration of the ordinal regression model entered all

EMT variables. Subsequent iterations removed EMT variables not contributing to the model or demonstrating asymptotic correlation of covariates (colinearity or redundancy). As noted previously a conservative approach was employed to limits the potential for erroneous rejection of variables during the iterative modelling process [411]. Once the final model had been fitted, only covariates with a significance $P<0.05$ were reported as significant.

The final iterations are presented in full in tabular form. Part one of the table indicates the goodness of fit of the model (where P **greater than** 0.05 indicates that the model **met** assumptions of fit), and the Cox and Snell pseudo-$R^2$ (analogous to the $R^2$, or 'coefficient of determination' in linear regression modelling). Part two of each table details the EMT covariates entered into the model, followed by the parameter estimate (B) and its 95% confidence interval followed by the significance value.

### FPI component one - Talar head palpation.

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

The combination of 14 EMT derived joint orientations explained collectively 78% of the variance in the FPI talar head palpation scores, with $TF_\alpha$, $CM_\alpha$ , $MF_\alpha$ , $MF_\beta$ and $CF_\alpha$ all demonstrating Wald statistic >2.0. These five variables were entered into a second and third iteration, which excluded $CM_\alpha$, $CF_\alpha$ and $MF_\alpha$. The fourth and final iteration was conducted using $TF_\alpha$, and $MF_\beta$.

*Ordinal regression model - Iteration four (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =277.736 (P=0.26 ) | 0.703 | 20 |

| Covariates | Estimate B | 95% CI (B) Lower Bound | Upper Bound | P value |
|---|---|---|---|---|
| $TF_\alpha$ | -.137 | -.275 | .000 | .049 |
| $MF_\beta$ | -.164 | -.227 | -.101 | <.001 |

*Link function: Logit.*

The two stronger predictors $TF_\alpha$, and $MF_\beta$ together predicted 70% of the variance in FPI talar head palpation scoring. Given that it is thought that the clinical assessment of talar head palpation is an estimate of the degree of congruence between the head of the talus and the navicular it is consistent with theory that this FPI component should correlate well with a measure of midfoot to forefoot congruence. It is also coherent with theory that tibia to forefoot flexion may contribute to variance in estimates of talar head palpation. It might have been expected however that the γ rotations, and the calcaneus to midfoot measures generally may have been more influential in predicting talar head position.

### FPI component two - Malleolar curves

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

For the FPI component estimating malleolar curvature, the combination of EMT derived joint orientations explained collectively, 74% of the variance in the FPI scores. A second iteration entered $MF_\beta$, $CF_\beta$ and $TC_\beta$ into the model, after which $TC_\beta$ was deleted. The third and final iteration entered $MF_\beta$ and $CF_\beta$.

*Ordinal regression model - Iteration three (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =119.56 (P=1.0 ) | 0.693 | 20 |

| Covariates | Estimate | 95% CI (B) Lower Bound | Upper Bound | P value |
|---|---|---|---|---|
| $MF_\beta$ | -.211 | -.290 | -.132 | <.001 |
| $CF_\beta$ | .131 | .027 | .236 | .014 |

The final model predicted 69% of the variance in FPI malleolar curve scoring, loaded on to two frontal plane EMT measures.

### FPI component three - Helbing's sign

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

The initial model explained nearly 80% of the variance in Helbing's sign variance. Four iterations were required to reach the final model in which 73.5% of the variance was explained by four variables.

*Ordinal regression model - Iteration four (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =187.26 (P=0.986 ) | 0.735 | 20 |

| Covariates | Estimate B | 95% CI (B) Lower Bound | Upper Bound | P value |
|---|---|---|---|---|
| $TC_\gamma$ | .252 | .076 | .428 | .005 |
| $CM_\beta$ | -.093 | -.190 | .000 | .048 |
| $MF_\beta$ | -.290 | -.423 | -.156 | <.001 |
| $CF_\beta$ | .191 | .025 | .357 | .024 |

For the FPI component estimating Helbing's sign, the final model predicted 73.5% of the variance. Although much of the contribution to the model came from frontal plane EMT measures that fit well with standard theory, it is of some concern that the EMT measure of Achilles tendon angle was eliminated at the third iteration, as Helbing's sign could be thought of as a direct clinical surrogate for AA.

### FPI component four - Calcaneal position

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

The initial model explained 83% of the variance in FPI scored calcaneal position. All five of the EMT variables with a Wald score >2 entered into the second model were found to be significant contributors in this second and final model.

*Ordinal regression model - Iteration two (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =86.22 (P=1.0 ) | 0.798 | 20 |

| Covariates | Estimate B | 95% CI (B) Lower Bound | Upper Bound | P value |
|---|---|---|---|---|
| $TC_\gamma$ | .160 | .009 | .311 | .038 |
| $TF_\alpha$ | -.290 | -.494 | -.086 | .005 |
| AA | -.131 | -.231 | -.031 | .010 |
| $MF_\beta$ | -.153 | -.240 | -.066 | .001 |
| $CF_\beta$ | .214 | .080 | .348 | .002 |

The FPI component estimating calcaneal angle in the frontal plane was again correlated well with the EMT measures, with the EMT data predicting 79.8%% of variance in the FPI component score. Five measures were significant contributors to the model, three of them reflecting the frontal plane predominance of this clinical measure. It is of note that the EMT measure of calcaneal angle relative to the tibia directly ($TC_\beta$), does not contribute to the model, whereas $MF_\beta$, the EMT measure referencing the rearfoot position relative to the floor (via the plantigrade forefoot), makes the most significant contribution to the regression model.

### FPI component five - Talonavicular joint congruence

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

The 14 EMT joint orientations explained collectively almost 80% of the variance in the FPI talar navicular joint congruence scores.

*Ordinal regression model - Iteration four (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =100.33 (P=1.0 ) | 0.72 | 20 |

| Covariates | Estimate | 95% CI (B) | | P value |
|---|---|---|---|---|
| | | Lower Bound | Upper Bound | |
| $TC_\gamma$ | .226 | .097 | .355 | .001 |
| AA | .085 | .006 | .165 | .036 |
| $MF_\beta$ | -.149 | -.212 | -.085 | <.001 |

The fourth iteration modelled three EMT variables predicting 72% of the variance in the FPI TNJ measure. The sagittal plane variables ($CM_\alpha$, $MF_\alpha$, $CF_\alpha$) which appear significant in the first iteration were highly co-linear and after reducing their number to $CM_\alpha$, the sagittal plane dropped from the model entirely.

### FPI component six - Medial arch height

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

The EMT measures in combination explained 69% of the variance in medial arch height, although there was poor model fit overall. $MF_\beta$, and $CF_\beta$ were entered into the second iteration, after which $CF_\beta$ was also excluded.

*Ordinal regression model - Iteration three (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =142.96 (P=1.0 ) | 0.579 | 20 |

| Covariates | Estimate B | 95% CI (B) | | P value |
|---|---|---|---|---|
| | | Lower Bound | Upper Bound | |
| $MF_\beta$ | -.147 | -.198 | -.096 | <.001 |

$MF_\beta$ alone predicts 58% of the variance in FPI observed arch height.

### FPI component seven - Lateral border shape

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =N/A* | 0.720 | 20 |

* There were insufficient threshold levels to fit a model to the data.

| Covariates | Estimate B | 95% CI (B) Lower Bound | Upper Bound | P value |
|---|---|---|---|---|
| $TC_\beta$ | -22.276 | -7285.872 | 7241.319 | .995 |
| $TC_\gamma$ | -37.302 | -25569.053 | 25494.449 | .998 |
| $TF_\alpha$ | -54.531 | -22293.779 | 22184.718 | .996 |
| AA | 20.565 | -45095.188 | 45136.318 | .999 |
| $CM_\alpha$ | 449.926 | -452436.004 | 453335.855 | .998 |
| $CM_\beta$ | 21.189 | -43808.149 | 43850.527 | .999 |
| $CM_\gamma$ | 1002.367 | -14502488.71 | 14504493.446 | 1.000 |
| $MF_\alpha$ | 508.915 | -444418.307 | 445436.138 | .998 |
| $MF_\beta$ | -75.939 | -21779.671 | 21627.793 | .995 |
| $MF_\gamma$ | 1041.585 | -14490458.69 | 14492541.861 | 1.000 |
| $CF_\alpha$ | -470.886 | -398064.581 | 397122.810 | .998 |
| $CF_\beta$ | 62.698 | -32383.198 | 32508.594 | .997 |
| $CF_\gamma$ | -1050.854 | -14476299.76 | 14474198.053 | 1.000 |
| $VL_{12}$ | 163.350 | -197665.502 | 197992.203 | .999 |

This component failed to differentiate foot postures well in this experiment, leading to problems with model fitting. This result raises questions over the appropriateness of this component in the FPI measure. This is discussed at the end of this section.

### FPI component eight - ab/adduction of forefoot

***Dependent variable: FPI component score***
***Independent variables: Multiple EMT segment positions (iterative)***

*Ordinal regression model - Iteration two (final)*

| Goodness of fit (sig) | Cox and Snell Pseudo $R^2$ | N |
|---|---|---|
| $X^2$ =41.89 (P=1.0 ) | 0.635 | 20 |

| Covariates | Estimate B | 95% CI (B) Lower Bound | Upper Bound | P value |
|---|---|---|---|---|
| $TF_\alpha$ | -.251 | -.496 | -.005 | .045 |
| $MF_\beta$ | -.176 | -.280 | -.073 | .001 |
| $CF_\beta$ | .220 | .030 | .411 | .024 |

The three EMT variables entered into the second iteration were significant contributors to the model. Between the three EMT variables, 63.5% of the variance in FPI scoring of forefoot position was predicted. It was notable that no transverse plane variables ($\gamma$) appeared in the final model.

### 6.1.5 The validity of the eight FPI components

*A review of candidates for retention or exclusion on the basis of concurrent, construct and content validity.*

The FPI components reflecting rearfoot relationships appeared better predicted by the EMT data, than did the FPI forefoot components. There were particular concerns over the weak relationship between the EMT data and variation in the FPI component measuring lateral border congruence (poor concurrent validity). The FPI measure of medial arch congruence had also performed less well than other measures during the concurrent validation study. Concerns over the reliability of the FPI components estimating Helbing's sign highlighted in Chapter Five, also recurred in the concurrent validation study where the EMT measure of Achilles angle, which is directly analogous to Helbing's sign, did not make a significant contribution to the ordinal regression model. The performance of the eight components over the course of the five feasibility, reliability and concurrent validation studies outlined in Chapters Four to Six is tabulated below.

| | Chapter 4 Clinician rating of usefulness | Chapter 5 Item total correlation (Cronbach's α) | Chapter 5 Multiple ordinal regression vs total score† | Chapter 5 Factor analysis (Factor loading) | Chapter 6 Concurrent validity vs EMT model (R2) | Comments |
|---|---|---|---|---|---|---|
| **Talar head palpation** | 5 | 0.62 | P<0.001 | Factor 1 | 0.70 | *Palpation of bony relationship* |
| **Malleolar curvature** | 5 | 0.62 | P<0.001 | Factor 1 | 0.69 | *Direct observation of bony segments* |
| **Helbing's sign** | 4.7 | 0.44 | P<0.001 | Factor 1 | 0.74 | *Direct observation of soft tissue* |
| **Calcaneal angle** | 5 | 0.75 | P<0.001 | Factor 1 | 0.80 | *Direct observation of bony segment* |
| **TNJ congruence** | 4.4 | 0.67 | P<0.001 | Factor 1 | 0.72 | *Direct observation of composite bony segments* |
| **MLA congruence** | 5 | 0.72 | P<0.001 | Factor 1 | 0.58 | *Direct observation of composite bony segments* |
| **Lateral border congruence** | 5 | 0.59 | P<0.001 | Factor 2 | N/A | *Direct observation of composite bony segments* |
| **Abduction/adduction** | 4.6 | 0.75 | P<0.001 | Factor 1 | 0.64 | *Indirect observation of composite bony segments* |

The FPI component estimating lateral border congruence had clearly performed significantly less well than the other seven components over the course of the five sets of evaluations. In addition to failing to differentiate scores adequately in the EMT study, it had demonstrated loading onto a separate factor in the factor analysis conducted in Chapter Five (poor construct validity), and had a relatively low inter item correlation of 0.59 (poor content validity). The theoretical overlap with the measure of forefoot abduction/adduction, also introduced a degree of redundancy (poor construct validity) and so the decision was taken to delete the forefoot component measuring lateral border congruence. Conversely, the FPI measure of medial arch congruence, which was among the weaker measures in the EMT concurrent validity study, had shown high inter-item correlation previously (better content validity). This measure has low redundancy, being the only measure of sagittal plane foot posture and was reported by the clinicians to be a useful component (better construct validity). The medial arch measure was therefore retained.

The FPI measure of Helbing's sign, first highlighted for its low inter-item correlation (poor content validity) had caused further concern by showing no significant relationship with its EMT measured direct surrogate, the Achilles angle (poor concurrent and construct validity). The fact that the Helbing's measure was the only FPI component to rely on observation of soft tissue relationships had also been of concern, as it is bony relationships that are considered theoretically more significant to foot posture. Ultimately, because of the weak concurrent validity combined with this reliance on observation of soft tissues rather than bony segments, and a degree of theoretical redundancy in the observation of multiple measures of rearfoot frontal plane position (poor construct validity), the decision was taken to remove this measure also. Removal of the Helbing's sign component led to the secondary advantage of maintaining the balance between the forefoot and rearfoot subscales, leaving a matching number of components in each subscale.

### 6.1.6 Discussion of FPI component score evaluation

In this section the two aims have been met. The first aim was to develop a static 3D reconstruction of key elements of the lower limb that would model the standing foot posture accurately, and by extension quantify objectively, systematic changes in foot posture. The EMT model has certainly gone some way towards addressing this, although the limitations imposed by even the best available technologies must be acknowledged. The technical error of the system at 2.54mm probably represents the best available solution, but the resulting errors in the reporting of segment orientation of up to 5.3° must still be considered a limitation of the EMT data as a gold-standard. There was some evidence of limited agreement between EMT variables that might be expected to be more closely related. For instance arch height and calcaneal position have been demonstrated to be well correlated previously (R=0.94), when sensors are mounted directly onto the skin [336]. An exploratory analysis of the EMT data in this study showed relatively poor agreement for similar measures such as arch height ($VL_{12}$) and calcaneal angle ($TF_\beta$) R=0.34, and arch height ($VL_{12}$) with Achilles angle (AA), R=0.54, suggesting the presence of error in the digitisation protocol. Further examples of limited agreement between other theoretically related measures in the EMT model such as $TC_\beta$ and AA (R=0.217), and consistently poor agreement between related CF and MF measures highlight the limitations of even the best available techniques.

The second aim, to determine the consistency between FPI scores and EMT data was achieved, within the limitations noted above. It is recognised that these data relate only to alterations in static posture, and that the changes in posture were achieved by artificial means. The method of changing the standing posture so as to facilitate large excursions in joint position was chosen to maximise the differentiation between the positions. Given the technical limitations of the method, the requirement for relatively large excursions was deemed paramount at this stage of the validation process. A method for changing foot posture that more closely approximates clinical practice is employed in Section 6.2.

The ordinal regression modelling allowed for the relationship to be explored between each FPI component score and the full set of EMT variables. This approach revealed both the presence and absence of several relationships that might not be expected in the context of current general theories of foot function. It is not clear whether these inconsistencies are a fault of the FPI, a product of the technical limitations of the system, or reflect shortcomings in current theory.

In summary, eight components were evaluated individually against the EMT static foot and ankle model. Six components had demonstrated adequate validity concurrent, content and construct validity to this stage, and were considered suitable for further evaluation in the form of a truncated, six-component version of the FPI (FPI-6). The detailed nature of the EMT foot and ankle model required for the component evaluations had limited this stage of the study to static studies. Further evaluation of the capacity of the FPI as a static measure to predict foot posture during walking was undertaken in a second stage.

# 6.2 *Chapter Six, Section Two – Concurrent Validity of the FPI, Evaluated Against Validated Static and Dynamic Models of the Ankle Joint Complex*

## 6.2.1 Introduction

The first part of the validation study had evaluated the FPI component measures in static stance, against a new, objective gold-standard and had resulted in rationalisation of the component measures. It was recognised however that in clinical practice, the FPI scores would be used in aggregate, with scores combined to give an overall quantification of standing or walking foot posture. The absence of explicit evaluations of the link between static clinical tests and dynamic function has been criticised previously [6]. A second stage was necessary therefore to determine the extent to which the FPI-6 total score, and the rearfoot and forefoot subscale scores might predict variance in both static posture and dynamic function according to a simpler but well-validated EMT model. In conjunction with the Bioengineering Division of the Rheumatology and Rehabilitation Research Unit (RRRU) at the University of Leeds, the capacity for the truncated six-item FPI to predict ankle joint complex kinematics during standing and level walking was investigated using a validated, dynamic EMT-based foot model [241 412 413].

## 6.2.2 Aims

1. To evaluate the concurrent validity of FPI-6 aggregate scores against a validated static EMT model of the ankle joint complex.

2. To establish the degree to which static FPI-6 scores predict variations in foot posture during normal walking.

## 6.2.3 Methods

Comparison of FPI measures (six-item version) with contemporaneous static and dynamic EMT data derived from surface mounted sensor data using a six degrees of freedom lower extremity model.

### 6.2.3.1 Equipment

The EMT hardware again consisted of a Fastrak™ (Polhemus Inc., Colchester VT) electromagnetic motion tracking system, in this study operating at 30Hz. Thirty Hertz is generally considered an adequately high frequency for capturing the motion of normal walking[241], although for studies of running or other high-speed events would be inappropriate. Data channels were routed through two MCUs modulated in a master/slave arrangement. For the dynamic studies, stance phase events were appended to the EMT datastream during capture, by employing force sensing resistors (Interlink Electronics Inc, Santa Barbara CA), taped to the hallux and the plantar surface of the heel of each foot and routed through to a four channel unit outputting a digital voltage signal synchronised to, and recorded with the motion data.

As noted in section 6.1, the system can be used with either a long-range or a short-range transmitter. Manufacturer's data suggests that the error for both transmitter set-ups should be comparable, so transmitter choice should depend in theory, only on the practical application. Previous studies have explored the error of the Fastrak system in collecting gait cycle data using the short-range transmitter configuration [405] and more recently with the long-range transmitter [247]. With the short-range transmitter, the maximum reliable functional radius of the electromagnetic field is only 75-80cms. The resulting limited capture volume can result in collection of data from more than one stance phase of one limb being unreliable. For evaluating the capacity of the FPI to predict aspects of dynamic gait, it was desirable to collect data for whole gait cycles for both limbs, and using the long-range transmitter it was possible to ensure that data capture occurred entirely within a reliable capture volume. The remainder of this section thus relates to the system configured with its long-range transmitter.

**Figure 6.65. Twin Polhemus motion capture units (below) and a 4 channel footswitch (above).**

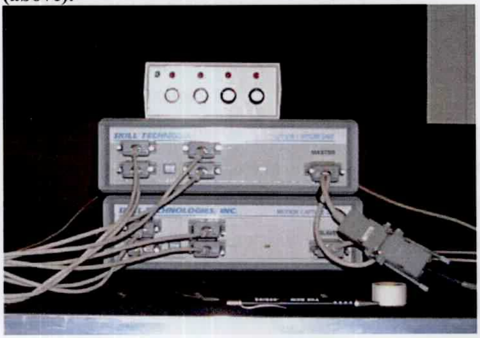
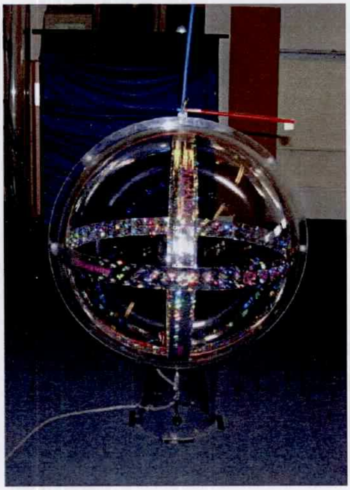


**Figure 6.66. The long range Fastrak transmitter**

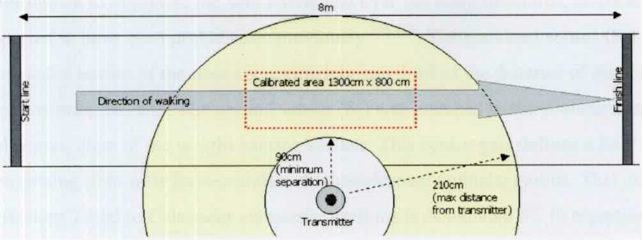


Sensor data were processed in the Fastrak MCUs as described in the previous section before being passed automatically to the 6D Research™ motion analysis software package (Skill Technologies Inc., Phoenix, AZ). Within the 6D software EMT data were filtered using a 6Hz low pass Butterworth filter to eliminate high frequency signals not related to joint motion. The data streams from multiple channels also time synchronised to eliminate latency, and stance phase events were integrated. Using the same ankle joint coordinate system defined in section 6.1, segmental models were constructed and angular rotations derived. Segment angular rotation data were output to a spreadsheet and inferential analyses were undertaken using SPSS v11.1 (SPSS Inc, Chicago. IL.)

### 6.2.3.2 Laboratory layout

The optimal layout of the data collection area was determined initially from manufacturers' data, and from iterative passages of sensors through the electromagnetic field. The manufacturers claim stability of the field with in a radius of 2300mm from the long-range transmitter. A minimum separation of 900mm is also required. It was established in pilot testing that the desirable width of the walkway to avoid undue constraints on the subjects is 750-900mm. Therefore, defining a straight path of this width within the functional capture volume of the transmitter, gave a theoretical capacity to collect accurate data from straight line walking for a capture volume with a base area of 900mm (X direction) by 3500mm (Y direction). In early trials it became immediately apparent however, that the accuracy at the margins of this theoretical field was lower than the manufacturer's data suggested (see Appendix F). To minimise error, a reduced capture volume, large enough to accommodate one full step from each limb, but smaller than the theoretical maximum was identified and defined for further analysis. Within this reduced volume of 800mm (X direction) by 1300mm (Y direction) by 600mm (Z direction), the mean RMS errors associated with angular rotation were determined to be 0.8° for $\alpha$ rotations, 0.6° for $\beta$ rotations, and 0.4° for $\gamma$ rotations. The mean absolute error in displacement was 5.8mm, figures in accord with those of Day et al [247] and Perie et al [242]. The investigative process used to define and calibrate the capture volume is described in full in Appendix F. On completion of the calibration, the base of the reduced capture volume was marked out with tape in the middle of an 8m walkway. For the walking trials, the participants started to walk at one end of the walkway and passed uninterrupted through the calibrated capture volume at normal walking pace, and continued to the far end of the walkway.

**Figure 6.67. The final configuration of the walkway, transmitter and calibrated capture volume.**

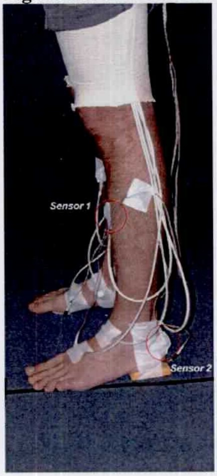


For the gait studies the transmitter was oriented so that the fields were aligned to provide a global reference frame such that the X axis is aligned parallel to the floor and is perpendicular to the long axis of the walkway. The Y axis is also aligned parallel to the floor but along the long axis of the walkway. The Z axis represents the vertical and is mutually perpendicular to the floor and the other two axes. The local anatomical joint coordinate system was that defined in the previous section and is defined so that it represents a similar alignment to the above global reference frame if the subject is in the so-called ‘anatomical position’ with the foot aligned along the Y axis. The orientation of the local AJC joint coordinate system will of course vary relative to the global reference frame according to the precise orientation of the body and the limb during gait. As mentioned previously in the AJC local joint coordinate system defined for this study, motion about the AJC x axis represents rotation (α) in the direction of plantarflexion or dorsiflexion. Motion about the y axis represents rotation (β) in the direction of inversion/ or eversion, and about the z axis represents rotation (γ) in the direction of adduction or abduction (internal /external rotation).

### *6.2.3.2.1* ***Participant preparation***

Fifteen otherwise healthy, normal volunteers were recruited from the staff and postgraduate students of the Rheumatology and Rehabilitation Research Unit, at the University of Leeds. Both limbs were instrumented on each participant. The Fastrak™ sensors were fixed to the leg and foot of each limb with double sided tape and an anchor strap was placed tightly over each sensor to hold it firmly against the skin. All cables were secured proximally with tape and passed to the control unit via elasticated straps attached to the thigh and via a belt around the waist. Cable movement was thus minimized. The sensors measuring AJC motions were placed according to the protocol described previously by Cornwall and McPoil [350]. These are sites known to minimize the skin movement over the bony structures, an issue that has been reported to have been problematic previously [366 414]. The proximal sensor ($S_1$) was attached to the medial border of the tibia approximately one third of the distance of the length of the bone from its proximal end. The second sensor ($S_2$) was attached to the posterior aspect of the calcaneus, clear of the weight bearing surface. This sensor pair defines a joint complex comprising tibio-talar (talo-crural) and talo-calcaneal (subtalar) joints. This joint complex reflecting Tibial to Calcaneus composite motions is designated TC in reporting the results. The force sensing resistors identifying gait cycle contact events were attached to the plantar surface of the hallux and the heel with tape.

**Figure 6.68. The location of the Fastrak sensors**



The EMT system was calibrated to zero or 'boresighted' prior to data collection for each participant, aligning the transmitter's global reference frame with the local joint coordinate system according to the preferred starting position. Boresighting was conducted as follows: The participant stood on a spot marked in the centre of the calibrated area, facing in the direction of walking along the walkway. While standing on this spot, the participant was manipulated into a position based on a zero score using Foot Posture Index (FPI), with the ankle at 90° and the knee straight. With the participant standing in this manipulated zero position the software was boresighted by a software procedure built into the 6D research package. This boresight position subsequently acted as a reference for all future concurrent validity measures.

Once the system was boresighted, the participant took several steps on the spot prior to recording five seconds of static data to allow for the adoption of a natural relaxed standing position. Participants then returned to the end of the walkway to undertake the walking trials. For each pass the participants walked the full length of the 8m walkway with the calibrated field at its centre. One full gait cycle was obtained for both limbs per pass, with five good gait cycles recorded for each of the barefoot and wedged states. The sequence for recording the wedged or barefoot, control states was randomized according to a predetermined randomization protocol.

Wedges were used to influence the foot into positions that were intended would reflect pronated (lateral wedge) or supinated (medial wedge) foot postures during gait. The wedged states were achieved by fixing a 100mm length of preformed 10° ethylene vinyl acetate (EVA) wedge to the heels with double sided tape and an anchor strap. The pre-wedged EVA is of the type commonly used to fabricate 'chairside' orthoses and is purchased in long strips which can be cut to the required length. The 6cm wide strip was fabricated from 450kg/m$^3$, high density ethylene vinyl acetate, with a consistent 10° angle along its length. The accuracy and the consistency of the angle were checked with an angle finder prior to the commencement of the study. Pairs cut to 100mm lengths were used in this study to ensure that the wedge covered the entire weightbearing surface of the heel, while the anterior border of the wedge reached the medial arch area, immediately anterior to the weightbearing surface of the heel. The wedges were fixed to the heel with double sided tape, and secured with an anchor strap which passed, stirrup-like from the medial side to the lateral side of the calf.

#### *6.2.3.2.2* ***Data collection protocols***

**Collection of data from static stance**

In each wedged state the subject first stood on a mark in the centre of the calibrated area, with the feet aligned with the Y axis. The subject took four or five steps on the spot and settled into a relaxed quiet stance. Five seconds of data were recorded to capture the joint positions in each of the three standing states.

**Collection of data from dynamic evaluations**

Participants undertook two practice passes of the length of the walkway in order to acclimatize to walking with the cables in place. Once the participant was comfortable, the trial was started. The participant stood at one end of the 8m walkway and on a signal from the investigator, walked at a self selected speed along a Y axis guideline running the full length of the walkway (see Figure 6.69). The base of the calibrated capture volume was marked on the walkway with tape enabling the investigator to monitor each pass carefully. Any passes in which the participant did not stay entirely within the capture volume were repeated. An immediate preliminary analysis of the motion curves was also undertaken for each pass to assess the face validity. If there was any noise from loosening of sensors, or inappropriate data from foot switches operating incorrectly, these passes were also repeated.

**Figure 6.69. A subject participating in the trial protocol**

[redacted]

[redacted]

Once all trials for each state were completed the data were prepared using the 6D Research software. Joint angle data, and sensor positional data were further processed using Cornwall's '6DNorm' software (©M. Cornwall, Northern Arizona University, AZ) as described by Woodburn et al [241], and results were output to a spreadsheet. The 6D Norm utility normalized motions about the three axes and at each joint complex for each stance phase to 100 centiles. Multiple trials from each subject were aggregated into a single averaged, and normalized file. The coefficients of multiple correlation (CMCs)`were calculated as described by Kadaba et al. [415], providing a coefficient indicating the consistency of the measures throughout the averaged motion/time curve.

## 6.2.4 Results

### 6.2.4.1 Results of the concurrent scoring of FPI-6 and collection of EMT static data

Data were obtained from both limbs of 15 of the subjects, and descriptive outputs (such as the motion time curves) were calculated based on pooled data from both limbs. Where inferential analyses were performed, data from the right limb only were entered into analyses to avoid paired observations leading to breaches of the assumption of independence in the data. Static data for one of the participants were found at post-processing to be corrupted and were not suitable for analysis. All results from the static stance section of this report relate therefore to data from 14 participants. There were five female and ten male participants (five female and nine male where N=14). Data obtained from left and right sides were homogenous and t-tests yielded no significant systematic differences in left and right side means for $TC_\alpha$, $TC_\beta$ or $TC_\gamma$. Differences in mean joint positions in the three experimental static states were explored to evaluate the extent to, and the direction in which, the input (the EVA wedging) had affected output motion. This stage in the analysis was undertaken to ensure the validity of the motion data prior to its use as a benchmark for the concurrent validity of the FPI. The differences were explored using a repeated measures analysis of variance (ANOVA) model, and the significance of the individual differences between states (within-subject contrasts) were calculated using a comparison of main effects with a Bonferroni adjustment for multiple comparisons.

The final evaluation of concurrent validity employed linear regression modeling rather than the ordinal regression approach used in Section 6.1.4.2. Consideration was given to the relative merits of ordinal and linear regression models due to the debate in the literature regarding the appropriateness of the two approaches for data such as yielded by the FPI. The final decision was informed by the large number of levels in the FPI total score (25), which represent an underlying scale that is effectively continuous, and a growing acceptance of the robustness of parametric approaches for this type of application[410 416 417].

### *6.2.4.1.1* ***Rearfoot complex static positions in the three wedge states*** *($TC_\alpha$, $TC_\beta$ and $TC_\gamma$)*

**Table 6.60. Means and significance of differences between TCα, TCβ and TCγ positions in the three states (N=14)**

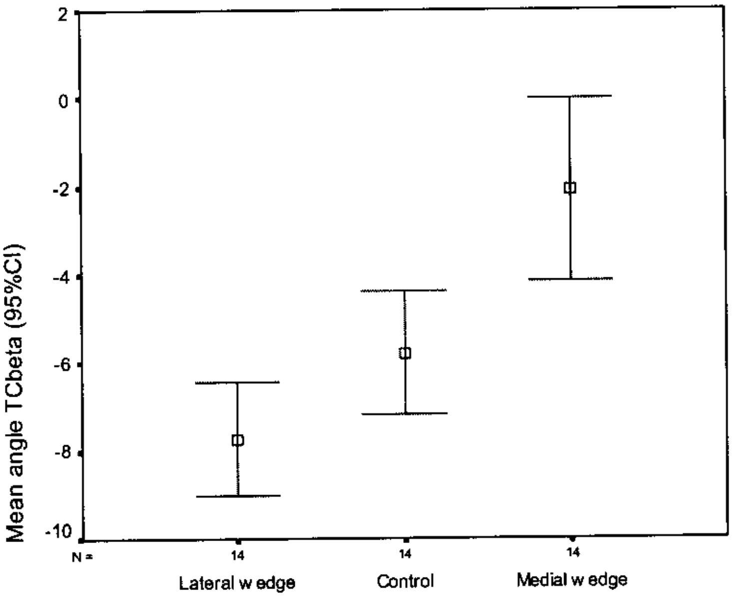
| **Joint complex** | **Lateral wedge (95% CI)** | **No wedge (95% CI)** | **Medial wedge (95% CI)** | **Significance of contrasts *** |
|---|---|---|---|---|
| $TC_\alpha$[a] | -4.39 (-5.11 to –3.76) | -0.66(-2.12 to 0.81) | -3.66 (-4.98 to –2.34) | L-C, and C-M, P<0.001, L-M, P=0.489 |
| $TC_\beta$[b] | -7.74 (-9.03 to –6.44) | -5.79 (-7.18 to –4.39) | -2.09 (-4.16 to –0.02) | L-C, P<0.002, C-M and L-M, P<0.001 |
| $TC_\gamma$[c] | 6.8 (5.5 to 8.2) | 6.1 (5.0 to 7.4) | 4.2(2.8 to 5.5) | L-C, P=0.996, C-M, P=0.001, L-M, P=0.004 |

[a] F = 32.54 (P<0.001), [b] F = 46.91 (P<0.001), [c] F = 13.36 (P<0.001)

**State L = lateral wedge (inducing a nominally pronated foot state), state C = control (the no wedged state), state M = medially wedged (inducing a nominally supinated state)*

For $TC_\beta$ position there was a consistent effect demonstrating increased inversion with progression from the pronated (laterally wedged) state, through the control state, to the supinated (medially wedged) state. The mean of each state was highly significantly different from all other states.

**Figure 6.70. Mean TCβ angle with 95%CI for each of the three states.**



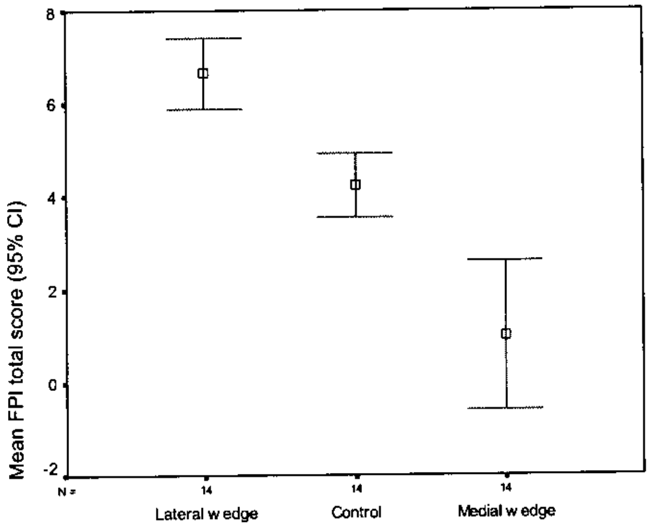
Position about the z axis ($TC_\gamma$) also showed a linear trend in the expected direction, although the difference between the laterally wedged and control static states is small and not significantly different. The medially wedged supinated state is 1.9° to 2.6° more adducted than the other two states. This smaller difference seen in the $TC_{\gamma}$ positions is to be expected as the input force was directed at y axis ($\beta$) position only. It is expected that motion about other axes, even in a triplanar joint complex, would be attenuated by the local anatomy [285]. Both wedged states promoted increased $TC_{\alpha}$ plantarflexion position due to the bulk of the device under the heel.

**Table 6.61. Foot Posture Index (six item version) total scores in the three states.**

| | **Lateral wedge (95% CI)** | **No wedge (95% CI)** | **Medial wedge (95% CI)** | **Significance of contrasts** |
|---|---|---|---|---|
| **FPI-6 Total score** | **6.6 (5.9 to 7.4)** | **4.2 (3.5 to 4.9)** | **1.0 (-0.6 to 2.6)** | **All P<0.001** |

F = 71.13.09 (P<0.001)

**Figure 6.71. Mean FPI-6 score with 95% CI in each of the three states**



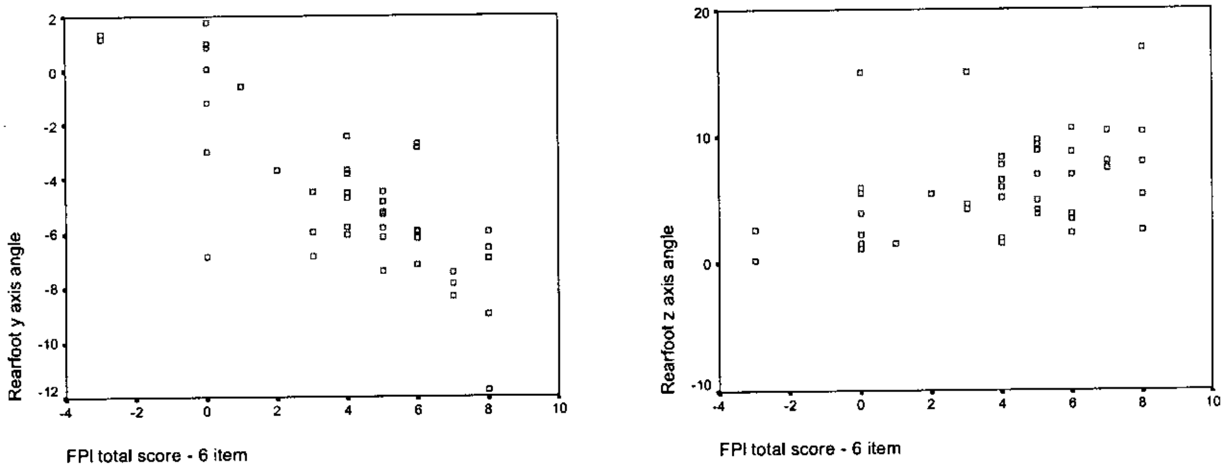
There was a systematic progression of all FPI-6 scores from the pronated state, through the resting state to the supinated state, supporting the hypothesis that the FPI-6 score will change systematically with a change in foot posture. The relationship between the systematic change in FPI-6 score and the linear change for many of the EMT data is explored in the next section.

### *6.2.4.1.2* ***Concurrent validity: FPI-6 scores and static EMT data.***

Prior to undertaking the linear regressions the linearity of the relationship and homogeneity of variances was checked graphically and using Levene's test. The relationships between the EMT data and the FPI-6 total scores appeared linear (Figure 6.72), and the correlations were significant (FPI-6 total vs $TC_{\beta}$, Spearman's $\rho = -0.729$, ($P<0.001$), FPI-6 total vs $TC_{\gamma}$, Spearman's $\rho = -0.380$, ($P=0.013$))

**Figure 6.72. Scatterplots of rearfoot $\beta$ (y axis) and $\gamma$ (z axis) position against the FPI-6 total score (N=15, 3 states).**

Neither the TC$_\beta$ data nor the FPI total score demonstrated good homogeneity of variance, (TC$_\beta$ Levene's statistic 3.5, P=0.04 and FPI-6 total score Levene's statistic 5.1, P=0.011) but the two data sets could not be transformed to homogeneity by any standard transformation. The homogeneity of variance for the TC$\gamma$ position was acceptable (Levene's statistic ranging from 0.8, P=0.92). The linearity of the relationship between FPI and EMT data suggests that a linear regression is appropriate but the poor homogeneity of variances must be considered in the interpretation of the results.



**$TC_\beta$ vs FPI TOTAL SCORE (6 item version)**

**Dependent variable: Static $TC_\beta$**
**Independent variable : FPI total score (6 item version)**

*Linear regression model (N=15)*

| Adjusted $R^2$ | F Statistic | P value |
|---|---|---|
| 0.64 | 73.529 | <0.001 |

**$TC_\gamma$ vs FPI TOTAL SCORE (6 item version)**

**Dependent variable: Static $TC_\gamma$**
**Independent variable : FPI total score (6 item version)**

*Linear regression model (N=15)*

| Adjusted $R^2$ | F Statistic | P value |
|---|---|---|
| 0.12 | 6.74 | 0.013 |

For the main variable against which the concurrent validity of the FPI can be gauged ($TC_\beta$), the FPI scores and AJC EMT values appeared closely related, with the FPI-6 score predicting 64% of the variance in the EMT data. For the $TC\gamma$ positions, there was weaker evidence of a relationship between FPI-6 score and the EMT data, although the contribution of $TC\gamma$ motions to changes in foot posture has been suggested previously to be limited [286 418].

### 6.2.4.2 Results of scoring foot posture using the FPI-6 with subsequent collection of dynamic EMT data

#### 6.2.4.2.1 *Reliability of the gait trial data*

Gait data were derived from three passes of the walkway in each state. The coefficients of multiple correlation (CMCs) for ankle joint angular rotations derived from the within-subject repeat passes ranged from 0.93 to 0.80 (Table 6.62). Data for both limbs and for all 15 participants were used for these analyses.

**Table 6.62. Intra-subject CMCs (95%CI) of measures at the AJC. (N=30)**

| $TC_\alpha$ motion | $TC_\beta$ motion | $TC_\gamma$ motion |
|---|---|---|
| 0.93 (0.92-0.94), | 0.90 (0.88-0.91), | 0.80 (0.77-0.83) |

#### 6.2.4.2.2 *Between-subject variation in dynamic foot joint motion*

The intra-subject reliability was higher than for previous studies using video techniques [237] and very similar to the previous study of Cornwall and McPoil using a similar protocol [350]. Between-subject variation followed a pattern similar to that reported previously in the literature. It would be expected that there would be greater consistency for repeat passes for the same subject, than for comparisons between subjects. Differences in motion consistency were also observed according to the direction of motion. α rotation was the most consistent, with β and γ motions during gait much more variable between subjects. Some of this axis related difference may be explained by the overall ranges of motion occurring in the three planes, with larger rotations about the x axis (α motion) observed during a gait cycle, a factor that would inherently contribute to higher reliability coefficients.

**Table 6.63. Between-subject CMCs (95%CI) illustrating consistency of measures at the AJC (N=30).**

| TCα motion | TCβ motion | TCγ motion |
|---|---|---|
| 0.75 (0.71-0.79), | 0.59 (0.51-0.67), | 0.38 (0.33-0.44) |

###### *6.2.4.2.3* ***Comparisons of the wedged and control (barefoot only) states***

The systematic nature of any response in the foot motions to the lateral wedge input, control /no wedge state, and medial wedge input was assessed in a similar manner to that used for the static data. TC$\alpha$ data is explored and presented first, followed by TC$_{\beta}$ and TC$\gamma$ in sequence. Data are presented for each rotation, with a figure illustrating the entire gait cycle for each state. Key events from the gait cycle are summarised in tabular form with statistical analysis of the differences between states at each of these gait cycle events. The inferential statistics were based on a Repeated Measures ANOVA model, with Bonferroni adjusted multiple comparisons.

**The gait cycle events presented are :**

Max = Maximum value for rotation about the joint/ axis

Min = Minimum value for rotation about the joint/ axis

HS = The joint position at Heel Strike (first contact of the heel with the ground)

FF= The joint position at Foot Flat (first contact of the forefoot with the ground)

MS = The joint position at Mid Stance (a temporal point at 50% of the stance phase)

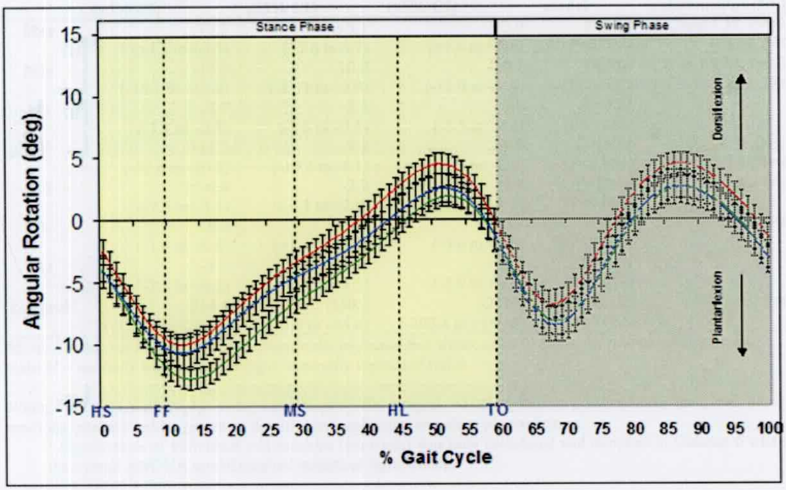
HL = The joint position at Heel Lift (the point at which the heel lifts off the ground and all weight is borne on the forefoot)

TO = The joint position at Toe-Off (the point at which the foot is first lifted clear of the ground)

In addition, the integral of the motions is also presented. This represents the area under the curve for the entire gait cycle curve. It is used to infer the summative effect of the shift in joint position.

## Stance events for $TC_\alpha$

**Figure 6.73. Motion time curve for $TC_\alpha$ (N=30)**



Key

| | |
|---|---|
| 🟩 | Lateral wedge state |
| 🟥 | No wedge state |
| 🟦 | Medial wedge state |

**Table 6.64. Key stance events in $TC_\alpha$ motion.**

| | **Lateral wedge (95% CI)** | **Control (95% CI)** | **Medial wedge (95% CI)** | **ANOVA model** | **Significance of relationships (N=15)*** |
|---|---|---|---|---|---|
| **Max** | +2.5<br>(+1.1 to +3.9) | +5.1<br>(+3.6 to 6.7) | +3.0<br>(+1.4 to +4.6) | F=5.68<br>P=0.024) | LC and CM, P=<0.001, LM, P=0.072 |
| **Min** | -12.9<br>(-14.1 to –11.8) | -10.0<br>(-11.1 to –9.0) | -10.7<br>(-12.0 to –9.4) | F=30.4<br>(P<0.001) | LC and CM, P=<0.001, LM, P=0.131 |
| **HS** | -3.7<br>(-5.1 to –2.4) | -2.2<br>(-3.6 to –0.8) | -3.8<br>(-5.3 to –2.3) | F=0.03<br>(P<0.857) | N/A |
| **FF** | -11.3<br>(-12.6 to -10.0) | -9.2<br>(-10.2 to -8.1) | -9.9<br>(-11.3 to –8.6) | F=16.81<br>(P<0.001) | LC, P<0.001, CM, P=0.053, LM, P=0.001 |
| **MS** | -6.4<br>(-7.6 to –5.1) | -3.2<br>(-4,3 to –2.0) | -4.4<br>(-5.5 to –3.2) | F=35.94<br>(P<0.001) | All P<0.001 |
| **HL** | -0.4<br>(-1.6 to +0.8) | +2.8<br>(+1.4 to +4.2) | +0.7<br>(-0.6 to +1.9) | F=20.0<br>(P<0.001) | All P<0.001 |
| **TO** | -1.3<br>(-2.8 to +0.2) | +0.01<br>(-1.5 to +1.5) | -1.2<br>(-2.9 to +0.4) | F=0.01<br>(P=0.919) | N/A |
| **Integral** | -314.4<br>(-379.6 to –249.3) | -150.2<br>(-216.0 to –84.4) | -232.0<br>(-303.4 to –160.6) | F=36.125<br>(P<0.001) | All P<0.001 |

**State L = lateral wedge (inducing a nominally pronated foot state), state C = control (the no wedged state), state M = medially wedged (inducing a nominally supinated state)*

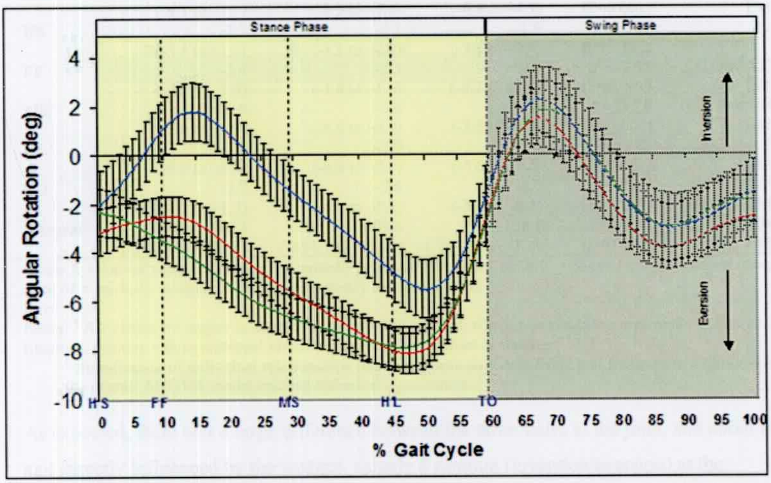
Notes: [1] All values are angles in degrees except for the integral, which represents the area under the curve. For α rotations, positive values represent dorsiflexion, and negative values plantarflexion.

[2] Significance of individual relationships (contrasts) was only calculated and itemised in Column 6 where the overall ANOVA model reached statistical significance.

The dynamic data showed a similar trend to the static data, in that the mere presence of a wedge rather than the direction of the wedge had the greatest influence on motion, reducing $TC_\alpha$ consistently throughout the stance phase of gait.

## Stance events for $TC_\beta$ motion

Figure 6.74. Motion time curve for $TC_\beta$ (N=30).



Key

🟩 Lateral wedge state
🟥 No wedge state
🟦 Medial wedge state

**Table 6.65. Key stance events in $TC_{\beta}$ motion.**

| | Lateral wedge (95% CI) | Control (95% CI) | Medial wedge (95% CI) | ANOVA model | Significance of relationships (N=15) |
|---|---|---|---|---|---|
| **Max** | -1.3<br>(-2.4 to -0.1) | -0.7<br>(-1.8 to -0.3) | +2.1<br>(+1.0 to +3.3) | F=47.42<br>(P<0.001) | LC, P=0.592, CM and LM, P<0.001 |
| **Min** | -8.3<br>(-9.3 to -7.1) | -8.5<br>(-9.5 to -7.6) | -5.8<br>(-6.9 to -4.7) | F=52.47<br>(P<0.001) | LC, P=1.0, CM and LM, P<0.001 |
| **HS** | -2.3<br>(-3.5 to -1.1) | -3.1<br>(-4.1 to -2.1) | -1.9<br>(-3.1 to -0.8) | F=2.247<br>(P<0.145) | N/A |
| **FF** | -3.4<br>(-4.5 to -2.3) | -2.5<br>(-3.4 to -1.6) | +0.9<br>(-0.2 to +2.1) | F=12.58<br>(P=0.001) | LC, P=0.102, CM and LM, P<0.001 |
| **MS** | -6.6<br>(-7.6 to -5.7) | -5.6<br>(-6.4 to -4.7) | -1.5<br>(-2.5 to -0.4) | F=135.9<br>(P<0.001) | LC, P=0.104, CM and LM, P<0.001 |
| **HL** | -7.8<br>(-8.9 to -6.7) | -7.9<br>(-8.8 to -7.1) | -4.6<br>(-5.6 to -3.6) | 250.78<br>(P<0.001) | LC, P=1.0, CM and LM, P<0.001 |
| **TO** | -2.7<br>(-4.2 to -1.3) | -2.6<br>(-4.0 to -1.1) | -1.7<br>(-3.2 to -0.2) | F=11.45<br>(P=0.002) | LC, P=1.0, CM P=0.047, LM, P=0.006 |
| **Integral** | -336.2<br>(-397.3 to -275.4) | -303.8<br>(-354.1 to -253.6) | -108.1<br>(-167.8 to -48.4) | F=98.83<br>(P<0.001) | LC, P=<0.538, CM and LM, P<0.001 |

**State L = lateral wedge (inducing a nominally pronated foot state), state C = control (the no wedged state), state M = medially wedged (inducing a nominally supinated state)*

Notes: [1] All values are angles in degrees except for the integral, which represents the area under the curve. For β rotations, positive values represent inversion, and negative values eversion.

[2] Significance of individual relationships (contrasts) was only calculated and itemised in Column 6 where the overall ANOVA model reached statistical significance.

As expected, there was a large difference between the three states at the joint, and about the axis directly influenced by the wedges, namely β rotation (inversion/eversion) at the ankle/rearfoot complex (Table 6.65). It is also significant that the change in $TC_{\beta}$ from the control 'no wedge' state produced by the addition of lateral wedges, was much smaller than the change in $TC_{\beta}$ produced by the addition of medial wedges. This suggests that in this sample at least, the control state tended toward the pronated position (lower values of $TC_{\beta}$). This is in agreement with data from the literature and from the findings of the earlier validity evaluation using Rose's Valgus Index outlined in Chapter Five.

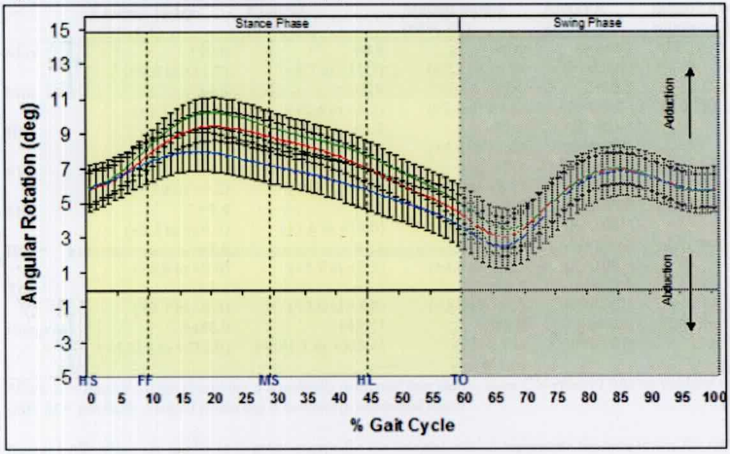
The change in $TC_{\beta}$ produced by the lateral wedge was minimal at the time of heel strike, but the difference increased rapidly to reach a maximum difference between the pronated and control states of 1.6°, at 22% of stance phase (13% of the total gait cycle). Thereafter the two curves steadily converge and by the time of heel lift through to toe-off and the swing phase there was no significant difference between the $TC_{\beta}$ joint rotations in the pronated and control state.

The addition of a medial wedge to supinate the rearfoot had a marked affect. A relatively small difference was seen between the states at heel strike but this difference increased rapidly to a maximum difference in $TC_{\beta}$ position of 4.6° by 25% of the stance phase (15% of the total gait cycle), shortly after foot flat. The difference between the states decreased steadily throughout the stance phase but was still a significant 3.1° at heel lift. After heel lift the gap closed rapidly and the difference at toe-off was only 0.9°.

The integral and the positions at foot flat and midstance, all demonstrated some systematic progression from the pronated, through the control state to the supinated state, although the difference between the pronated and control state was not statistically significant for these measures. Conversely, the difference between the supinated and both the relaxed and pronated states respectively, were highly significant. In evaluating the concurrent validity of the FPI, the most representative time-point was considered to be midstance, the instant in the gait cycle most closely resembling the posture adopted in relaxed standing.

## Stance events for TC$_\gamma$ motion.

Figure 6.75. Motion time curve for TC$_\gamma$ (N=30).



Key

🟩 Lateral wedge state

🟥 No wedge state

🟦 Medial wedge state

**Table 6.66. Key stance events in $TC_\gamma$ motion.**

| | Lateral wedge (95% CI) | Control (95% CI) | Medial wedge (95% CI) | ANOVA model | Significance of relationships (N=15) |
|---|---|---|---|---|---|
| **Max** | +10.6<br>(+9.5 to +11.7) | +9.9<br>(+8.7 to +11.1) | +8.6<br>(+7.3 to +9.8) | F=36.03<br>(P<0.001) | LC, P=0.136 CM, and LM, P<0.001 |
| **Min** | +4.3<br>(+3.1 to +5.6) | +3.9<br>(+2.6 to +5.2) | +3.4<br>(+2.0 to +4.8) | F=15.8<br>(P<0.001) | LC, P=0.178, CM, P=0.283, LM, P=0.001 |
| **HS** | +5.9<br>(+4.7 to +7.1) | +5.8<br>(+4.6 to +7.0) | +5.9<br>(+4.6 to +7.2) | F=0.05<br>(P=0.824) | N/A |
| **FF** | +8.1<br>(+7.0 to +9.2) | +7.7<br>(+6.5 to +8.8) | +7.3<br>(+6.1 to +8.5) | F=9.86<br>(P=0.004) | LC, P=0.37, CM, P=0.22, LM, P=0.012 |
| **MS** | +9.4<br>(+8.2 to +10.5) | +8.8<br>(+7.6 to +10.0) | +7.2<br>(+5.9 to +8.4) | F=38.8<br>(P<0.001) | LC, P=0.357, CM and LM, P<0.001 |
| **HL** | +7.8<br>(+6.6 to +9.0) | +7.1<br>(+5.7 to +8.3) | +5.8<br>(+4.4 to +7.1) | F=53.53<br>(P<0.001) | LC, P=0.047, CM and LM, P<0.001 |
| **TO** | +5.1<br>(+3.7 to +6.4) | +4.5<br>(+3.0 to +5.9) | +3.8<br>(+2.3 to +5.3) | F=22.5<br>(P<0.001) | LC, P=0.140, CM, P=0.044, LM, P=0.001 |
| **Integral** | +486.9<br>(+420.8 to +552.9) | +451.7<br>(+381.3 to +522.1) | +388.0<br>(+314.5 to +461.6) | F=44.28<br>(P<0.001) | LC, P=0.093, CM and LM, P<0.001 |

**State L = lateral wedge (inducing a nominally pronated foot state), state C = control (the no wedged state), state M = medially wedged (inducing a nominally supinated state)*

Notes: [1] All values are angles in degrees except for the integral, which represents the area under the curve. For $\gamma$ rotations, positive values represent adduction, and negative values abduction.

[2] Significance of individual relationships (contrasts) was only calculated and itemised in Column 6 where the overall ANOVA model reached statistical significance.

For all the gait cycle events after heel strike, the data again demonstrated the same systematic progression of the $TC\gamma$ values from the pronated state through the control state, to the supinated state. Again there was a larger change from the control state evident on addition of the supinating medial wedges, than after the addition of the lateral wedges. It should also be noted that while the change progressed systematically through the states, the differences in $TC_\gamma$ rotations are much smaller than $TC_\beta$ rotations and the differences at several of the events are less than one degree. The between subject CMCs were low (0.38) for $TC\gamma$, and the high between-subject variability, coupled with the error of the system means that caution must exercised in interpreting joint rotations about the z axis as a gold standard.

Having explored and described the EMT data in detail, the final analysis of concurrent validity was undertaken using the most robust of the EMT data ($TC_\beta$) as the best available gold-standard, and the FPI total score from the revised six item FPI instrument.

#### 6.2.4.2.4 *Concurrent validity of FPI-6 using the dynamic EMT $TC_\beta$ data as the gold standard*

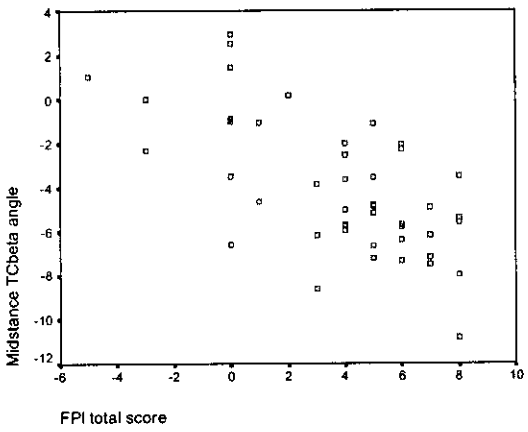
Having established the coefficient of determination for the FPI-6 in relation to the EMT static data, it was appropriate to extend the concurrent validity study to quantify the amount of variance in AJC walking kinematics that can be predicted by the static clinical FPI assessment. It has been suggested previously that the midstance instant of the stance phase might be related theoretically to the position assumed by the foot in static stance[188]. To identify the point in the gait cycle that might best reflect the relationship between the static assessment and a dynamic counterpart, the FPI-6 scores were correlated with $TC_\beta$ at a number of instantaneous stance phase events (see Table 6.67).

**Table 6.67. Correlations (Pearson's R) for TCβ motion data at the key gait cycle events with FPI-6 total scores (N=15, 3 states).**

| Minimum | Maximum | Heel Strike | Foot Flat | Midstance | Heel Lift | Toe-Off | Integral |
|---|---|---|---|---|---|---|---|
| R=-0.458<br>(P<0.001) | R=-0.520<br>(P<0.001) | R=-0.520<br>(P=0.694) | R=-0.060<br>(P=0.001) | R=-0.652<br>(P<0.001) | R=-0.544<br>(P<0.001) | R=-0.222<br>(P=0.142) | R=-0.565<br>(P<0.001) |

As might be expected from the assertions in the literature, the highest correlation between FPI scores and $TC_\beta$ was seen at midstance. $TC_\beta$ at the instant of midstance was chosen therefore as the dependent variable for exploration in the predictive regression modelling. The linearity of the relationship was again checked by scatterplotting (Figure 6.76).

Figure 6.76. Scatterplot of EMT derived TCβ midstance position versus FPI total score.



Finally, data for $TC_\beta$ midstance were tested for homogeneity of variances prior to entry into a linear regression model, as described in the previous analysis of the static EMT data. The variance was homogenous for the $TC_\beta$ midstance data (Levene's statistic 0.321, P=0.727), and borderline for the FPI-6 total score (Levene's statistic 4.21, P=0.021).

*LINEAR REGRESSION MODEL (N=15)*

**Dependent variable: $TC_\beta$ at midstance**
**Independent variable : FPI total score (6 item version)**

| Adjusted $R^2$ | F Statistic | P value |
|---|---|---|
| 0.41 | 31.786 | <0.001 |

### 6.2.4.3 Summary

The dynamic EMT data obtained in this study were in close accord with the data of Cornwall and McPoil, both for the reliability of the measures and the absolute values observed [350], the data also reflected the findings of other studies [243 415]. The total range for the directly comparable measures $TC_\alpha$, $TC_\beta$ and $TC_\gamma$ were within 2° of the values reported by Cornwall and McPoil and again, were in agreement with other previous data [10 243 419].

In the linear regression models the FPI-6 total scores predicted 64% of the variance in the static postural positions at the most representative joint complex/axis combination ($TC_\beta$), and 41% of the change in dynamic $TC_\beta$ motion at midstance. These coefficients of determination indicated that the FPI scores reflect adequately well, the underlying change in joint relationships.

## *6.3 CHAPTER SIX, SECTION THREE. PREDICTIVE VALIDITY OF THE FPI*

### 6.3.1 Introduction

In this final section, FPI data derived from the experiment in section 6.1 were used to evaluate the predictive validity (sensitivity and specificity) of the FPI total score (six item version) in categorizing the foot posture. Sensitivity and specificity evaluations must be based on dichotomous outcomes, whereas the clinical categorisation of foot type relates to at least three categories (i.e. pronated, neutral/normal, supinated). The analysis is thus undertaken in two stages, separating out firstly the abnormally pronated state, and secondly the abnormally supinated state.

### 6.3.2 Methods

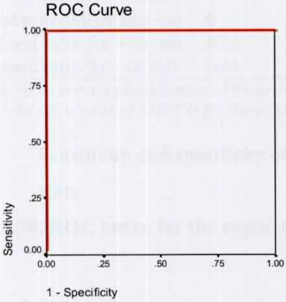
The cut-off points for the FPI six-item total scores were first determined through the construction of a Receiver-Operator Characteristic (ROC) curve. The ROC curve allows identification of the value at which exists the best balance between sensitivity and specificity. Once the cut-off has been established, a two by two table is constructed for each of the dichotomous pairs and the precision indices are calculated.

## 6.3.3 Results

### 6.3.3.1 Sensitivity and specificity of the FPI total score in predicting the pronated state

From the graph in Figure 6.77 and the table of curve coordinates it can be seen that for an FPI score of +4.0, the area under the curve was 1, with sensitivity = 1 and 1-specificity = 0 . This value of +4.0 was thus chosen as the cut-off for the definition of the non-neutral state in the direction of pronation for the subsequent analysis.

**Figure 6.77. ROC curve for the pronated state vs the combined neutral and supinated states.**



Coordinates of the Curve

| FPI Score | Sensitivity | 1 - Specificity |
|---|---|---|
| -11.0000 | 1.000 | 1.000 |
| -8.5000 | 1.000 | .950 |
| -6.5000 | 1.000 | .900 |
| -5.5000 | 1.000 | .875 |
| -4.0000 | 1.000 | .800 |
| -2.5000 | 1.000 | .700 |
| -1.5000 | 1.000 | .575 |
| -.5000 | 1.000 | .450 |
| .5000 | 1.000 | .175 |
| 1.5000 | 1.000 | .050 |
| 2.5000 | 1.000 | .025 |
| 4.0000 | 1.000 | .000 |
| 5.5000 | .950 | .000 |
| 6.5000 | .850 | .000 |
| 7.5000 | .550 | .000 |
| 8.5000 | .400 | .000 |
| 9.5000 | .150 | .000 |
| 10.5000 | .050 | .000 |
| 12.0000 | .000 | .000 |

Based on the cut-offs derived from the ROC curves, the following two-by-two table was constructed. This demonstrates the capacity of the FPI score to correctly assign the foot type to the appropriate known state.

**Table 6.68. Two-by-two table for the pronated state vs the combined neutral and supinated states (N=20, 3 states).**

| | | Pronated known state | |
|---|---|---|---|
| | | Not pronated | Pronated |
| Pronated FPI predicted state | Not pronated | 40 | 0 |
| | Pronated | 0 | 20 |

From the data in Table 6.68, the precision indices were constructed for the FPI scoring capacity to correctly predict the pronated state (Table 6.69).

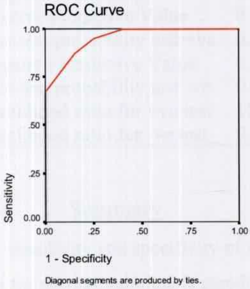
**Table 6.69. Precision indices for the pronated state vs the combined neutral and supinated states.**

| Summary of diagnostic test indices of precision | |
|---|---|
| Sensitivity | 1 |
| Specificity | 1 |
| Diagnostic accuracy | 1 |
| Positive Predictive Value | 1 |
| Post-test probability test +ve | 1 |
| Negative Predictive Value | 1 |
| Post-test probability test -ve | 0 |
| Likelihood ratio for +ve test | N/A |
| Likelihood ratio for -ve test | N/A |

*Note: The 100% correct classification of the pronated known state by the FPI total score, precluded the calculation of 95% CIs for these data.*

### 6.3.3.2 Sensitivity and specificity of the FPI total score in identifying the supinated state

**Figure 6.78. ROC curve for the supinated state vs the combined neutral and pronated states.**



Coordinates of the Curve

| FPI Score | Sensitivity | 1 - Specificity |
|---|---|---|
| -11.0000 | 1.000 | 1.000 |
| -8.5000 | 1.000 | .900 |
| -6.5000 | 1.000 | .800 |
| -5.5000 | 1.000 | .750 |
| -4.0000 | 1.000 | .600 |
| -2.5000 | 1.000 | .400 |
| -1.5000 | .950 | .250 |
| -.5000 | .875 | .150 |
| .5000 | .675 | .000 |
| 1.5000 | .550 | .000 |
| 2.5000 | .525 | .000 |
| 4.0000 | .500 | .000 |
| 5.5000 | .475 | .000 |
| 6.5000 | .425 | .000 |
| 7.5000 | .275 | .000 |
| 8.5000 | .200 | .000 |
| 9.5000 | .075 | .000 |
| 10.5000 | .025 | .000 |
| 12.0000 | .000 | .000 |

Area under the curve = 0.954 (95%CI=0.96-1.0, P<0.001)

From the curve coordinates, the FPI score of $-1.5$ was found to yield a sensitivity of 0.95 and $1-$ specificity of 0.25, this value was chosen as the cut-off for the subsequent exploration.

**Table 6.70. Two-by-two table for the supinated state vs the combined neutral and pronated states (N=20, 3 states).**

| | | Supinated known state | |
|---|---|---|---|
| | | Not Supinated | Supinated |
| Supinated FPI predicted state | Not Supinated | 38 | 5 |
| | Supinated | 2 | 15 |

Again, from the table data, the precision indices for the FPI diagnostic capacity for the supinated state were constructed.

**Table 6.71. Precision indices for the supinated state vs the combined neutral and pronated states.**

| Summary of diagnostic test indices of precision | Value (95%CI) |
|---|---|
| Sensitivity | 0.75 (0.56-0.94) |
| Specificity | 0.95 (0.88-1.00) |
| Diagnostic accuracy | 0.88 (0.80-0.96) |
| Positive Predictive Value | 0.88 (0.73-1.00) |
| Post-test probability test +ve | 0.88 (0.73-1.00) |
| Negative Predictive Value | 0.88 (0.79-0.98) |
| Post-test probability test -ve | 0.12 (0.02-0.21) |
| Likelihood ratio for +ve test | 15.00 (4.39-55.23) |
| Likelihood ratio for -ve test | 0.26 (0.12-0.50) |

### 6.3.4 Summary

The sensitivity and specificity of the FPI is high with regard to correct categorisation of foot type for normal individuals standing in induced pronated or supinated positions. This is of course an artificial study, and the sensitivity and specificity will, in future, need to be re-evaluated for each clinical sub-population in which the FPI is to be used. Nevertheless the exercise provides some supporting evidence for the construct validity of the new measure.

## 6.4 *CHAPTER SIX, SECTION FOUR. DISCUSSION*

### 6.4.1 Objective measurement of lower limb posture and dynamic function - the gold standard

The industry standard for gait evaluations, has long been a multiple camera high-speed video setup (usually 4-6 cameras), each simultaneously recording the images derived from the motion of walking. The joints and segments are defined, not usually by the full image, but by passive reflective or light emitting markers mounted on the skin overlying the relevant bony segment, at suitable anatomical locations. Using the video /marker approach, a minimum of three, non-contiguous markers are required to define a single segment, with the software comparing images from the multiple cameras to identify and track markers, and to construct a three-dimensional model from the resulting data. This approach has proven useful for establishing motions about large joints such as the hip and knee where the anatomical segments are large and well defined, but for smaller joints such as the joints of the foot, the requirement for three markers to define any single bony segment has resulted in significant problems with the definition of marker sets and contributes to unacceptable levels of error [13 237 366 420]. In most cases it is simply not possible to locate three reflective markers on a small bone such as the navicular, or the other bones of the forefoot, and alternative approaches using skin mounted 'wands' and plates [421], have proven only moderately reliable in the forefoot [420]. Consequently, to maintain the technical reliability of analyses, researchers using video based systems often rely on simplifying the model by modelling the foot as a single rigid segment [18]. This is clearly not appropriate to the study at hand.

The limitations imposed by the requirement for three non-contiguous reference points per segment doubtless compounds error in the stylus protocol outlined in 6.1. In addition to the accrual of error from the multiple measures required to define neighbouring segments, the stylus protocol is further limited by its reliance on accurate reporting of sensor translation, which was reported in the literature and confirmed by our experiments, to be less reliable in EMT systems than reporting of angular rotation, as is discussed below. The ordinal regression modelling described some relationships between FPI components and static EMT joint angles that might not have been predicted, and also failed to find associations between some components and EMT joint angles that might have been expected to be relatively strong. The fact that there were large correlations between some FPI and EMT variable pairs supports the contention that systematic associations were occurring. It is less clear though why associations varied across the EMT measures. It may be the case of course that the FPI components simply do not measure precisely segmental relationships predicted in the theory, and if the gold standard were truly gold then this would be an inevitable conclusion. It must also be noted however that there was relatively poor agreement between some EMT measures even when describing similar positions in similar segments (such as the tibia to calcaneal angle and the Achilles angle). In the case of these two EMT measures, although it must be recognised that one measures bony relationships and the other a soft tissue to bony segment relationship, it might have been expected that they would have been more closely related than the R=0.217 that was observed. Furthermore, given that the error in determining segment orientation was determined to be as high as 5.3° in the worst case, the role of error in the gold standard probably warrants some acknowledgment. Nevertheless, the EMT data overall provided a generally acceptable 3D model, and the strength of some FPI –EMT relationships was fundamental in identifying poorly performing FPI components.

Electromagnetic motion tracking with the sensors mounted directly onto the skin offers some theoretical advantages over stylus digitisation because only one sensor is required to define an anatomical segment, and the attachment of the sensors to the body allows tracking of changes in sensor position in real time, which frees the experiment from static constraints. Skin-mounted-sensor EMT has been used previously in the evaluation of movement at the shoulder and spine, but only recently has the technology been applied in the foot [240 241 336].

Requiring only the mounting of a single sensor, rather than clusters of markers, electromagnetic motion tracking systems may offer some advantages over video systems in the study of the kinematics of the foot, particularly for applications where older, single rigid segment foot models are inappropriate. The reliability study reported here suggested that when using a Fastrak system with the long-range transmitter, the angular data are more robust than positional data. This is in agreement with the two studies investigating the use of EMT over the distances employed in this protocol [242 247]. The positional data were adequately reliable (RMS <5mm), over the small distances encountered during measurement of a single limb over one isolated stance phase, but error of 10-20mm over the larger volume of the field highlights the technical limitations associated, even using what is considered 'state-of-the-art' equipment.

The intra-subject reliability for the dynamic ankle joint complex data collected in this study was better than noted in the video gait analysis literature. Ankle joint complex ($TC_\beta$) data described in the literature varies considerably due to the issues discussed previously, such as error, skin movement and the definition of reference positions. Our data are however consistent with the data of Pierrynowski and Smith, and Mosely et al, with regards to the $TC_\beta$ motion [10 419], and support the suggestion that the rearfoot complex does not function about a 'subtalar joint neutral' position but about a position some 4°-8° everted. [10 394 419]. This tendency toward a slightly pronated relaxed standing position was also reflected in the FPI scoring (mean 4.9).

The addition of the wedges under the heel made a statistically significant difference to all of the parameters of rearfoot joint motion and in all planes. The capacity for insoles to alter rearfoot motions had been contested in previous, small-sample, video based studies [190], but our data are similar to a growing body of published studies suggesting that medial or supinatory wedging can affect the rearfoot systematically [243 358 374 422]. The $TC_\beta$ motion time curve produced by the pronation inducing wedge is similar to the curve seen in naturally occurring pronated feet [423], and in the valgus feet of patients with rheumatoid arthritis [413]. The agreement between the midstance data obtained in this study, and the data in the literature appears to confirm the appropriateness of $TC_\beta$ as a gold-standard.

The wedges exerted only a small effect on the rearfoot position in any plane at heel strike suggesting that there is little carry-over of their effect through the swing phase. The difference in $TC_\beta$ between the all three states was both statistically and clinically different after foot flat, through to toe-off, although differences were smaller after midstance in agreement with other studies[422]. The minimum and maximum eversion, and the integral of the joint range of motion throughout stance phase were also profoundly different in the three states. There is evidence however, of moderation of the input force, and no more than 4° alteration in $TC_\beta$ output motion was seen in the static and dynamic measures, despite an input intervention of +/-10° about the y axis.

The data for the midstance point are in close agreement with the static standing results of Lundberg et al, whose detailed radiographic studies probably represent the most reliable data to-date [358]. Lundberg et al had also noted that the rearfoot $\beta$ motion output did not change linearly with change in input motion, and in particular reported that 10° of pronatory input resulted in less change (output change =1.2°) than 10° of supinatory input (output change =2.6° ), a finding confirmed in our own data.

Systematic changes in $TC_\alpha$ and $TC_\gamma$ motions are less relevant to the validation of the FPI than $TC_\beta$, but warrant some discussion. It is of note that the presence of a wedge under the heel increases plantarflexion throughout stance phase regardless of the orientation of the wedge as noted in previous studies[243]. The effects of increased plantarflexion on the mechanics of the foot cannot be ignored, as the systematic change brought about by the wedging represents some 19% of the total range of $TC_{\alpha}$ during stance phase. It is known however, that motions in the same plane at other lower limb joints such as the hip, knee and 1st metatarsophalangeal joints are large by comparison, typically exceeding 30° at each joint[21 423 424], and it is possible that <3° change in $TC_{\alpha}$ presents less challenge to the sagittal plane motions of the limb as a whole. $TC_{\gamma}$ rotations were less influenced by the wedging than $TC_{\beta}$ rotations in this and previous studies[243 422], reflecting the orientation of the wedge effect, and the limited coupling between rotations about the two axes. That $TC_{\beta}$ rotations are only moderately associated with $TC\gamma$ has been noted previously in the literature and was discussed earlier in Section 6.1 and 6.2. A post-hoc check of the relationship between midstance $TC_{\beta}$ and $TC_{\gamma}$ in the dataset presented in section 6.2 yielded a non-significant Pearson's product moment correlation of R=-0.275 (N=15, 3 states, P=0.067). It cannot be considered surprising therefore, that the relationship between the FPI scores and EMT measures of $TC_{\gamma}$ are weaker than the relationship between the FPI scores and EMT measures of $TC_{\beta}$.

### 6.4.2 Predictive validity of the FPI

The linear regressions support the validity of the FPI for predicting dynamic $TC_{\beta}$ motion. The association between the tri-planar FPI and midstance foot posture in dynamic gait was better than reported previously using traditional techniques for quantifying standing foot posture. In contrast to the data presented in this chapter, Cashmere et al had reported that a single plane measure (static standing measurement of arch height), predicted only 1% of the variation in the dynamic equivalent [337]. Other data from video studies had reported similar, or only marginally higher associations of $R^2=0.06$ [200], and $R^2=0.17$ [24].

Hunt et al [338 425 426] have demonstrated moderate agreement between two dynamic measures of foot posture (medial arch height and calcaneal eversion, R= -0.62) measured with a video based system, although Cornwall and McPoil had previously demonstrated a higher correlation (R=-0.942) between navicular bone motion and hindfoot motion using an EMT system [336].

Prediction of variation in plantar pressure by measures of static radiographs has been studied by Cavanagh et al [258]. While no single radiographic measure predicted more than 13% of the dynamic variation, up to 35% of the variance in plantar pressures at the first mtp joint was predicted by a combination of four radiographic measures. The data from the FPI study are much closer to the data of Cavanagh et al, and seem to emphasise the merit in combining multiple observations into a composite when attempting to predict dynamic function.

The results of the sensitivity and specificity evaluations were favourable, although it must be recognised that the experimental conditions were artificial. It was necessary to manipulate the categorisation of the variables to reduce the three original states (pronation/ neutral/ supination) into dichotomous states suitable for entry into the sensitivity and specificity analysis. It would be preferable, in future studies to identify study samples in which there was a greater tendency to dichotomy of foot posture. It must also be acknowledged that the manipulation into each of the three states was artificial, rather than reflecting natural disease states. These shortcomings limit the conclusions that can be drawn from this phase of the analysis. The sensitivity and specificity of a test is also a product of the specific application of the test, and it is recognised that the FPI will need further sensitivity and specificity evaluations in the specific clinical populations for which it is ultimately intended.

The internal reliability of the truncated instrument was found to be improved over that of the original eight item version, indicating that the validation process had not only investigated the existing instrument but had contributed to its development.

### 6.4.3 Summary

In summary, this chapter met the main aims, which were to establish a standard against which to benchmark the new measure, and to evaluate the concurrent validity of the FPI. Lower limb models were employed that allowed an evaluation of the degree to which the FPI components reflected changes in joint positions, and to illustrate the degree to which FPI measure can predict variation in dynamic ankle joint complex kinematics. The FPI scores were highly correlated with the concurrent AJC measures derived from the static lower limb model, and the coefficient of determination of 0.64 must be considered acceptable for a simple clinical screening tool, especially when the limitations of the gold-standard are considered.

The FPI proved more successful at predicting variation in dynamic AJC motion than previous single plane or single component measures, and the $R^2$ of 0.41 seems acceptable for a static measure predicting dynamic motion. The sensitivity and specificity of the FPI was, in this artificial setting at least, good. Further studies are required to determine the predictive validity of the FPI in specific clinical populations.

# CHAPTER SEVEN. EXPLORATION OF THE CLINICAL UTILITY OF THE NEW MEASURE IN A RANDOMISED TRIAL OF CALF FLEXOR SPLINTING IN PEOPLE WITH CMT.

---

***Chapter overview***

*It has been noted in previous chapters that the new foot posture index should demonstrate clinical utility if it is to represent any improvement on existing instruments. The absence of satisfactory outcome measures has contributed to the lack of good randomised trial data for many of the conservative interventions used in CMT, so it was decided to conduct the final phase of this study within the context of a randomised controlled trial. Ongoing collaborations with a second team at the Concord Repatriation General Hospital (CRGH) in NSW had identified existing plans by the Concord group for a pilot study, investigating the effect on ankle joint dorsiflexion of a six-week regimen of night splinting for people with CMT. Duplication of aspects of the method between the two centres would, it was considered, ease the burden of recruitment, increase the power of the sample leading to more meaningful results, and provide a broader range of patient age groups than would be possible in either centre individually. A protocol was negotiated which facilitated enough overlap between the groups to allow pooling of key data.*

---

*Note: Combined data from both centres are to be analysed elsewhere for publication, but data from the Children's Hospital centre only are presented in this thesis. This chapter represents the candidate's sole work, and reports progress to late 2003. Recruitment continues, with the full trial continuing beyond the period of candidature.*

## *7.1* *INTRODUCTION*

One of the more common conservative treatments used in CMT is ankle-foot night splinting, used in an attempt to provide a long-term stretch to tight calf musculature. This modality is used widely, despite absence of any evidence for its effect [164] and, as described in Chapter Three, despite splinting also being regarded as ineffective by people with CMT.

Calf muscle splinting was chosen as the appropriate vehicle for this evaluation for a number of reasons. As well as a general need to evaluate the effectiveness of the treatment, it is considered by some that preventing or reversing calf muscle contracture may have more general effects on the foot, reducing the tendency toward cavus changes [3 162]. It was hoped therefore that changes in ankle joint range of motion may also be reflected in foot posture and therefore may be detectable by the FPI-6.

## *7.2 AIMS*

The aims of the splinting trial were to provide a context in which to:

1. Evaluate the utility of the Foot Posture Index in the clinical setting.
2. Evaluate the reliability of the Foot Posture Index in a sample of patients with CMT to complement the previous studies in normal populations.
3. Contribute to an evaluation of the merit of night splinting in the management of calf flexor tightness.

Expressed in the null form, the hypothesis of the splinting trial was:

> *$H_0$ - The limb subjected to night splinting will demonstrate no change in the primary measure (ankle joint dorsiflexion) or the secondary measures (including FPI) over the period of the study, compared either to baseline or to the control limb.*

## *7.3 METHODS*

A single blind, randomised controlled trial method was used. The observer responsible for measurements (the candidate) was blinded to treatment/control limb allocation, with randomisation codes held in escrow by the departmental administrator until the completion of the data collection and processing. Participants could not be blinded because the splint is a physical device, which is applied to the relevant limb each evening. A three-month continuous regimen of night splinting was randomly allocated to a single limb for each participant, with the contralateral limb acting as the control. No cross-over was employed at the Children's Hospital centre.

### 7.3.1 Sample

When complete, the trial will have recruited up to 30 participants between the Children's Hospital and CRGH centres. For the purposes of this thesis preliminary data are presented for twelve participants completed at CHW to-date. A preliminary power analysis undertaken using data provided by the authors of the Lidcombe protocol and its normative data [427] indicated that N=18 would power the study to detect a 5° change (Δ) in the primary outcome at ß=0.8.

### 7.3.2 Recruitment

Potential participants were recruited from screening of the hospital records, from direct contact with children attending the peripheral neuropathy clinic at CHW, and via a short piece in the CMTAA newsletter. The full flow of patients through the trial recruitment and participation process is detailed in the trial profile diagram (see Figure 7.81).

### 7.3.3 Inclusion and exclusion criteria

Participants were recruited who:

- Were aged five years or older at the time of recruitment
- Had a diagnosis of CMT type 1A confirmed by a positive test for the Chromosome 17 duplication in themselves or a first degree relative.
- Were able to give full informed consent to participate

Exclusion criteria:

- History of foot surgery in the past twelve months
- Any previous history of arthrodesive foot surgery
- History of any splinting or casting in the past six months
- Inability to comply with the physical demands of the splinting and evaluation protocol

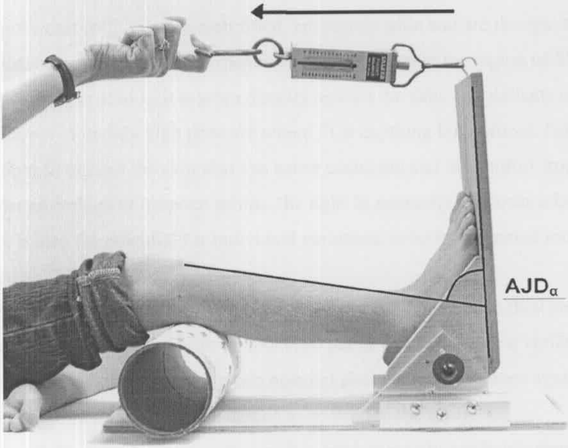
### 7.3.4 Consent

Full, informed, written consent was obtained from all participants, and from the parents of participants where the child was aged less than 18 years. All participants received a lengthy explanatory letter outlining the requirements of the study and advising them fully of their rights to withdraw. Ethics committee approval for the conduct of this study was obtained from the Human Ethics Committees of the University of Sydney, and the Children's Hospital at Westmead.

### 7.3.5 Outcome measures

The treatment is intended to stretch out tight posterior calf musculature, thus the primary outcome was ankle joint dorsiflexion, alpha rotation ( designated AJDα - comparable to TCα in Chapter Six). Ankle dorsiflexion was measured non-weightbearing in a supine position using the Lidcombe template, a bespoke jig consisting of two hinged plates with an adjustable axis which is fitted to the calf and plantar surface of the foot [428] (see Figure 7.79). The Lidcombe template employs a validated standardised protocol in which a known force is applied slowly while the participant attempts to fully relax the calf muscles. A force of 12 kg is used for participants over 12 years of age and 7 kg for participants younger than 12. When the maximum input force is reached, or calf muscle tightness causes the heel to raise from the foot plate, a photograph is taken from the lateral side capturing the angle between the leg and the footplate ($AJD_\alpha$). In this study a digital camera was used to record this position, and the angular position measurement was undertaken using the UTHSCSA software package, ImageTool for Windows version 2.00.

**Figure 7.79 The jig and measurement protocol used to measure AJDα.**



The Foot Posture Index was employed as a measure of foot posture, with the intention of documenting the existing foot position, but also to investigate the possibility of quantifying any change in foot posture that may occur over the duration of the splinting program. For comparison with current practice the FPI measures were supplemented with a range of existing clinical measures.

The heel bisection was marked using a straight edge and a palpation protocol described previously by Ball [344] and many others [186]. The total range of non-weightbearing rearfoot range of motion (RF $ROM_{NWB}$) was recorded. The position of the heel bisection during standing was also recorded with the patient standing in double support in a relaxed position (the relaxed calcaneal stance position or RCSP) and in a 'subtalar neutral' position obtained by manipulating the foot while using indicators such as palpation of the head of the talus, and visualisation of the various curves (the so-called neutral calcaneal stance position or NCSP).

### 7.3.6 Intervention

The limb allocated to the intervention arm of the study was treated with a commercially available, off-the-shelf, thermoplastic night splint manufactured by OTS Pty, Melbourne Victoria (see Figure 7.80). Historically, night splints have been made either to a cast of the patient's lower leg, onto which is moulded a tight fitting thermoplastic shell, or are of the off-the-shelf variety usually available in a range of sizes. Both types of device have advantages and disadvantages.

Bespoke cast splints, when well fitted, are comfortable and are thought to produce good clinical outcomes. They are expensive however, often in the region of $200 per splint. Fit of the device is crucial as it is worn directly against the skin, and patients often report problems with areas of unduly high pressure where fit is anything but optimal. Patients also report that the tight fit against the skin also can cause occlusion and discomfort from excessive sweating. To the advantage of bespoke splints, the tight fit generally produces a low bulk device, and there is also the potential for individual variations to be incorporated into the manufacturing process.

The main advantage of the off-the-shelf devices is naturally that they are significantly cheaper, usually in the region of $50-$100 per device. There are a variety of splints on the market, and clinical staff at the two hospital sites evaluated a range against the following criteria before deciding on the device to be used in the study.

**Bulk** – the device was for use in a predominantly paediatric sample and bulk was a major consideration. Patients had reported that the bulk of devices used previously had been detrimental to compliance.

**Stability** – the device had to be robust enough to provide a consistent stretch over at least the three-month period of the study. There was some concern that the hinge piece of some of the adjustable devices (see below) compromised the required stability.

**Adjustability** – this was a desirable criterion, rather than an essential criterion. To ensure the optimal trade-off between compliance and correction, there is thought to be some merit in using devices in which the amount of corrective force can be altered through the course of the regimen.

**Comfort** – as a factor contributing to compliance, comfort is clearly an important requirement.

**Cost** – the economics of treatment provision is naturally a factor. While the cost of the devices to be used in this study was incorporated into the trial budget, value for money is important in the real-world evaluation of such treatments.

The device most commonly used for splinting adults with CMT at the Concord RGH is a Rolyan™ splint sourced from Smith and Nephew Orthopedics inc (Memphis, TN), and this splint was the splint chosen for evaluation at the Concord centre. This device is preferred for the adults at this centre as it is adjustable and extremely stable. For younger patients the Smith and Nephew Rolyan device is often considered unacceptably bulky and causes problems with compliance. Night splints supplied to patients at the Children's Hospital are usually of the bespoke variety, although a range of off-the-shelf splints have been tried in the department. For this study, having defined desirable criteria, the candidate contacted a range of manufacturers. After careful consideration and consultation with staff at both centres an adjustable 'Grenace' model splint (OTS pty, Melbourne VIC), was chosen for use in this study as meeting the best combination of the desirable criteria (see Figure 7.80).

**Figure 7.80. The OTS 'Grenace' splint used in this study.**

*Note: Two further straps (not shown in picture so as not to obscure the hinge mechanism) similar to the strap at the top of the device were also attached immediately proximal and distal to the ankle, to hold the ankle joint firmly into the splint.*

The Grenace splint has a hinged ankle component, adjustable by means of a medial and lateral strip with detachable rivets that enable the angle of ankle dorsiflexion to be adjusted through six points. Other positive features of the device were an adjustable system of straps that could be used to cross the anterior aspect of the ankle for improved control of the heel position, and incorporation of a soft, washable, fleecy lining to improve comfort and reduce skin occlusion. Grenace splints are not side-specific and may be interchanged between left and right limbs.

### 7.3.7 Randomisation

The randomisation was age stratified according to three age groups; 0-9 years, 10-15, 16+. In each age stratum, five sets each of four digit codes identifying left or right limbs were generated using a computer random number generator, and these codes were used to complete a series of pro forma letters for the patients, instructing them of the limb on which the device was to be worn. The letter also contained backup information on how to wear the device, and advice to ensure that blinding was not broken at subsequent appointments. The letters were put into opaque envelopes by an administrator and marked on the exterior only with the randomisation code to be noted later on the participants' data sheet, and the age group to which the randomisation pertained.

All potential enrolees in the trial were given the same assessment protocol, and received the same advice about wearing splints. The application of the splint was demonstrated on both legs and the fit of the device was checked carefully on both limbs. All baseline outcome measures were derived prior to randomisation. Randomisation occurred as late as possible, in line with good research practice guidelines. Only at the completion of the enrolment appointment, and immediately before the patient was due to leave did they choose one of the envelopes appropriate to their age stratum. The participants were instructed not to open the envelope until they had left the clinic and not to discuss the allocation with anyone connected with the trial. The randomisation code on the envelope was recorded by the investigator for comparison with the code list for the final analysis.

The participants were given comprehensive verbal instructions on the importance of maintaining the practitioner blind, and were given instructions on how to avoid breaking the blind. At follow up, any potential problems with splints were to be dealt with a) by the candidate only where there was no limb-specific input required or b) by a physiotherapist independent of the study who would provide backup if limb-specific attention were required. An assurance was also given that the participant's well being was paramount, and that in the event of a break with blinding being required, the participant would be withdrawn from the study.

### 7.3.8 Compliance

Obviously, compliance with the wearing protocol was an important factor, both in determining the efficacy of the treatment for those who were able to comply, but also for estimating the degree to which patients are likely to use any such device if prescribed in practice. Compliance was recorded over the period of participation, in a diary in which the participant (or parent) estimated the number of hours the splint was worn every night. The compliance diary was submitted at the final appointment. In an attempt to minimise the degree to which guilt might bias the responses, the participants and parents were assured that truthful reporting was the most important aspect in the interest of the study, and that the compliance diary would not be examined until after the patients had left the study.

### 7.3.9 Follow up

Patients returned for four visits. At visit one all baseline measures were recorded, including demographics and descriptive clinical scores. At visit four, all outcome measures were again recorded ($AJD_\alpha$, non-weightbearing heel range of motion - RF $ROM_{NWB}$, standing heel positions and FPI score). At visit two and three, only the primary outcome measure, $AJD_\alpha$ was recorded. Information about any adverse events (not side-specific to avoid breaking the blind) was also solicited at all appointments after the issue of devices.

## RESULTS

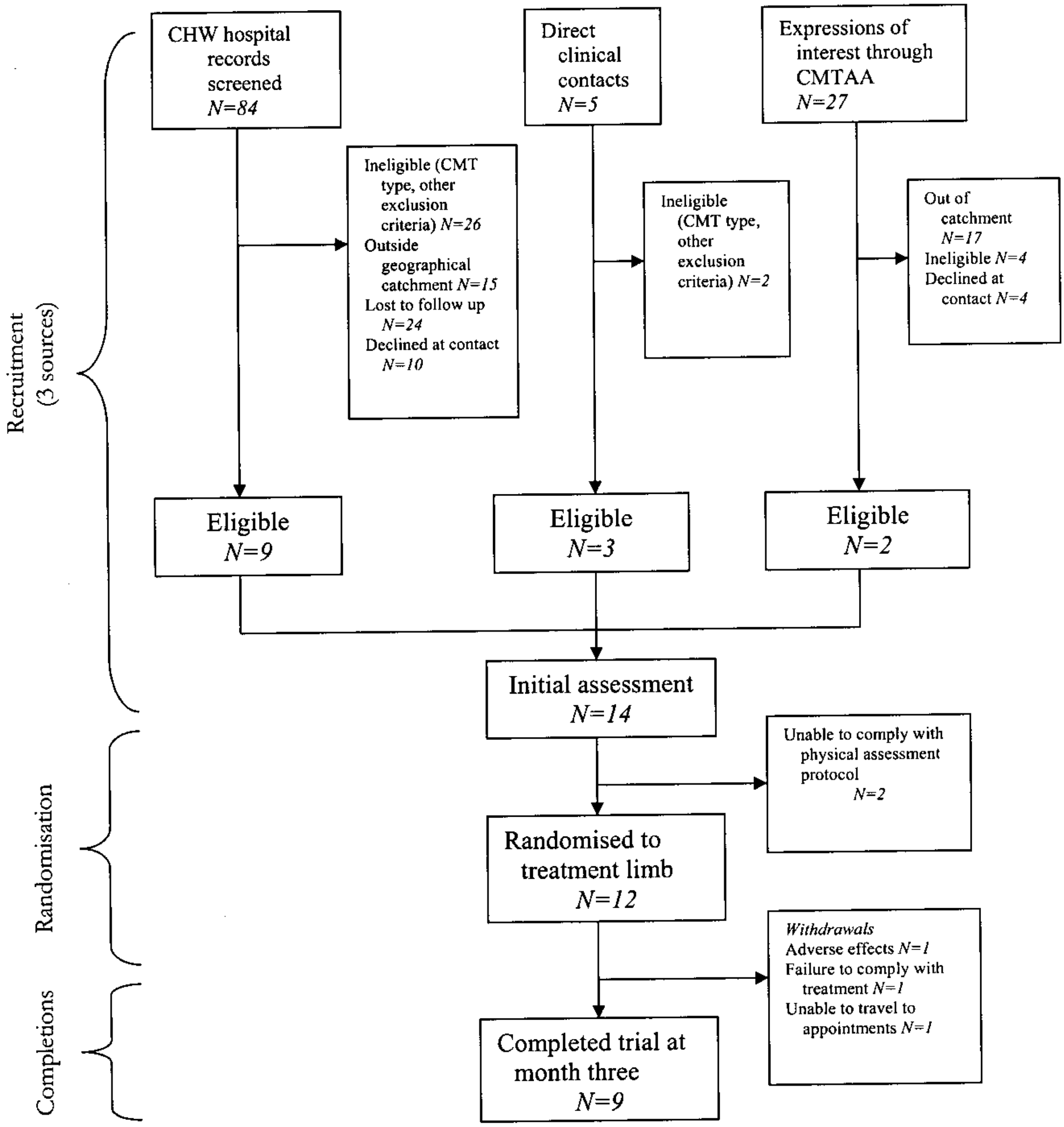
The results section is presented in three parts. In the first part, the overall trial composition and baseline characteristics are outlined. A definition is presented of how the data from the control and intervention arms was entered into in the clinical utility evaluation. In part two, the clinical utility of the new measure and existing measures are evaluated, and the clinical meaning of the FPI scores are presented. Finally in part three, the trial data are examined and the effect of the intervention evaluated.

## 7.4.1 Results part 1. Sample characteristics

### 7.4.1.1 Trial profile

From an original 126 potential participants, twelve were finally randomised to treatment. Twenty-four patients were not contactable at the address or telephone number indicated in hospital records, thirty-two did not meet inclusion criteria, and 41 lived too great a distance from the hospital to travel for the four appointments. Of the remainder, 14 declined to participate when contacted by the investigator. Two participants underwent the preliminary evaluation but were found to be physically unable to comply with the requirements of the evaluation protocol and were withdrawn prior to randomisation. Three participants withdrew during the evaluation phase. One withdrew in week one, complaining of discomfort in the hip on the intervention side. One withdrew in week two, not wishing to continue further with the treatment. The last participant to withdraw did so because of difficulties with travel to the hospital appointments. Nine patients completed the three-month splinting regimen. The full trial profile is presented in Figure 7.81.

**Figure 7.81 Trial profile (modified CONSORT statement) for the Westmead centre.**



### 7.4.1.2 Baseline characteristics

The median age was 13 years (range 7 to 57), with seven males and five females randomised to treatment. Three participants aged less than ten years were randomised, six participants aged 10-16, and three adults. At baseline, the foot measures were similar for both intervention and control limbs and there were no statistically significant differences.

**Table 7.72 Baseline characteristics of the trial sample (median values)**

| | **Intervention limb** | **Control limb** |
|---|---|---|
| **AJDα** | 82.4° | 82.0° |
| **RF ROM$_{NWB}$** | 26.5° | 21.5° |
| **RCSP** | 0° | 0° |
| **NCSP** | -0.5° | -1.5° |
| **FPI** | 0.5 | -1 |

In the next section, the clinical utility of the FPI was assessed relative to the other measures. Evaluation of the reliability of the various measures and illustrations of the FPI scores was based on test-retest data from the control limbs at repeat appointments. The clinical trial evaluation compared data from the baseline visit to visit four (at three months) in both trial arms.

### 7.4.2 Results part 2. Clinical utility of the FPI and existing measures

As noted in the introduction to this chapter, the main purpose of the trial was to provide a context for further evaluating the clinical utility of the new measure. Reliability is clearly important to the applicability of the measure to the clinical setting, and this section starts therefore with a report of the reliability of the FPI in the trial sample of patients with CMT. Subsequently, examples of the range of FPI scores encountered in the study sample are presented for illustration, and the FPI ratings from the CMT population are compared to the data from other (non CMT) samples reported in previous chapters.

#### 7.4.2.1 Reliability of measures

The reliability of the investigator in performing the FPI ratings and three other foot measures (non-weightbearing rearfoot motion, RCSP and NCSP) was examined. The intra-rater reliability evaluations were undertaken using the control limb data, comparing measures taken three months apart, at visit one and visit four. The datasheets from previous evaluations were not made available to the investigator at the time of the fourth visit.

These data are based on the small sample to complete the trial (N=9), and are provided as a guide only. It is understood that intraclass correlation coefficients (ICCs) would not normally be the preferred method of analysis for a sample of this size, however for continuity, and for comparability with the reliability data presented in Chapter Four, the ICC's are provided here for illustration purposes. The ICCs are calculated using the Shrout and Fleiss model 3,1 as described previously using a two-way ANOVA, with the rater entered as mixed effects and the consistency option set.

**Table 7.73 Reliability of the clinical measures**

| | ICC | ICC 95% CI | F statistic | DF | Measurement Error (95%CI) |
|---|---|---|---|---|---|
| **FPI** | 0.97 | 0.86 to 0.99 | 59.56 | 8 | 0.59 (-0.56 to 1.74) |
| **RF ROM** $_{NWB}$ | 0.83 | 0.42 to 0.96 | 10.88 | 8 | 4.00° (-3.84° to 11.84°) |
| **RCSP** | 0.60 | -0.05 to 0.89 | 4.04 | 8 | 3.29° (-3.15° to 9.73°) |
| **NCSP** | -0.09 | -.79 to 0.71 | 0.82 | 5 | 1.51° (-1.45° to 4.47°) |

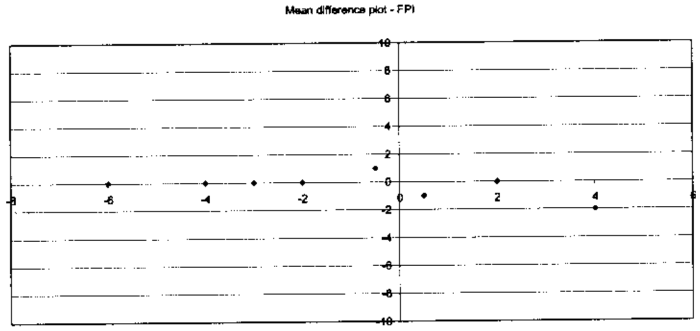
There was no evidence of systematic differences in any of the three weightbearing variables investigated, but the median measure of RF ROM$_{NWB}$ in the control limb was significantly larger at visit four than at visit one.

**Table 7.74 Evaluation of systematic differences in the four foot measures**

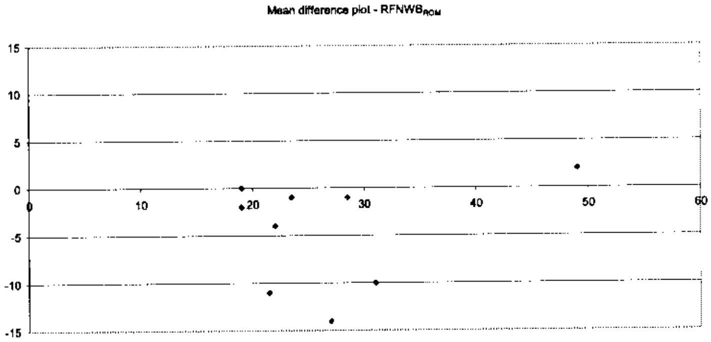
| | Median visit 1 | Median visit 4 | Wilcoxon's Z | P |
|---|---|---|---|---|
| **FPI** | -1 | -2 | -0.82 | 0.414 |
| **RF ROM$_{\text{NWB}}$** | 21.5° | 27.0° | -2.04 | 0.042 |
| **RCSP** | 0.0° | 2.0° | -1.88 | 0.235 |
| **NCSP** | -1.5° | 0.0° | -1.63 | 0.102 |

**Figure 7.82 a–d Mean-difference plots illustrating the relative reliability of the four measures.**

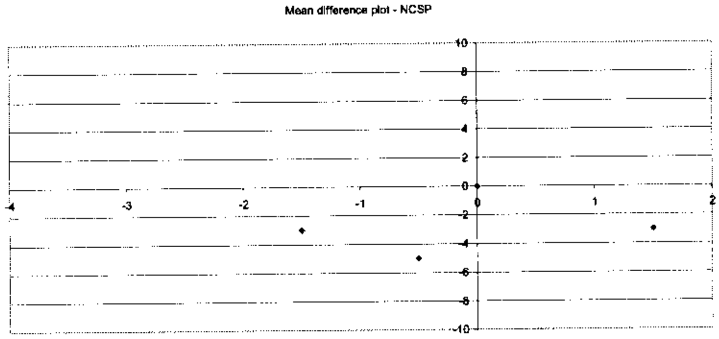
(Note change in y axis scale for plot b)



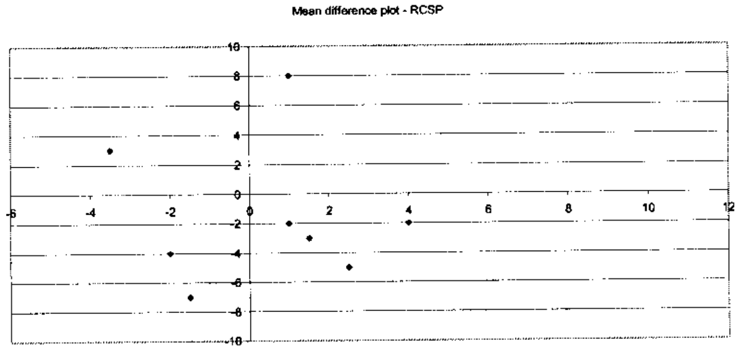
(a) FPI scores



(b) RF $\mathrm{ROM}_{NWB}$



(c) NCSP

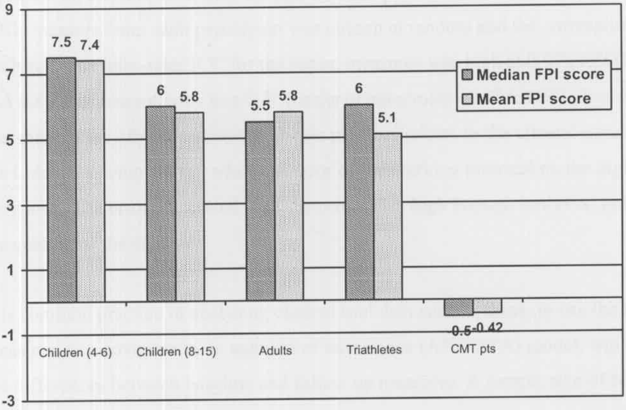


(d) RCSP

### 7.4.2.2 Comparison with other data

In order to illustrate the discrimination of scores obtained using the new measure, the figure below recapitulates median FPI scores from previous sections of the thesis, and compares them with the scores from the CMT sample.

Figure 7.83. Median and mean FPI values from the various study samples



There is a clear relationship between the FPI scores and age/disease status, a relationship which is in close agreement with the literature. The youngest group demonstrate the highest FPI scores, indicating the most pronated or planus foot characteristics in this group. By later childhood the foot has stabilised and the FPI scores remain consistent in the 8-15 age group, the healthy adults, and our sample of triathletes. In contrast the median and mean FPI scores in the CMT sample are substantially reduced, indicating that the foot posture in this group tends towards the cavoid.

### 7.4.3 Results part 3. Clinical trial

### 7.4.3.1 Primary outcome – Ankle joint dorsiflexion

The reliability of the ankle joint dorsiflexion measurement protocol was examined from the repeat measures of the control limb over the study period. The intra-rater ICC (3,1) for the repeat measures was 0.62 (95%CI 0.23 to 0.89, DF 8) and the measurement error was 3.4° (limits of agreement –3.3° to 10°). The error of the technical method of software evaluation of the images was also evaluated as it was felt that the measurement in software might represent an enhancement over the pen-line and protractor method described originally. One $AJD_{\alpha}$ measure from each participant was chosen at random and the corresponding image re-analysed. The intra-rater ICC for the repeat measures was high at 0.97 (95%CI 0.91 to 0.99) and the measurement error was 0.5° (limits of agreement –0.5° to1.5°). It is thus apparent that most of the error associated with this protocol relates to the clinical measurement using the Lidcombe template jig, while the error of the marking protocol on the digital images is very low. The error associated with the protocol is high enough however, to be of concern in the context of the study.

It is common practice in analysing clinical trial data such as these, to use the baseline measures as a covariate in an analysis of covariance (ANCOVA) model, while investigating the differences between baseline and follow up measures. A sample size of N=12 clearly breaches the assumptions required for an ANCOVA, however an alternative technique is to evaluate just change from baseline in the two treatment arms, and investigate for differences in change between the two groups. This is the approach used in this small sample evaluation. These data were therefore be explored descriptively at first, with non-parametric comparisons of change from baseline performed where appropriate using Wilcoxon's test.

**Table 7.75 Median and mean $AJD_{\alpha}$ at the four measurement points.**

| | | Baseline | 3 weeks | 6 weeks | 3 months |
|---|---|---|---|---|---|
| **Intervention limb** | **Median** | 82.4° | 84.1° | 84.8° | 80.0° |
| | **Mean** | 84.1° | 82.6° | 82.0° | 81.0° |
| **Control limb** | **Median** | 82.0° | 81.6° | 83.2° | 83.9° |
| | **Mean** | 81.7° | 82.7° | 83.8° | 82.4° |

**Figure 7.84. Median change in AJDα over the trial period in the intervention and control limbs**

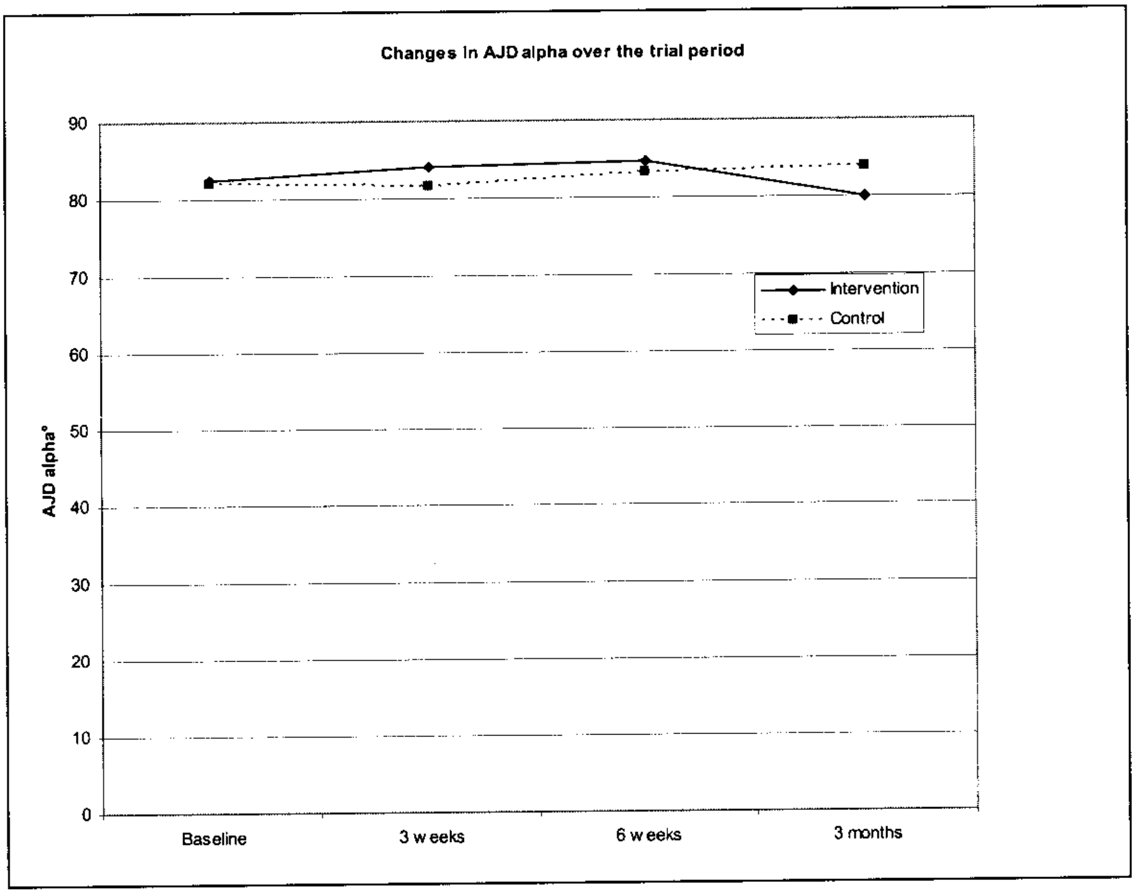
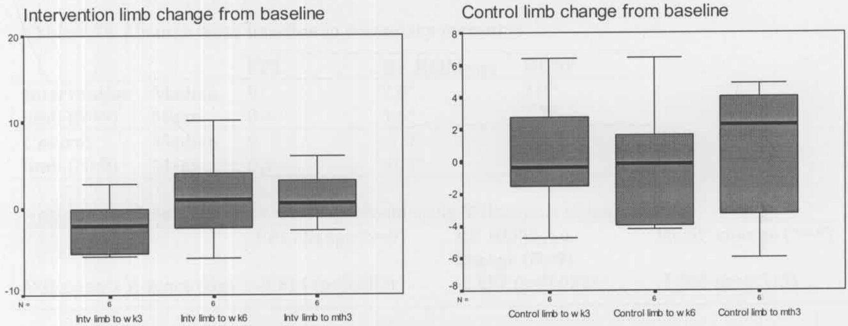


**Table 7.76. AJD$_\alpha$ change from baseline (positive values equate to gain/improvement)**

| | Change from baseline | 0-3 weeks | 0-6 weeks | 0-12 weeks |
|---|---|---|---|---|
| **Intervention Limb** | **Median** | -1.3° | 1.1° | 1.9° |
| | **Mean** | -1.1° | 1.4° | 0.6° |
| **Control limb** | **Median** | -0.7° | -0.1° | +0.9° |
| | **Mean** | -1.0° | -0.1° | -0.7° |

**Figure 7.85 Box plots indicating change from baseline (median and interquartile range) in the intervention and control trial arms.**



The minimum meaningful clinical difference has been determined previously to be a five-degree gain in AJD$_\alpha$[429]. There are only small differences between the change from baseline and the change between intervention and control limb at any time point, and in the intervention limb there is little change from baseline. The differences between control and intervention limb AJD$_\alpha$ values were not significant at any time point using the Wilcoxon's sign rank test.

**Table 7.77. Intervention vs control limb, change in AJD$_\alpha$ from baseline, Wilcoxon's test.**

| | To week 3 (N=9) | To week 6 (N=6) | To month 3 (N=9) |
|---|---|---|---|
| **Wilcoxon's Z score (sig)** | -0.178 (p=0.0859) | -0.943 (p=0.345) | -1.008 (p=0.314) |

The small numbers preclude generalisation of these results to the rest of the CMT population. It is worth noting however, that only one of the nine participants demonstrated a gain in AJD$_\alpha$ of greater than five degrees over the three-month trial period, and only five of the nine demonstrated any gain. The measurement error of 3.4° presented previously, combined with the small changes noted in this sample means that the null hypothesis cannot be rejected.

### 7.4.3.2 Secondary outcomes- Foot posture (FPI total score, RF ROM$_{NWB}$, RCSP)

The secondary outcomes were measured only at baseline and month three. Data is not presented further for the measurement of NCSP because of the poor performance of this measure in the reliability evaluations, and because it is less applicable to patients with more rigid cavo-varus deformity. Changes in each of the three other measures from baseline to month 3 are presented in Table 7.78.

**Table 7.78 Change from baseline in secondary measures**

| | | FPI | RF ROM$_{NWB}$ | RCSP |
|---|---|---|---|---|
| **Intervention limb (N=9)** | **Median** | 0 | 2.0° | 2.0° |
| | **Mean** | 0.4 | 4.6° | 1.7° |
| **Control limb (N=9)** | **Median** | 0 | -1.0° | 3.0° |
| | **Mean** | 0.2 | -0.9° | 1.9° |

Again none of the differences were significant using Wilcoxon's signed rank test.

| | FPI change(N=9) | RF ROM$_{NWB}$ change (N=9) | RCSP change (N=9) |
|---|---|---|---|
| **Wilcoxon's Z score (sig)** | -0.514 (p=0.607) | -1.897 (p=0.058) | -1.005 (p=0.315) |

It would not be expected, in the absence of any significant effect in the primary outcome measure, to see any significant change in any of the secondary measures. Neither of the weightbearing measures demonstrated any change of note, and while there was a small increase in RF ROMNWB, the median change of 2° from baseline and 3° from control was less than the 4° of measurement error determined previously. This small change in rearfoot non-weightbearing range cannot be considered clinically significant.

### 7.4.3.3 Compliance and adverse events

Of the twelve patients randomised to treatment, only nine completed the three month regimen. Two withdrew because of difficulties with the device, while the third withdrew because of difficulties with attending the clinic. Of the two who withdrew because of lack of treatment compliance, one reported pain in the hip of the limb being splinted, while the second just 'did not like' wearing the splint.

Compliance within the nine who completed the study was varied. Generally the participants who had worn splints previously felt this specific model of splint to be more comfortable than others that had been tried previously. However, only two were able to wear the splints without any problems.

As a result the splints were not worn all of the time by most of the participants. Only one patient wore the splint every night of the trial. The median compliance was five nights/week and 6.5 hrs per night. Four participants reported that the splints interfered with sleep, either making it difficult to get to sleep, or interrupting sleep during the night. Three of these patients sometimes chose to remove the splint to improve sleep patterns. The most commonly reported problem was difficulty in achieving a correct balance in the strap tension to maintain control, but without strap tightness compromising comfort unduly. This problem did not prevent splint use in any patient, but impaired comfort and resulted in reduced satisfaction. Three patients needed intervention to assist with comfort, requiring the addition of foam patches or alteration to the strap configuration.

At the completion of the trial, participants were asked whether they wished to continue wearing the splints. Six did express a desire to continue, although most would do so with a less demanding protocol. Techniques proposed to ease the demands of splint wearing included alternating splints between limbs and not necessarily wearing the splints every night. Two stated that they would not continue wearing the splints at all, and one was not sure.

## *7.4 DISCUSSION*

This chapter outlines a study in which the clinical utility of the FPI was explored in a sample of patients with CMT, extending previous validations. The clinical trial method is limited but reflects both the primary requirement of providing a context for the utility of the FPI, and the necessary compromises involved in acting as one centre in a dual centre study. The interpretation of the results presented in this section must also take into account the small sample of patients completing the treatment program, and the limitations of the clinical measures employed. The reliability of the Lidcombe protocol was lower in this study of CMT patients (ICC=0.62 (95%CI 0.23 to 0.89, DF 8) and measurement error = 3.4° (limits of agreement –3.3° to 10°), than had been demonstrated by the original authors (ICCs = 0.91 to 0.98, and 95% inter-rater agreement at an error of 8° to 9 °) [419]. It is difficult to regard the data of Moseley et al as definitive however, as their reliability data were obtained from three samples of N=5, and the authors noted that the reliability varied between normal and pathological patients. It is also well recognised that field applications of measurement techniques rarely demonstrate the degree of reliability proposed by originators of the technique. Nevertheless, the protocol for measuring ankle joint dorsiflexion must be said to be to be of questionable adequacy for detecting the relatively small amounts of change that might be obtained with splinting in people with CMT.

Ultimately the FPI can be considered to have performed adequately in this study, and the reliability of the FPI in people with CMT appears comparable with its reliability in the general population. In the absence of change in the primary outcome (AJDα), investigation of the responsiveness to change of the FPI, was not possible. Although one must be careful not to overstate these results until confirmed in larger samples and by independent studies, the FPI appeared to offer a reliable alternative to existing clinical measures for quantifying CMT foot posture. It was stable over time and offers a measure that is capable of documenting multi-planar and multi-segment variations in foot posture to within one point on the 33 point scale.

The range of scores derived from FPI ratings appeared to have face validity, and comparison with the samples investigated in previous parts of the thesis suggests that the group medians are consistent with previous clinical descriptions of the presentation of foot types in these groups.

The secondary aims of the chapter have been met as far as the small sample allows, and this part of the twin centre study has been able to contribute to the body of knowledge regarding night splinting in the management of calf flexor tightness. Sixty three percent of respondents in the CMTAA survey had suggested that night splints were ‘useless’ or of ‘little help’ and it was certainly appropriate to express the trial hypothesis in the null form. Ultimately it was not possible to reject the null hypothesis, and while conclusions should not be overstated in an underpowered study, the absolute group median change of less than two degrees, particularly when considered in light of the measurement error of the ankle dorsiflexion measurement technique, does call further into question the efficacy of night splinting in the management of the CMT foot.

There are several other methodological considerations that also warrant further discussion in the context of reporting a clinical trial, however limited in scope. These will be taken in order of importance to the foundation principles of randomised controlled trial method.

*Randomisation.* The sample was randomised according to a computer generated randomisation protocol with the codes held in escrow by an administrator independent of the study. The randomisation was stratified according to three age groups because the foot is thought to change in both shape and rigidity with age, a factor potentially influencing the outcome. Short of out-sourcing the entire randomisation process, the third-party mediated randomisation protocol was as robust as possible.

*Control arm.* In this sample the control state was allocated to the contralateral limb rather than to control patients. Allocation to control limbs would be inappropriate if 'whole body' outcomes were being evaluated, but in the context of a local effect, maintaining a within-subject control reduces between subject variability and represents best practice.

*Blinding.* When evaluating a physical intervention such as a splint it is not practicable to blind the patient to treatment allocation and such studies can be considered single blind. To maximise adherence to the single blind, the investigator was at all times blinded to the allocation of treatment limb, and participants were counselled on the importance of maintaining the blind in their interactions with the investigator. Supplementary arrangements were made for a clinician, uninvolved in the study to be available to patients in need of input or advice on the splints that might reveal to the investigator, the side of the limb allocated to active treatment. As consequence, the investigator remained blind to the treatment allocation until the final data analysis in all cases. The potential for patients to influence the outcome through their being unblinded is real, but can be considered limited for an objective method such as was employed here for measuring ankle dorsiflexion. It is possible that patients may have consciously exerted more or less effort during the measures, but this would require active commitment to subvert the research process and is considered a low risk.

*Sample construction.* Clearly this sample is powered inadequately for drawing any substantive conclusions regarding the efficacy or otherwise of night splinting, although the factors leading to the smaller than expected sample warrant discussion. Recruitment proved more problematic than anticipated, at least in part because of the need to fit in with the requirements of the partner centre (CRGH), but also because of the clinical heterogeneity of the CMT population. In itself this has implications for the application of night splinting therapies, as it is less appropriate to generalise findings in such a heterogeneous group to individuals within the population at large. The low rate of recruitment from the initial pool of potential candidates identified from hospital records was of concern to the candidate, but probably reflects no more than the limitations of most public health record systems. It is worth noting that there was some differentiation between recruitment/retention on purely clinical grounds, and recruitment/retention on grounds relating to the specific demands of participating in the study. This is highlighted by the low recruitment of patients from the direct contacts to the CMTAA (2 participants from 27 contacts) because the majority of contacts came from enquirers outside of a realistic geographical catchment. In the event, and despite initial counselling for participants travelling longer distances, one enrolled participant did still withdraw because travelling for clinic appointments became too onerous. A further two participants withdrew because of their ability to comply with the demanding assessment process associated with the trial protocol, rather than because of the treatment, and ultimately only two of the patients randomised to treatment withdrew because of failure to comply with treatment or an adverse event (transient hip pain). It should be noted also, that in addition to the two who withdrew because of inability to comply with the treatment regime, eight of the remaining 10 reported some problems with wearing night splints. This has significant implications for clinicians prescribing these devices, and difficulties with compliance are ignored at the prescriber's own peril. It is interesting to note that at the debriefing sessions, when asked whether they would continue wearing the splints once their participation in the trial had ceased, six indicated that they would do so, but all but one would adopt a less demanding protocol.

The apparent lack of efficacy of the night splinting regime would call into question current practice, and more recent data further calls into question the theoretical basis for this therapy. Radiographic study of the CMT foot has shown that in the anterior-type cavus deformity typical of many CMT patients, the ankle joint may be dorsiflexed rather than restricted [142]. If this is the case, then stretching the tendo Achilles would be expected to offer little benefit. It is of course possible that real gains in ankle joint dorsiflexion were made, but that the method used to evaluate ankle dorsiflexion was not precise enough to detect the degree of change. The Lidcombe template method has been described in detail [428], and is a creditable attempt to reduce the error associated with measurement of AJD. The candidate attempted to further enhance the Lidcombe protocol by making highly accurate electronic measures (measurement error =0.5°) rather than traditional manual measures. The reliability of the enhanced Lidcombe protocol in this patient group was still less than ideal however, with a measurement error over the entire protocol slightly greater than 3° (limits of agreement –3.3° to 10°).

Furthermore it is not possible however, to remove entirely the variation associated with participant involvement, and between-day factors such as fatigue, motivation and discomfort must be considered, particularly in a group such as those with CMT. During trial planning, a five change of degrees was decided upon as the minimal clinically important difference [429 430], and only one patient demonstrated a change of this magnitude. It is likely that shortcomings in the measurement of ankle motion alone will preclude the detection of any change of less than five degrees magnitude.

None of the secondary outcomes demonstrated any statistically significant systematic change over time, although in the absence of change in the primary outcome, this is not surprising.

The device itself was generally well-liked by participants, particularly by those who had worn splints previously. Its light weight, and cushioned interior resulted in several comments praising its comfort compared to experiences with previous splints. The adjustable nature of the device also allowed for the ankle dorsiflexion angle to be altered. This is an important feature if progressive change is sought, as the degree of corrective force can be increased once the patient had grown accustomed to the device. Conversely the angle can also be reduced if the device is uncomfortable and two patients made use of this facility. Strap placement was felt to be an improvement on their previous experiences, although four participants required adjustment to strap placement or the addition of further padding. Ultimately, despite a generally favourable response from patients regarding the comfort of the device, compliance was not especially high (median 5 nights/week) and only one patient wore the splint nightly throughout the entire trial period. The issue of compliance is of great concern for clinicians relying on physical patient-administered therapies, with rates of compliance with splinting regimes known to be lower than for drug regimes [431], and sometimes as low as 25% [432]. Regardless of individual efficacy data, patient compliance remains a barrier to the use of splints in clinical practice.

## 7.5 *CONCLUSIONS*

In this chapter the three defined aims were met as far as the small sample allowed. The FPI proved useful, and was not unduly time consuming to conduct, fitting in well with the battery of clinical evaluations. The range of FPI scores demonstrated adequate face validity in CMT patients, and the profile of scores in comparison to the various populations studied during the preparation of this thesis, further supported the contention that FPI is a valid tool for quantifying foot posture.

The FPI repeat measures on the control limbs were stable over time, indicating satisfactory reliability, and the mean difference plots for the FPI demonstrated better scalar stability than did those of the existing measures such as non-weightbearing ROM, RCSP and NCSP.

For the evaluation of calf flexor splinting, it was not possible to reject the null hypothesis, although the candidate's data are of course intended to be combined with the CRGH data, and firm conclusions are inappropriate at this stage. It is noteworthy however that only one of 14 patients randomised to treatment demonstrated improved ankle dorsiflexion greater than the minimum clinically important difference.

To summarise, this small study gives a useful insight into the utility of the FPI, and demonstrated that the instrument can be used in the CMT population. The splinting trial continues and the resulting data will ultimately contribute to a better understanding of the role of splinting in CMT, a widely used but unsupported treatment modality.

# CHAPTER EIGHT. DISCUSSION AND CONCLUSIONS

---

***Chapter overview***

*A separate discussion section has already been developed within each chapter detailing those specific issues relevant to the chapter and dealing with these in depth. In this final chapter, the discussion focuses on the broader issues that have been identified within the thesis, and returns to the overarching aims and research questions identified in Chapter One.*

*Each of the six initial research questions is discussed in turn, with an assessment of the degree to which the questions have been answered, and commentary on the implications of any remaining gaps in the knowledge base.*

*The six research questions detailed in Chapter One recapped:*

*i. What is the current state of knowledge regarding the effects of CMT on the lower limb and foot?*
*ii. What are the effects of CMT on sufferers' general HRQoL, and on the health status of the lower limb?*
*iii. What are the shortcomings of existing measures of foot and ankle posture and function?*
*iv. What are the desirable characteristics of a clinical measure of foot and ankle pathology?*
*v. Can a non-technological, low-cost clinical tool provide data of adequate validity and reliability for use in clinical practice?*
*vi. Can the new measure be used to evaluate the foot deformity of this group of people in a clinical trial context?*

*Fulfilment of the overarching aims is also debated, along with justification where appropriate, before a critique of the limitations of the study process pursued in the thesis.*

*Aims recapped*

1. *To obtain comprehensive descriptive data relating to the common physical problems encountered in patients with CMT, with an emphasis on those problems associated with the lower limb and foot.*
2. *To develop and validate a tool for better assessing baseline foot deformity and evaluating existing treatments.*

*The implications for future research are identified, with reference to the technological advances that have been made in recent years, and the supplementary role of the new measure.*

*Finally the main conclusions from the thesis are presented, summarising the research process, the key findings, and their implications.*

## *8.1* *DISCUSSION*

### 8.1.1 What is the current state of knowledge regarding the effects of CMT on the lower limb and foot?

Data relating to the foot are fairly limited in scope and quality for both CMT and the population at large. It has already been established that CMT is the most common inherited neuropathy[7 43], and that foot problems have a high prevalence in this population[2 43]. The high prevalence of foot pathology was confirmed in our large survey sample, which also evaluated the link with disease-related leg weakness (Chapter Three). The prevalence of foot deformity in CMT alone highlights the need for a better understanding of such structural changes, although foot posture is important far beyond this specific clinical group. Foot related morbidity secondary to structural anomalies occurs in association with congenital systemic disorders such as neural tube defects [433], acquired systemic disease such as rheumatoid arthritis[434], in idiopathic clinical populations[435 436], and even in fit, healthy and athletic populations[145 194 197 437].

CMT is generally well described as a disease, especially in terms of its pathological features such as the electrophysiological and histopathological findings [31 438], and increasingly its genetics and molecular biology[70]. Despite this detailed characterisation at cellular level however, studies of functional impact are fewer and less robust, with detailed study of the structural change in the CMT foot - the most common presenting symptom - a rarity. These limitations in turn, hamper the informed planning and evaluation of treatments leading to undue variability in clinical practice [1 69 439-443].

**What are the effects of CMT on sufferers' general HRQoL, and on the health status of the lower limb?**

The effects of CMT on general HRQoL and lower limb specific HRQoL are varied, and may be more important to patients than might have been expected. Leg weakness was reported by the vast majority of our sample, and was reported by more than half to affect them in the two highest categories of severity offered by the survey. Furthermore, the lower limb was more severely affected than the upper limb across a range of physical presentations. Many clinicians would take little convincing of the central role of muscle weakness in the disease process, but it was interesting to note the recurrence of this feature in the predictive modelling undertaken in Chapter Three. Empirical estimation of muscle weakness is undertaken routinely as part of the clinical assessment[136], but given the strength of many of the relationships explored in the survey analysis, there may be merit in deriving better quantitative data on muscle strength and applying such data in a more structured clinically. At the Children's Hospital,Westmead, dynanometric evaluation of muscle strength in CMT patients has, as a consequence of these studies, become part of routine practice.

In combination, the various lower limb manifestations of CMT contributed to significant diminution of patients' HRQoL in comparison to the normal population, and it was useful to place CMT in this context. Impairment was greatest in the physical dimensions, although some impact on the mental health dimensions was also apparent, substantiating the prior observation that there is some psychological cost associated with living with CMT [114]. SF-36 scores for the CMT population lay in the mid range for comparable chronic diseases, in both the physical and mental health dimensions, as had scores when evaluated with the SIP[114]. Gender differences were minimal in the general health dimensions, and in most dimensions of foot health with the exception of footwear, for which female respondents reported significantly lower scores than males. The issues relating to gender-specific footwear factors were discussed in the chapter, but given that CMT sufferers often report in clinic their dissatisfaction with footwear, it is clear that this area warrants more structured evaluation in the future. Reliance on aids and devices was lower than might have been expected, although no age-matched data were available for a more substantive comparison. It would be appropriate in the future to match data on wheelchair, scooter and walking stick/frame use with age matched data from the general and other clinical populations. Among the physical manifestations, cramps figured more highly than might have been expected. Leg cramps have been reported previously in the CMT literature [133], but in this sample the prevalence was striking at some 79%. Perhaps even more significant was the degree to which leg cramps contributed to diminished quality of life scores in the HRQoL modelling, reportedly through increased pain and disturbances to sleep. This suggests that the prevalence of leg cramps is probably being underestimated during clinical consultations, and that the significance to the individual is being underplayed. Drug treatments and physical therapies are available to aid with leg cramps[444-447] but are not prescribed routinely, despite severe and episodic cramps contributing to reduced quality of life.

### What are the shortcomings of existing measures of foot and ankle posture and function?

Any shortfall in the understanding of foot function in CMT is underpinned by the general paucity of our understanding of foot function in the general population. This understanding is, in turn, restricted both by the limitations of methods currently available to quantitate foot changes, and the relatively slow rate at which structural changes occur in the human foot[434 448]. Static measures are inherently limited in their capacity to predict the subtle variations in motion associated with dynamic function[9 258], and recent studies of neuro-proprioceptive pathways[449] and sophisticated models of adaptations to perturbations to gait [450] suggest that subtle factors currently at a rudimentary level of understanding may also need to be factored into future models.

There have been welcome developments recently in the technologies that will aid dynamic, objective measures of foot function, and these methods will likely provide new insights into the mechanisms underpinning foot pathology. Digital video techniques, developed with the financial backing of the animation, computer games, and film industries, are contributing to the development of systems for medical research, and allow for higher resolution studies and greater accuracy than was attainable previously. These advances in motion tracking, coupled with complex engineering models have led to initial attempts to describe the complex kinetics of the foot [451], and kinetic models are likely to grow more sophisticated. For the foreseeable future however, instrumented dynamic assessment is likely to remain the preserve of the laboratory setting, and clinicians will continue to rely on simple clinical measures for the majority of their assessments[189]. It is apparent that clinicians require data from clinical measures that better represent the overall foot posture, and it appears from the data in Chapter Six and in the recent literature [258], that collating multiple observations will help to close the gap between the ideal dynamic laboratory examination and current single-plane predominant clinical examinations.

### What are the desirable characteristics of a clinical measure of foot and ankle pathology?

The desirable characteristics of the new measure were in the main derived from two sources, an initial review[263] and a consensus statement [9], published at the beginning of the program of work (Chapter Two). The fit of the new measure as far as possible to these predetermined characteristics enhances its face validity, and should enhance the uptake of the FPI among clinicians. Toro et al in a survey of 1826 physiotherapists reported that more than 90% identified as a priority the need for a new gait assessment tool that can be used quickly and easily[189]. Given the limitations associated with extracting quantitative data from a dynamic assessment without complex instrumentation, the FPI represents an advance towards addressing the needs of clinicians. Ultimately, there will remain some tension between the desirable characteristics that might be identified by scientists and those identified by the groups of clinicians reported in the three papers noted above. The FPI does however, bring something of the scientific rigor to the clinical assessment, and in this context represents a clear advance on the current state.

### Can a non-technological, low-cost clinical tool provide data of adequate validity and reliability for use in clinical practice?

The initial face validity and ease of use studies in Chapter Four were useful in informing the development of the measure, although the results cannot be considered to apply to the FPI in its later drafts. The reliability exercise outlined in Chapter Five then quantified the technical reliability of the draft measure. This gives the reader an idea of the likely performance of the measure in clinical practice, and illustrates broadly the measurement error that might be expected to accrue when using the measure in practice. It must be remembered however, that the reliability of an instrument is a function both of its internal characteristics, and the specific characteristics of the setting and population in which it is being used. The limitations with the specific set-up used in this study, particularly with the first, adult group, reflect a learning process on the part of the rating clinicians, and the continued refinement of the scoring criteria. It should also be appreciated that the reliability of clinical measures might be expected to be higher within the constraints of a research study than in routine clinical practice. The data provided in this thesis should therefore be considered indicative of the technical merits of the measure, but before the FPI is used in a clinical setting, any prospective user should evaluate their own test-retest reliability. Where results are to be compared between raters, there is also a strong case for further evaluations of the inter-rater reliability for that specific clinical population.

The concurrent validity evaluations can conversely, probably be regarded as more definitive, as it is unlikely that researchers will undertake these types of confirmatory studies in a range of different clinical populations. The coefficients of determination for the static measure ($R^2$=0.64) is sufficient to draw the conclusion that the FPI, as a quick and easy clinical measure is quantifying an adequate proportion of the variability in standing foot posture. The dynamic EMT section provides the clinician with a clearer idea of the degree to which the pragmatic clinical approach should limit any inference drawn regarding dynamic function in a patient. The $R^2$ of 0.41 is higher than that reported in the literature for previous studies of the degree to which static measures predict dynamic function [200 337 394], and supports the case that the FPI is a more valid clinical measure than those in current use. The validation of the individual components informed a redraft of the FPI, reducing the number of components. The final six-item version includes only those measures that were demonstrated to contribute significantly to the various regression models, and to show adequate reliability.

**Can the new measure be used to evaluate the foot deformity of this group of people in a clinical trial context?**

It was noted previously that clinical utility (features such as ease of use and time taken to conduct the examination, as well as responsiveness) was rated by physiotherapist clinicians to be more important than reliability and validity [189]. The clinical trial that was conducted, in part at least, to assess the responsiveness of the FPI yielded too little change in the primary measure for any meaningful evaluation of responsiveness in the FPI as the secondary measure. The illustrations of the foot types and the associated FPI scores are useful however, in enabling the reader to form an impression of the FPI scoring, and in providing examples of the range of scores that might be encountered in the typical clinical assessment of CMT foot. The examples range from pronounced and fixed cavus in a 34 year old male, with associated FPI scores of -6 and -9, through more normal presentations with FPI scores around zero, to a planovalgus foot in a child with profound muscle weakness and FPI scores of +9. The sample of CMT patients included in the trial demonstrated a median FPI score of -0.5, which was, as might be expected, some five points lower than the FPI scores observed in the other populations investigated in the course of the validation process. The FPI data from the non-CMT samples are in agreement with previous literature indicating that the ‘average’ foot in the normal population stands in, and functions about a moderately pronated position [10 347 394 452]. It is also noteworthy that the standing FPI scores of the 4-6 year old children was significantly higher (i.e. more pronated) than those of the older children and adults, a finding also mirroring that reported widely in the literature [254 266 453 454].

### 8.1.2 Fulfilment of the aims of the thesis

Both the overarching aims have been fulfilled through this program of work.

**Aim 1. To obtain comprehensive descriptive data relating to the common physical problems encountered in patients with CMT, with an emphasis on those problems associated with the lower limb and foot.**

The survey collated responses from the largest cohort of CMT patients to have provided data on this range of presentations. The clinical features of CMT were described in detail, and some of the relationships between these features have been evaluated for the first time. The effects of CMT on health related quality of life have also been described and related to disease features, as well as placing CMT in the broader spectrum of chronic diseases. It was apparent that leg-weakness, even self reported weakness, was a valuable marker for presence and severity of secondary features, and that the importance of leg cramps to people with CMT has perhaps been underestimated by clinicians. The effects of CMT on foot-related quality of life was noted to be particularly profound, and the gender specific differences in footwear-related HRQoL raises questions as to how some of the immediate requirements of patients might be better considered and addressed by clinicians.

**Aim 2. To develop and validate a tool for better assessing baseline foot deformity and evaluating existing treatments.**

The technical limitations of current motion analysis technologies presented a barrier to the definitive evaluation of the new instrument, but this had been anticipated at the outset and the validation process was more robust than for any existing measure of foot posture. The instrument received a positive response from clinicians, performed well in the validation experiments and represents an advance on available methods for establishing baseline foot posture and deformity. It has not been possible to establish definitively whether the instrument will contribute to future evaluations of treatment, but its clinical utility appears adequate, and early uptake is encouraging (see Section 8.1.4. 'Implications for future research', for a list of recent applications of the FPI in clinical research).

### 8.1.3 Limitations of the research process

**Reconciling clinical and scientific demands**

Probably the most significant of the limitations arising from the program of work are the absence of a truly definitive gold standard against which the measure could be evaluated, and the conflicts arising from the requirement for the new measure to be quick and easy to apply in clinical practice. If the FPI were simply extending the accuracy or objectivity of existing measures, the process of validation may have been more straightforward, as such incremental gains are potentially easier to demonstrate. Difficulties were encountered because of the technical limitations of what is regarded as the state-of-the-art, and also because of ongoing definitional issues relating to foot pathologies that are ill-defined and poorly characterised.

Having accepted the need for some compromise so that the new instrument would address the needs of clinicians, it was relatively straightforward to ground the new instrument in the existing literature. Having accepted compromise however, it became less straightforward to validate the instrument according to best scientific principles. At the outset, the factors used to define the new measure had been well described, and the candidate was able to adopt these with a minimum of modification. In particular, the publication of the APTA foot and ankle special interest group consensus statement[9] went some way towards providing a solid foundation upon which to base the development of the new measure. In identifying component measures that might be suitable for inclusion in the new FPI, the process of defining the components and the scoring system for was undertaken systematically. The earliest stages of development described in Chapter Four reflect an initially cautious approach in which clinicians were given the opportunity to comment on the measure in a structured but relatively informal manner. It would clearly not be appropriate for the full validation process to have been conducted in such a way, but for the early evolutionary stages this approach was justifiable and indeed proved helpful, facilitating discourse between testers and the candidate, and allowing for rapid evolution of the concept in response to feedback.

The increasing formality and investment that was applied to the development of the measure as it became clear that the concept was viable, is reflected in Chapters Five and Six.

**Limitations in the gold standards employed in the validations.**

The initial concurrent validation study was performed using a measure, the valgus index, with known limitations as a gold standard[387], but which allowed for concurrent evaluation with an objective static measure in a large sample. The limitations of the gold standard restricted the role of this part of the process to informing the development of the measure rather than providing evidence of the validity of the final instrument. The agreement between the two measures was high, and does support the validity of the FPI to a degree, but it is not clear from these data how much of the unexplained variance is the result of error in the FPI ratings, and how much the is error associated with the valgus index. In the statistical modelling used, the assumption is made that all the error is due to the new measure, although given the published limitations of the VI this is unlikely to be the case. There are also some limitations in the reliability studies, as these were undertaken to illustrate the technical reliability of the new measure but cannot be extrapolated to predict the reliability of the measure in multiple specific clinical populations.

The main study of concurrent validity described in Chapter Six is fairly robust methodologically, and reflects, arguably, the best science achievable within the limitations of current technology. In future it would be anticipated that through technological advances, it will become possible to evaluate individual FPI components against joint-specific segmental measures derived from video or EMT motion capture. This would represent a considerable advance on the approach described in this thesis, but is not yet possible. In trying to create a joint-specific model using existing technology, some new limitations were identified, as illustrated by the stylus digitisation protocol used in Chapter Six, Section One. This stylus driven approach allowed for study of highly localised segments, but limitations were imposed by the error associated with multiple manual placing of the stylus against anatomical landmarks. A model with sensors fixed to the segment removes this source of error as well as permitting dynamic study, and detailed multi-segment dynamic modelling would ultimately be more informative. Preliminary attempts have already been made to describe the foot dynamically in more than one segment [240 420], but these data are not yet well enough understood or of sufficient validity in their own right to be used as a benchmark in concurrent validation experiments. It is a strength of this validation process, that the validity of the FPI was assessed by determining the extent to which the static measure predicts dynamic function[6], even if only against an ankle joint complex model. Few such static measures have been subjected to such a rigorous evaluation.

The technical limitations of the EMT system have been noted previously in Chapter Six, but the most important of them warrant some further discussion, namely sampling rate and system accuracy. The sampling rate of 30Hz is relatively low compared with the sampling rate of typical force plate evaluations (~1000Hz) and even video motion tracking (typically 50-250Hz). A low sampling rate such as 30Hz would certainly have the potential to be problematic for any studies involving rapid motion such as running or jumping studies. For walking studies, 30 Hz has been reported to be adequate however [241], and for this study of low frequency motions the motion tracking system yielded data that was adequate for the purpose.

The system accuracy was evaluated in detail as presented in Appendix F, and was found to be acceptably high. Again some error must be acknowledged however, and included in any interpretation of these data, particularly as the assumption in the statistical modelling is again that the EMT measures were an unimpeachable gold-standard. As was noted above for the stylus digitisation protocol, all the residual variance is therefore attributed to the new instrument in the analysis, although in practice some of the unexplained variance in the EMT measured ankle joint complex motions is actually due to random or technical error inherent to the EMT system.

### Application to the CMT and general populations

Undertaking the majority of the validation studies outside the CMT population allowed for a collection of data in larger samples than would have been possible using CMT population alone. It was important to evaluate the FPI in at least one group with CMT, to ensure the applicability of the measure to this group but given the relatively low prevalence of the disease in the population, and the requirement for three reliability cohorts and two validation cohorts, in addition to the subjects required for the final clinical utility chapter, it was not practical to attempt to conduct the full set of validation experiments in patients with CMT.

With the variable presentation of CMT in the lower limb[86 114] and in the absence of any accepted existing system for categorising foot posture, it would also have been impossible to have achieved in a CMT sample, clear and non-overlapping groups of pronated, supinated or 'normal' feet. The methods used in this study to create states of pronation and supination are artificial and could therefore be criticised as being unrepresentative of natural foot function, however the data demonstrate that the range of foot postures induced artificially was similar to that seen in the large sample evaluated in the initial concurrent validation study, in the reliability studies, and the range of foot postures illustrated at the end of Chapter Seven. The discrete nature of the categories resulting from the artificially induced positions was ultimately of benefit to the validation process.

Conducting the evaluations in both normal and CMT samples has demonstrated the merits of the approach in this specific clinical group, and potentially, in the population at large.

**Clinical trial phase**

The final investigation of the clinical utility of the FPI was limited by both the small size of the sample in this part of what is a multicentre trial, and also by the absence of any effect in the primary outcome as a consequence of the splinting. It had been hoped that there might be some systematic effect associated with splinting, and although it might be expected that any effect in the global foot posture would be less than in the primary outcome, it was hoped that any effect may have been measurable in the FPI scores. Ultimately however the minimal effect of the splinting intervention precluded the derivation of any measure of responsiveness. The final chapter therefore is limited to an empirical estimation of the merit of the new instrument in the clinical setting, appraisal of its reliability in the CMT population, and illustration of the range of FPI scores that might be encountered in people with CMT.

### 8.1.4 Implications for future research

The purpose of defining and validating a new measure was to provide the clinical community with a new instrument that may be used to provide quantitative data for both routine practice and clinical research. Clearly, for detailed lower limb studies, dynamic motion tracking will remain the preferred gold standard for the foreseeable future [189 242 422], although even in laboratory studies the FPI has already found some favour as a preliminary screening tool for use prior to instrumented analysis. Where there is a need for a quick quantitative measure to provide data on a large scale, such as in population studies or cohort studies, the FPI has some advantages that are already being exploited. Several research groups are applying the FPI in a range of clinical research situations already at a number of institutions in Australia, Europe and North America. Some examples of outputs arising from independent users of the FPI include:

- Payne C., Oates M., Noakes, H. Static Stance Response to Different Types of Foot Orthoses. Journal of the American Podiatric Medical Association. Volume 93 Number 6 492-498 2003

- Noakes H.,Payne C. The Reliability of the Manual Supination Resistance Test . Journal of the American Podiatric Medical Association. Volume 93 Number 3 185-189 2003
- Payne C, Aquino C. Significance and Clinical Application of the Forces Needed to Supinate the Foot. Prescription Foot Orthoses Laboratory Association, Annual meeting Las Vegas, NV. 2003
- Yates B., White S. The incidence and risk factors of Medial Tibial Stress Syndrome among naval recruits. Sports Medicine Australia National Conference, Melbourne, October 2002
- Payne C., Oates M., Mitchel A. The response of the foot to prefabricated orthoses of different arch heights. Australasian Journal of Podiatric Medicine; Vol 36, No.1 : 7-12. 2001
- Bickerstaffe J. Effect of a change in foot posture on a patients pain scale. MSc thesis, University of Stafford
- Brown C, The effect of a functional foot orthoses (FO) on balance parameters in subjects with pronated feet. MSc thesis, University of Teeside
- Froggat-Bailey J. A randomised controlled trial to investigate the role of orthoses in knee pain management. MSc, Manchester Metropolitan University
- Warne D The relationship between childhood obesity and abnormal pronation BSc (Hons) thesis, University of Salford
- Bain J. Comparison of foot type/posture between Rheumatoid Arthritis patients and non-Rheumatoid Arthritis patients using the Foot Posture Index" BSc (Hons) thesis, University of Salford.
- Targett R. Foot posture changes in younger children BSc (Hons) thesis, University of Wales Institute, Cardiff
- Halstead J. Relationship between foot posture and passive hallux dorsiflexion BSc (Hons) thesis, University of Huddersfield.
- Rankin C. Incidence of medial tibial stress syndrome (MTSS) and its relationship to pronation. BSc (Hons) thesis, Auckland University

## Key areas for future research.

*Hypothesis generating research.*

There are a variety of theoretical models that purport to explain the function of the foot in health and disease. To-date most of the activity directed toward generating explanatory models of foot function have been based, in the absence of good clinical data, on development of 'blue-sky' theory [395 455 456], rather than testing of observations. The availability of a valid, quantitative instrument that can be used to evaluate large numbers of subjects in a range of clinical populations offers some scope for the generation of new hypotheses based on observation rather than theory.

*Epidemiology 1. Population screening and descriptive studies.*

Cardinal studies of the incidence and prevalence of the various foot postures are needed to inform clinicians of the range of presentations seen in the population at large and in clinical sub-populations. To-date studies of this type have been limited because of dissatisfaction with operational definitions of foot type, foot pathology, and disease classification, and concerns over the validity of the available clinical measures [6 16 186].

*Epidemiology 2. Associative epidemiological studies.*
Studies evaluating the links between structural variables such as foot posture, and musculoskeletal symptoms have also been inhibited by the absence of satisfactory clinical measures[338 401 449]. Routine collection of foot posture data may allow for future record review, and extraction of previously unrecognised relationships.

*Cohort studies.*
The FPI might have a role in cohort studies, evaluating large numbers of subjects to quantify foot posture at outset and monitoring change over time. Studies arising from this type of application might include prospective cohorts investigating the role of foot posture as a risk factor for developmental pathology such as hallux valgus formation, or studies monitoring change over time in foot posture in progressive disorders such as CMT or Rheumatoid Arthritis.

*Treatment evaluations.*
As noted previously, robust prospective scientific evaluations of foot treatments are likely to be best conducted using dynamic objective measures and in smaller, tightly controlled samples[420 457]. There is a role however, for large scale collection of data describing, for example, postural effects such as might be seen with functional foot orthotic therapy, and for prospective studies aimed at identifying predictive markers for successful outcomes in patients undergoing a range of treatments. Evaluations of changes induced by therapies such as foot surgeries in CMT may also be aided by clinical evaluation using the FPI[458].

## *8.2* *CONCLUSIONS*

Foot pathologies are prevalent in the CMT population and to a lesser extent in the general population. Many such foot problems are a consequence of altered foot posture or foot function[145 459 460]. Although not life threatening, foot problems are the source of significant morbidity, and contribute to reduced health related quality of life. Foot problems in both the general population and in the CMT population are poorly understood and are often trivialised.

Existing clinical measures are inadequate for measuring foot posture as they are either not of acceptable reliability/accuracy, or are too time consuming and costly to undertake routinely. The need for the new measure was established from clinician requirements and a consensus statement published in the literature. The new measure was grounded in the existing literature from the outset, and while retaining some of the inherent limitations of a simple clinical examination, has proven more reliable and valid than any existing measures.

The FPI was demonstrated to reflect well the standing posture when evaluated concurrently with a sophisticated digital model. Importantly, the FPI derived standing foot posture also predicted more completely than any existing measure, the proportion of variance in foot motion during normal walking.

The foot postures seen in CMT and the other groups studied encompassed a wide range of presentations and allowed for illustration of a range of FPI scores. The measure has acceptable face validity and has proven popular with clinicians and clinical researchers.

In summary, the Foot Posture Index is an instrument for quantifying foot posture simply and quickly, that addresses a deficit well documented in the literature. The new measure requires little special training and is applicable to arrange of clinical settings. The FPI has performed well in a quantitative validation process more rigorous than for any similar measure of foot posture, allowing potential users to make an informed choice over its suitability to specific purposes. The availability of a validated instrument that describes foot posture in multiple segments and planes offers opportunities for developing a better understanding of the foot, its disorders and its treatments, in CMT and in other clinical populations.

# REFERENCES

1. Alvarez RG, Little JP. Neuromuscular disease. In: Mizel MS, Miller RA, Scioli MW, editors. *Orthopedic knowledge update, foot and ankle 2*. Illinois: American Academy of Orthopedic Surgeons, 1998:90-100.
2. Sabir M, Lyttle D. Pathogenesis of pes cavus in Charcot-Marie-Tooth disease. *Clinical Orthopaedics & Related Research* 1983(175):173-8.
3. Holmes JR, Hansen ST, Jr. Foot and ankle manifestations of Charcot-Marie-Tooth disease. *Foot & Ankle* 1993;14(8):476-86.
4. Munro BJ, Steele JR. Foot-care awareness. A survey of persons aged 65 years and older. *Journal of the American Podiatric Medical Association.* 1998;88(5):242-8.
5. Benvenuti F, Ferrucci L, Guralnik JM, Gangemi S, Baroni A. Foot pain and disability in older persons: an epidemiologic survey. *Journal of the American Geriatrics Society.* 1995;43(5):479-84.
6. Razeghi M, Batt ME. Foot type classification: a critical review of current methods. *Gait & Posture* 2002;15:282-291.
7. Berciano J, Combarros O. Prevalence of Charcot-Marie-Tooth disorders in Cantabria, Spain. *Neurology and Neurobiology: Charcot-Marie-Tooth Disorders* 1990;53:65-72.
8. Saltzman CL, Domsic RT, Baumhauer JF, Deland JT, Gill LH, Hurwitz SR, et al. Foot and ankle research priority: report from the Research Council of the American Orthopaedic Foot and Ankle Society. *Foot & Ankle International* 1997;18(7):447-8.
9. McClay IS. Report of "Static and dynamic classification of the foot" meeting, Annapolis, Maryland.May 2000. *Journal of Orthopedic and Sports Physical Therapy* 2001;31(3):158.
10. Pierrynowski MR, Smith SB. Rear foot inversion/eversion during gait relative to the subtalar joint neutral position. *Foot & Ankle International* 1996;17(7):406-12.
11. LaPointe SJ, Peebles C, Nakra A, Hillstrom H. The reliability of clinical and caliper-based calcaneal bisection measurements. *Journal of the American Podiatric Medical Association* 2001;91(3):121-126.
12. McDowell BC, Hewitt V, Nurse A, Weston T, Baker R. The variability of goniometric measurements in ambulatory children with spastic cerebral palsy. *Gait & Posture* 2000;12(2):114-21.
13. Williams D, McClay I, Laughton C.A comparison of between day reliability of different types of lower extremity kinematic variables in runners. 23rd Annual Meeting of the American Society of Biomechanics; 1999 21-23 October; University of Pittsburgh.
14. Weiner-Ogilvie S, Rome K. The reliability of three techniques for measuring foot position. *Journal of the American Podiatric Medical Association* 1998;88(8):381-6.
15. Menz HB. Alternative techniques for the clinical assessment of foot pronation. *Journal of the American Podiatric Medical Association* 1998;88(3):119-29.
16. Keenan A-M. A clinician's guide to the practical implications of the recent controversy of foot function. *Australasian Journal of Podiatric Medicine* 1997;31(3):87-93.
17. Kitaoka HB, Patzer GL. Analysis of clinical grading scales for the foot and ankle. *Foot & Ankle International* 1997;18(7):443-446.
18. Reischl SF, Powers CM, Rao S, Perry J. Relationship between foot pronation and rotation of the tibia and femur during walking. *Foot & Ankle International* 1999;20(8):513-20.
19. Erdemir A, Piazza SJ.Simulation based design of a pointer for accurate determination of anatomical landmarks. 23rd Annual Meeting of the American Society of Biomechanics; 1999 21 -23 October; University of Pittsburgh.
20. McClay I, Manal K. The influence of foot abduction on differences between two-dimensional and three-dimensional rearfoot motion. *Foot & Ankle International* 1998;19(1):26-31.
21. Reinschmidt C, Van den Bogert AJ, Lundberg A, Nigg BM, Murphy N, Stacoff A, et al. Tibiofemoral and tibiocalcaneal motion during walking: External vs. Skeletal markers. *Gait & Posture* 1997;6(2):98-109.
22. Reinschmidt C, Van den Bogert AJ, Murphy N, Lundberg A, Nigg BM. Tibiocalcaneal motion during running, measured with external and bone markers. *Clinical Biomechanics* 1997;12(1):8-16.
23. Mannon K, Anderson T, Cheetham P, Cornwall MW, McPoil TG. A comparison of two motion analysis systems for the measurement of two-dimensional rearfoot motion during walking. *Foot & Ankle International* 1997;18(7):427-31.
24. McPoil TG, Cornwall MW. The relationship between static lower extremity measurements and rearfoot motion during walking. *Journal of Orthopaedic & Sports Physical Therapy* 1996;24(5):309-14.
25. Keenan A, Bach TM. Video assessment of rearfoot movements during walking: a reliability study. *Archives of Physical Medicine & Rehabilitation* 1996;77(7):651-5.

26. Ware J. SF-36 Health Survey. Manual and interpretation guide. Boston: Boston Health Institute, New England Medical Center, 1993.
27. Bennett PJ, Patterson C, Wearing S, Baglioni T. Development and validation of a questionnaire designed to measure foot-health status. *Journal of the American Podiatric Medical Association* 1998;88(9):419-28.
28. Virchow R. Ein fall von progressiver musculoskelatrophie. *Archives of Pathology and Anatomy* 1856;8:537-540.
29. Charcot JM, Marie P. Sur une forme particuliere d'atrophie musculaire progressive, souvant familiale de'butant par les pieds et les jambes et atteignant plus tard les maines. *Rev. Med (Paris)* 1886;6:97-138.
30. Tooth HH. The Peroneal Type of Progressive Muscular Atrophy, 1886.
31. Dyck PJ, Lambert EH. Lower motor and primary sensory neuron diseases with peroneal muscular atrophy. I. Neurologic, genetic, and electrophysiologic findings in hereditary polyneuropathies. *Archives of Neurology* 1968;18(6):603-18.
32. Dyck PJ, Lambert EH. Lower motor and primary sensory neuron diseases with peroneal muscular atrophy. II. Neurologic, genetic, and electrophysiologic findings in various neuronal degenerations. *Archives of Neurology* 1968;18(6):619-25.
33. Raeymaekers P, Timmerman V, De Jonghe P, Swerts L, Gheuens J, Martin JJ, et al. Localization of the mutation in an extended family with Charcot-Marie-Tooth neuropathy (HMSN I). *American Journal of Human Genetics* 1989;45(6):953-8.
34. Vance JM, Nicholson GA, Yamaoka LH, Stajich J, Stewart CS, Speer MC, et al. Linkage of Charcot-Marie-Tooth neuropathy type 1a to chromosome 17. *Experimental Neurology* 1989;104(2):186-9.
35. Valentijn LJ, Baas F, Wolterman RA, Hoogendijk JE, van den Bosch NH, Zorn I, et al. Identical point mutations of PMP-22 in Trembler-J mouse and Charcot-Marie-Tooth disease type 1A. *Nature Genetics* 1992;2(4):288-91.
36. Nagamatsu M, Jenkins RB, Schaid DJ, Klein DM, Dyck PJ. Hereditary motor and sensory neuropathy type 2C is genetically distinct from types 2B and 2D. *Archives of Neurology* 2000;57(5):669-72.
37. Saito M, Hayashi Y, Suzuki T, Tanaka H, Hozumi I, Tsuji S. Linkage mapping of the gene for Charcot-Marie-Tooth disease type 2 to chromosome 1p (CMT2A) and the clinical features of CMT2A. *Neurology* 1997;49(6):1630-5.
38. Kennerson ML, Zhu D, Gardner RJ, Storey E, Merory J, Robertson SP, et al. Dominant intermediate Charcot-Marie-Tooth neuropathy maps to chromosome 19p12-p13.2. *American Journal of Human Genetics.* 2001;69(4):883-8.
39. Online Mendelian Inheritance in Man database, OMIM (TM). McKusick-Nathans Institute for Genetic Medicine, Johns Hopkins University (Baltimore, MD) and National Center for Biotechnology Information, National Library of Medicine (Bethesda, MD). 2003.
40. Aiyesimoju AB, Osuntokun BO, Bademosi O, Adeuja AO. Hereditary neurodegenerative disorders in Nigerian Africans. *Neurology* 1984;34(3):361-2.
41. Radhakrishnan K, el-Mangoush MA, Gerryo SE. Descriptive epidemiology of selected neuromuscular disorders in Benghazi, Libya. *Acta Neurologica Scandinavica* 1987;75(2):95-100.
42. Skre H. Genetic and clinical aspects of CMT. *Clinical Genetics* 1974;6:98-118.
43. MacMillan JC, Harper PS. The Charcot-Marie-Tooth syndrome: clinical aspects from a population study in South Wales, UK. *Clinical Genetics* 1994;45(3):128-34.
44. Combarros O, Calleja J, Polo JM, Berciano J. Prevalence of hereditary motor and sensory neuropathy in Cantabria. *Acta Neurologica Scandinavica* 1987;75(1):9-12.
45. Holmberg BH. Charcot-Marie-Tooth disease in northern Sweden: an epidemiological and clinical study. *Acta Neurologica Scandinavica* 1993;87(5):416-22.
46. Buchthal F, Behse F. Peroneal muscular atrophy (PMA) and related disorders. I. Clinical manifestations as related to biopsy findings, nerve conduction and electromyography. *Brain* 1977;100(Pt 1):41-66.
47. Hagberg B, Westerberg B. Hereditary motor and sensory neuropathies in Swedish children. I. Prevalence and distribution by disability groups. *Acta Paediatrica Scandinavica* 1983;72(3):379-83.
48. Hagberg B, Lyon G. Pooled European series of hereditary peripheral neuropathies in infancy and childhood. A "correspondence work shop" report of the European Federation of Child Neurology Societies (EFCNS). *Neuropediatrics* 1981;12(1):9-17.
49. Mostacciuolo ML, Schiavon F, Angelini C, Miccoli B, Piccolo F, Danieli GA. Frequency of duplication at 17p11.2 in families of northeast Italy with Charcot-Marie-Tooth disease type 1. *Neuroepidemiology* 1995;14(2):49-53.
50. Wise CA, Garcia CA, Davis SN, Heju Z, Pentao L, Patel PI, et al. Molecular analyses of unrelated Charcot-Marie-Tooth (CMT) disease patients suggest a high frequency of the CMTIA duplication. *American Journal of Human Genetics* 1993;53(4):853-63.

51. Middleton-Price HR, Harding AE, Monteiro C, Berciano J, Malcolm S. Linkage of hereditary motor and sensory neuropathy type I to the pericentromeric region of chromosome 17. *American Journal of Human Genetics* 1990;46(1):92-4.
52. Lupski JR, de Oca-Luna RM, Slaugenhaupt S, Pentao L, Guzzetta V, Trask BJ, et al. DNA duplication associated with Charcot-Marie-Tooth disease type 1A. *Cell* 1991;66(2):219-32.
53. Patel PI, Franco B, Garcia C, Slaugenhaupt SA, Nakamura Y, Ledbetter DH, et al. Genetic mapping of autosomal dominant Charcot-Marie-Tooth disease in a large French-Acadian kindred: identification of new linked markers on chromosome 17. *American Journal of Human Genetics* 1990;46(4):801-9.
54. Raeymaekers P, Timmerman V, Nelis E, De Jonghe P, Hoogendijk JE, Baas F, et al. Duplication in chromosome 17p11.2 in Charcot-Marie-Tooth neuropathy type 1a (CMT 1a). The HMSN Collaborative Research Group. *Neuromuscular Disorders* 1991;1(2):93-7.
55. Timmerman V, Raeymaekers P, De Jonghe P, De Winter G, Swerts L, Jacobs K, et al. Assignment of the Charcot-Marie-Tooth neuropathy type 1 (CMT 1a) gene to 17p11.2-p12. *American Journal of Human Genetics* 1990;47(4):680-5.
56. Nicholson GA. Penetrance of the hereditary motor and sensory neuropathy Ia mutation: assessment by nerve conduction studies. *Neurology* 1991;41(4):547-52.
57. Bissar-Tadmouri N, Parman Y, Boutrand L, Deymeer F, Serdaroglu P, Vandenberghe A, et al. Mutational analysis and genotype/phenotype correlation in Turkish Charcot-Marie-Tooth Type 1 and HNPP patients. *Clinical Genetics* 2000;58(5):396-402.
58. Killian JM, Kloepfer HW. Homozygous expression of a dominant gene for Charcot-Marie-Tooth neuropathy. *Annals of Neurology* 1979;5(6):515-22.
59. LeGuern E, Gouider R, Mabin D, Tardieu S, Birouk N, Parent P, et al. Patients homozygous for the 17p11.2 duplication in Charcot-Marie-Tooth type 1A disease. *Annals of Neurology* 1997;41(1):104-8.
60. Scherer SS, Chance PF. Myelin genes: getting the dosage right. *Nature Genetics* 1995;11(3):226-8.
61. Patel PI, Roa BB, Welcher AA, Schoener-Scott R, Trask BJ, Pentao L, et al. The gene for the peripheral myelin protein PMP-22 is a candidate for Charcot-Marie-Tooth disease type 1A. *Nature Genetics* 1992;1(3):159-65.
62. Lupski JR, Wise CA, Kuwano A, Pentao L, Parke JT, Glaze DG, et al. Gene dosage is a mechanism for Charcot-Marie-Tooth disease type 1A. *Nature Genetics* 1992;1(1):29-33.
63. Lupski JR, Garcia CA. Molecular genetics and neuropathology of Charcot-Marie-Tooth disease type 1A. *Brain Pathology* 1992;2(4):337-49.
64. Matsunami N, Smith B, Ballard L, Lensch MW, Robertson M, Albertsen H, et al. Peripheral myelin protein-22 gene maps in the duplication in chromosome 17p11.2 associated with Charcot-Marie-Tooth 1A. *Nature Genetics* 1992;1(3):176-9.
65. Suter U, Nave KA. Transgenic mouse models of CMT1A and HNPP. *Annals of the New York Academy of Sciences* 1999;883:247-53.
66. Umehara F, Kiwaki T, Yoshikawa H, Nishimura T, Nakagawa M, Matsumoto W, et al. Deletion in chromosome 17p11.2 including the peripheral myelin protein-22 (PMP-22) gene in hereditary neuropathy with liability to pressure palsies. *Journal of the Neurological Sciences* 1995;133(1-2):173-6.
67. Ouvrier R. Correlation between the histopathologic, genotypic, and phenotypic features of hereditary peripheral neuropathies in childhood. *Journal of Child Neurology* 1996;11(2):133-46.
68. Warner LE, Hilz MJ, Appel SH, Killian JM, Kolodry EH, Karpati G, et al. Clinical phenotypes of different MPZ (P0) mutations may include Charcot-Marie-Tooth type 1B, Dejerine-Sottas, and congenital hypomyelination. *Neuron* 1996;17(3):451-60.
69. Chance PF, Reilly M. Inherited neuropathies. *Current Opinion in Neurology* 1994;7(5):372-80.
70. Boerkoel CF, Takashima H, Garcia CA, Olney RK, Johnson J, Berry K, et al. Charcot-Marie-Tooth disease and related neuropathies: mutation distribution and genotype-phenotype correlation. *Annals of Neurology.* 2002;51(2):190-201.
71. Bolino A, Levy ER, Muglia M, Conforti FL, LeGuern E, Salih MA, et al. Genetic refinement and physical mapping of the CMT4B gene on chromosome 11q22. *Genomics* 2000;63(2):271-8.
72. Othmane KB, Loeb D, Hayworth-Hodgte R, Hentati F, Rao N, Roses AD, et al. Physical and genetic mapping of the CMT4A locus and exclusion of PMP-2 as the defect in CMT4A. *Genomics* 1995;28(2):286-90.
73. Murakami T, Garcia CA, Reiter LT, Lupski JR. Charcot-Marie-Tooth disease and related inherited neuropathies. *Medicine* 1996;75(5):233-250.
74. Mancardi GL, Uccelli A, Bellone E, Sghirlanzoni A, Mandich P, Pareyson D, et al. 17p11.2 duplication is a common finding in sporadic cases of Charcot-Marie-Tooth type 1. *European Neurology* 1994;34(3):135-9.

75. Pentao L, Wise CA, Chinault AC, Patel PI, Lupski JR. Charcot-Marie-Tooth type 1A duplication appears to arise from recombination at repeat sequences flanking the 1.5 Mb monomer unit. *Nature Genetics* 1992;2(4):292-300.

76. Tachi N, Kozuka N, Ohya K, Chiba S. De novo mutation of Charcot-Marie-Tooth disease type 1A. *Pediatric Neurology* 1997;17(1):67-9.

77. De Jonghe P, Nelis E, Timmerman V, Lofgren A, Martin JJ, Van Broeckhoven C. Molecular diagnostic testing in Charcot-Marie-Tooth disease and related disorders. Approaches and results. *Annals of the New York Academy of Sciences* 1999;883:389-96.

78. Kimura J. Nerve conduction studies and electromyography. In: Dyck P, Thomas P, Lambert E, Bunge R, editors. *Peripheral Neuropathy.* 2nd ed. Philadelphia: WB Saunders, 1984:919-966.

79. Thomas PK. Overview of Charcot-Marie-Tooth disease type 1A. *Annals of the New York Academy of Sciences* 1999;883:1-5.

80. Shy ME, Krajewski K, Turansky C, Garbern J, Kamholz J, Lewis R. CMT1A phenotype correlates with secondary axonal degeneration but not demyelination. *Neurology Supplement American Academy of Neurology, 51st Annual Meeting* 1999;52(6 (suppl 2)):A217.

81. Killian JM, Tiwari PS, Jacobson S, Jackson RD, Lupski JR. Longitudinal studies of the duplication form of Charcot-Marie-Tooth polyneuropathy. *Muscle & Nerve* 1996;19(1):74-8.

82. Baker RS, Upton AR. Variation of phenotype in Charcot-Marie-Tooth disease. *Neuropadiatrie* 1979;10(3):290-5.

83. Auer-Grumbach M, Strasser-Fuchs S, Wagner K, Korner E, Fazekas F. Roussy-Levy syndrome is a phenotypic variant of Charcot-Marie-Tooth syndrome IA associated with a duplication on chromosome 17p11.2. *Journal of the Neurological Sciences* 1998;154(1):72-5.

84. Bouche P, Gherardi R, Cathala HP, Lhermitte F, Castaigne P. Peroneal muscular atrophy. Part 1. Clinical and electrophysiological study. *Journal of the Neurological Sciences* 1983;61(3):389-99.

85. Kaku DA, Parry GJ, Malamut R, Lupski JR, Garcia CA. Nerve conduction studies in Charcot-Marie-Tooth polyneuropathy associated with a segmental duplication of chromosome 17. *Neurology* 1993;43(9):1806-8.

86. Birouk N, Gouider R, Le Guern E, Gugenheim M, Tardieu S, Maisonobe T, et al. Charcot-Marie-Tooth disease type 1A with 17p11.2 duplication. Clinical and electrophysiological phenotype study and factors influencing disease severity in 119 cases. *Brain* 1997;120:813-23.

87. Ouvrier R, McLeod JG, Pollard JD. *Peripheral neuropathy in childhood.* 2nd ed. London: Mac Keith Press, 1999.

88. Krajewski K, Turansky C, Lewis R, Garbern J, Hinderer S, Kamholz J, et al. Correlation between weakness and axonal loss in patients with CMT1A. *Annals of the New York Academy of Sciences* 1999;883:490-2.

89. Kamholz J, Awatramani R, Menichella D, Jiang H, Xu W, Shy M. Regulation of myelin-specific gene expression. Relevance to CMT1. *Annals of the New York Academy of Sciences* 1999;883:91-108.

90. Griffin JW, Sheikh K. Schwann cell-axon interactions in Charcot-Marie-Tooth disease. *Annals of the New York Academy of Sciences* 1999;883:77-90.

91. Sahenk Z, Serrano-Munuera C, Chen L, Kakabadze I, Najagara HN. Evidence for impaired axonal regeneration in PMP22 duplication: studies in nerve xenografts. *Journal of the Peripheral Nervous System.* 2003;8(2):116-27.

92. Muller HW. New vistas on the pathomechanism of Charcot-Marie-Tooth and related peripheral neuropathies. *Annals of the New York Academy of Sciences* 1999;883:152-9.

93. Thomas PK, King RH, Small JR, Robertson AM. The pathology of Charcot-Marie-Tooth disease and related disorders. *Neuropathology & Applied Neurobiology* 1996;22(4):269-84.

94. Muller HW, Suter U, Van Broeckhoven C. Advances in Charcot-Marie-Tooth disease research: cellular function of CMT-related proteins, transgenic animal models, and pathomechanisms. *Neurobiology of Disease* 1997;4(3-4):215-20.

95. Sander S, Ouvrier RA, McLeod JG, Nicholson GA, Pollard JD. Clinical syndromes associated with tomacula or myelin swellings in sural nerve biopsies. *Journal of Neurology, Neurosurgery & Psychiatry* 2000;68(4):483-488.

96. Schenone A, Mancardi GL. Molecular basis of inherited neuropathies. *Current Opinion in Neurology* 1999;12(5):603-16.

97. Sander S, Nicholson GA, Ouvrier RA, McLeod JG, Pollard JD. Charcot-Marie-Tooth disease: histopathological features of the peripheral myelin protein (PMP22) duplication (CMT1A) and connexin32 mutations (CMTX1). *Muscle & Nerve* 1998;21(2):217-25.

98. Fabrizi GM, Simonati A, Taioli F, Cavallaro T, Ferrarini M, Rigatelli F, et al. PMP22 related congenital hypomyelination neuropathy. *Journal of Neurology, Neurosurgery & Psychiatry* 2001;70(1):123-126.

99. Ouvrier RA, McLeod JG, Conchin TE. The hypertrophic forms of hereditary motor and sensory neuropathy. A study of hypertrophic Charcot-Marie-Tooth disease (HMSN type I) and Dejerine-Sottas disease (HMSN type III) in childhood. *Brain* 1987;110(1):121-48.
100. Low PA, McLeod JG, Prineas JW. Hypertrophic Charcot-Marie-Tooth disease. Light and electron microscope studies of the sural nerve. *Journal of the Neurological Sciences* 1978;35(1):93-115.
101. Bell C, Haites N. Genetic aspects of Charcot-Marie-Tooth disease. *Archives of Disease in Childhood* 1998;78(4):296-300.
102. Lagueny A, Latour P, Vital A, Rajabally Y, Le Masson G, Ferrer X, et al. Peripheral myelin modification in CMT1B correlates with MPZ gene mutations. *Neuromuscular Disorders* 1999;9(6-7):361-7.
103. Hayasaka K, Himoro M, Sato W, Takada G, Uyemura K, Shimizu N, et al. Charcot-Marie-Tooth neuropathy type 1B is associated with mutations of the myelin P0 gene. *Nature Genetics* 1993;5(1):31-4.
104. Ohnishi A, Yamamoto T, Yamamori S, Sudo K, Fukushima Y, Ikeda M. Myelinated fibers in Charcot-Marie-Tooth disease type 1B with Arg98His mutation of Po protein. *Journal of the Neurological Sciences* 1999;171(2):97-109.
105. Hahn AF, Bolton CF, White CM, Brown WF, Tuuha SE, Tan CC, et al. Genotype/phenotype correlations in X-linked dominant Charcot-Marie-Tooth disease. *Annals of the New York Academy of Sciences* 1999;883:366-82.
106. Niewiadomski LA, Kelly TE. X-linked Charcot-Marie-Tooth disease: molecular analysis of interfamilial variability. *American Journal of Medical Genetics* 1996;66(2):175-8.
107. Ericson U, Borg J, Borg K. Macro-EMG and muscle biopsy of paretic foot dorsiflexors in Charcot-Marie-Tooth disease. *Muscle & Nerve* 2000;23(2):217-22.
108. Vance JM. The many faces of Charcot-Marie-Tooth disease. *Archives of Neurology* 2000;57(5):638-40.
109. Paraskevas GP, Panousopoulou A, Karandreas N, Piperos P, Lygidakis C, Papageorgiou C. Correlation between denervation activity and compound muscle action potential amplitude in hereditary motor and sensory neuropathy I and II. *Electromyography & Clinical Neurophysiology* 1998;38(6):343-7.
110. Stilwell G, Kilcoyne RF, Sherman JL. Patterns of muscle atrophy in the lower limbs in patients with Charcot-Marie-Tooth disease as measured by magnetic resonance imaging. *Journal of Foot & Ankle Surgery* 1995;34(6):583-6; discussion 596.
111. Hughes JT, Brownell B. Pathology of peroneal muscular atrophy (Charcot-Marie-Tooth disease). *Journal of Neurology, Neurosurgery & Psychiatry* 1972;35(5):648-57.
112. De Jonghe P, Timmerman V, Nelis E, De Vriendt E, Lofgren A, Ceuterick C, et al. A novel type of hereditary motor and sensory neuropathy characterized by a mild phenotype. *Archives of Neurology* 1999;56(10):1283-8.
113. Pleasure D. Hereditary motor and sensory neuropathy: the plot thickens. *Archives of Neurology* 1999;56(10):1195.
114. Pfeiffer G, Wicklein EM, Ratusinski T, Schmitt L, Kunze K. Disability and quality of life in Charcot-Marie-Tooth disease type 1. *Journal of Neurology, Neurosurgery & Psychiatry April 1* 2001;70(4):548-550.
115. Bradley WG, Madrid R, Davis CJ. The peroneal muscular atrophy syndrome. Clinical genetic, electrophysiological and nerve biopsy studies. Part 3. Clinical, electrophysiological and pathological correlations. *Journal of the Neurological Sciences* 1977;32(1):123-36.
116. Chance PF. Molecular basis of hereditary neuropathies. *Physical Medicine & Rehabilitation Clinics of North America.* 2001;12(2):277-91.
117. Vinci P, Perelli SL. Footdrop, foot rotation, and plantarflexor failure in Charcot-Marie-Tooth disease. *Archives of Physical Medicine & Rehabilitation.* 2002;83(4):513-6.
118. Walker JL, Nelson KR, Stevens DB, Lubicky JP, Ogden JA, VandenBrink KD. Spinal deformity in Charcot-Marie-Tooth disease. *Spine* 1994;19(9):1044-7.
119. Hoogendijk JE, De Visser M, Bolhuis PA, Hart AA, Ongerboer de Visser BW. Hereditary motor and sensory neuropathy type I: clinical and neurographical features of the 17p duplication subtype. *Muscle & Nerve* 1994;17(1):85-90.
120. Thomas PK, Marques W, Jr., Davis MB, Sweeney MG, King RH, Bradley JL, et al. The phenotypic manifestations of chromosome 17p11.2 duplication. *Brain* 1997;120(Pt 3):465-78.
121. Kilmer DD, McCrory MA, Wright NC, Rosko RA, Kim HR, Aitkens SG. Hand-held dynamometry reliability in persons with neuropathic weakness. *Archives of Physical Medicine & Rehabilitation* 1997;78(12):1364-8.
122. Ericson U, Borg K. Analysis of sensory function in Charcot-Marie-Tooth disease. *Acta Neurologica Scandinavica* 1999;99(5):291-6.

123. Garcia CA, Malamut RE, England JD, Parry GS, Liu P, Lupski JR. Clinical variability in two pairs of identical twins with the Charcot-Marie-Tooth disease type 1A duplication. *Neurology* 1995;45(11):2090-3.
124. Fowler WMJ, Abresch RT, Koch TR, Brewer MLP, Bowden RK, Wanlass RL. Employment profiles in neuromuscular diseases 1. *American Journal of Physical Medicine & Rehabilitation* 1997;76(1):26-37.
125. Kumar SJ, Marks HG, Bowen JR, MacEwen GD. Hip dysplasia associated with Charcot-Marie-Tooth disease in the older child and adolescent. *Journal of Pediatric Orthopedics* 1985;5(5):511-4.
126. Fuller JE, DeLuca PA. Acetabular Dysplasia and Charcot-Marie-Tooth Disease in a Family. A Report of Four Cases. *Journal of Bone & Joint Surgery - American Volume Jul* 1995;77-A(7):1087-1091.
127. Goodman WW, Robertson WWJ. Acetabular dysplasia and hip subluxation in children with Charcot-Marie-Tooth disease. *Pediatrics* 1996;98(3)):568.
128. Shapiro F, Specht L. The diagnosis and orthopaedic treatment of childhood spinal muscular atrophy, peripheral neuropathy, Friedreich ataxia, and arthrogryposis. *Journal of Bone & Joint Surgery - American Volume* 1993;75(11):1699-714.
129. Walker JL, Nelson KR, Heavilon JA, Stevens DB, Lubicky JP, Ogden JA, et al. Hip abnormalities in children with Charcot-Marie-Tooth disease. *Journal of Pediatric Orthopedics* 1994;14(1):54-9.
130. Williams LL, Vieth RF, Wright FS. Abnormal responses to cold stress in Charcot-Marie-Tooth I syndrome. *Archives of Physical Medicine & Rehabilitation* 1994;75(7):787-91.
131. Brooks AP. Abnormal vascular reflexes in Charcot-Marie-Tooth disease. *Journal of Neurology, Neurosurgery & Psychiatry* 1980;43(4):348-50.
132. Ingall TJ, McLeod JG. Autonomic function in hereditary motor and sensory neuropathy (Charcot-Marie-Tooth disease). *Muscle & Nerve* 1991;14(11):1080-3.
133. Krampitz DE, Wolfe GI, Fleckenstein JL, Barohn RJ. Charcot-Marie-Tooth disease type 1A presenting as calf hypertrophy and muscle cramps. *Neurology* 1998;51(5):1508-9.
134. Hardie R, Harding AE, Hirsch N, Gelder C, Macrae AD, Thomas PK. Diaphragmatic weakness in hereditary motor and sensory neuropathy. *Journal of Neurology, Neurosurgery & Psychiatry* 1990;53(4):348-50.
135. Schwend RM, Drennan JC. Cavus foot deformity in children. *Journal of the American Academy of Orthopaedic Surgeons.* 2003;11(3):201-11.
136. Alexander IJ, Johnson KA. Assessment and management of pes cavus in Charcot-Marie-Tooth disease. *Clinical Orthopaedics & Related Research* 1989(246):273-81.
137. Coleman SS, Chesnut WJ. A simple test for hindfoot flexibility in the cavovarus foot. *Clinical Orthopaedics & Related Research* 1977(123):60-2.
138. Olney B. Treatment of the cavus foot. Deformity in the pediatric patient with Charcot-Marie-Tooth. *Foot & Ankle Clinics* 2000;5(2):305-15.
139. Samilson RL, Dillin W. Cavus, cavovarus, and calcaneocavus. An update. *Clinical Orthopaedics & Related Research* 1983(177):125-32.
140. Atkinson-Smith C, Betts RP. The relationship between footprints, foot pressure distributions, rearfoot motion and foot function in runners. *The Foot* 1992;2:148-154.
141. Sabir M, Lyttle D. Pathogenesis of Charcot-Marie-Tooth disease. Gait analysis and electrophysiologic, genetic, histopathologic, and enzyme studies in a kinship. *Clinical Orthopaedics & Related Research* 1984(184):223-35.
142. Aktas S, Sussman MD. The radiological analysis of pes cavus deformity in Charcot Marie Tooth disease. *Journal of Pediatric Orthopaedics. Part B* 2000;9(2):137-40.
143. Franco AH. Pes cavus and pes planus. Analyses and treatment. *Physical Therapy* 1987;67(5):688-94.
144. Arangio GA, Phillippy DC, Xiao D, Gu W-K, Salathe EP. Subtalar pronation - Relationship to the medial longitudinal arch loading in the normal foot. *Foot & Ankle International March* 2000;21(3):216-220.
145. Williams DS, 3rd, McClay IS, Hamill J. Arch structure and injury patterns in runners. *Clinical Biomechanics* 2001;16(4):341-7.
146. Ledoux WR, Shofer JB, Ahroni JH, Smith DG, Sangeorzan BJ, Boyko EJ. Biomechanical differences among pes cavus, neutrally aligned, and pes planus feet in subjects with diabetes. *Foot & Ankle International.* 2003;24(11):845-50.
147. De Visser M, Hoogendijk JE, Ongerboer BW, Verbeeten BJ. Calf enlargement in hereditary motor and sensory neuropathy. *Muscle & Nerve* 1990;13(1):40-6.
148. Dwyer FC. The present status of the problem of pes cavus. *Clinical Orthopaedics & Related Research* 1975(106):254-75.
149. Mann RA, Missirian J. Pathophysiology of Charcot-Marie-Tooth disease. *Clinical Orthopaedics & Related Research* 1988(234):221-8.

150. Price AE, Maisel R, Drennan JC. Computed tomographic analysis of pes cavus. *Journal of Pediatric Orthopedics* 1993;13(5):646-53.
151. Silver RL, de la Garza J, Rang M. The myth of muscle balance. A study of relative strengths and excursions of normal muscles about the foot and ankle. *Journal of Bone & Joint Surgery - British Volume* 1985;67(3):432-7.
152. Tynan MC, Klenerman L, Helliwell TR, Edwards RH, Hayward M. Investigation of muscle imbalance in the leg in symptomatic forefoot pes cavus: a multidisciplinary study. *Foot & Ankle* 1992;13(9):489-501.
153. Helliwell TR, Tynan M, Hayward M, Klenerman L, Whitehouse G, Edwards RH. The pathology of the lower leg muscles in pure forefoot pes cavus. *Acta Neuropathologica* 1995;89(6):552-9.
154. Tachdjian MO. The neuromuscular system. *Pediatric Orthopedics.* Philadelphia: WB Saunders, 1990:1982-8.
155. Siegel IM. Cavus versus planus in the neuropathic foot (peroneal muscular atrophy reconsidered). *Muscle & Nerve* 1996;19(6):797.
156. Meehan PL. The cavus foot. In: Morrisy RT, editor. *Lovell and Winter's Pediatric Orthopaedics.* 3rd ed. Philadelphia: J.B. Lippincott, 1990.
157. Mizel MS, Temple HT, Scranton PE, Gellman RE, Hecht PJ, Horton GA, et al. Role of the peroneal tendons in the production of the deformed foot with posterior tibial tendon deficiency. *Foot & Ankle International* 1999;20(5):285-9.
158. Carroll KL, Shea KG, Stevens PM. Postraumatic cavovarus deformity of the foot. *Journal of Pediatric Orthopaedics* 1999;19(1):39-41.
159. DeLuca PA, Banta JV. Pes cavovarus as a late consequence of peroneus longus tendon laceration. *Journal of Pediatric Orthopedics* 1985;5(5):582-3.
160. Larsen E, Angermann P. Association of ankle instability and foot deformity. *Acta Orthopaedica Scandinavica* 1990;61(2):136-9.
161. Kuruvilla A, Costa JL, Wright RB, Yoder DM, Andriacchi TP. Characterization of gait parameters in patients with Charcot-Marie-Tooth disease. *Neurology India* 2000;48(1):49-55.
162. Oatis C. Conservative management of the functional manifestations of Charcot-Marie-Tooth disease. *Neurology and Neurobiology: Charcot-Marie-Tooth Disorders* 1990;53:417-427.
163. Wetmore RS, Drennan JC. Long-term results of triple arthrodesis in Charcot-Marie-Tooth disease. *Journal of Bone & Joint Surgery - American Volume* 1989;71(3):417-22.
164. Birch JG. Orthopedic management of neuromuscular disorders in children. *Seminars in Pediatric Neurology* 1998;5(2):78-91.
165. McCluskey WP, Lovell WW, Cummings RJ. The cavovarus foot deformity. Etiology and management. *Clinical Orthopaedics & Related Research* 1989(247):27-37.
166. Lindeman E, Spaans F, Reulen J, Leffers P, Drukker J. Progressive resistance training in neuromuscular patients. Effects on force and surface EMG. *Journal of Electromyography & Kinesiology* 1999;9(6):379-84.
167. Lindeman E, Leffers P, Spaans F, Drukker J, Reulen J, Kerckhoffs M, et al. Strength training in patients with myotonic dystrophy and hereditary motor and sensory neuropathy: a randomized clinical trial. *Archives of Physical Medicine & Rehabilitation* 1995;76(7):612-20.
168. Cottalorda J, Gautheron V, Metton G, Charmet E, Chavrier Y. Toe-walking in children younger than six years with cerebral palsy: the contribution of serial corrective casts. *Journal of Bone & Joint Surgery* 2000;82-B(4):541-544.
169. Brouwer B, Davidson LK, Olney SJ. Serial Casting in Idiopathic Toe-Walkers and Children with Spastic Cerebral Palsy. *Journal of Pediatric Orthopedics* 2000;20(2):221-225.
170. Cusick B. *Serial casts: their use in the management of spasticity-induced foot deformity.* Tucson, AZ: Communication Skill Builders, 1990.
171. Sobel E, Caselli MA, Velez Z. Effect of persistent toe walking on ankle equinus. Analysis of 60 idiopathic toe walkers. *Journal of the American Podiatric Medical Association* 1997;87(1):17-22.
172. Njegovan ME, Leonard EI, Joseph FB. Rehabilitation medicine approach to Charcot-Marie-Tooth disease. *Clinics in Podiatric Medicine & Surgery* 1997;14(1):99-116.
173. Bean J, Walsh A, Frontera W. Brace modification improves aerobic performance in Charcot-Marie-Tooth disease: a single-subject design. *American Journal of Physical Medicine & Rehabilitation.* 2001;80(8):578-82.
174. Wu KK. Morton neuroma and metatarsalgia. *Current Opinion in Rheumatology* 2000;12(2):131-42.
175. Redmond AC, Lumb P, Landorf KB. 2000 William J. Stickel, Silver Award:Effect of cast and non-cast foot orthoses on pressure and force during normal gait. *Journal of the American Podiatric Medical Association* 2000;90(9):441-449.

176. Wukich DK, Bowen JR. A long-term study of triple arthrodesis for correction of pes cavovarus in Charcot-Marie-Tooth disease. *Journal of Pediatric Orthopedics* 1989;9(4):433-7.
177. Fenton CFd, Schlefman BS, McGlamry ED. Surgical considerations in the presence of Charcot-Marie-Tooth disease. *Journal of the American Podiatry Association* 1984;74(10):490-8.
178. Saltzman CL, Fehrle MJ, Cooper RR, Spencer EC, Ponseti IV. Triple Arthrodesis: Twenty-five and Forty-four-Year Average Follow-up of the Same Patients. *Journal of Bone & Joint Surgery - American Volume October* 1999;81-A(10):1391-1402.
179. Roper BA, Tibrewal SB. Soft tissue surgery in Charcot-Marie-Tooth disease. *Journal of Bone & Joint Surgery - British Volume* 1989;71(1):17-20.
180. Shapiro F, Bresnan MJ. Orthopaedic management of childhood neuromuscular disease. Part II: peripheral neuropathies, Friedreich's ataxia, and arthrogryposis multiplex congenita. *Journal of Bone & Joint Surgery - American Volume* 1982;64(6):949-53.
181. Levitt RL, Canale ST, Cooke AJ, Gartland JJ. The role of foot surgery in progressive neuromuscular disorders in children. *Journal of Bone & Joint Surgery - American Volume* 1973;55(7):1396-410.
182. Ghanem I, Zeller R, Seringe R. Le pied dans les neuropathies peripheriques hereditaires sensitivo-motrices chez l'enfant. *Revue de Chirurgie Orthopedique et Reparatrice de l Appareil Moteur* 1996;82(2):152-60.
183. Sangeorzan BJ, Smith D, Veith R, Hansen ST, Jr. Triple arthrodesis using internal fixation in treatment of adult foot disorders. *Clinical Orthopaedics & Related Research* 1993(294):299-307.
184. Kitaoka HB, Zong Ping L, An KN. Effect of the posterior tibial tendon on the arch of the foot during simulated weightbearing: Biomechanical analysis. *Foot & Ankle International* 1997;18(1):43-46.
185. Saltzman CL, Nawoczenski DA, Talbot KD. Measurement of the medial longitudinal arch. *Archives of Physical Medicine & Rehabilitation* 1995;76(1):45-9.
186. Menz HB. Clinical hindfoot measurement: a review of the literature. *The Foot: International Journal of Clinical Foot Science* 1995;5:57-64.
187. Staheli LT. Evaluation of planovalgus foot deformities with special reference to the natural history. *Journal of the American Podiatric Medical Association* 1987;77(1):2-6.
188. McPoil TG, Hunt GC. Evaluation and management of foot and ankle disorders: present problems and future directions. *Journal of Orthopaedic & Sports Physical Therapy* 1995;21(6):381-8.
189. Toro B, Nester CJ, Farren PC. The Status of Gait Assessment among Physiotherapists in the United Kingdom. *Archives of Physical Medicine & Rehabilitation* 2003;84(12):1878-1884.
190. Nigg BM, Cole GK, Nachbauer W. Effects of arch height of the foot on angular motion of the lower extremities in running. *Journal of Biomechanics* 1993;26(8):909-16.
191. McKenzie DC, Clement DB, Taunton JE. Running shoes, orthotics, and injuries. *Sports Medicine* 1985;2(5):334-47.
192. Busseuil C, Freychat P, Guedj EB, Lacour JR. Rearfoot-forefoot orientation and traumatic risk for runners. *Foot & Ankle International* 1998;19(1):32-7.
193. Cowan DN, Jones BH, Robinson JR. Foot morphologic characteristics and risk of exercise-related injury. *Archives of Family Medicine* 1993;2(7):773-7.
194. Cowan DN, Jones BH, Frykman PN, Polly DWJ, Harman EA, Rosenstein RM, et al. Lower limb morphology and risk of overuse injury among male infantry trainees. *Medicine & Science in Sports & Exercise* 1996;28(8):945-952.
195. Dahle LK, Mueller M, Delitto A, Diamond JE. Visual assessment of foot type and relationship of foot type to lower extremity injury. *Journal of Orthopaedic & Sports Physical Therapy* 1991;14(2):70-4.
196. Griffin LY. Common sports injuries of the foot and ankle seen in children and adolescents. *Orthopedic Clinics of North America* 1994;25(1):83-93.
197. Hreljac A, Marshall RN, Hume PA. Evaluation of lower extremity overuse injury potential in runners. *Medicine & Science in Sports & Exercise* 2000;32(9):1635-41.
198. Ilahi OA, Kohl HW, 3rd. Lower extremity morphology and alignment and risk of overuse injury. *Clinical Journal of Sport Medicine* 1998;8(1):38-42.
199. Kaufman KR, Brodine SK, Shaffer RA, Johnson CW, Cullison TR. The effect of foot structure and range of motion on musculoskeletal overuse injuries. *American Journal of Sports Medicine* 1999;27(5):585-93.
200. Nachbauer W, Nigg BM. Effects of arch height of the foot on ground reaction forces in running. *Medicine & Science in Sports & Exercise* 1992;24(11):1264-9.
201. Novacheck TF. Running injuries: a biomechanical approach. *Instructional Course Lectures* 1998;47:397-406.
202. Ogon M, Aleksiev AR, Pope MH, Wimmer C, Saltzman CL. Does arch height affect impact loading at the lower back level in running? *Foot & Ankle International* 1999;20(4):263-6.

203. Simkin A, Leichter I, Giladi M, Stein M, Milgrom C. Combined effect of foot arch structure and an orthotic device on stress fractures. *Foot & Ankle* 1989;10(1):25-9.
204. Sommer HM, Vallentyne SW. Effect of foot posture on the incidence of medial tibial stress syndrome. *Medicine & Science in Sports & Exercise* 1995;27(6):800-4.
205. Stergiou N, Bates BT. The relationship between subtalar and knee joint function as a possible mechanism for running injuries. *Gait & Posture* 1997;6(3):177-185.
206. Tomaro J. Measurement of tibiofibular varum in subjects with unilateral overuse symptoms. *Journal of Orthopaedic & Sports Physical Therapy* 1995;21(2):86-89.
207. Viitasalo JT, Kvist M. Some biomechanical aspects of the foot and ankle in athletes with and without shin splints. *American Journal of Sports Medicine* 1983;11(3):125-30.
208. Warren BL, Jones CJ. Predicting plantar fasciitis in runners. *Medicine & Science in Sports & Exercise* 1987;19(1):71-3.
209. Wen DY, Puffer JC, Schmalzried TP. Lower extremity alignment and risk of overuse injuries in runners. *Medicine & Science in Sports & Exercise* 1997;29(10):1291-8.
210. Root ML. An approach to foot orthopedics. *Journal of the American Podiatry Association* 1964;54(2):115-118.
211. Root ML, Orien WP, Weed JH, Hughes RJ. *Biomechanical Examination of the Foot.* Los Angeles: Clinical Biomechanics Corporation, 1971.
212. Ball P, Johnson GR. Reliability of hindfoot goniometry when using a flexible electrogoniometer. *Clinical Biomechanics* 1993;8(1):13-19.
213. Elveru RA, Rothstein JM, Lamb RL. Goniometric reliability in a clinical setting. Subtalar and ankle joint measurements. *Physical Therapy* 1988;68(5):672-7.
214. Pearce TJ, Buckley RE. Subtalar joint movement: clinical and computed tomography scan correlation. *Foot & Ankle International* 1999;20(7):428-32.
215. Hamill J, Bates B, Knutzen K, Kirkpatrick G. Relationship between selected static and dynamic lower extremity measures. *Clinical Biomechanics* 1989;4(4):217-225.
216. Kitaoka HB, Luo ZP, An KN. Three-dimensional analysis of flatfoot deformity: cadaver study. *Foot & Ankle International* 1998;19(7):447-51.
217. Engsberg JR. A biomechanical analysis of the talocalcaneal joint--in vitro. *Journal of Biomechanics* 1987;20(4):429-42.
218. Engsberg JR, Andrews JG. Kinematic analysis of the talocalcaneal/talocrural joint during running support. *Medicine & Science in Sports & Exercise* 1987;19(3):275-84.
219. Kessler RM. The ankle and hindfoot. In: Kessler RM, Hertling D, editors. *Management of common muscular disorders.* Philadelphia: Harper Row, 1983.
220. Nester CJ. Rearfoot complex: A review of its interdependent components, axis orientation and functional model. *Foot* 1997;7(2):86-96.
221. Kitaoka HB, Lundberg A, Zong Ping L, An KN. Kinematics of the normal arch of the foot and ankle under physiologic loading. *Foot & Ankle International* 1995;16(8):492-499.
222. Kelly ED. A comparative study of the structure and function of normal, pronated and painful feet among children. *Research Quarterly* 1947;18:291-312.
223. Cook A, Gorman I, Morris J. Evaluation of the neutral position of the subtalar joint. *Journal of the American Podiatric Medical Association* 1988;78(9):449-51.
224. Williams DS, McClay IS. Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. *Physical Therapy* 2000;80(9):864-71.
225. Scherer PR, Morris JL. The classification of human foot types, abnormal foot function, and pathology. In: Valmassy RL, editor. *Clinical Biomechanics of the Lower Extremities.* St Louis: Mosby, 1996:86-93.
226. Perry MD, Mont MA, Einhorn TA, Waller JD. The validity of measurements made on standard foot orthoroentgenograms. *Foot & Ankle* 1992;13(9):502-7.
227. Camasta CA, Pontious J, Boyd RB. Quantifying magnification in pedal radiographs. *Journal of the American Podiatric Medical Association* 1991;81(10):545-8.
228. Sirois JP, Allard P, Duhaime M, Geoffroy G, Kofman J. Evaluation of foot deformity using a three-dimensional geometric model. *Canadian Journal of Neurological Sciences* 1984;11(4 Suppl):578-81.
229. Johnson JE, Timins ME. Optimal computed tomography imaging of the midfoot: An improved technique. *Foot & Ankle International* 1998;19(12):825-829.
230. Nawoczenski DA, Saltzman CL, Cook TM. The effect of foot structure on the three-dimensional kinematic coupling behavior of the leg and rear foot. *Physical Therapy* 1998;78(4):404-16.
231. Steel MWd, Johnson KA, DeWitz MA, Ilstrup DM. Radiographic measurements of the normal adult foot. *Foot & Ankle* 1980;1(3):151-8.
232. Vanderwilde R, Staheli LT, Chew DE, Malagon V. Measurements on radiographs of the foot in normal infants and children. *Journal of Bone & Joint Surgery - American Volume* 1988;70(3):407-15.

233. Demp PH. Geometric models that classify structural variations of the foot. *Journal of the American Podiatric Medical Association* 1998;88(9):437-41.

234. Woodburn J, Udupa JK, Hirsch BE, Wakefield RJ, Helliwell PS, Reay N, et al. The geometric architecture of the subtalar and midtarsal joints in rheumatoid arthritis based on magnetic resonance imaging. *Arthritis & Rheumatism.* 2002;46(12):3168-77.

235. Johnston CE, 2nd, Hobatho MC, Baker KJ, Baunin C. Three-dimensional analysis of clubfoot deformity by computed tomography. *Journal of Pediatric Orthopaedics. Part B* 1995;4(1):39-48.

236. Anderson JG, Harrington R, Ching RP, Tencer A, Sangeorzan BJ. Alterations in talar morphology associated with adult flatfoot. *Foot & Ankle International* 1997;18(11):705-9.

237. Growney E, Meglan D, Johnson M, Cahalan T, An KN. Repeated measures of adult normal walking using a video tracking system. *Gait & Posture* 1997;6(2):147-162.

238. Hoffinger SA. Gait analysis in rehabilitation. *Physical Medicine and Rehabilitation Clinics of North America* 1991;2(4):817-845.

239. Cornwall MW, McPhoil TG. Comparison of 2-dimensional and 3-dimensional rearfoot motion during walking. *Clinical Biomechanics* 1995;10(1):36-40.

240. Cornwall MW, McPoil TG. Motion of the calcaneus, navicular, and first metatarsal during the stance phase of walking. *Journal of the American Podiatric Medical Association* 2002;92(2):67-76.

241. Woodburn J, Turner DE, Helliwell PS, Barker S. A preliminary study determining the feasibility of electromagnetic tracking for kinematics at the ankle joint complex. *Rheumatology* 1999;38(12):1260-1268.

242. Perie D, Tate AJ, Cheng PL, Dumas GA. Evaluation and calibration of an electromagnetic tracking device for biomechanical analysis of lifting tasks. *Journal of Biomechanics* 2002;35(2):293-7.

243. Nester CJ, van der Linden ML, Bowker P. Effect of foot orthoses on the kinematics and kinetics of normal walking gait. *Gait & Posture.* 2003;17(2):180-7.

244. Areblad M, Nigg BM, Ekstrand J, Olsson KO, Ekstrom H. Three-dimensional measurement of rearfoot motion during running. *Journal of Biomechanics* 1990;23(9):933-40.

245. Lemke K, Cornwall MW, McPoil TG, Schuit D. Comparison of rearfoot motion in overground versus treadmill walking. *Journal of the American Podiatric Medical Association* 1995;85(5):243-8.

246. Mueller MJ, Norton BJ. Reliability of kinematic measurements of rear-foot motion. *Physical Therapy* 1992;72(10):731-7.

247. Day JS, Murdoch DJ, Dumas GA. Calibration of position and angular data from a magnetic tracking device. *Journal of Biomechanics* 2000;33(8):1039-45.

248. Nester CJ, Findlow A, Bowker P. Scientific approach to the axis of rotation at the midtarsal joint. *Journal of the American Podiatric Medical Association* 2001;91(2):68-71.

249. Cavanagh PR, Rodgers MM. The arch index: a useful measure from footprints. *Journal of Biomechanics* 1987;20(5):547-51.

250. Freychat P, Belli A, Carret JP, Lacour JR. Relationship between rearfoot and forefoot orientation and ground reaction forces during running. *Medicine & Science in Sports & Exercise* 1996;28(2):225-32.

251. Kouchi M, Tsutsumi E. Relation between the medial axis of the foot outline and 3-D foot shape. *Ergonomics* 1996;39(6):853-861.

252. Viale F, Belli A, Lacour JR, Freychat P. Foot orientation and lower limb kinematics during running. *Foot & Ankle International* 1997;18(3):157-62.

253. Kernozek TW, Ricard MD. Foot placement angle and arch type: effect on rearfoot motion. *Archives of Physical Medicine & Rehabilitation* 1990;71(12):988-91.

254. Forriol F, Pascual J. Footprint analysis between three and seventeen years of age. *Foot & Ankle* 1990;11(2):101-4.

255. Hawes MR, Nachbauer W, Sovak D, Nigg BM. Footprint parameters as a measure of arch height. *Foot & Ankle* 1992;13(1):22-6.

256. Volpon JB. Footprint analysis during the growth period. *Journal of Pediatric Orthopedics* 1994;14(1):83-5.

257. Alexander IJ, Chao EY, Johnson KA. The assessment of dynamic foot-to-ground contact forces and plantar pressure distribution: a review of the evolution of current techniques and clinical applications. *Foot & Ankle* 1990;11(3):152-67.

258. Cavanagh PR, Morag E, Boulton AJ, Young MJ, Deffner KT, Pammer SE. The relationship of static foot structure to dynamic foot function. *Journal of Biomechanics* 1997;30(3):243-50.

259. Hennig EM, Staats A, Rosenbaum D. Plantar pressure distribution patterns of young school children in comparison to adults. *Foot & Ankle International* 1994;15(1):35-40.

260. Morag E, Cavanangh PR. Structural and functional predictors of regional peak pressures under the foot during walking. *Journal of Biomechanics* 1999;32:359-370.

261. Scherer PR, Sobiesk GA. The center of pressure index in the evaluation of foot orthoses in shoes. *Clinics in Podiatric Medicine & Surgery* 1994;11(2):355-63.

262. McCrory JL, Young MJ, Boulton AJM, Cavanagh PR. Arch index as a predictor of arch height. *The Foot: International Journal of Clinical Foot Science* 1997;7(2):79-81.

263. Kitaoka HB, Alexander IJ, Adelaar RS, Nunley JA, Myerson MS, Sanders M. Clinical rating systems for the ankle-hindfoot, midfoot, hallux, and lesser toes. *Foot & Ankle International* 1994;15(7):349-53.

264. Smith SD, Ocampo RF. Subtalar arthrorisis and associated procedures. *Clinics in Podiatric Medicine & Surgery* 1997;14(1):87-98.

265. Tareco JM, Miller NH, MacWilliams BA, Michelson JD. Defining flatfoot. *Foot & Ankle International* 1999;20(7):456-60.

266. Forriol Campos F, Maiques JP, Dankloff C, Gomez Pellico L. Foot morphology development with age. *Gegenbaurs Morphologisches Jahrbuch* 1990;136(6):669-76.

267. Staheli LT, Chew DE, Corbett M. The longitudinal arch. A survey of eight hundred and eighty-two feet in normal children and adults. *Journal of Bone & Joint Surgery - American Volume* 1987;69(3):426-8.

268. Jonson SR, Gross MT. Intraexaminer reliability, interexaminer reliability, and mean values for nine lower extremity skeletal measures in healthy naval midshipmen. *Journal of Orthopaedic & Sports Physical Therapy* 1997;25(4):253-63.

269. Pierrynowski MR, Smith SB, Mlynarczyk JH. Proficiency of foot care specialists to place the rearfoot at subtalar neutral. *Journal of the American Podiatric Medical Association* 1996;86(5):217-23.

270. Picciano AM, Rowlands MS, Worrell T. Reliability of open and closed kinetic chain subtalar joint neutral positions and navicular drop test. *Journal of Orthopaedic & Sports Physical Therapy* 1993;18(4):553-8.

271. Mueller MJ, Host JV, Norton BJ. Navicular drop as a composite measure of excessive pronation. *Journal of the American Podiatric Medical Association* 1993;83(4):198-202.

272. Sell KE, Verity TM, Worrell TW, Pease BJ, Wigglesworth J. Two measurement techniques for assessing subtalar joint position: a reliability study. *Journal of Orthopaedic & Sports Physical Therapy* 1994;19(3):162-7.

273. Song J, Hillstrom HJ, Secord D, Levitt J. Foot type biomechanics. comparison of planus and rectus foot types. *Journal of the American Podiatric Medical Association* 1996;86(1):16-23.

274. Coplan JA. Rotational motion of the knee: A comparison of normal and pronating subjects. *Journal of Orthopaedic & Sports Physical Therapy* 1989;10(9):366-369.

275. Giallonardo LM. Clinical evaluation of foot and ankle dysfunction. *Physical Therapy* 1988;68(12):1850-6.

276. Nigg BM, Khan A, Fisher V, Stefanyshyn D. Effect of shoe insert construction on foot and leg movement. *Medicine & Science in Sports & Exercise* 1998;30(4):550-5.

277. Sanner WH. Clinical methods for predicting the effectiveness of functional foot orthoses. *Clinics in Podiatric Medicine & Surgery* 1994;11(2):279-95.

278. Spinner SM, Chussid F, Long DH. Criteria for combined procedure selection in the surgical correction of the acquired flatfoot. *Clinics in Podiatric Medicine & Surgery* 1989;6(3):561-75.

279. Morris JL, Jones LJ. New techniques to establish the subtalar joint's functional axis. *Clinics in Podiatric Medicine and Surgery* 1994;11(2):301-309.

280. Lundberg A, Svensson S. The axes of rotation of the talocalcaneal and talonavicular joints. *The Foot: International Journal of Clinical Foot Science* 1993;3:65-70.

281. Nester CJ, van der Linden ML, Bowker P.Some effects of foot orthoses on joint motion and moments, and ground reaction forces. 24th Annual Meeting, American Society of Biomechanics; 2000 July 19-22, 2000; Chicago, IL.

282. Isman RE, Inman VT. Anthropometric studies of the human foot and ankle. *Bulletin of Prosthetics Research* 1969;Spring:97-104.

283. Manter JT. Movements of the subtalar and transverse tarsal joints. *The Anatomical Record* 1941;80(4):397-410.

284. Aquino A, Payne CB. Function of the windlass mechanism in excessively pronated feet. *Journal of the American Podiatric Medical Association* 2001;91(5):245-250.

285. Lundberg A, Svensson OK, Bylund C, Selvik G. Kinematics of the ankle/foot complex. Part 3: Influence of leg rotation. *Foot & Ankle* 1989;9(6):304-309.

286. Hintermann B, Nigg BM, Sommer C, Cole GK. Transfer of movement between calcaneus and tibia in vitro. *Clinical Biomechanics* 1994;9(6):349-355.

287. Ware J, Snow KK, Kosinski M, Gandek B. SF-36 Health Survey. Manual and interpretation guide. Boston: Boston Health Institute, New England Medical Center, 1993.

288. Bergner M, Bobbitt RA, Pollard WE, Martin DP, Gilson BS. The Sickness Impact Profile: validation of a health status measure. *Medical Care* 1976;19(1):57-67.

289. Fries J, Spitz P, Kraines R, Guy, Holman H. Measurement of patient outcome in arthritis. *Arthritis and Rheumatism* 1980;23(2).

290. Jenkinson C, Wright L, Coulter A. Criterion validity and reliability of the SF-36 in a population sample. *Quality of Life Research* 1994;3(1):7-12.

291. McCallum J. The SF-36 in an Australian sample: validating a new, generic health status measure. *Australian Journal of Public Health* 1995;19(2):160-6.

292. National Health Survey - SF-36 Population Norms. Canberra: Australian Bureau of Statistics, 1995.

293. McHorney CA, Kosinski M, Ware JE. Comparisons of the costs and quality of norms for the SF-36 health survey collected by mail versus telephone interview: results fomr a national survey. *Medical Care* 1994;32(6):551-567.

294. Shadbolt B, McCallum J, Singh M. Health outcomes by self-report: validity of the SF-36 among Australian hospital patients. *Quality of Life Research* 1997;6(4):343-52.

295. Hurst NP, Jobanputra P, Hunter M, Lambert M, Lochhead A, Brown H. Validity of Euroqol--a generic health status instrument--in patients with rheumatoid arthritis. Economic and Health Outcomes Research Group. *British Journal of Rheumatology.* 1994;33(7):655-62.

296. Kind P, Dolan P, Gudex C, Williams A. Variations in population health status: results from a United Kingdom national questionnaire survey. *British Medical Journal* 1998;316(7133):736-41.

297. Devlin N, Hansen P, Herbison P. Variations in self-reported health status: results from a New Zealand survey. *New Zealand Medical Journal.* 2000;113(1123):517-20.

298. Brazier J, Jones N, Kind P. Testing the validity of the Euroqol and comparing it with the SF-36 health survey questionnaire. *Quality of Life Research.* 1993;2(3):169-80.

299. Essink-Bot ML, Krabbe PF, Bonsel GJ, Aaronson NK. An empirical comparison of four generic health status measures. The Nottingham Health Profile, the Medical Outcomes Study 36-item Short-Form Health Survey, the COOP/WONCA charts, and the EuroQol instrument. *Medical Care.* 1997;35(5):522-37.

300. Deyo RA, Inui TS, Leininger J, Overman S. Physical and psychosocial function in rheumatoid arthritis. *Archives of Internal Medicine* 1982;142:879-882.

301. Andresen EM, Rothenberg BM, Panzer R, Katz P, McDermott MP. Selecting a generic measure of health-related quality of life for use among older adults. A comparison of candidate instruments. *Evaluation & the Health Professions.* 1998;21(2):244-64.

302. Beaton DE, Hogg-Johnson S, Bombardier C. Evaluating changes in health status: reliability and responsiveness of five generic health status measures in workers with musculoskeletal disorders. *Journal of Clinical Epidemiology.* 1997;50(1):79-93.

303. Wiles NJ, Scott DG, Barrett EM, Merry P, Arie E, Gaffney K, et al. Benchmarking: the five year outcome of rheumatoid arthritis assessed using a pain score, the Health Assessment Questionnaire, and the Short Form-36 (SF-36) in a community and a clinic based sample. *Annals of the Rheumatic Diseases.* 2001;60(10):956-61.

304. Wolfe F, Cathey M. The assessment and prediction of functional disability in rheumatoid arthritis. *Journal of Rheumatology* 1991;18(9):1298-1306.

305. Hawker G, Melfi C, Paul J, Green R, Bombardier C. Comparison of a generic (SF-36) and a disease specific (WOMAC) (Western Ontario and McMaster Universities Osteoarthritis Index) instrument in the measurement of outcomes after knee replacement surgery. *Journal of Rheumatology.* 1995;22(6):1193-6.

306. Budiman-Mak E, Conrad KJ, Roach KE. The Foot Function Index: a measure of foot pain and disability. *Journal of Clinical Epidemiology* 1991;44(6):561-70.

307. Caselli MA, Levitz SJ, Clark N, Lazarus S, Velez Z, Venegas L. Comparison of Viscoped and PORON for painful submetatarsal hyperkeratotic lesions. *Journal of the American Podiatric Medical Association.* 1997;87(1):6-10.

308. Landorf KB, Keenan AM. An evaluation of two foot-specific, health-related quality-of-life measuring instruments. *Foot & Ankle International* 2002;23(6):538-546.

309. Guyton GP. Theoretical limitations of the AOFAS scoring systems: an analysis using Monte Carlo modeling. *Foot & Ankle International.* 2001;22(10):779-87.

310. Bennett PJ, Patterson C, Dunne MP. Health-related quality of life following podiatric surgery. *Journal of the American Podiatric Medical Association.* 2001;91(4):164-73.

311. Garrow AP, Papageorgiou AC, Silman AJ, Thomas E, Jayson MI, Macfarlane GJ. Development and validation of a questionnaire to assess disabling foot pain. *Pain* 2000;85(1-2):107-13.

312. Likert RA. A technique for the development of attitude scales. *Educational and psychological measurement* 1952;12:313-315.

313. Flynn TC, Gerrity MS, Berkowitz LR. What do applicants look for when selecting internal medicine residency programs? A comparison of rating scale and open-ended responses. *Journal of General Internal Medicine.* 1993;8(5):249-54.
314. Hu WH, Lam KF, Wong YH, Lam CL, WM HU, Lai KC, et al. The Hong Kong index of dyspepsia: a validated symptom severity questionnaire for patients with dyspepsia. *Journal of Gastroenterology & Hepatology.* 2002;17(5):545-51.
315. Bennett ME, Tulloch JF, Vig KW, Phillips CL. Measuring orthodontic treatment satisfaction: questionnaire development and preliminary validation. *Journal of Public Health Dentistry.* 2001;61(3):155-60.
316. Hernandez L, Chang CH, Cella D, Corona M, Shiomoto G, McGuire DB. Development and validation of the satisfaction with pharmacist scale. *Pharmacotherapy.* 2000;20(7):837-43.
317. Gadbury-Amyot CC, Williams KB, Krust-Bray K, Manne D, Collins P. Validity and reliability of the oral health-related quality of life instrument for dental hygiene. *Journal of Dental Hygiene.* 1999;73(3):126-34.
318. Climent JM, Reig A, Sanchez J, Roda C. Construction and validation of a specific quality of life instrument for adolescents with spine deformities. *Spine.* 1995;20(18):2006-11.
319. Haag GP, Schoeps NB. Development of a reliable nurse anesthesia clinical instructor evaluation instrument. *AANA Journal.* 1993;61(2):158-64.
320. Schrag A, Jahanshahi M, Quinn N. How does Parkinson's disease affect quality of life? A comparison with quality of life in the general population. *Movement Disorders.* 2000;15(6):1112-8.
321. Dougherty PJ. Transtibial amputees from the Vietnam War. Twenty-eight-year follow-up. *Journal of Bone & Joint Surgery.* 2001;83-A(3):383-9.
322. Jones CA, Voaklander DC, Johnston DW, Suarez-Almazor ME. The effect of age on pain, function, and quality of life after total hip and knee arthroplasty. *Archives of Internal Medicine.* 2001;161(3):454-60.
323. Angst F, Aeschlimann A, Steiner W, Stucki G. Responsiveness of the WOMAC osteoarthritis index as compared with the SF-36 in patients with osteoarthritis of the legs undergoing a comprehensive rehabilitation intervention. *Annals of the Rheumatic Diseases.* 2001;60(9):834-40.
324. Mayo NE, Wood-Dauphinee S, Cote R, Gayton D, Carlton J, Buttery J, et al. There's no place like home : an evaluation of early supported discharge for stroke. *Stroke.* 2000;31(5):1016-23.
325. Anderson C, Rubenach S, Mhurchu CN, Clark M, Spencer C, Winsor A. Home or hospital for stroke rehabilitation? results of a randomized controlled trial : I: health outcomes at 6 months. *Stroke.* 2000;31(5):1024-31.
326. Dardik A, Minor J, Watson C, Hands LJ. Improved quality of life among patients with symptomatic carotid artery disease undergoing carotid endarterectomy. *Journal of Vascular Surgery.* 2001;33(2):329-33.
327. Patterson RB, Pinto B, Marcus B, Colucci A, Braun T, Roberts M. Value of a supervised exercise program for the therapy of arterial claudication. *Journal of Vascular Surgery.* 1997;25(2):312-8; discussion 318-9.
328. Gemignani F, Marbini A, Di Giovanni G, Salih S, Terzano MG. Charcot-Marie-Tooth disease type 2 with restless legs syndrome. *Neurology* 1999;52(5):1064-6.
329. Skaggs D, Rethlefsen S, Kay RM, Dennis S, Reynolds R, Tolo V. Variability in Gait Analysis Interpretation. *Journal of Pediatric Orthopedics November/December* 2000;20(6):759-764.
330. Saleh M, Murdoch G. In defence of gait analysis. Observation and measurement in gait assessment. *Journal of Bone & Joint Surgery - British Volume* 1985;67(2):237-41.
331. Novacheck TF, Walker KR. Progress in neuromuscular disorders. *Current Opinion in Orthopedics December* 2000;11(6):454-460.
332. Wearing SC, Urry S, Perlman P, Smeathers J, Dubois P. Sagittal plane motion of the human arch during gait - a videofluoroscopic analysis. *Foot & Ankle International* 1998;19(11):738-742.
333. McPoil TG, Cornwall MW. Relationship between three static angles of the rearfoot and the pattern of rearfoot motion during walking. *Journal of Orthopaedic & Sports Physical Therapy* 1996;23(6):370-5.
334. Walker M, Fan HJ. Relationship between foot pressure pattern and foot type. *Foot & Ankle International* 1998;19(6):379-83.
335. Donatelli R, Wooden M, Ekedahl SR, Wilkes JS, Cooper J, Bush AJ. Relationship between static and dynamic foot postures in professional baseball players. *Journal of Orthopaedics and Sports Physical Therapy* 1999;29(6):316-330.
336. Cornwall MW, McPoil TG. Relative movement of the navicular bone during normal walking. *Foot & Ankle International August* 1999;20(8):507-512.

337. Cashmere T, Smith R, Hunt A. Medial longitudinal arch of the foot: stationary versus walking measures. *Foot & Ankle International* 1999;20(2):112-8.
338. Hunt AE, Fahey AJ, Smith RM. Static measures of calcaneal deviation and arch angle as predictors of rearfoot motion during walking. *Australian Journal of Physiotherapy* 2000;46(1):9-16.
339. Nawoczenski DA, Baumhauer JF, Umberger BR. Relationship between clinical measurements and motion of the first metatarsophalangeal joint during gait. *Patient Care Management* 1999;81(3):370-6.
340. Viale F, Dalleau G, Freychat P, Lacour JR, Belli A. Leg stiffness and foot orientations during running. *Foot & Ankle International* 1998;19(11):761-5.
341. Sharkey NA, Donahue SW, Ferris L. Biomechanical consequences of plantar fascial release or rupture during gait. Part II: alterations in forefoot loading. *Foot & Ankle International* 1999;20(2):86-96.
342. Huang CK, Kitaoka HB, An KN, Chao EY. Biomechanical evaluation of longitudinal arch stability. *Foot & Ankle* 1993;14(6):353-7.
343. Nigg BM, Nurse MA, Stefanyshyn DJ. Shoe inserts and orthotics for sport and physical activities. *Medicine & Science in Sports & Exercise* 1999;31(7 Suppl):S421-8.
344. Ball P, Johnson GR. Technique for the measurement of hindfoot inversion and eversion and its use to study a normal population. *Clinical Biomechanics* 1996;11(3):165-169.
345. Lattanza L, Gray GW, Kantner RM. Closed versus open kinematic chain measurements of subtalar joint eversion: implications for clinical practice... nonweightbearing (NWB) and weightbearing (WB) positions. *Journal of Orthopaedic & Sports Physical Therapy* 1988;9(9):310-4.
346. Freeman A. A study of inter-observer and intra-observer reliabiltiy in the measurement of resting calcaneal stance position, and neutral calcaneal stance position. *Australian Podiatrist* 1990((June)):10.
347. Astrom M, Arvidson T. Alignment and joint motion in the normal foot. *Journal of Orthopaedic & Sports Physical Therapy* 1995;22(5):216-22.
348. Elveru RA, Rothstein JM, Lamb RL, Riddle DL. Methods for taking subtalar joint measurements. A clinical report. *Physical Therapy* 1988;68(5):678-82.
349. Sobel E, Levitz SJ. Reappraisal of the negative impression cast and the subtalar joint neutral position. *Journal of the American Podiatric Medical Association* 1997;87(1):32-3.
350. Cornwall MW, McPoil TG. Three dimensional movement of the foot during the stance phase of gait. *Journal of the American Podiatric Medical Association* 1999;89(2):56-66.
351. Cobey JC. Standardizing methods of measurement of foot shape including the effects of subtalar joint rotation. *Foot & Ankle International* 1981;2(2):30-36.
352. Beighton P, Solomon L, Soskolne CL. Articular mobility in an African population. *Annals of the Rheumatic Diseases* 1973;32(5):413-8.
353. Biro F, Gewanter HL, Baum J. The hypermobility syndrome. *Pediatrics* 1983;72(5):701-6.
354. Dijkstra PU, de Bont LG, van der Weele LT, Boering G. Joint mobility measurements: reliability of a standardized method. *Cranio* 1994;12(1):52-7.
355. Fairbank JC, Pynsent PB, Phillips H. Quantitative measurements of joint mobility in adolescents. *Annals of the Rheumatic Diseases* 1984;43(2):288-94.
356. Bojsen-Moller F. Calcaneocuboid joint and stability of the longitudinal arch of the foot at high and low gear push off. *Journal of Anatomy* 1979;129(1):165-76.
357. Benink RJ. The constraint-mechanism of the human tarsus. A roentgenological experimental study. *Acta Orthopaedica Scandinavica. Supplementum* 1985;215:1-135.
358. Lundberg A, Svensson OK, Bylund C, Goldie I, Selvik G. Kinematics of the ankle/foot complex. Part 2: Pronation and supination. *Foot & Ankle* 1989;9(5):248-253.
359. Elftman H. The transverse tarsal joint and its control. *Clinical Orthopedics* 1960;16:41-45.
360. Ouzounian TJ, Shereff MJ. In vitro determination of midfoot motion. *Foot & Ankle* 1989;10(3):140-6.
361. Winson IG, Lundberg A, Bylund C. The pattern of motion of the longitudinal arch of the foot. *Foot* 1994;4(3):151-154.
362. Astion DJ, Deland JT, Otis JC, Kenneally S. Motion of the hindfoot after simulated arthrodesis. *Journal of Bone & Joint Surgery - American Volume* 1997;79(2):241-6.
363. Engsberg JR, Grimston SK, Wackwitz JH. Predicting talocalcaneal joint orientations from talocalcaneal/talocrural joint orientations. *Journal of Orthopaedic Research* 1988;6(5):749-57.
364. Bailey DS, Perillo JT, Forman M. Subtalar joint neutral. A study using tomography. *Journal of the American Podiatry Association* 1984;74(2):59-64.
365. Schon LC, Weinfeld SB, Horton GA, Resch S. Radiographic and clinical classification of acquired midtarsus deformities. *Foot & Ankle International* 1998;19(6):394-404.
366. Maslen BA, Ackland TR. Radiographic study of skin displacement errors in the foot and ankle during standing. *Clinical Biomechanics* 1994;9(5):291-296.

367. Bevans JS. Biomechanics and plantar ulcers in diabetes. *The Foot* 1992;2:166-172.

368. Diamond JE, Mueller MJ, Delitto A, Sinacore DR. Reliability of a diabetic foot evaluation. *Physical Therapy* 1989;69(10):797-802.

369. Gould N. Evaluation of hyperpronation and pes planus in adults. *Clinical Orthopaedics & Related Research* 1983(181):37-45.

370. Jahss MH. Evaluation of the cavus foot for orthopedic treatment. *Clinical Orthopaedics & Related Research* 1983(181):52-63.

371. Leppilahti J, Korpelainen R, Karpakka J, Kvist M, Orava S. Ruptures of the Achilles Tendon - Relationship to Inequality in Length of Legs and to Patterns in the Foot and Ankle. *Foot & Ankle International* 1998;19(10):683-687.

372. Lepow GM, Valenza PL. Flatfoot overview. *Clinics in Podiatric Medicine & Surgery* 1989;6(3):477-89.

373. Merriman LM, Tollafield DR, editors. *Assessment of the Lower Limb.* Edinburgh: Churchill Livingstone, 1995.

374. Novick A, Kelley DL. Position and movement changes of the foot with orthotic intervention during the loading response of gait. *Journal of Orthopaedic & Sports Physical Therapy* 1990;11(7):301-312.

375. Ross AS, Jones LJ. Non-weightbearing negative cast evaluation. *Journal of the American Podiatry Association* 1982;72(12):634-8.

376. Sobel E, Levitz S. Rear foot inversion/eversion during gait relative to the subtalar joint neutral position. *Foot & Ankle International* 1996;17(12):786.

377. Yamamoto H, Muneta T, Ishibashi T, Furuya K. Posteromedial release of congenital club foot in children over five years of age. *Journal of Bone & Joint Surgery - British Volume* 1994;76(4):555-8.

378. Magee DJ. *Orthopedic physical assessment.* Philadelphia: WB Saunders, 1992.

379. McPoil TG, Schuit D, Knecht HG. Comparison of three methods used to obtain a neutral plaster foot impression. *Physical Therapy* 1989;69(6):448-52.

380. Fraser RK, Menelaus MB, Williams PF, Cole WG. The Miller procedure for mobile flat feet. *Journal of Bone & Joint Surgery - British Volume* 1995;77(3):396-9.

381. Connors JF, Wernick E, Lowy LJ, Falcone J, Volpe RG. Guidelines for evaluation and management of five common podopediatric conditions. *Journal of the American Podiatric Medical Association* 1998;88(5):206-22.

382. Gross MT. Lower quarter screening for skeletal malalignment--suggestions for orthotics and shoewear. *Journal of Orthopaedic & Sports Physical Therapy* 1995;21(6):389-405.

383. Katchis SD. Posterior tibial tendon dysfunction. In: Ranawat CS, Positano RG, editors. *Disorders of the heel, rearfoot and ankle.* Philadelphia: Churchill Livingstone, 1999.

384. Johnson KA. Tibialis posterior tendon rupture. *Clinical Orthopaedics & Related Research* 1983(177):140-7.

385. Bordelon RL. Hypermobile flatfoot in children. Comprehension, evaluation, and treatment. *Clinical Orthopaedics & Related Research* 1983(181):7-14.

386. Rose GK. Pes Planus. In: Jahss M, editor. *Disorders of the foot and ankle:Medical and surgical management.* 2nd ed. Philadelphia: WB Saunders, 1991:892-920.

387. Thomson CE. An investigation into the reliability of the valgus index and its validity as a clinical measurement. *Foot* 1994;4(4):191-197.

388. Rossi WA. Podometrics: a new methodology for foot typing. *Contemporary Podiatric Physician (Reprinted from Journal of Testing and Evaluation 1992:2;4)* 1992(November):28-39.

389. Duckworth T. The hindfoot and its relation to rotational deformities of the forefoot. *Clinical Orthopaedics & Related Research* 1983(177):39-48.

390. Beals T, Manoli A. The 'peek-a-boo' sign in the evaluation of hindfoot varus. *The Foot: International Journal of Clinical Foot Science* 1996;6(4):205-206.

391. McPoil TG, Cornwall MW. The use of lower leg rotation rather than subtalar neutral position when assessing navicular drop. *Journal of Orthopaedic & Sports Physical Therapy January* 1998;27(1):67.

392. Nester CJ, Hutchins S, Bowker P. Shank Rotation: A Measure of Rearfoot Motion During Normal Walking. *Foot & Ankle International July* 2000;21(7):578-583.

393. Talbot KD, Saltzman CL. Hallucal rotation: a method of measurement and relationship to bunion deformity. *Foot & Ankle International* 1997;18(9):550-6.

394. McPoil T, Cornwall MW. Relationship between neutral subtalar joint position and pattern of rearfoot motion during walking. *Foot & Ankle International* 1994;15(3):141-5.

395. Root ML. Development of the functional orthosis. *Clinics in Podiatric Medicine and Surgery* 1994;11(2):183-210.

396. Grumbine NA, Santoro JP. The tendo achillis as it relates to rearfoot position: A new classification for evaluation of calcaneal stance position. *Clinics in Podiatric Medicine & Surgery* 1990;7(2):203-216.

397. Jack EA. Naviculo-cuneiform fusion in the treatment of flat foot. *Journal of Bone and Joint Surgery* 1953;35B:75- 82.
398. Alexander IJ. *The foot- examination and diagnosis*. 2nd ed. New York: Churchill Livingstone, 1997.
399. Hicks J. The mechanics of the foot II: the plantar aponeurosis and the arch. *Journal of Anatomy* 1954;88:25-31.
400. Price BD, Price CT. A simple demonstration of hindfoot flexibility in the cavovarus foot. *Journal of Pediatric Orthopedics* 1997;17(1):18-9.
401. Cowan DN, Robinson JR, Jones BH, Polly DW, Jr., Berrey BH. Consistency of visual assessments of arch height among clinicians. *Foot & Ankle International* 1994;15(4):213-7.
402. Evans AM, Copper AW, Scharfbillig RW, Scutter SD, Williams MT. The reliability of the foot posture index and traditional measures of foot position. *Journal of the American Podiatric Medical Association* 2003;93(3):203-13.
403. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;33(1):159-74.
404. Kanatli U, Yetkin H, Cila E. Footprint and radiographic analysis of the feet. *Journal of Pediatric Orthopedics* 2001;21(2):225-8.
405. Rendall G, Abboud RJ. The development of a three plane system for the measurement of the ankle/subtalar joint complex in gait. *The Foot* 1999;9(1):31-39.
406. Poulin F, Amiot LP. Interference during the use of an electromagnetic tracking system under OR conditions. *Journal of Biomechanics* 2002;35(6):733-7.
407. Allard P, Kirtley C, Rosenbaum D, Siegler S, Whittle M. A joint coordinate system for the ankle complex. *ISB* 1995;59:6-8.
408. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definition of joint coordinate system of various joints for the reporting of human joint motion - part I: ankle, hip and spine. *Journal of Biomechanics* 2002;35:543-548.
409. Liu W, Miller J, Stefanyshyn D, Nigg BM. Accuracy and reliability of a technique for quantifying foot shape, dimensions and structural characteristics. *Ergonomics* 1999;42(2):346-358.
410. Walters SJ, Campbell MJ, Lall R. Design and analysis of trials with quality of life as an outcome: a practical guide. *Journal of Biopharmaceutical Statistics.* 2001;11(3):155-76.
411. Menard S. *Applied logistic regression analysis. Series: Quantitative Applications in the Social Sciences, No. 106. First ed., 1995.* 2nd ed: Sage Publications., 2002.
412. Woodburn J. Kinematics at the ankle joint in rheumatoid arthritis. [PhD thesis]. University of Leeds, 2000.
413. Woodburn J, Helliwell PS, Barker S. Improvement in three-dimensional joint kinematics supports the continuous use of foot orthoses in the management of painful rearfoot deformity in rheumatoid arthritis. *Arthritis and Rheumatism* 2001;44(S9):371.
414. Cappozzo A, F. C, U. DC, A. L. Position and orientation in space bones during movement: anatomical frame definition and determination. *Clinical Biomechanics* 1995;10(4):171-8.
415. Kadaba M, Ramakrishnan H, Wootten ME, Gainey J, Gorton G, Cochran GV. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research* 1989;7(6):849-60.
416. Sullivan LM, D'Agostino RB, Sr. Robustness and power of analysis of covariance applied to ordinal scaled data as arising in randomized controlled trials. *Statistics in Medicine.* 2003;22(8):1317-34.
417. Cohen ME. Analysis of ordinal dental data: evaluation of conflicting recommendations. *Journal of Dental Research.* 2001;80(1):309-13.
418. McPoil TG, Cornwall MW. The effect of foot orthoses on transverse tibial rotation during walking. *Journal of the American Podiatric Medical Association* 2000;90(1):2-11.
419. Moseley L, Smith R, Hunt A, Gant R. Three-dimensional kinematics of the rearfoot during the stance phase of walking in normal young adult males. *Clinical Biomechanics* 1996;11(1):39-45.
420. Carson MC, Harrington ME, Thompson N, O'Connor JJ, Theologis TN. Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. *Journal of Biomechanics* 2001;34(10):1299-307.
421. Manal K, McClay I, Stanhope S, Richards J, Galinat B. Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: An in vivo study. *Gait & Posture* 2000;11(1):38-45.
422. Mundermann A, Nigg BM, Humble RN, Stefanyshyn DJ. Foot orthotics affect lower extremity kinematics and kinetics during running. *Clinical Biomechanics.* 2003;18(3):254-62.
423. McClay I, Manal K. A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals. *Clinical Biomechanics* 1998;13(3):195-203.

424. Umberger BR, Nawoczenski DA, Baumhauer JF. Reliability and validity of first metatarsophalangeal joint orientation measured with an electromagnetic tracking device. *Clinical Biomechanics* 1999;14(1):74-6.
425. Hunt AE, Smith RM, Torode M, Keenan AM. Inter-segment foot motion and ground reaction forces over the stance phase of walking. *Clinical Biomechanics.* 2001;16(7):592-600.
426. Hunt AE, Smith RM, Torode M. Extrinsic muscle activity, foot motion and ankle joint moments during the stance phase of walking. *Foot & Ankle International.* 2001;22(1):31-41.
427. Moseley AM, Crosbie J, Adams R. Normative data for passive ankle plantarflexion--dorsiflexion flexibility. *Clinical Biomechanics.* 2001;16(6):514-21.
428. Moseley AM, Adams R. Measurement of passive ankle dorsiflexion: procedure and reliability. *Australian Journal of Physiotherapy* 1991;37:175-181.
429. Hainsworth F, Harrison MJ, Sheldon TA, Roussounis SH. A preliminary evaluation of ankle orthoses in the management of children with cerebral palsy. *Developmental Medicine & Child Neurology* 1997;39(4):243-7.
430. Redelmeier DA, Guyatt GH, Goldstein RS. Assessing the minimal important difference in symptoms: a comparison of two techniques. *Journal of Clinical Epidemiology* 1996;49(11):1215-9.
431. Rapoff MA, Lindsley CB, Christophersen ER. Parent perceptions of problems experienced by their children in complying with treatments for juvenile rheumatoid arthritis. *Archives of Physical Medicine & Rehabilitation.* 1985;66(7):427-9.
432. Belcon MC, Haynes RB, Tugwell P. A critical review of compliance studies in rheumatoid arthritis. *Arthritis & Rheumatism.* 1984;27(11):1227-33.
433. Gregerson DM. Clinical consequences of spina bifida occulta. *Journal of Manipulative & Physiological Therapeutics* 1997;20(8):546-50.
434. Woodburn J, Barker S, Helliwell PS. A randomised controlled trial of foot orthoses in RA. *Journal of Rheumatology* 2002;29(7):1377-1383.
435. Coughlin MJ, Mann RA. The pathophysiology of the juvenile bunion. *Instructional Course Lectures* 1987;36:123-36.
436. Bennett PJ. A randomized clinical assessment of foot pronation and its relationship to patellofemoral syndrome. *J Curr Podiatr Med* 1988;37(8):8-11.
437. Lin C-J, Lai K-A, Kuan T-S, Chou Y-L. Correlating Factors and Clinical Significance of Flexible Flatfoot in Preschool Children. *Journal of Pediatric Orthopedics May/June* 2001;21(3):378-382.
438. Lewis RA, Sumner AJ. Electrophysiologic features of inherited demyelinating neuropathies: a reappraisal. *Annals of the New York Academy of Sciences* 1999;883:321-35.
439. Colon MJ, Whitton KE, Schwartz N. Treatment of pes cavus in a patient with Charcot-Marie-Tooth disease. *Journal of Foot Surgery* 1980;19(1):41-4.
440. Farber DC, Wallach DM. Neuromuscular disorders of the foot and ankle. *Current Opinion in Orthopedics April* 2001;12(2):120-124.
441. Quirk RP. The pathomechanics and treatment of pes cavus. *Journal of Bone & Joint Surgery - British Volume November* 1997;79-B(4S):383.
442. Wicklein EM, Pfeiffer G, Ratusinski T, Kunze K. Type I Charcot-Marie-Tooth syndrome. Disability and management. *Nervenarzt* 1997;68(4):358-62.
443. Fenton CF, McGlamry ED, Perrone M. Severe pes cavus deformity secondary to Charcot-Marie-Tooth disease: a case report. *Journal of the American Podiatry Association* 1982;72(4):171-5.
444. Butler JV, Mulkerrin EC, O'Keeffe ST. Nocturnal leg cramps in older people. *Postgraduate Medical Journal.* 2002;78(924):596-8.
445. Roffe C, Sills S, Crome P, Jones P. Randomised, cross-over, placebo controlled trial of magnesium citrate in the treatment of chronic persistent leg cramps. *Medical Science Monitor.* 2002;8(5):CR326-30.
446. Chan P, Huang TY, Chen YJ, Huang WP, Liu YC. Randomized, double-blind, placebo-controlled study of the safety and efficacy of vitamin B complex in the treatment of nocturnal leg cramps in elderly patients with hypertension. *Journal of Clinical Pharmacology.* 1998;38(12):1151-4.
447. Connolly PS, Shirley EA, Wasson JH, Nierenberg DW. Treatment of nocturnal leg cramps. A crossover trial of quinine vs vitamin E. *Archives of Internal Medicine.* 1992;152(9):1877-80.
448. Karlstrom G, Lonnerholm T, Olerud S. Cavus deformity of the foot after fracture of the tibial shaft. *Journal of Bone & Joint Surgery - American Volume* 1975;57(7):893-900.
449. Mundermann A, Stefanyshyn DJ, Nigg BM. Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. *Medicine & Science in Sports & Exercise* 2001;33(11):1939-45.
450. Urry SR. Redistribution of foot pressure in healthy adults during sideslope walking. *Foot & Ankle International.* 2002;23(12):1112-8.
451. Chen WP, Tang FT, Ju CW. Stress distribution of the foot during mid-stance to push-off in barefoot gait: a 3-D finite element analysis. *Clinical Biomechanics.* 2001;16(7):614-20.

452. Sobel E, Levitz S, Caselli M, Brentnall Z, Tran MQ. Natural history of the rearfoot angle: preliminary values in 150 children. *Foot & Ankle International* 1999;20(2):119-125.

453. Bleck EE. Developmental orthopaedics. III: Toddlers. *Developmental Medicine & Child Neurology* 1982;24(4):533-55.

454. Gould N, Moreland M, Alvarez R, Trevino S, Fenwick J. Development of the child's arch. *Foot & Ankle* 1989;9(5):241-5.

455. Dananberg HJ. Gait style as an etiology to chronic postural pain. Part II. Postural compensatory process. *Journal of the American Podiatric Medical Association* 1993;83(11):615-24.

456. Kirby KA. Rotational equilibrium across the subtalar joint axis. *Journal of the American Podiatric Medical Association* 1989;79(1):1-14.

457. Ubhi T, Bhakta BB, Ives HL, Allgar V, Roussounis SH. Randomised double blind placebo controlled trial of the effect of botulinum toxin on walking in cerebral palsy. *Archives of Disease in Childhood* 2000;83(6):481-7.

458. Kreder HJ, Wright JG, McLeod R. Outcome studies in surgical research. *Surgery* 1997;121(2):223-5.

459. Asperheim MS, Moore C, Carroll NC, Dias L. Evaluation of residual clubfoot deformities using gait analysis. *Journal of Pediatric Orthopaedics. Part B* 1995;4(1):49-54.

460. Pattinson R, Bates E. Painful feet in childhood. *Australian Family Physician* 1996;25(6):887-9; 892-3.

# APPENDICES

## *Appendix A. FPI-8 first draft (1997)*

## PATIENT ASSESSMENT

There are eight observable features which can enable the observer to estimate the subtalar and midtarsal position in RCSP. These are

1. Supra and infra lateral malleolar curvature.
2. Helbing's sign
3. Prominence of the sustentaculum tali
4. Height of the medial longitudinal arch
5. Congruence of the lateral border of the foot
6. Abduction/adduction of the fore foot on the rear foot.
7. Talar head palpation
8. Rear foot frontal plane position

We are aiming to evaluate whether these can be combined into a scoring system that can be used in clinic.

We are testing the eight signs in combination. They are to be scored on a grading scale with 0 (zero) representing the signs that you might expect to see in a neutral foot. Positive scores are used to denote pronated features, with negative scores for supinated features.
Scores can be graded +/- 1 or 2 according to the severity of the presenting feature.

Tony will go through the scoring criteria with you prior to the evaluation session.

## *Appendix B. FPI-8 refined draft datasheet (2000)*

***Patient name*** ***ID number*** ***Date***

***Non weightbearing*** - *Prior to FPI assessment, look at the feet and legs for signs of fixed pathology that should to be factored into the functional assessment.*

### *Weightbearing*

| | ***FACTOR*** | ***PLANE*** | **YOUR SCORE** -2 to +2 | |
|---|---|---|---|---|
| | | | ***Left*** | ***Right*** |
| **Rearfoot** | 1. Talar head palpation | *Transverse* | | |
| | 2. Supra and infra lateral malleolar curvature. | *Frontal/ trans* | | |
| | 3. Helbing's sign | *Frontal* | | |
| | 4. Inversion/eversion of the calcaneus | *Frontal* | | |
| **Midfoot/forefoot** | 5. Prominence in the region of the TNJ | *Transverse* | | |
| | 6. Congruence of the medial longitudinal arch | *Sagittal* | | |
| | 7. Congruence of the lateral border of the foot | *Transverse* | | |
| | 8. Abduction/adduction of the forefoot on the rear foot. | *Transverse* | | |
| | **TOTAL** | | | |

*Normal = -1 to +4*
*Pronated = +5 to +9, Highly pronated 10+*
*Supinated = -2 to –6, Highly supinated –6 to -16*

## *Appendix C. FPI-6 datasheet*

## PLEASE NOTE

This draft is provided to interested parties in confidence and with the *caveat* that the FPI may change as the various stages of the evaluation are undertaken. When the development is complete it is the author's intention that the FPI concept and data sheets will be released into the public domain.

The copyright holder permits free copying of the datasheet overleaf for clinical or research purposes, however amendments to the FPI format or concept must be made only with the copyright holder's express permission

Once the validation process is complete and the FPI is finalized, manuals and user guides will be available through a mainstream publisher and book distributors. If you wish to be kept informed of developments and/or you wish to arrange a workshop on the use of the finalized FPI please contact the author (see below).

## ACKNOWLEDGEMENTS

The FPI was developed with funding from the following agencies:

The CMT Association of the USA
The Australasian Podiatry Council, Australian Podiatry Education and Research Fund
The Podiatry Education and Research Account of the NSW Podiatrists' Registration Board.

Sincere thanks are due to the following institutions and individuals for their assistance in the development and testing of the FPI

All staff and students at the UWS podiatry department
All of the other clinicians in the many disciplines who have contributed with their time, suggestions and expertise in the development of the FPI to date.

University of Sydney, Australia
University of Western Sydney, Australia
University of South Australia
University of Huddersfield, United Kingdom
University of Leeds, United Kingdom
Royal Alexandra Hospital for Children, Sydney, Australia

Robert Ouvrier
Jack Crosbie
Jennifer Peat
Joshua Burns
Rolf Scharfbillig
Angela Evans
Alex Copper
Anne-Maree Keenan
Jim Woodburn
Liz Barr

**For further information, manuals and workshops please contact**

**Anthony Redmond**
Arthritis research campaign lecturer, Rheumatology and Rehabilitation Research Unit,
School of Medicine, University of Leeds
36 Clarendon Rd
LEEDS LS2 9NZ

Tel : ++44 1132 334 938
Email: a.redmond@leeds.ac.uk

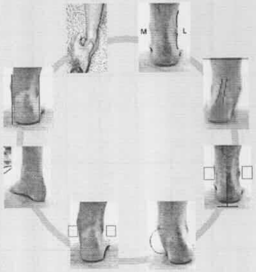
---

# THE FOOT POSTURE INDEX©

## *Easy quantification of standing foot posture*

## *6 item version*

## *DATA SHEETS*



*DRAFT VERSION May 2004*

# Foot Posture Index Datasheet

*tient name* *ID number*

| | FACTOR | PLANE | SCORE 1<br>Date____________<br>Comment__________ | | SCORE 2<br>Date____________<br>Comment__________ | | SCORE 3<br>Date____________<br>Comment__________ | |
|---|---|---|---|---|---|---|---|---|
| | | | **Left** (-2 to +2) | **Right** (-2 to +2) | **Left** (-2 to +2) | **Right** (-2 to +2) | **Left** (-2 to +2) | **Right** (-2 to +2) |
| Rearfoot | Talar head palpation | *Transverse* | | | | | | |
| | Curves above and below lateral malleoli. | *Frontal/ trans* | | | | | | |
| | Inversion/eversion of the calcaneus | *Frontal* | | | | | | |
| Forefoot | Bulge in the region of the TNJ | *Transverse* | | | | | | |
| | Congruence of the medial longitudinal arch | *Sagittal* | | | | | | |
| | Abduction/adduction of the forefoot on the rear foot (too-many-toes). | *Transverse* | | | | | | |
| | **TOTAL** | | | | | | | |

**Reference values**
*Normal = 0 to +4*
*Pronated = +5 to +9 Highly pronated 10+*
*Supinated = -1 to -4, Highly supinated -5 to -12*

# Foot Posture Index Datasheet

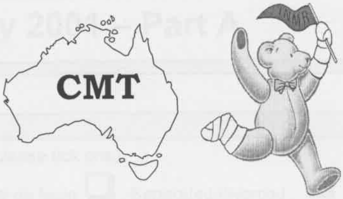
*tient name* *ID number*

| | FACTOR | PLANE | SCORE 1<br>Date____________<br>Comment__________ | | SCORE 2<br>Date____________<br>Comment__________ | | SCORE 3<br>Date____________<br>Comment__________ | |
|---|---|---|---|---|---|---|---|---|
| | | | **Left** (-2 to +2) | **Right** (-2 to +2) | **Left** (-2 to +2) | **Right** (-2 to +2) | **Left** (-2 to +2) | **Right** (-2 to +2) |
| Rearfoot | Talar head palpation | *Transverse* | | | | | | |
| | Curves above and below lateral malleoli. | *Frontal/ trans* | | | | | | |
| | Inversion/eversion of the calcaneus | *Frontal* | | | | | | |
| Forefoot | Bulge in the region of the TNJ | *Transverse* | | | | | | |
| | Congruence of the medial longitudinal arch | *Sagittal* | | | | | | |
| | Abduction/adduction of the forefoot on the rear foot (too-many-toes). | *Transverse* | | | | | | |
| | **TOTAL** | | | | | | | |

**Reference values**
*Normal = 0 to +4*
*Pronated = +5 to +9 Highly pronated 10+*
*Supinated = -1 to -4, Highly supinated -5 to -12*

*©Anthony Redmond 1998*
*(May be copied for clinical use, and adapted with the permission of the copyright holder)*

## *Appendix D. CMTAA survey – Section A and SF-36 and FHSQ forms*



**CMT Association of Australia and the Children's Hospital at Westmead, Institute for Neuromuscular Research**

# Australian CMT Health Survey 2001

The Australian CMT Health Survey 2001 consists of three parts:

- Part A. Some questions about your CMT and the treatments you may have received,
- Part B. A general health questionnaire
- Part C. A leg and foot specific questionnaire.

Please try to answer all three parts.

If some of the questions seem a little strange this may be because two of the questionnaires are not designed specifically for use in evaluating the effects of CMT. However they have been widely used in conjunction with other conditions. If you can try to persevere through them, the information we will gain from them will be very valuable in comparing the effects of CMT with existing studies of other disorders.

# Part A

## CMT specific Questions

Please attempt to complete all questions.

# Australian CMT Health Survey 2001 – Part A

## *About you*

*Y1.* **What is your gender?**

Male ☐ Female ☐

*Y2.* **What is your marital status?** (please tick one)

Single- never married ☐ Married/ de facto ☐ Separated/divorced ☐

*Y3.*
**What was your age last birthday?**

*Y4.* **At approximately what age did you first notice signs of CMT?**

*Y5.* **At approximately what age was your CMT formally diagnosed?**

*Y6.* **Were you incorrectly diagnosed as having another condition before being diagnosed as having CMT?**

No ☐ Yes ☐

*Y6a.* <u>If yes, please provide details</u>. (Examples might include muscular dystrophy, polio, arthritis)

*Y7.* **Which type of CMT do you have?**

Not sure ☐ CMT1A ☐ CMT1(other) ☐ CMT2 ☐ CMT3 (Dejerine-Sottas) ☐ CMTX ☐

<u>Other – please provide details</u>

## *About your family*

*F1.*
**Is there a history of CMT in your family?**

No ☐ Not sure ☐ Yes ☐

*F1a.* <u>If yes, please provide details.</u>

*F2.*
**Is yours considered a 'sporadic' case?**

No ☐ Not sure ☐ Yes ☐

*F3.*
**Do you have any children?**

No ☐ Yes ☐

*F3a.*
**How many children do you have?**

*F3b.*
**How many of your children have CMT?**

*F4.*
**Do you have any other significant medical problems in addition to your CMT?**

No ☐ Yes ☐

*F4a.* <u>If yes, please provide details.</u>

**Please turn the page and continue**

## *Women and pregnancy*

*If you are male, or a woman who has never been pregnant please skip this section and go straight to question B1 at the bottom of this page – 'CMT and your body'*

*P1.* **Were you diagnosed with CMT before your 1st pregnancy**

No ☐ Yes ☐

*P1a.* **Did you receive any genetic counselling?**

Yes ☐ No ☐

*P1b.* **Would you have liked to have had some genetic counselling?**

No ☐ Yes ☐ Not sure ☐

*P2.* **For each of your pregnancies please indicate whether you experienced any worsening of your CMT symptoms while pregnant** (eg weakness, more severe muscle wasting, pins and needles etc)

| | Your age at the time | Not Applicable | No change | A little worse | Worse | Much worse | A lot worse |
|---|---|---|---|---|---|---|---|
| Pregnancy number 1 | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 2 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 3 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 4 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 5 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 6 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 7 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 8 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 9 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Pregnancy number 10 | | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

*If there was any change* in your CMT due to pregnancy, please provide some information on the type of changes you experienced.

## *CMT and your body*

**Please indicate how severely you are affected by the following common features of CMT.**

| | Not at all | A little | A moderate amount | Quite a lot | Severely |
|---|---|---|---|---|---|
| *B1.* **Scoliosis** (a twist in your back) | ☐ | ☐ | ☐ | ☐ | ☐ |
| In your arms/hands - | | | | | |
| *B2.* **Weakness** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B3.* **Muscle wasting** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B4.* **Tremor** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B5.* **Sensitivity to cold** | ☐ | ☐ | ☐ | ☐ | ☐ |
| In your feet/legs - | | | | | |
| *B6.* **Weakness** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B7.* **Muscle wasting** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B8.* **Sensitivity to cold** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B9.* **Flat feet** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *B10.* **High arches** | ☐ | ☐ | ☐ | ☐ | ☐ |

Other (please comment)

**Please turn the page and continue**

## *CMT and your body - sensation*

All of the questions in this section relate to how often you experience problems with <u>sensation</u>
Please tick the box which you feels best applies to you for each of the questions.

| | Never | Occasionally | Often | Very often | Constantly |
|---|---|---|---|---|---|
| **Do you have problems with your:** | | | | | |
| *S1.* **Hearing** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S2.* **Vision** (with seeing) | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Do you suffer from loss of sensation in:** | | | | | |
| *S3.* **Your hands** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S4.* **Your feet** | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Do you have any problems with any of the following?** | | | | | |
| *S5.* **Bladder control** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S6.* **Bowel control** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S7.* **Sexual function** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S8.* **Do you burn yourself?** (eg your hands while cooking, or feet when stepping into the bath) | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S9.* **Do you have slow reactions to pain?** (eg stub your toe and take a few steps before noticing pain) | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Do you experience shooting pains:** | | | | | |
| *S10.* **In your arms/hands?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S11.* **In your legs/feet?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Do you experience 'pins and needles' or other strange sensations:** | | | | | |
| *S12.* **In your arms/hands?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S13.* **In your legs/feet?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *S14.* **Do you have 'restless' legs at night or when sitting?** | ☐ | ☐ | ☐ | ☐ | ☐ |

<u>Please add any comments you would like to make about the changes in sensation associated with your CMT</u>

**Please turn the page and continue**

## *CMT and you – impacts on daily function*

*F1.* **Do you use any of the following aids or devices?** (please tick all that apply)

| | | | |
|---|---|---|---|
| **Wheelchair** | ☐ | **Mobility scooter** | ☐ |
| **Walking stick** | ☐ | **Walking frame** | ☐ |
| | | **Stair lift** | ☐ |
| **Orthoses** | | | |
| **Low-cut 'in-shoe' orthoses** | ☐ | **Other orthoses** | |
| **Splints coming above the ankle**<br>(back slab or AFO type) | ☐ | (please specify) | ________________ |
| **Kitchen aids**<br>(jar openers, large handled cutlery etc) | ☐ | **Dressing aids**<br>(shoe horns, button aids etc) | ☐ |

Please add any comments you would like to make about aids and devices.

Many people with CMT have problems finding comfortable footwear. Questions about problems you may have encountered with footwear are dealt with again in Part C, the Foot Health Status Questionnaire. For the benefit of other members however, **if you have found a type of shoe or a supplier who you feel has helped you, please supply details below.**

(**This information will not form part of the survey analysis but the list will be held by the CMTAA and provided to members.**)

| | Never | Occasionally | Often | Very often | Constantly |
|---|---|---|---|---|---|
| **Do you lose your balance when:** | | | | | |
| *L1.* **You are walking on flat surfaces?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *L2.* **You are standing still?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *L3.* **You are walking on uneven surfaces?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *L4.* **Do you bend your knees to assist with your balance?** | ☐ | ☐ | ☐ | ☐ | ☐ |
| *L5.* **Do you fall to the ground because of balance problems** | ☐ | ☐ | ☐ | ☐ | ☐ |

Please add any comments you would like to make about your CMT and daily function

**Please turn the page and continue**

## *CMT and you – treatments (non-surgical)*

Please indicate which of the following treatments you have tried. It would be very helpful if you could indicate **how easy you found it to go through the treatment** and **how effective** the treatment was for you.

**Have you tried:**

*C1.* **Stretching exercises?**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No** | **Yes** | **Approx date(s)** | **Ease** | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*C2.* **Ankle/foot splints (daytime wear)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No** | **Yes** | **Approx date(s)** | **Ease** | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*C3.* **Ankle/foot splints (night-time wear)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No** | **Yes** | **Approx date(s)** | **Ease** | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*C4.* **Shoe inserts (not above the ankle)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No** | **Yes** | **Approx date(s)** | **Ease** | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*C5.* **Plaster casts (to stretch muscles and tendons)**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No** | **Yes** | **Approx date(s)** | **Ease** | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*C6.* **Leg strengthening exercises** (seated or lying down)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| No | Yes | Approx date(s) | Ease | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*C7.* **Leg strengthening exercises** (standing)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **No** | **Yes** | **Approx date(s)** | **Ease** | No difficulty | Minimal difficulty | Difficult | Very difficult | Impossible |
| ☐ | ☐ | | | ☐ | ☐ | ☐ | ☐ | ☐ |
| | | | **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

**Please turn the page and continue**

## *CMT and you – treatments (alternative therapies)*

Please indicate below if you have tried any alternative therapies (acupuncture, traditional Chinese medicine, naturopathy, aromatherapy, homoeopathy etc. ) and indicate how easy you found it to go through the treatment and how effective the treatment was for you. If you have not tried any alternative therapies go straight to the next section.

**Type of alternative therapy and date**

*A1.*

| | | | | | |
|---|---|---|---|---|---|
| **Ease** | No difficulty<br>☐ | Minimal difficulty<br>☐ | Difficult<br>☐ | Very difficult<br>☐ | Impossible<br>☐ |
| **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*A2.*

| | | | | | |
|---|---|---|---|---|---|
| **Ease** | No difficulty<br>☐ | Minimal difficulty<br>☐ | Difficult<br>☐ | Very difficult<br>☐ | Impossible<br>☐ |
| **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

*A3.*

| | | | | | |
|---|---|---|---|---|---|
| **Ease** | No difficulty<br>☐ | Minimal difficulty<br>☐ | Difficult<br>☐ | Very difficult<br>☐ | Impossible<br>☐ |
| **Effectiveness** | Useless<br>☐ | A little help<br>☐ | Quite helpful<br>☐ | Very helpful<br>☐ | 100% effective<br>☐ |

Please add any comments about the conservative (non-surgical), and alternative treatments you have tried.

**Please turn the page and continue**

## *CMT and you – treatments (surgery) foot only*

**Please indicate which of the following surgical treatments have been tried with you to improve your feet.** For many people there will be a complex history of several different approaches on several occasions. For the sake of keeping the form a manageable size, the list of options have been kept to a minimum. *If you wish to continue on a separate sheet please feel free to do so. (If you do add extra sheets listing multiple episodes of surgery, it would help us enormously if you can use the same format as in questionnaire.)*

In this section you are asked to tell us when you had the various surgeries, what age you were, what type of surgery you had, who performed it and where, how traumatic the process was, how effective was the surgery technically, and how worthwhile you now consider subjecting your self to the surgery. In deciding how traumatic it was undergoing the surgery you should include: the amount of pain you suffered, the impact on your day-to-day life while you were healing from the surgery, and the length of time you were disabled by the surgery.

Please put a number in the box corresponding to the type of surgery you had, and then score your experience of the surgery.

**11** Muscle/tendon surgery – not sure what kind
**12** Bone surgery (osteotomy) – not sure what kind
**13** Joint fusion – not sure what kind

**21** Tendon lengthening without transfer to a different place
**22** Tendon or muscle transfer without bony surgery

**31** Bone surgery (osteotomy) without any joints fused- many bones operated on a the same time
**32** Bone surgery (osteotomy) without any joints fused- heel only
**33** Bone surgery (osteotomy) without any joints fused- arch area only
**34** Bone surgery (osteotomy) without any joints fused – front of foot only
**35** Bone surgery (osteotomy) and muscle/ tendon lengthening or transfer
**36** Toe straightening

**41** Joint fusion – 'Triple arthrodesis'
**42** Joint fusion – Ankle
**43** Joint fusion – Heel
**44** Joint fusion – Arch area
**45** Joint fusion – Front of foot only

**50** Other – (please specify)

## EXAMPLE

**Surgery type, surgeon, place and approx date**

*22 – tendon transfer*
*–aged 17 (1980)*
*Dr Ambiguity, West*
*Coast Hosp ,Sydney*

| | | | | | |
|---|---|---|---|---|---|
| **Trauma** | None ☐ | Some but manageable ☐ | Unpleasant ☒ | Very unpleasant ☐ | Terrible ☐ |
| **Effectiveness** | Useless ☐ | A little help ☒ | Quite helpful ☐ | Very helpful ☐ | 100% effective ☐ |
| **Worthwhile** | Definitely no ☐ | Not really ☐ | Neutral ☒ | Yes ☐ | Definitely yes ☐ |

Comments
*It was very painful at first. I was able to walk within a month though so it could have been worse. It didn't really work as I have had to have a joint fusion since, but I suppose it bought me some time.*

---

*S1*. **Surgery type, surgeon, place and approx date**

| | | | | | |
|---|---|---|---|---|---|
| **Trauma** | None ☐ | Some but manageable ☐ | Unpleasant ☐ | Very unpleasant ☐ | Terrible ☐ |
| **Effectiveness** | Useless ☐ | A little help ☐ | Quite helpful ☐ | Very helpful ☐ | 100% effective ☐ |
| **Worthwhile** | Definitely no ☐ | Not really ☐ | Neutral ☐ | Yes ☐ | Definitely yes ☐ |

Comments

**Please turn the page and continue**

## *CMT and you – treatments (surgery) foot only*

### *S2.* Surgery type, surgeon, place and approx date

| | | | | | |
|---|---|---|---|---|---|
| **Trauma** | None ☐ | Some but manageable ☐ | Unpleasant ☐ | Very unpleasant ☐ | Terrible ☐ |
| **Effectiveness** | Useless ☐ | A little help ☐ | Quite helpful ☐ | Very helpful ☐ | 100% effective ☐ |
| **Worthwhile** | Definitely no ☐ | Not really ☐ | Neutral ☐ | Yes ☐ | Definitely yes ☐ |

Comments

### *S3.* Surgery type, surgeon, place and approx date

| | | | | | |
|---|---|---|---|---|---|
| **Trauma** | None ☐ | Some but manageable ☐ | Unpleasant ☐ | Very unpleasant ☐ | Terrible ☐ |
| **Effectiveness** | Useless ☐ | A little help ☐ | Quite helpful ☐ | Very helpful ☐ | 100% effective ☐ |
| **Worthwhile** | Definitely no ☐ | Not really ☐ | Neutral ☐ | Yes ☐ | Definitely yes ☐ |

Comments

### *S4.* Surgery type, surgeon, place and approx date

| | | | | | |
|---|---|---|---|---|---|
| **Trauma** | None ☐ | Some but manageable ☐ | Unpleasant ☐ | Very unpleasant ☐ | Terrible ☐ |
| **Effectiveness** | Useless ☐ | A little help ☐ | Quite helpful ☐ | Very helpful ☐ | 100% effective ☐ |
| **Worthwhile** | Definitely no ☐ | Not really ☐ | Neutral ☐ | Yes ☐ | Definitely yes ☐ |

Comments

*Please continue on a separate sheet if necessary (in the same format if possible)*

**Please turn the page and continue**

# *CMT and you – treatments (surgery) foot only*

**Please tell us about the <u>three most successful</u> approaches to treatment you have tried.** Please try to include why these approaches have been more successful than others.

*M1*

*M2*

*M3*

**Please tell us about the <u>two least successful</u> approaches you have tried.** Please try to include why these approaches have been less successful than others.

*U1*

*U2*

<u>Please feel free to add any other comments regarding you, your experiences with CMT, or this survey</u> (continue on a separate sheet if necessary).

**END OF PART A – Please continue to Parts B and C**

**Thankyou for answering the CMT specific questions.**
Next please turn the page and answer the questions in Part B, the SF-36 Health Survey.

# Part B

## The SF-36

**About the SF-36:**
The SF-36 is a widely used general health survey and will enable us to compare the answers given in this study with previous studies of other conditions. Please note that because this survey is from a different source, the way you provide your answers is slightly different.

# The SF-36™ Health Survey

## Instructions for Completing the Questionnaire

Please answer every question. Some questions may look like others, but each one is different. Please take the time to read and answer each question carefully by filling in the bubble that best represents your response.

### EXAMPLE

**This is for your review.** Do not answer this question. The questionnaire begins with the section ***Your Health in General*** below.

For each question you will be asked to fill in a bubble in each line:

1. How strongly do you agree or disagree with each of the following statements?

| | **Strongly agree** | **Agree** | **Uncertain** | **Disagree** | **Strongly disagree** |
|---|---|---|---|---|---|
| a) I enjoy listening to music. | ○ | ● | ○ | ○ | ○ |
| b) I enjoy reading magazines. | ● | ○ | ○ | ○ | ○ |

Please begin answering the questions now.

# Your Health in General

1. In general, would you say your health is:

| **Excellent** | **Very good** | **Good** | **Fair** | **Poor** |
|---|---|---|---|---|
| ○ | ○ | ○ | ○ | ○ |

2. **Compared to one year ago**, how would you rate your health in general now?

| **Much better now than one year ago** | **Somewhat better now than one year ago** | **About the same as one year ago** | **Somewhat worse now than one year ago** | **Much worse now than one year ago** |
|---|---|---|---|---|
| ○ | ○ | ○ | ○ | ○ |

***Please turn the page and continue.***

3. The following items are about activities you might do during a typical day. Does **your health now limit you** in these activities? If so, how much?

| | **Yes, Limited a lot** | **Yes, limited a little** | **No, not limited at all** |
|---|---|---|---|
| a) **Vigorous activities**, such as running, lifting heavy objects, participating in strenuous sports | ○ | ○ | ○ |
| b) **Moderate activities**, such as moving a table, pushing a vacuum cleaner, bowling, or playing golf | ○ | ○ | ○ |
| c) Lifting or carrying groceries | ○ | ○ | ○ |
| d) Climbing **several** flights of stairs | ○ | ○ | ○ |
| e) Climbing **one** flight of stairs | ○ | ○ | ○ |
| f) Bending, kneeling, or stooping | ○ | ○ | ○ |
| g) Walking **more than a mile** | ○ | ○ | ○ |
| h) Walking **several blocks** | ○ | ○ | ○ |
| i) Walking **one block** | ○ | ○ | ○ |
| j) Bathing or dressing yourself | ○ | ○ | ○ |

4. During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities as a result of your physical health?

| | **Yes** | **No** |
|---|---|---|
| a) Cut down on the **amount of time** you spent on work or other activities | ○ | ○ |
| b) **Accomplished less** than you would like | ○ | ○ |
| c) Were limited in the **kind** of work or other activities | ○ | ○ |
| d) Had **difficulty** performing the work or other activities (for example, it took extra time) | ○ | ○ |

5. During the **past 4 weeks**, have you had any of the following problems with your work or other regular daily activities as a result of any emotional problems (such as feeling depressed or anxious)?

| | **Yes** | **No** |
|---|---|---|
| a) Cut down on the **amount of time** you spent on work or other activities | ○ | ○ |
| b) **Accomplished less** than you would like | ○ | ○ |
| c) Didn't do work or other activities as **carefully** as usual | ○ | ○ |

***Please turn the page to continue.***

6. During the **past 4 weeks**, to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbors, or groups?

| **Not at all** | **Slightly** | **Moderately** | **Quite a bit** | **Extremely** |
|---|---|---|---|---|
| ○ | ○ | ○ | ○ | ○ |

7. How much bodily pain have you had during the **past 4 weeks**?

| **None** | **Very mild** | **Mild** | **Moderate** | **Severe** | **Very severe** |
|---|---|---|---|---|---|
| ○ | ○ | ○ | ○ | ○ | ○ |

8. During the **past 4 weeks**, how much did pain interfere with your normal work (including both work outside the home and housework)?

| **Not at all** | **A little bit** | **Moderately** | **Quite a bit** | **Extremely** |
|---|---|---|---|---|
| ○ | ○ | ○ | ○ | ○ |

9. These questions are about how you feel and how things have been with you during the **past 4 weeks**. For each question, please give the one answer that comes closest to the way you have been feeling. How much of the time during the **past 4 weeks**...

| | **All of the time** | **Most of the time** | **A good bit of the time** | **Some of the time** | **A little of the time** | **None of the time** |
|---|---|---|---|---|---|---|
| a) did you feel full of pep? | ○ | ○ | ○ | ○ | ○ | ○ |
| b) have you been a very nervous person? | ○ | ○ | ○ | ○ | ○ | ○ |
| c) have you felt so down in the dumps nothing could cheer you up? | ○ | ○ | ○ | ○ | ○ | ○ |
| d) have you felt calm and peaceful? | ○ | ○ | ○ | ○ | ○ | ○ |
| e) did you have a lot of energy? | ○ | ○ | ○ | ○ | ○ | ○ |
| f) have you felt downhearted and blue? | ○ | ○ | ○ | ○ | ○ | ○ |
| g) did you feel worn out? | ○ | ○ | ○ | ○ | ○ | ○ |
| h) have you been a happy person? | ○ | ○ | ○ | ○ | ○ | ○ |
| i) did you feel tired? | ○ | ○ | ○ | ○ | ○ | ○ |

10. During the **past 4 weeks**, how much of the time has your physical health or emotional problems interfered with your social activities (like visiting friends, relatives, etc.)?

| **All of the time** | **Most of the time** | **Some of the time** | **A little of the time** | **None of the time** |
|---|---|---|---|---|
| ○ | ○ | ○ | ○ | ○ |

11. How TRUE or FALSE is each of the following statements for you?

| | **Definitely true** | **Mostly true** | **Don't know** | **Mostly false** | **Definitely false** |
|---|---|---|---|---|---|
| a) I seem to get sick a little easier than other people | ○ | ○ | ○ | ○ | ○ |
| b) I am as healthy as anybody I know | ○ | ○ | ○ | ○ | ○ |
| c) I expect my health to get worse | ○ | ○ | ○ | ○ | ○ |
| d) My health is excellent | ○ | ○ | ○ | ○ | ○ |

***THANK YOU*** **FOR COMPLETING THIS QUESTIONNAIRE!**

**Thankyou for completing part B.**

The final part of this questionnaire, Part C, ask questions about the impact of CMT on your legs and feet, and how this affects you in day-to-day life.

# Part C

# The Foot Health Status Questionnaire

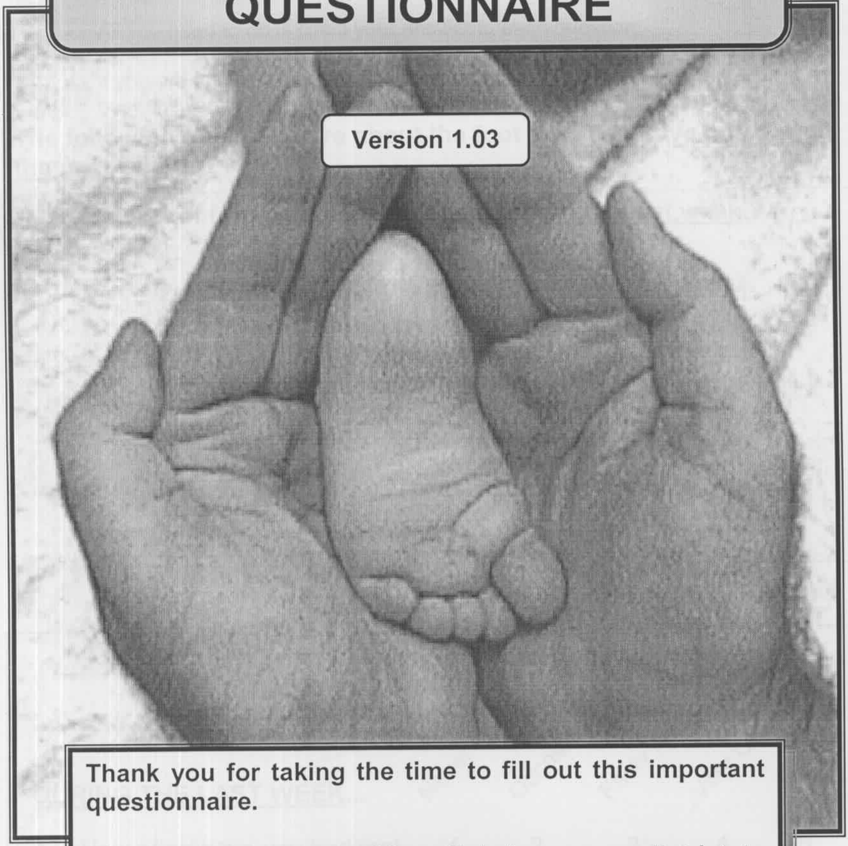
**About the Foot Health Status Questionnaire (FHSQ):**

The FHSQ is similar to the SF-36 and is used to compare different conditions affecting the feet and legs.

A few of the questions in the Foot Health Status Questionnaire (Part C) are identical to questions you have just answered in Part B, and a few other questions are also similar. We do appreciate your patience and cooperation in providing answers to these duplicated questions.

By answering these questions in both Part B and in Part C you will help to maintain the integrity of the two questionnaires.

# THE FOOT HEALTH STATUS QUESTIONNAIRE



Version 1.03

Thank you for taking the time to fill out this important questionnaire.

The answers you provide will help your podiatrist to understand how to care for your foot problems.

The questionnaire is very simple to complete and there are no right or wrong answers. The questionnaire takes less than 10 minutes to complete.

# The Foot Health Status Questionnaire

## INSTRUCTIONS

- This questionnaire asks for your views about your foot health.
- All you need to do is circle your answer to each question.
- If you are unsure about how to answer a question, please give the best answer you can.

**The following questions are about the foot pain you have had during the past week.**

**1. What level of foot pain have you had during the past week ?**

(circle number)

None........................................1

Very Mild.................................. 2

Mild.......................................... 3

Moderate.................................. 4

Severe...................................... 5

(circle a number for each question below)

| **DURING THE LAST WEEK...** | Never | Occasionally | Fairly Many Times | Very Often | Always |
|---|---|---|---|---|---|
| **2.** How often have you had foot pain ? | 1 | 2 | 3 | 4 | 5 |
| **3.** How often did your feet ache? | 1 | 2 | 3 | 4 | 5 |
| **4.** How often did you get sharp pains in your feet ? | 1 | 2 | 3 | 4 | 5 |

**These questions are about how much your feet interfere with activities you might do during a typical day.**

(circle a number for each question below)

**DURING THE LAST WEEK.......**

| | Not at All | Slightly | Moderately | Quite a bit | Extremel |
|---|---|---|---|---|---|
| **5.** Have your feet caused you to have difficulties in your work or activities ? | 1 | 2 | 3 | 4 | 5 |
| **6.** Were you limited in the kind of work you could do because of your feet ? | 1 | 2 | 3 | 4 | 5 |

**DURING THE LAST WEEK...**

| | Not at All | Slightly | Moderately | Quite a bit | Extremely |
|---|---|---|---|---|---|
| **7.** How much does your foot health limit you walking ? | 1 | 2 | 3 | 4 | 5 |
| **8.** How much does your foot health limit you climbing stairs ? | 1 | 2 | 3 | 4 | 5 |

**9.** How would you rate your overall foot health ? (circle number)

| | |
|---|---|
| Excellent | 1 |
| Very Good | 2 |
| Good | 3 |
| Fair | 4 |
| Poor | 5 |

**Please turn to the next page**

**The following questions are about the shoes that you wear. Please circle the response which best describes your situation.**

| | | Strongly Agree | Agree | Neither Agree nor Disagree | Disagree | Strongly Disagree |
|---|---|---|---|---|---|---|
| **10.** | It is hard to find shoes that do not hurt my feet. | 1 | 2 | 3 | 4 | 5 |
| **11.** | I have difficulty in finding shoes that fit my feet. | 1 | 2 | 3 | 4 | 5 |
| **12.** | I am limited in the number of shoes I can wear. | 1 | 2 | 3 | 4 | 5 |

**13.** In general, what condition would you say your feet are in ?

(circle number)

Excellent.......................... 1

Very Good....................... 2

Good.............................. 3

Fair................................ 4

Poor............................... 5

Please write some comments about the current state of your feet:

.......................................................................................................

.......................................................................................................

.......................................................................................................

.......................................................................................................

.......................................................................................................

**14.** In general, how would you rate your health :

(circle number)

Very Good............................................................ 1
Fair.......................................................................... 2
Poor......................................................................... 3

**15.** The following questions ask about activities you might do during a typical day. Does your health now limit you in these activities? If so, how much?

(circle a number on each line)

| **ACTIVITIES** | Yes, Limited A Lot | Yes, Limited A Little | No, Not Limited At All |
|---|---|---|---|
| a. **Vigorous activities**, such as running, lifting heavy objects, or (if you wanted to) your ability to participate in strenuous sports | 1 | 2 | 3 |
| b. **Moderate activities**, such as cleaning the house, lifting a chair, playing golf or swimming | 1 | 2 | 3 |
| c. Lifting or carrying bags of shopping | 1 | 2 | 3 |
| d. Climbing a steep hill | 1 | 2 | 3 |
| e. Climbing **one** flight of stairs | 1 | 2 | 3 |
| f. Getting up from a sitting position | 1 | 2 | 3 |
| g. Walking **more than a kilometre** | 1 | 2 | 3 |
| h. Walking **one hundred meters** | 1 | 2 | 3 |
| i. Showering or dressing yourself | 1 | 2 | 3 |

**16.** This next question asks to what extent has your physical health or emotional problems interfered with your normal social activities with family, friends, neighbours or social groups?

(circle number)

Not at all.............................................................. 1
Slightly................................................................. 2
Moderately............................................................ 3
Quite a bit............................................................ 4
Extremely.............................................................. 5

**Please turn to the next page**

**17**. These questions are about how you "feel" and how things have been with you during the past month. For each question, please give the one answer that comes closest to the way you have been "feeling". How much of the time during the past 4 weeks:

| | **All of the time** | **Most of the Time** | **Some of the Time** | **A little of the Time** | **None of the Time** |
|---|---|---|---|---|---|
| a. Did you feel tired? | 1 | 2 | 3 | 4 | 5 |
| b. Did you have a lot of energy? | 1 | 2 | 3 | 4 | 5 |
| c. Did you feel worn out? | 1 | 2 | 3 | 4 | 5 |
| d. Did you feel full of life? | 1 | 2 | 3 | 4 | 5 |

**18.** During the past 4 weeks, how much of the time has your emotional problems or physical health interfered with your social activities (like visiting with friends, relatives, etc.)?

| | (circle number) |
|---|---|
| No time at all.................................................................. | 1 |
| A small amount of time.................................................... | 2 |
| Moderate amount of time................................................. | 3 |
| Quite a bit of the time..................................................... | 4 |
| All of the time.................................................................. | 5 |

**19.** How TRUE or FALSE is each of the following statements for you?

(circle a number on each line)

| | **True or Mostly True** | **Don't Know** | **False or Mostly False** |
|---|---|---|---|
| a. I seem to get sick a little easier than other people | 1 | 2 | 3 |
| b. I am as healthy as anybody I know | 1 | 2 | 3 |
| c. I expect my health to get worse | 1 | 2 | 3 |
| d. My health is excellent | 1 | 2 | 3 |

**Please complete the following details.**

**20.** Full Name:________________________________

**21.** Address:________________________________________ Postcode:_________

**22.** Date of Birth:_______________ Sex: Male ○ Female ○

**23.** What is the date when you filled out this survey? Please write here → _________

**24.** Do you currently take any medicine prescribed by your doctor for any of the following conditions ;

(please tick the appropriate box/s)

Diabetes ○

Osteoarthritis ○

Blood Pressure ○

Heart Disease ○

Lung Disease ○

Hormone Replacement Therapy ○

High Cholesterol ○

Rheumatoid Arthritis ○

Back Pain ○

Depression ○

Any other conditions you take medicine for, please list .......

1.
2.
3.

For the next questions, please tick either **YES** or **NO**

| | Yes | No |
|---|---|---|
| **25.** Are you a pensioner or health care cardholder ? | ○ | ○ |
| **26.** Do you smoke cigarettes ? | ○ | ○ |
| **27.** Do you do any regular physical exercise ? | ○ | ○ |
| **28.** Do you have private health insurance ? | ○ | ○ |
| **29.** Have you<br>educatio | | ○ |

**Thank you for completing this questionnaire**

# You have now finished completing the forms.

Thank you very much for your assistance in completing the questionnaires.

Please return the forms in the envelope provided, or by mail to:

Postal Survey
CMT Association of Australia
Building 51
Concord Hospital
Concord
NSW 2139

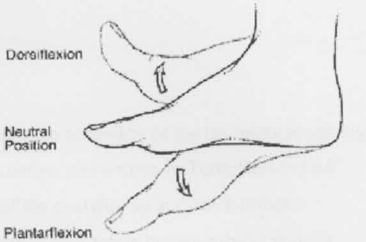
If you require further copies you can arrange for them to be sent you by contacting the CMTAA at the address above, or:

Telephone: (02) 9767 5105
Fax: (02) 9767 5105
Email: cmtaa@lycos.com

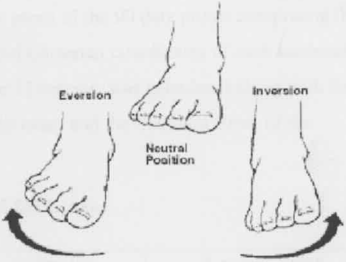
Alternatively you can also download copies of the forms from the Internet at http://e-bility.com/cmtaa

## *Appendix E. Motions occurring at the foot and ankle joints.*

Motions occurring about the axis designated X result in the foot moving parallel with the cardinal **sagittal** plane. Motion of the foot upward toward the tibia is referred to as dorsiflexion and is quantified in the EMT studies with positive values. Movement downward away from the tibia is plantarflexion, and is quantified using negative values.

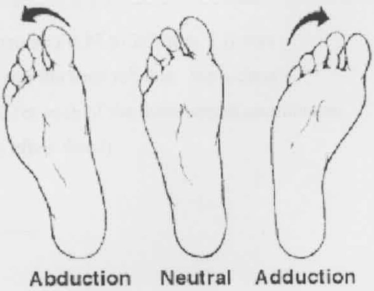


Motions occurring about the axis designated Y result in the foot moving parallel with the cardinal **frontal** plane. Motion of the foot toward the midline of the body is referred to as inversion and is quantified in the EMT studies with positive values. Movement away from the midline is eversion, and is quantified using negative values.



Motions occurring about the axis designated Z result in the foot moving parallel with the floor and the cardinal **transverse** plane. Motion of the foot or part of the foot toward the midline of the body is referred to as adduction, and motion away from the midline is abduction.

*Note that the ISB ankle joint coordinate system used in the EMT studies embeds this axis in the calcaneus and is quantified using the convention that movement of the tibia is described relative to the fixed calcaneus. In the motion-time curves therefore, positive values denote adduction or internal rotation of the tibia on the calcaneus, and negative values denote abduction or external rotation of the tibia.*



# *Appendix F. Reliability of the EMT protocols employed in Chapter Six.*

**Supporting data to Chapter Six, Section One.**

**Reliability of the landmark digitisation process**

Prior to writing the software for the entire marker set, the reliability of the landmark recording process was undertaken in a preliminary study. A routine was written in TurboBasic v10.0 that recorded the calibrated Cartesian coordinates of the $c_2$ stylus tip at three forefoot landmarks ($L_{15}$, $L_{16}$ and $L_{17}$) during 15 repeat measures on a single human subject in quiet stance. Five seconds of data were recorded for each ordered repeat of $L_{15}$, $L_{16}$ and $L_{17}$. The first and last second of data were discarded and the mean of the 90 data points comprising the middle three seconds was used to define the reported Cartesian coordinates of each landmark. The mean of each Cartesian coordinate set over the 15 repeats, was calculated along with the root mean square (RMS) of the differences from the mean and the Standard Error of the Measure (SEM).

**Table 6.1. Mean position in mm, RMS and SEM for $L_{15}$-$L_{17}$**

| | X coordinates | | | Y coordinates | | | Z coordinates | | |
|---|---|---|---|---|---|---|---|---|---|
| **Landmark** | **Mean** | **RMS** | **SEM** | **Mean** | **RMS** | **SEM** | **Mean** | **RMS** | **SEM** |
| $L_{15}$ | 206.23 | 0.87 | 0.63 | 348.93 | 1.45 | 1.05 | 124.20 | 1.04 | 0.76 |
| $L_{16}$ | 289.13 | 1.45 | 1.06 | 272.53 | 1.71 | 1.24 | 120.67 | 1.25 | 0.91 |
| $L_{17}$ | 293.80 | 2.26 | 1.65 | 333.27 | 2.54 | 1.86 | 123.47 | 1.68 | 1.22 |

The 3 sets of coordinate data demonstrated RMS errors of 0.87 to 2.54mm. $L_{15}$ was consistently the most reliable landmark, while $L_{17}$ was the least reliable. Intra-class correlation coefficients (ICCs) were also calculated for each of the three sets of coordinates using ICC model 3,1 (rater effect random, measure effect fixed).

**Table 6.2. Intraclass correlation coefficients for the coordinate and landmark sets**

| *Overall ICC (95%CI)* | *X coords ICC (95%CI)* | *Y coords ICC (95%CI)* | *Z coords ICC (95%CI)* | *$L_{15}$ ICC (95%CI)* | *$L_{16}$ ICC (95%CI)* | *$L_{17}$ ICC (95%CI)* |
|---|---|---|---|---|---|---|
| 0.997 (0.992 –0.999) | 0.998 (0.994 –0.999) | 0.9897 (0.987 – 0.999) | ***0.670 * (0.301 – 0.988)*** | 0.999 (0.999 –1.0) | 0.999 (0.999 –1.0) | 0.999 (0.999 –1.0) |

*The between-group variation in the Z coordinates was lower than for the X and Y coordinate data. This is to be expected as all the measures were taken from landmarks in the forefoot at a very similar height from the floor. Conversely, the X coordinate difference between, for example, the first and fifth metatarsal, and Y coordinate difference between the head and base of the fifth metatarsal would be far greater. Low between-group variation is widely accepted as adversely affecting ICC calculations. The SEMs for the Z coordinate data was lower than the X coordinate data SEM at both $L_{16}$ and $L_{17}$; and the SEMs were lower than for the Y coordinate data at $L_{15}$, $L_{16}$ and $L_{17}$. It is thus likely that the low ICC value for the Z coordinate data reflects the low between group variability rather than any inherent deficit in the reliability of the Z coordinate data.

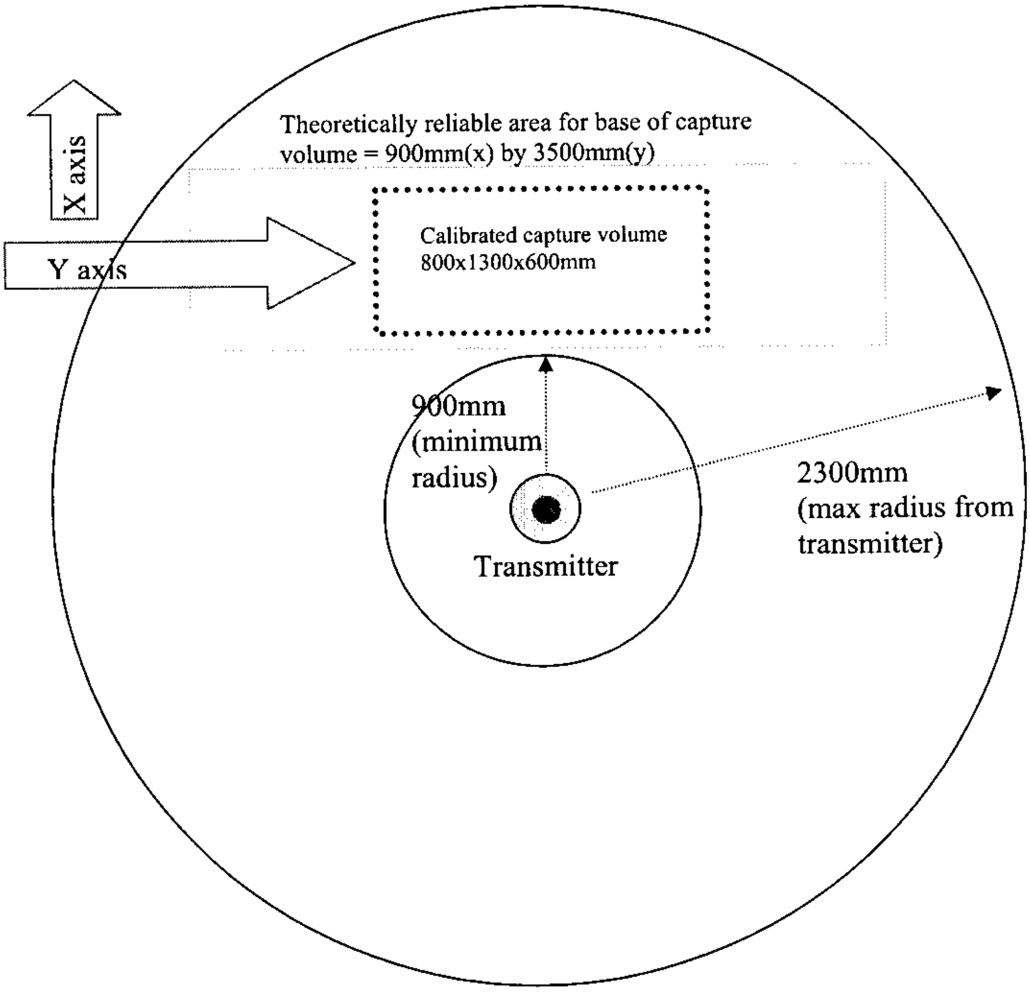
The reliability analysis suggests that the capacity of the observer to reliably place the point of the stylus at each of the landmarks evaluated is acceptable. A root mean square error of between 1 and 2.5mm will however, factor into the calculation of each of three or four landmarks for each segment, and by extension in the calculation of the relative segment orientations representing the benchmark foot posture. The variability in the calculated angular orientations of the forefoot segment derived from the Cartesian coordinates, ranged from +/- 5.3° for the shortest segment side, to+/- 2.9° for the longer side. This potential error is not especially high, but in the context of the small motions occurring in the joints of the foot, was potentially significant in a benchmarking exercise. It must also be noted that in defining a joint complex the orientation of two segments is required, further compounding the error. The potential error in defining five segments accurately, highlights the difficulties in establishing a true gold-standard.

**Supporting data to Chapter 6, Section 2. The reliability and accuracy of the EMT system using the skin mounted sensor protocol, and calibration of the capture volume.**

Analysis of locomotor function using an EMT system involves a) the calculation of joint angles derived from the relative orientation of two sensors either side of the single joint or joint complex of interest, and b) the reporting of the displacement of sensors, and the calculation of resultants for the associated segments.

The Fastrak system allows for data capture in a large volume (up to 3m diameter) however, accuracy is known to be reduced at the margins of this volume. To maximise the accuracy of the data, a reduced capture volume was defined, which was adequate for capturing normal walking but which reduced separation between transmitter and sensors. The size of this reduced volume was 800mm (x) 1300mm (y) and 600mm (z), and the accuracy of the system within this area was explored in detail.

Figure 6.1. The layout of the capture volume explored in the error quantitation experiment.



The calibration of the capture volume involved quantifying the error associated with the measurement of joint angles and segment displacements within the volume, and was undertaken in two stages.

**Sensor definition and mounting**

In the first stage, two sensors ($S_1$ and $S_2$) were mounted with plastic screws, to a rigid non-metallic bar at a separation of 301mm, simulating the approximate separation between sensors mounted on an average human tibia and forefoot. The bar and sensors were, in turn, mounted to a plastic sled to smooth the motion along the line of progression. For each trial the bar was drawn through the field along a line parallel to the Y axis of the global reference frame, in a direction representing normal forward walking. The trials were repeated with the handle of the bar oriented parallel to the X,Y, and Z axes of the global reference frame. Five repetitions were undertaken for each orientation. A final set of passes was undertaken with the wand waved through the field in a random pattern incorporating orientation of the handle of the bar in all three directions.

Prior to each of the sets of trials, the angular orientation of the sensors relative to one another and to the global reference frame was calibrated or 'boresighted' to zero with the bar oriented along the axis being investigated.

**'Joint' definition**

Consequently, for this stage of the study the rotations of the joints within the local reference frame (about axes x,y, and z) closely approximated motions about the axes of global reference frame (X,Y and Z). Rotations occurring about the x axis are signified in the text by $\alpha$ (corresponding to plantar flexion/dorsiflexion in the JCS described by Allard), rotations about the y axis by $\beta$ (corresponding to inversion/eversion), and rotations about the z axis by $\gamma$(corresponding to internal/external rotation).

A nominal 'joint' (J) was defined, described by the $\alpha$, $\beta$ and $\gamma$ orientation of $S_1$ and $S_2$. In an error free system the observed angles ($J_\alpha$, $J_\beta$ and $J_\gamma$) would equal zero for all trials.

**Evaluation of displacement error.**

To calibrate the error associated with recording positional data, the separation of the two sensors was recorded by description of the Cartesian co-ordinates and the directional cosines of each sensor relative to the global reference frame. This enabled the calculation of the resultant Euclidian distance between sensors (denoted by $D_E$). This is undertaken automatically within the motion analysis software. In an error free system $D_E$ for the setup used in this study would be constant at 301mm as the bar moved through the calibrated area and at all orientations.

In practice, when positional changes are being recorded during a gait analysis, accurate tracking of a single sensor is more important than the relative separation of the different sensors. To determine the error associated with the system's reporting of absolute displacement a second stage evaluation was set up. The maximum range of displacement of $VL_{12}$ for a single subject in Section 1 was 19°, so a sensor placed, for example, on the navicular might be expected to displace 20 to 25mm during a single stance phase if the foot were moved from a fully pronated to a fully supinated position. The accuracy of the electromagnetic tracking system in reporting such ranges was evaluated.

To establish the absolute error over this range, a stepped Perspex model was created and the true height, the z axis displacement between the steps ($H_z$), accurately determined using a Mitutoyo vertical calliper. The accuracy of the electromagnetic measure in reporting $H_z$ was determined for six points at the borders of the gait area described above. The benchmark height of the step was determined from the mean of five measures made with the Mitutoyo callipers. The step apparatus was placed at the centre of border of the walking area nearest the transmitter. Two sensors ($S_3$ and $S_4$) were placed on the lower step, $S_3$ secured firmly, $S_4$ held by hand, and the system calibrated to zero. The sensor $S_4$ was then moved to the top step (TS) and back to the bottom step (BS) five times, with the observed vertical displacement ($H_{z\ obs}$) = $TS_i - BS_i$ where $i = 1$ to 5. The five repeats constituted one trial at each site. Trials were undertaken at six sites around the perimeter of the walking area to quantify the error across the field. Error was calculated for the absolute change in position for $S_4$.

$S_3$ was not used in the calculations but acted as a control to prove the absence of field fluctuations during the data collection period.

**Figure 6.2. The protocol for establishing the absolute error for $H_{z\,obs}$.**

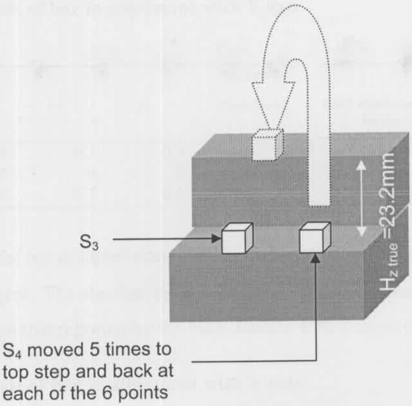
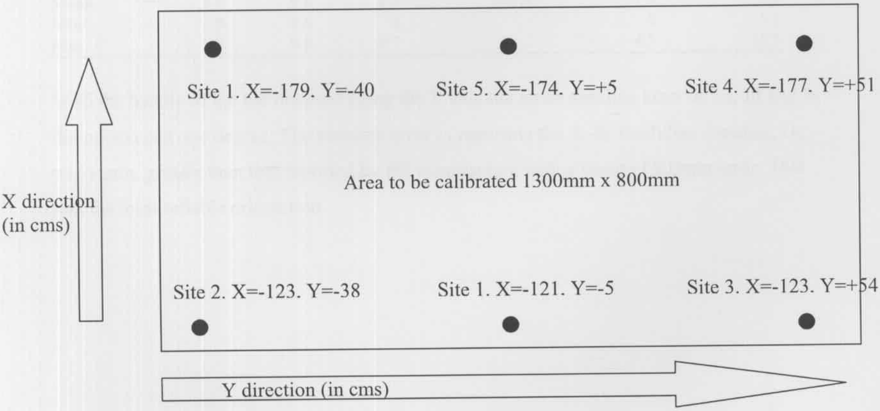


Figure 6.3. The six sites at which Z axis calibration was conducted.



## *Results of the reliability evaluations*

**Error associated with angular rotation and relative sensor displacement (translation) for five passes through the calibrated walkway area at each orientation.**

### Calibration with axis of bar in alignment with X axis

Mean of five passes

| | JOINT ANGLE (°) Jα | Jβ | Jγ | $D_E$ (mm) Mean (mm) | RMS relative error for $D_E$ | RMS absolute error for $D_E$ |
|---|---|---|---|---|---|---|
| **Mean** | 0.4 | 0.3 | 0.3 | 303.5 | 0.9 | 3.5 |
| **Min** | 0 | 0 | 0 | | 0 | 1.3 |
| **Max** | 0.6 | 0.7 | 0.5 | | 2.2 | 5.7 |

With the handle of the bar oriented along the X axis the absolute error of Jα, Jβ and Jγ at no time exceed one degree. The absolute error in reporting the $S_1$-$S_2$ Euclidian distance, $D_E$ was however, greater than that reported by the manufacture with a mean of 3.5mm error.

### Calibration with axis of bar in alignment with Y axis

Mean of five passes

| | JOINT ANGLE (°) Jα | Jβ | Jγ | $D_E$ (mm) Mean (mm) | RMS relative error for $D_E$ | RMS absolute error for $D_E$ |
|---|---|---|---|---|---|---|
| **Mean** | 0.4 | 0.6 | 0.3 | 309.0 | 1.8 | 9.0 |
| **Min** | 0 | 0.4 | 0 | | 0 | 5.3 |
| **Max** | 1.0 | 0.8 | 0.7 | | 4.5 | 13.5 |

With the handle of the bar oriented along the Y axis the mean absolute error of Jα, Jβ and Jγ did not exceed one degree. The absolute error in reporting the $S_1$-$S_2$ Euclidian distance, $D_E$ was again, greater than that reported by the manufacture with a mean of 9.0mm error. This was the least reliable orientation.

Calibration with axis of bar in alignment with Z axis

Mean of five passes

| | JOINT ANGLE (°)<br>Jα | Jβ | Jγ | $D_E$ (mm)<br>Mean (mm) | RMS relative error for $D_E$ | RMS absolute error for $D_E$ |
|---|---|---|---|---|---|---|
| **Mean** | 0.2 | 0.8 | 0.4 | 298.8 | 1.7 | 1.7 |
| **Min** | 0 | 0.5 | 0.1 | | 0 | 0 |
| **Max** | 0.6 | 1.3 | 0.8 | | 5.7 | 6.9 |

With the handle of the bar oriented along the Z axis the mean absolute error of Jα, Jβ and Jγ did not exceed one degree. The absolute error in reporting $D_E$ was lowest at this orientation with a mean of only 1.7mm error.

**Bar moved at random through the field**

Mean of three passes

| | JOINT ANGLE (°)<br>Jα | Jβ | Jγ | $D_E$ (mm)<br>Mean (mm) | RMS relative error for $D_E$ | RMS absolute error for $D_E$ |
|---|---|---|---|---|---|---|
| **Mean** | 0.8 | 0.6 | 0.4 | 301.2 | 5.8 | 5.8 |
| **Min** | 0 | 0 | 0 | | 0 | 0 |
| **Max** | 5.8 | 1.9 | 1.4 | | 16.4 | 16.1 |

With the bar waved at random through the field the mean absolute error of Jα, Jβ and Jγ was again less than one degree. The minimum and maximum errors for Jα, Jβ and Jγ were higher than with the previously tightly controlled passes. The absolute error for $D_E$ was high in this series, with the mean absolute error of $D_E$ 5.5 to 6mm, and up to 16mm at worst. These figures are in accord with those of Day et al [1] and Perie et al [2].

**Error associated with absolute sensor displacement at six sites in the calibrated walkway area.**

**Measurements (and absolute error) at the various sites (mm)**

| Measurement number | $H_{z1}$ | $H_{z2}$ | $H_{z3}$ | $H_{z4}$ | $H_{z5}$ | Mean | RMS Mean error |
|---|---|---|---|---|---|---|---|
| **Calliper ($H_{z\,true}$)** | 24.0 | 23.0 | 22.5 | 23.0 | 23.5 | 23.2 | - |
| **Site 1** | 23.8 (0.6) | 23.6 (0.4) | 23.7 (0.5) | 23.8 (0.6) | 23.9 (0.7) | 23.8 | 0.6 |
| **Site 2** | 23.1 (0.1) | 23.2 (0) | 23.1 (0.1) | 23.2 (0) | 23.2 (0) | 23.2 | 0.0 |
| **Site 3** | 23.2 (0) | 23.0 (0.2) | 23.2 (0) | 23.1 (0.1) | 23.1 (0.1) | 23.1 | 0.1 |
| **Site 4** | 21.9 (1.3) | 22.0 (1.2) | 21.9 (1.3) | 21.9 (1.3) | 22.1 (1.1) | 22.0 | 1.2 |
| **Site 5** | 20.3 (2.9) | 20.9 (2.3) | 20.8 (2.4) | 20.7 (2.5) | 20.7 (2.5) | 20.7 | 2.5 |
| **Site 6** | 20.8 (2.4) | 20.4 (2.8) | 20.6 (2.6) | 20.4 (2.8) | 20.6 (2.6) | 20.6 | 2.6 |

The error associated with $H_{z\,obs}$ increases with X axis separation from the transmitter. The absolute error for $H_{z\,obs}$ ranges from less than 1mm within 130 cms X axis separation from the transmitter, to 3mm at 175-180cms X axis separation from the transmitter.

## Reliability testing summary

The data reported here suggest that there is less error associated with the electromagnetic tracking of motions in the small joints of the foot than has been reported for video based systems. The values determined for error in reporting $J\alpha$, $J\beta$ and $J\gamma$, are not much greater than those provided by the manufacturers data, although single values of maximum error in the random waves trials suggest that significant variations from the mean values may occur when using the system in real world situations. The error associated with the reporting of $D_E$ is higher than the manufacturers estimate with, for the handle oriented parallel to the Y axis, a mean of 9.0mm error and the error of $D_E$ approaching 14mm in the worst case. These data are in agreement with the independent data of Day et al [1].

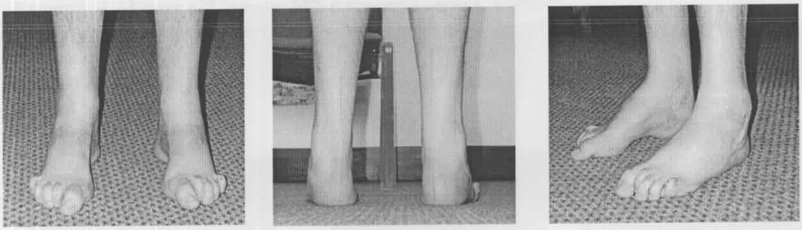
## References

1. Day JS, Murdoch DJ, Dumas GA. Calibration of position and angular data from a magnetic tracking device. *Journal of Biomechanics* 2000;33(8):1039-45.
2. Perie D, Tate AJ, Cheng PL, Dumas GA. Evaluation and calibration of an electromagnetic tracking device for biomechanical analysis of lifting tasks. *Journal of Biomechanics* 2002;35(2):293-7.

## *Appendix G. Illustration of FPI-6 scores*

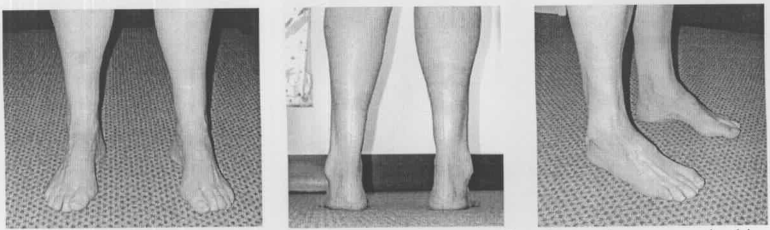
To illustrate the degree of face validity of the FPI scores, a series of digital images were taken for each participant when they attended for trial evaluations. The FPI scores in this small sample ranged from –9 to +8. A cross-section of the images are presented for illustrative purposes, in order of FPI score and along with the FPI scores pertaining to those participants. The final three images in the series (example 7) are from a patient attending the peripheral neuropathy clinic, but not included in this trial, who has a planus type foot associated with an atypical form of peripheral neuropathy. This patient is included simply to better illustrate the spectrum of foot postures and FPI scores seen in CMT.

**Example 1. 34 year old male. FPI-6 scores: Left=-9, Right=-6**



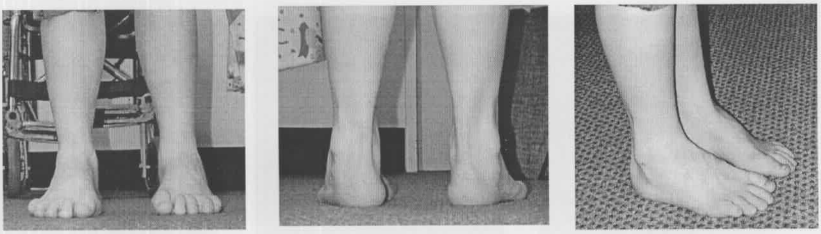
This is a significantly negative FPI-6 score reflecting the pronounced cavoid foot type in this patient with classic CMT1A. The greater clawing of the left foot (reflected in the more negative FPI score) is evident in the anterior view. Note also the tension in the tendon of Peroneus Longus in the oblique view.

**Example 2. 59 year old female. FPI-6 scores: Left=-3, Right=-4**



In this example the moderately negative FPI total scores reflect the moderate cavus in this older patient with mild CMT1A. The two FPI scores are similar reflecting the symmetry of the foot postures.

### Example 3. 11 year old male. FPI-6 scores: Left=-4 , Right=-3



In this young man with severe CMT1A the marked muscle imbalances have already lead to significant change in foot posture. Although the clinical picture is fairly symmetrical, the left foot is slightly worse than the right as evidenced in the FPI score and visible in the anterior view.

### Example 4. 13 year old female. FPI-6 scores: Left=+1, Right=0

In this example, the effects of CMT are minimal. The foot posture is essentially normal, demonstrating the typical characteristics of an older child's foot type.

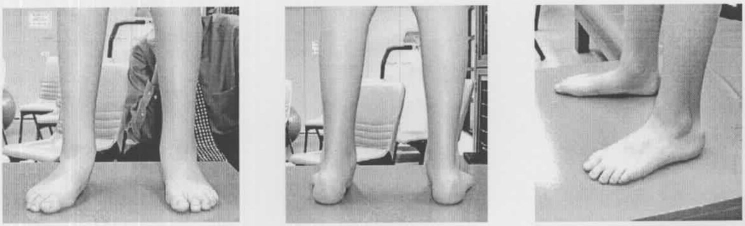
### Example 5. 7 year old female. FPI-6 scores: Left=+2, Right=+4

This young girl with early CMT1A has clinical weakness of the anterior lower-leg musculature but has not yet developed any foot posture changes associated with CMT. The foot is in the mild planus position normal for this age, with right foot just slightly more planus/pronated than the left.

### Example 6. 9 year old female. FPI-6 score Left=+8, Right=+3

This young patient has severe CMT with profound loss of muscle power in all muscle groups. Patients with profound muscle weakness often develop a ‘flail’ type flatfoot. Note that while the right foot still shows a robust arch, this patient exhibits signs of planus changes in the left foot.

### Example 7. 11 year old female. FPI-6 score Left=+9, Right=+9



This young lady was not part of the study as she has an atypical but severe peripheral neuropathy with a profound drop-foot and significant bilateral muscle weakness. Her parents report that she was developing a cavus foot type until recent years, but has rapidly adopted a marked and worsening planus foot posture. This flattening is reflected in her highly positive FPI scores.