Biomechanical Assessment of Passive

Ankle Joint Complex Dorsiflexion

Alfred Gatt

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Abstract

The measurement of ankle joint dorsiflexion is an important component of the clinical examination of the foot and is also an outcome measure often employed in research. Diagnosis of ankle equinus or limited ankle dorsiflexion is based solely on this measurement. Although a great majority of research papers in this field utilise normal clinical goniometers for obtaining the maximum ankle dorsiflexion angle (MADA) and important clinical decisions are based on these findings, there is overwhelming evidence that this method is highly unreliable. Thus this thesis aimed to investigate alternative methods of measuring ankle dorsiflexion and various issues that affect the MADA in order to obtain a clear picture of foot segment movement from which an Ankle Goniometer could be consequently designed and validated.

Ten different techniques were identified that included various apparatuses designed specifically for measuring ankle dorsiflexion. However, during validation, their methodological quality would have benefitted from the use of an actual patient population and comparison with a reference standard, which caused papers to score poorly on methodological quality assessment. It was concluded that issues affecting this measurement and that needed to be researched further include: foot posture, the amount of moment applied and the stretching characteristics of the calf muscle tendon unit.

Experiments within this study indicated that in adults, the mean maximum pronated angles were always higher than in other postures, with 8.27^{o} difference between the pronated and supinated postures ($p=0.032$) and 5.78^{o} between pronated and neutral ($p=0.000$). However, the reported difference between neutral and supinated (mean angle of 2.49^{o}) is of little clinical significance. It was observed that the forefoot always travels through a greater angle than the hindfoot in all 3 foot postures, while the hindfoot to forefoot angle increases during the application of a moment, indicating that the 'midtarsal joint locking mechanism' cannot be applied to passive dorsiflexion of the foot. In adolescents, there are no significant differences in the mean MADA between the 3 postures, implying that this measurement technique may be performed in any of these postures. It was also concluded that there is no need to control moment applied during this measurement procedure to produce consistent results between raters and that the calf muscle tendon unit does not stretch significantly following brief repetitive passive stretching.

An ankle goniometer that measured purely hindfoot movement by eliminating forefoot influence and that increased reliability by holding the foot in the chosen posture, was consequently designed. This was validated by synchronizing with an electrogoniometer and an optoelectronic motion capture system. Reliability testing, with the foot held in a supinated posture as opposed to the traditional Rootian method of placing the foot at subtalar joint neutral position, spanned a number of different trials, including intra-tester and inter-tester reliability studies utilising both controlled and uncontrolled conditions, in convenience samples of healthy participants and a random sample of patients. Reliability testing between 4 raters with little experience on the utilization of this device was finally conducted. It has been shown that the Ankle Goniometer is a valid and reliable device for measuring ankle joint complex dorsiflexion both in healthy adults and in a patient population.

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Glossary

ANOVA	Analysis of Variance
Ankle Dorsiflexion	Sagittal plane, upward movement of the foot occurring only at the ankle joint.
Dorsiflexion	Upward movement of the foot in the sagittal plane
Foot Dorsiflexion	Dorsiflexion of the foot occurring through the ankle, subtalar and midtarsal joints
Goniometer	A device shaped like a protractor to measure joint angles
Greenhouse-Geisser Test	Statistical test to be used when Sphericity has been violated. Provides corrections for violations of sphericity
Mauchly's Test of Sphericity	A statistical test for testing the assumption of sphericity
Maximum Ankle Dorsiflexion Angle	The maximum angle attained by the ankle during passive dorsiflexion
Maximum Foot Dorsiflexion Angle	The maximum angle attained by the foot during passive dorsiflexion, with movement occurring at the ankle, subtalar and midtarsal joints. Kinematically, the foot is treated as a single segment.
Pronated Position	A position in which the foot is abducted, everted and dorsiflexed.
Pronation	Triplanar movement comprising abduction, eversion and dorsiflexion. Typically occurs in 'flat feet'
ROM	Range of Motion
Root Theory of Biomechanics	A highly-criticized theory of podiatric biomechanics first put forth by Root, Orien and Weed in 1977 in their book "Normal and Abnormal Function of the Foot".
Sphericity	A condition where the variances of the differences between all combinations of related groups (levels) are equal. Sphericity can be likened to homogeneity of variances in a between-subjects ANOVA
Subtalar Joint	Joint formed by the inferior aspect of the talus and superior aspect of the calcaneus. Principally responsible for pronation and supination of the foot
Subtalar Joint Neutral Position	A position where the subtalar joint is neither pronated nor supinated.
Supinated Position	A position in which the foot is adducted, inverted and plantarflexed
Supination	Triplanar movement comprising adduction, inversion and plantarflexion. Typically

	occurs in ‘high arched’ feet
Vicon	A proprietry brand of motion capture systems comprising multiple infra-red emitting cameras. Vicon software include “Nexus” for capturing movement and “Polygon” for analysing movement.

Publications arising from this Dissertation

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Gatt, A, Chockalingam N. 2012. Assessment of Ankle Joint Dorsiflexion: An Overview. *Revista Internacional de Ciencias Podológicas.* Vol. 6, Núm. 1, 25-29.

Gatt A, Chockalingam N. The effect of uncontrolled moment and short-term, repeated passive stretching on maximum ankle joint dorsiflexion angle. *Foot*. (2012), doi:10.1016/j.foot.2012.12.001 (In Press).

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Chapter 1

Introduction

Aspects of this chapter have been published as follows:

Gatt A, Chockalingam N. 2012. Assessment of Ankle Joint Dorsiflexion: An Overview. Revista Internacional de Ciencias Podológicas. 6(1):25-29

1.0 Introduction

This introductory chapter provides an overview of a common condition affecting the foot, referred to as "ankle equinus" or "limited ankle dorsiflexion" and its effects on the lower extremities, then explores some of the important issues involved in the clinical measurement of ankle dorsiflexion.

1.1 Background to the Thesis

The ankle joint is an important component of the musculoskeletal system necessary for normal ambulation. It is formed by the articulation between the mortise of the lower tibia and fibula and the trochlear surface of the talus. Actually composed of 3 joints - the tibiotalar, tibiofibular and fibulotalar joints (Donatelli and Wolf 1990) ¯ it plays an essential role during walking, and is of great importance during physical activities (Leardini et al. 1999b). It is generally believed that the upward and downward movement of the foot, referred to as dorsiflexion and plantarflexion respectively, occurs mainly at this joint (Leardini et al. 1999b; Root et al. 1977). This Tibio-talar movement involves the rotation of the talus within the ankle mortise (Hamel et al. 2004) with unresisted mobility being obtained by the sliding of the articular surfaces upon each other (Leardini et al. 1998).

The ankle moves through an average of 20 ^{o} to 40 ^{o} total range of motion during walking (Weir and Chockalingam 2007). Whilst this is a triplanar joint, i.e. with movement occurring in all 3 body planes, the orientation of its axis, which runs from the medial to the lateral malleolus, facilitates the majority of this motion to occur in the sagittal plane. It is claimed that during normal locomotion, 10^{o} of ankle dorsiflexion is required for the forward translation of the centre of gravity of the body to occur during single limb support (Root et al. 1977), although this has been challenged (Weir and Chockalingam 2007). This forward translation occurs in the sagittal plane, and this is said to occur using a 3 rocker system to permit advancement (Perry 1992). This sagittal plane movement at the ankle occurs during the 2nd rocker (Dananberg 2004).

Reduced range of movement at this joint has been termed as *gastrocnemius contracture*, *limited ankle dorsiflexion* and *ankle equinus*. This condition has been related to various functional lower extremity musculoskeletal conditions. Measurement of ankle dorsiflexion involves the use of a measuring device called a "goniometer" (a protractor with a stable and a moving arm that quantifies an angle), which has been criticized as being highly unreliable. Hence various other measuring techniques have been developed.

1.1.1 Limited Ankle Dorsiflexion

Clinically, lack of ankle joint dorsiflexion is known by many terms, including *equinus*, *gastrocnaemius contracture* and *limited ankle dorsiflexion*. The classical orthopaedic definition of ankle equinus is a plantarflexed foot as is often seen in neurological conditions such as cerebral palsy. Another definition is '*<10^o of dorsiflexion with the subtalar joint placed at neutral position*.' It has been hypothesised that placing the foot at subtalar joint neutral position with the midtarsal joint loaded will reduce any movement extraneous to the ankle joint (Root et al. 1977). While Lavery et al. (2002) defined equinus as <0^o of dorsiflexion, DiGiovanni et al. (2002) defined this condition as <5° of ankle dorsiflexion with the knee extended or <10° with the knee flexed and used the term '*gastrocnaemius tightness'*.

The most common cause of Equinus is tightening or shortening of the gastrocnaemius/soleus group (collectively known as the *triceps surae*), causing premature activity of ankle plantarflexors (Hill 1995). In fact, the term *muscular* ankle equinus has also been coined. This is thought to result from modern lifestyle factors in the daily environment, which put patients at risk of developing this condition. These factors include overtraining of muscles, sleeping with the feet in a plantarflexed position for long hours and sitting for long hours at desks with the knees flexed and the feet in an equinus position. Even during standing, the gastrocnaemius is being used to maintain the centre of gravity anterior to the ankle joint axis (Kirby 2000; Kirtley 2006) and to oppose the dorsiflexing moment imposed on the foot (Kirtley 2006).

1.1.2 Effects of Ankle Equinus

Lack of ankle dorsiflexion is compensated for by altering gait, including early heel-off in mild cases (bouncy gait) or even a total lack of heel strike in severe cases (such as in cerebral palsy); triplanar rearfoot motion (pronation) and an adducted gait pattern (Root et al. 1977). Equinus can be uncompensated, with the patient walking on the toes, or compensated by various methods, including foot abduction, significant pronation of the mid foot and rearfoot, resulting in the loss of the medial longitudinal arch and abduction of the forefoot (Sullivan 1997).

Once the ankle is restricted, the midtarsal joint is the next joint through which dorsiflexion may occur. This is achieved by excessive pronation of the foot (Dananberg 2004), which turns it into a mobile adaptor to facilitate dorsiflexion at this joint. Forces on the midtarsal joint may eventually lead to the midfoot break and significant structural foot problems (Harrison et al. 2001).

Lack of ankle dorsiflexion is said to produce a sagittal plane blockage (Dananberg 2004). This refers to a restriction of rotational motion of the foot or any part of it – such as the ankle and first metatarsophalangeal joint - within the sagittal plane. As the forward movement of the foot occurs mainly in the sagittal plane, anything that prevents this is likely to cause a change in gait and produce compensatory patterns of walking. In fact, *muscular* ankle equinus, or gastrocnaemius contracture, has been associated with various foot conditions. In a study of 209 consecutive patients with musculoskeletal problems in the foot, a prevalence of 96.5% of this condition was found and has been linked to foot problems including plantar fasciitis and metatarsalagia (Hill 1995).

Various authors claim that ankle equinus may be a significant causative factor of a variety of lower extremity conditions, ranging from low back pain, hyperextended knees, hallux rigidus, calcaneal spurs (Wrobel et al. 2004), chronic plantar heel pain (Irving et al. 2006), foot nerve entrapment (Barrett and Jarvis 2005), Achilles tendinopathy, Posterior Tibial Tendon Dysfunction, plantar fasciitis (Hill 1995), metatarsalgia (Subotnick 1971) and forefoot callus (Sgarlato et al. 1975). It has been shown that diabetic patients with equinus have significantly higher pressures in the forefoot than those without (Lavery et al. 2002).

Although highly evident equinus may be a presentation of neurological conditions, including toe walking (Sobel et al. 1997) and cerebral palsy (Allington et al. 2002), the milder form of equinus does not normally become apparent except through a thorough lower limb examination. This form of equinus can affect anyone, from diabetics (Lavery et al. 2002; Pham et al. 2000), adolescent athletes and children (Saxena and Kim 2003). In individuals with neurological conditions, contracture of the triceps surae is well documented. The impact of contracture of the gastrocnaemius in the normal patient needs to be researched more because it can have deleterious effects such as pain in the forefoot and/or midfoot (Digiovanni et al. 2002).

1.1.3 Examination

Thus it is evident that ankle joint assessment, including the accurate measurement of the range of motion of this joint, is an important aspect of any musculoskeletal examination. A biomechanical evaluation of the foot normally starts with passive examination of the range of movement of this joint. Ankle joint movement examination may be performed using various methods. The procedures mostly used in clinics and research include goniometry (Gastwirth 1996; Root et al. 1977) and visual estimation. (Digiovanni et al. 2001). This may be because goniometers can be found easily in clinics and are relatively inexpensive. During goniometric examination, one arm of the goniometer is placed along a bisection of the lateral aspect of the lower leg, and the other arm along the lateral margin of the foot (Gastwirth 1996; Root et al. 1977). The subtalar joint is held in neutral position, with the midtarsal joint locked. An upward force is applied until the maximum ankle joint range of motion is reached. This examination is initially done with the knee extended and then with the knee flexed in order to differentiate between gastrocnaemius (the former) and soleus tightening (Gastwirth 1996; Root et al. 1977; Silverskiold 1924).

However, there is ample evidence in literature that goniometer based measurements for ankle joint movement are not reliable (Kim et al. 2011; Martin and Mcpoil 2005; Rome 1996; Van Gheluwe et al. 2002; Wrobel and Armstrong 2008). Although hand-held goniometers have introduced quantification (Woodburn et al. 2002) they have major drawbacks in measuring ROM; goniometric reliability is unproven with reliability studies often having major flaws in design or analysis (Jordan et al. 2001). In fact, goniometry has been shown to be unreliable for rearfoot assessment (Ball and Johnson 1993; Buckley and Hunt 1997) and the responsiveness of ankle range of motion measurements is uncertain (Martin and Mcpoil 2005).

These problems with reliability have spurred the design of a number of devices and procedures aimed at measuring ankle dorsiflexion. These include, among others:

- The Equinometer (Assal et al. 2003; Weaver et al. 2001)
- The Mechanical Equinometer (Meyer et al. 2006)

- The Biplane Goniometer (Donnery and Spencer 1988)
- The Iowa Ankle Device (Wilken et al. 2004)
- The Lunge Test (Bennell et al. 1998)

It is evident that there is still a paucity of information in quantifying Ankle Joint dorsiflexion. An inappropriate measurement using an inappropriate technique could have important repercussions. Wrong techniques for measurement and the use of poorly-validated instruments may provide a mis-diagnosis from which wrong treatment modalities could ensue.

1.2 Rationale for the Study

The measurement of ankle joint dorsiflexion is an essential component of the orthopaedic examination of the foot. This measurement procedure is normally done by dorsiflexing the foot through the application of a force to the metatarsophalangeal joint area (the "ball" of the foot). For many years, the normal standard for measuring this movement has been the goniometer, which is cheap to buy and is easily found in the majority of musculoskeletal clinics. However, it has been clearly demonstrated through various scientific papers (Elveru et al. 1988; Kim et al. 2011; Martin and Mcpoil 2005; Rome 1996; Wrobel and Armstrong 2008) that this goniometric method is not reliable for various reasons, including: errors in placement, non-standardized placement of the goniometer and various issues with establishing subtalar joint neutral position. Perhaps because of this, various devices that claim to measure ankle dorsiflexion, have been presented in literature (Assal et al. 2003; Meyer et al. 2006; Wilken et al. 2011); some of these include very sophisticated and specialized equipment which makes them very expensive and thus out of reach of many clinics (Mayhew et al. (1994) quoted their use of an isokinetic dynamometer to assess ankle range of motion as costing $25,000).

It is quite alarming to note that, notwithstanding the evidence of high unreliability of the traditional goniometer, there is still a large proportion of research being done to-date that relies on goniometric ankle dorsiflexion measurement, making the results of, often, very valid research, also unreliable and inconsistent (Johanson et al. 2006b; Wessling et al. 1987). This would have been easily avoided if the respective researchers had used some type of validated ankle goniometer which, however, to date, is not very easily found.

Another important issue that possibly influences the use of goniometers for research and clinical practice is the lack of freely-available information regarding this issue. Indeed, the use of normal goniometers is still being taught and presented in textbooks (Gastwirth 1996).

Although this clinical examination is routinely carried out, little is known as to what actually occurs when the foot is dorsiflexed passively. Root Theory (Root et al. 1977) advocates the use of subtalar joint neutral position and locking of the midtarsal joint by the application of a force underneath the 4th and 5th metatarsophalangeal joints when measuring ankle dorsiflexion, so that forefoot movement is eliminated and there remains only movement at the ankle. This claim of over 30 years has never been thoroughly investigated. Nowadays, however, with accurate opto-electronic motion capture systems and the use of kinematic foot models, it is possible to investigate inter-segmental foot movement so that it can be determined where and how much movement results from the application of a moment of force at the metatarsophalangeal joint area.

This thesis will thus investigate foot kinematics and the effect on foot segment motion upon the application of a force to dorsiflex the foot. The moment applied to the forefoot causes a rotational movement around the ankle joint, thus it is an important element that has to be explored. It has been noted that all goniometers that were designed specifically for measuring ankle joint dorsiflexion make use of a force gauge to ensure that a constant moment is applied to all subjects (Assal et al. 2003; Meyer et al. 2006; Scharfbillig and Scutter 2004; Wilken et al. 2011). Charles et al. (2010) insist that it is important that standardized torque be applied to the ankle to achieve valid and reliable estimates of range of motion (ROM).

This thesis challenges this approach, postulating that when a known moment is applied to the foot, high reliability results can be easily attained. It is hoped to prove that, since the nature of this examination procedure involves range of motion measurement of the joint, the application of a known moment is unnecessary as the only element that limits joint movement is the end of motion, which depends either on the extensibility of the calf tendon muscle unit or a bony stop as the talus wedges itself between the tibial and fibulalar mortise at the ankle joint.

The final results of this thesis will provide evidence that the ankle joint is not as simple to measure as it may appear, but in fact various elements, including foot posture and moment, must be looked at and that practitioners and researchers must be aware of issues regulating the measurement of this joint.

1.3 Scope of the investigation

The boundaries of this investigation were:

1. To investigate maximum ankle dorsiflexion as would occur during a clinical examination for range of movement of this joint and not to investigate ankle stiffness, which is calculated by the dorsiflexing angle and the moment applied.

2. To design an Ankle Goniometer suitable for the investigation of the various issues encountered during this thesis and for the completion of this thesis, and not for commercial use. The resultant goniometer may require additional ergonomic design to attain this stage.

3. To investigate foot and ankle dorsiflexion measurement in a non-neurological population. This is mainly because:

   - Equinus secondary to neurological conditions (cerebral palsy, stroke, etc) is easily diagnosed in the majority of instances since there is quite a distinct plantarflexion of the foot, accompanied by signs and symptoms of neurological impairment such as spasticity. Consequently there are no issues related to its diagnosis.

   - Ankle dorsiflexion in the neurological patient is being actively researched elsewhere.

   - The possibly high prevalence of limited ankle dorsiflexion (Hill 1995) and the condition remaining undetected because of wrong diagnostic techniques, has a major impact on the way foot conditions are being diagnosed and treated.

   - These forms of 'milder' equinus may be quite wide-ranging in the 'normal' population, often remaining undiagnosed because of this 'mild' nature of the condition. Notwithstanding this, equinus can have wide ranging effects on the patient, often being overlooked during clinical examination because of the serious issues related to goniometric measurement, which is the normal method of clinical assessment through which a proper diagnosis is reached.

1.4 Need for the study

Due to the importance of ankle joint examination and various lacunae that exist in research evidence in this area, there is a need to determine what exactly happens during this examination procedure. The identification and consequent resolving of issues involved during ankle joint measurement will enable us to provide more consistent results that are known to be reliable and that can be compared directly even if not arising through the same practitioner/s.

1.5 Aims and Objectives

The main aims of this investigation were:

- To investigate sagittal plane biomechanics of passive ankle joint dorsiflexion, as occurs when a practitioner examines the ankle for maximum range of motion
- To design and validate a new Ankle Goniometer for clinical and research purposes.

The objectives of this investigation include:

- To identify the various measurement techniques currently in use and any difficulties related to ankle joint measurement through a structured systematic review (Chapter 3).
- To measure sagittal maximum foot dorsiflexion and foot segment movement during passive ankle dorsiflexion, both in adults (Chapter 6) and children (Chapter 7).
- To quantify the effects of foot posture on maximum ankle angle during passive ankle joint examination (Chapters 6 and 7).
- To determine variation in the hindfoot to forefoot angle (Chapters 6 and 7).
- To investigate the application of force on the maximum foot dorsiflexion angle and maximum ankle angle during passive ankle joint examination (Chapter 8).

- To derive design criteria to enable the design of a suitable Ankle Goniometer (Chapter 9).
- To establish validity and reliability of the Ankle Goniometer to enable it to be used in clinical practice (Chapters 10 and 11).
- To devise an updated protocol for the measurement of ankle joint complex dorsiflexion (Chapter 14).

1.6 Ethical approval

Appropriate ethical approval was sought, and granted by the University Ethics Committee, depending where the study was held. All participants provided informed consent to participate in the various experimental studies. In the case of minors, a parent provided the informed consent, also with the approval of the child. Staffordshire University Research Ethics Committee provided ethical approval for the study carried out at the Biomechanics Laboratory (Chapter 6). Faculty of Health Sciences and University of Malta Research Ethics Committees provided ethical approval for the other studies, which were all carried out in Malta.

Information regarding ethics concerning each trial will be outlined in the method section of the corresponding chapter of this thesis and respective Ethical approvals, participant information sheets and consent forms may be found in Appendix 1.

1.7 Structure of this Thesis

This dissertation is set out over 14 chapters.

Chapter 1 introduces the subject matter, providing an overview of the various issues involved, i.e. the importance of ankle dorsiflexion during gait, the effect of ankle equinus on the feet and the various issues relating to ankle dorsiflexion measurement, mainly the unreliability of current goniometric techniques that may be providing wrong results, thus possibly wrong diagnosis and treatment.

Chapter 2 provides a literature review which presents those topics related to the main subject of this thesis, i.e. ankle dorsiflexion measurement. These topics introduce important background information on which this thesis will be based.

A systematic review of ankle measurement techniques is provided in **Chapter 3,** the backbone of information upon which this thesis was built and from which further scientific investigations ensued. The systematic review enabled the investigator to identify those factors that mostly influence ankle dorsiflexion measurement; i.e. foot posture and the moment applied to dorsiflex the foot. This consequently led to a series of scientific experiments in order to arrive at important conclusions that would provide the basis for a goniometric device and/or a measurement protocol, which was later designed and validated during the course of this investigation.

Chapter 4 describes and criticises the currently available methods of measuring ankle dorsiflexion in order to provide justification for the need of designing an innovative device for measuring ankle dorsiflexion, i.e. an Ankle Goniometer.

Following this outline, **Chapter 5** provides a background technical information and methodological issues around the equipment and the analysis procedure used within this study.

Chapter 6 describes the investigation that provides a kinematic segmental analysis of adult sagittal plane motion during passive ankle dorsiflexion. Two important factors affecting dorsiflexion are analyzed: the effect of foot posture and moment on maximum ankle dorsiflexion. From data collected, utilising a validated foot model, the forefoot to hindfoot angle, tibia to hindfoot angle and tibia to forefoot angle are studied.

There is a paucity of information regarding children's passive ankle dorsiflexion as most research concentrates on neurologically-induced ankle equinus and its measurement. The second investigation, presented in **Chapter 7**, replicated the previous trial, however on an adolescent population, as it was hypothesised that young feet, due to increased flexibility, would behave differently to adult feet during passive ankle joint dorsiflexion.

Chapter 8 investigates the effect of uncontrolled moment when it is applied to the forefoot during passive ankle joint dorsiflexion measurement. The great majority of ankle dorsiflexion techniques utilise a controlled moment to ensure reliability. However, it is hypothesised that applying a known moment is quite unnecessary as the ankle dorsiflexes to the end of its range of motion, which is determined mainly by the extensibility of the triceps surae. It has also been hypothesised that, as this examination technique involves repetitive movements to the end of travel of the ankle joint, there may be a stretching effect on the calf muscles which could affect the results of reliability testing of the new Ankle Goniometer. Thus this chapter also investigates whether repeated, short repetitive stretching causes a significant effect on the maximum ankle dorsiflexion angle. Data acquired from the trial in Chapter 5 will be utilised to this effect.

The various design iterations of the Ankle Goniometer will be presented in **Chapter 9** and the validity and reliability of this Ankle Goniometer will be investigated thoroughly in **Chapter 10**. Before any new diagnostic equipment is applied to patients, rigorous testing needs to be performed. This testing differs from reliability testing of other equipment, in that recommendations obtained from the Systematic Review will be employed for validity and reliability testing.

Following validation and inter-rater reliability testing with a controlled moment and intra-rater reliability, the Ankle Goniometer will be put to use to explore an important issue that has constantly arisen during this investigation: whether it can be reliably used by multiple raters with uncontrolled moment. This is considered to be an important issue because inability to produce consistent results would hinder clinicians from assessing effectiveness of treatment, for example in a pre- and post-intervention trial and would also prevent comparison of results between clinicians. This is outlined in **Chapter 11.**

Chapter 12 provides a summative discussion. Each trial will have its own discussion, where the various issues pertaining to the particular hypotheses under investigation will be considered. This chapter will provide a summative discussion which ties together the various findings of the whole investigation, outlining all the evidence resulting both from this thesis and other trials. This will result in a summary of evidence regarding foot and ankle dorsiflexion measurement that would be the basis for the synthesis of a protocol for the measurement of ankle joint complex dorsiflexion.

Whilst **Chapter 13** will summarize the various conclusions reached during the whole project and summative discussion, **Chapter 14** will synthesize findings and produce recommendations for performing ankle joint dorsiflexion measurement and will provide directions for further study in this challenging area.

Chapter 2

Literature Review

2.0 Literature Review

This chapter provides background information and a review of literature related to the various methods of measuring ankle dorsiflexion together with a description of the anatomical structures involved. This is necessary so as to present a complete picture of the subject matter.

The procedure of measuring ankle dorsiflexion is not as simple as it initially appears, so much so that various researchers have devised different methods of obtaining ankle/foot dorsiflexion angles. Indeed, few practitioners would consider the difference between an 'ankle dorsiflexion angle' and a 'foot dorsiflexion angle' and that foot segmental movement could interfere with the expected results. There exist various lacunae, some of which are obvious, and some of which are not, such as the movement of the various foot segments during passive dorsiflexion. The "midtarsal joint mechanism locking mechanism", which has been hypothesised by Root et al (1997) and accepted as standard so much so that it has been integrated into clinical practice, has never been investigated before and thus few are aware that there are issues that would affect the measured angle and, potentially, the resultant diagnosis and treatment given to the patient.

Thus this chapter aims to address and clarify these issues, some of which will later require to be resolved by the research project covered throughout this thesis.

2.1 The Ankle Joint

The ankle joint is formed by the articulation between the mortise of the lower tibia and fibula and the trochlear surface of the talus (Figures 2.1 and 2.2). It is in fact 3 joints: the tibiotalar, tibiofibular and fibulotalar joints (Donatelli and Wolf 1990). Referred to as the talocrural joint, it is the main joint through which sagittal movement of the foot, i.e. dorsiflexion and plantarflexion, occur.

Figure 2.1 Ankle Mortise: Adapted from http://www.pediatric-orthopedics.com/Topics/Bones/Ankle_Foot/ankle_foot.html

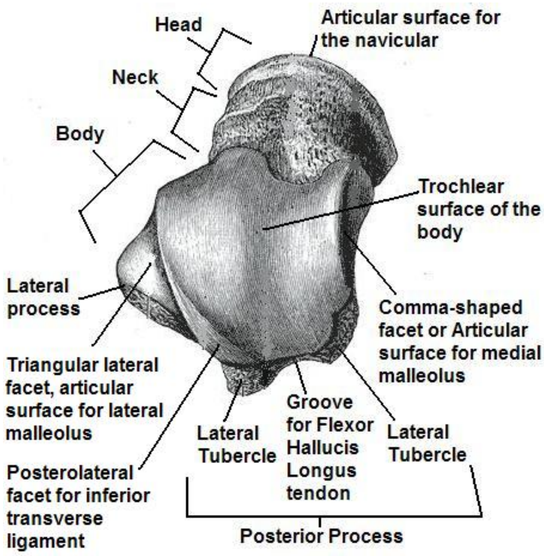
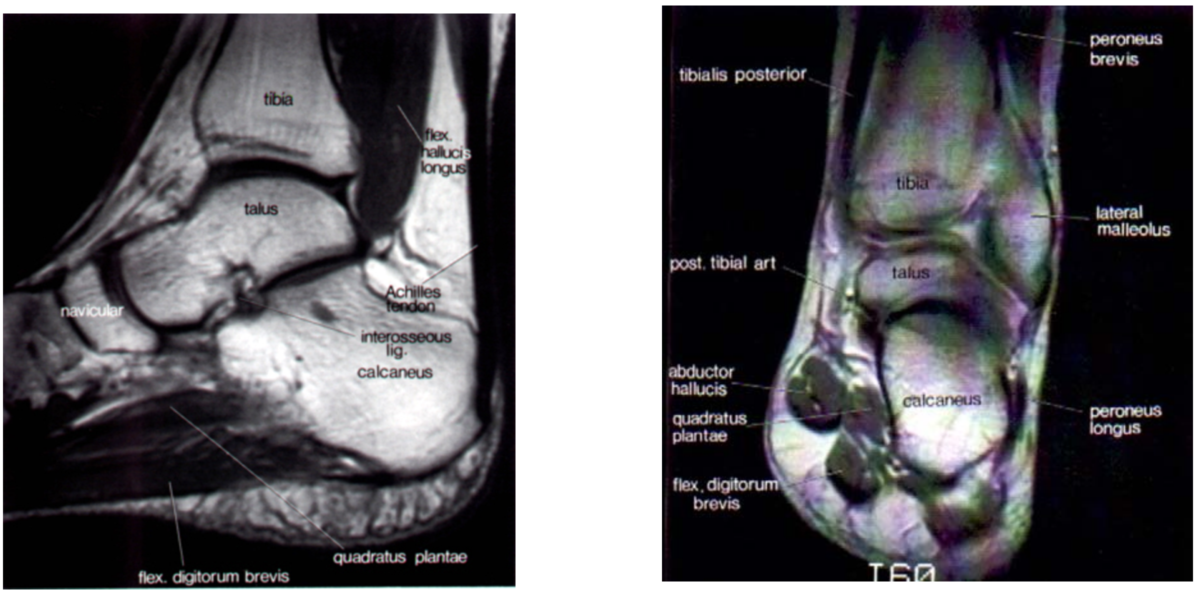


Figure 2.2: Talus. Adapted from http://podiatryboards.web.officelive.com/talus.aspx

The smooth trochlear surface of the talus is hemispherical in shape if viewed laterally. This allows for the smooth movement of the talus inside the mortise. Viewed from above, the trochlear surface is wider anteriorly. Thus with dorsiflexion, the anterior, wider part forms a boney stop. This causes a slight widening of the tibia and fibula, a movement allowed by the strong interosseous tibiofibular ligament and the anterior and posterior tibiofibular ligaments which hold the tibia and fibula together (Moore et al. 2006). Plantarflexion is limited by the posterior tubercle of the talus and tension applied to the anterior talofibular ligament (Wernick and Volpe 1996). Passive movement of the ankle complex is determined by the articular surfaces and ligaments (Leardini et al. 1999a).



A) B)

Figure 2.3: MRI of ankle joint. A) Lateral view B) Posterior View.
From: http://www.med.nagasaki-u.ac.jp/radiolgy/MRI%20of%20the%20FOOT/MRI-CDNUH/fig50.html

The medial malleolus is smaller and lies more proximal to the lateral malleolus. Because of its orientation, which runs from the fibular to the tibial malleolus, movement around the axis of the ankle joint is triplanar, with abduction and external rotation occurring with dorsiflexion, and adduction and internal rotation occurring with plantarflexion (Castro 2002; Donatelli and Wolf

1990). Although it is reported to lie an average of 8 degrees from the transverse plane and 20 to 30 degrees from the frontal plane (Wernick and Volpe 1996), it varies considerably across the population and changes continuously across the range of movement of the ankle joint (Lundberg et al. 1989b).

During loading response, the talus rotates inwards and the ankle axis rotates medially (Figure 2.5).

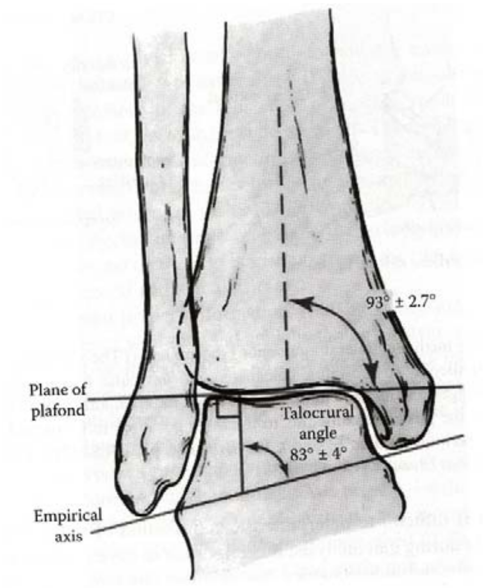


Figure 2.4: The tibiotalar articular surface usually has a slight lateral tilt, averaging 3^{o}. The talocrural angle indicates the empirical axis which averages 83+/-4^{o}. (adapted from Khazzam et al, 2008)

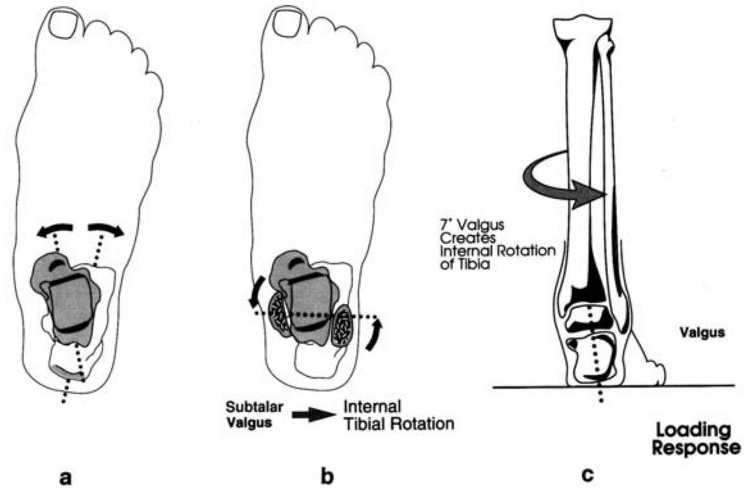


Figure 2.5: Rotation of talus and ankle axis during loading response (adapted from Perry, 1992)

The Finite Helical Axis (FHA) of the talo-crural joint is defined as the axis of rotation between two extreme static poses (e.g. extreme dorsiflexion to extreme plantarflexion) (Sheehan 2010). It is claimed that the ankle joint uses different axes for plantarflexion and dorsiflexion. The coronal plane axis passes approximately through the centre of both malleoli with, however, a possible 37^{o} variation between individuals. This axis of rotation also has a tendency to become more vertical when there is medial rotation of the leg (Lundberg et al. 1989b).

A comprehensive list of research studies that have investigated the ankle joint axis is presented in table format by Sheehan (2010), describing the various inclination angles of the axis reported by research over the years.

Even though early three-dimensional models represented the ankle joint complex by three degrees of freedom (3-DOF) (Van Den Bogert et al. 1994), the ankle can be modelled as a fixed-hinge joint (Sheehan 2010) with one degree of freedom (1-DOF) (Van Den Bogert et al. 1994). Measurement of ankle movement is difficult to achieve *in vivo* because this requires implantation of bone markers (Lundberg et al. 1989b) or more specialized apparatus such as a CT-based bone contour registration method (Tuijthof et al. 2009a), since the movement of the talus cannot be measured directly (Van Den Bogert et al. 1994).

The ankle joint is held together by a number of ligaments, namely the *deltoid ligament* on the medial aspect, which includes the *anterior* and *posterior tibiotalar ligaments*, the *tibiocalcaneal* and *tibiotalar ligaments*. On the lateral aspect lies the *lateral ligament* of the ankle, which consists of the *anterior* and *posterior tibiofibular ligaments* and the *calcaneofibular ligament* (Moore et al. 2006).

2.1.1 Muscular Control at the Ankle Joint

Movement at the ankle joint is powered by the Dorsiflexor and Plantarflexor muscles.

The **Dorsiflexors** are the Tibialis Anterior, Extensor Digitorum Longus and Extensor Hallucis Longus. Their function is determined by their position; i.e. they all pass in front of the ankle joint. The Tibialis Anterior has the largest cross section and thus provides the most torque (functional potential).

Table 2.1: Ankle Dorsiflexor Torques. (From Perry, 1992)

Relative Dorsiflexor Torque	
	(% Soleus)
Tibialis Anterior	6.9%
Extensor Digitorum Longus	2.7%
Extensor Hallucis Longus	1.1%

Dorsiflexor muscle activity is initiated in pre-swing, with contraction of the Extensor Hallucis Longus. Peak activity of the dorsiflexors is in the initial swing phase until by midswing activity decreases. Intensity of Tibialis Anterior rises again at Initial Contact, but by Loading Response phase all muscle activity is terminated (Perry 1992).

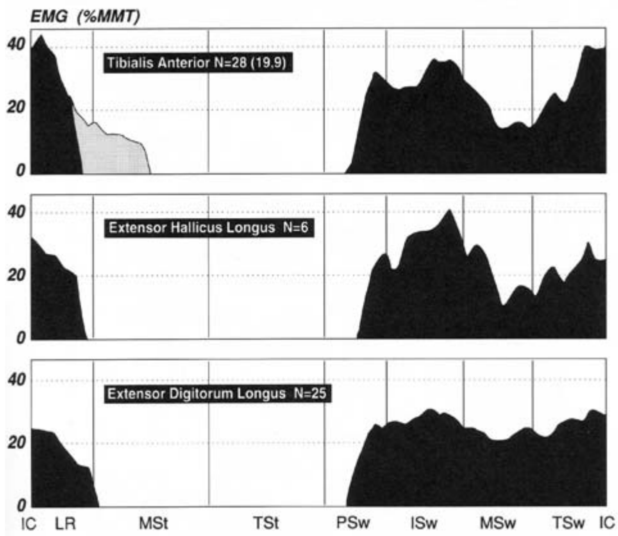


Figure 2.6: Ankle Dorsiflexor muscle activity (adapted from Perry, 1992)

The **Plantarflexors** include 7 muscles which pass posterior to the ankle. The main plantar flexor torque, however, is supplied by the Soleus and Gastrocnaemius which account for 93%, with the remainder supplying only 7% torque. These muscles include the Tibialis Posterior, Flexor Hallucis Longus, Flexor Digitorum Longus, Peroneus Longus and Peroneus Brevis (Perry 1992).

Table 2.2: Ankle Plantar Flexor Torques (from Perry, 1992)

Ankle Plantar Flexor Torques	
Soleus	100%
Gastrocnaemius	68.0%
Tibialis Posterior	1.8%
Flexor Hallucis Longus	6.1%
Flexor Digitorum Longus	1.8%
Peroneus Longus	2.4%
Peroneus Brevis	1.0%

The torque (functional potential) of ankle muscles is proportional to their physiological cross section and leverage. The Soleus, being the largest ankle muscle, provides the most torque (Table 2.2).

The Soleus and Gastrocnaemius, collectively known as the Triceps Surae, account for 93% of the total plantar flexor torque (Perry, 1992). Soleus action starts slightly before the Gastrocnaemius, towards the end of the Loading Response Phase, then continues throughout midstance. During Terminal stance, both muscles action increases, with Gastrocaemius action stopping before Soleus (Figure 2.7).

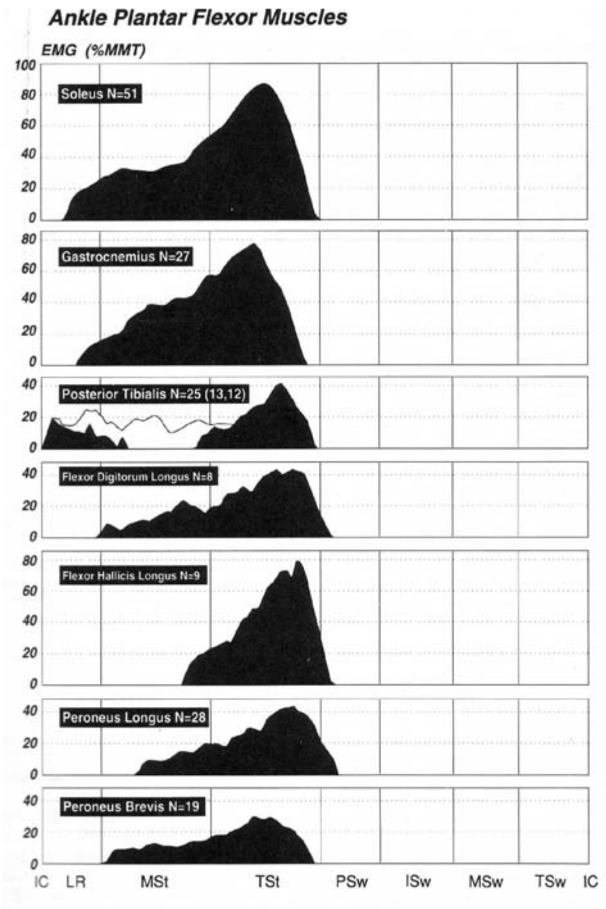


Figure 2.7: Ankle Plantarflexor muscle activity (adapted from Perry, 1992)

Neptune et al. (2001) have quantified contributions of individual ankle plantar flexors to support, forward progression and swing initiation during walking. The authors concluded that throughout single-leg stance both Soleus and Gastrocnaemius provide vertical support, in mid single-leg stance Soleus and Gastrocnaemius have opposite energetic effects on the leg and trunk to ensure support and forward progression of both the leg and trunk, and in pre-swing only Gastrocnaemius contributes to swing initiation.

In normal relaxed bipedal stance, the Centre of Mass of the body is anterior to ankle joint axis, causing a dorsiflexing moment of 20Nm in an 80Kg individual. In order to maintain equilibrium, the Gastrocnaemius must contract to exert a plantarflexion moment. Force generated by muscles is over 500N per foot (Kirtley 2006). Thus Gastrocnaemius is in constant use, even during standing (Figure 2.8).

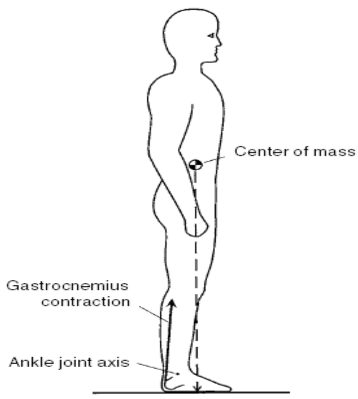


Figure 2.8: Centre of Mass (adapted from Kirtley, 2006)

2.1.2 The ankle during Gait

The ankle moves an average of 30^{o} total range of motion during walking (Kadaba et al. 1989), with the range of motion varying between 20^{o} and 40^{o} (Richards and Thewlis 2008).

During the stance phase, the ankle travels through three arcs of motion. Plantarflexion and dorsiflexion occur twice, with the last arc occurring during swing (Perry, 1992). These ‘arcs of motion’ have also been termed ‘phases of motion’ (Richards and Thewlis, 2008). Thus the ankle has 4 such phases of motion:

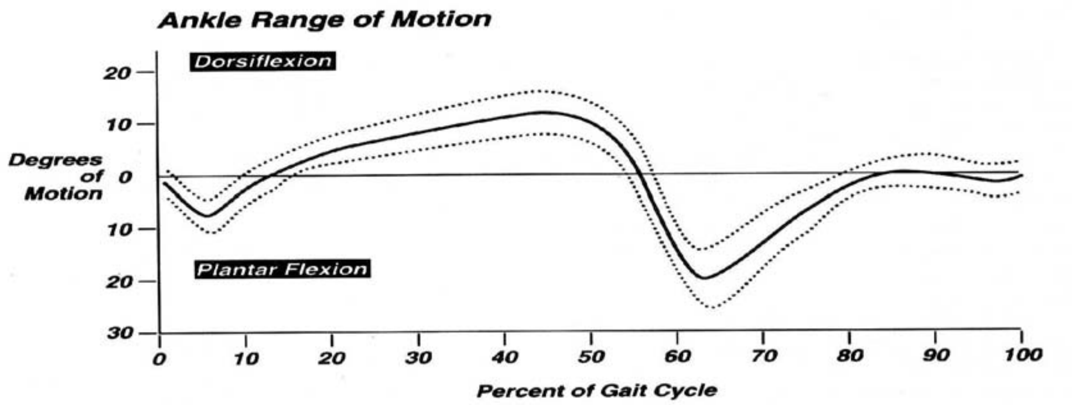


Figure 2.9: Ankle Range of Motion (adapted from Perrry, 1992)

Phase 1: At initial contact, the heel plantarflexes from neutral to 3^{o} to 5^{o} until the whole foot is in contact with the ground. This is also known as the 'Heel Rocker"

Phase 2: Ankle begins to dorsiflex during the 'second rocker' until 10^{o} is reached (Richards and Thelwis, 2008). Although this is the often-claimed required amount of dorsiflexion for normal foot function, Weir and Chockalingam (2007) performed a study which yielded ankle joint dorsiflexion value of between 12 and 22 degrees, with a wide variation between subjects.

Phase 3: At the beginning of double support, the heel begins to lift and plantarflexes an average of 20^{o}, in the phase referred to as the 'third rocker', with the foot pivot being now under the metatarsophalangeal joints. This is the period of active propulsion during which the plantar flexors are actively contracting to push the foot into plantarflexion and thus propelling the body forward.

Phase 4: During swing phase, dorsiflexion of the ankle allows the foot to clear the ground, reaching a neutral position of 0^{o} by mid swing (Richards and Thewlis, 2008).

2.2 Ankle vs Foot Dorsiflexion

The ankle plays an essential role during walking, being of strategic importance in human physical activities (Leardini et al. 1999b). It is generally believed that dorsiflexion and plantarflexion, occur mainly at this joint (Leardini et al. 1999b; Root et al. 1977). In fact, practitioners refer to 'Ankle joint flexibility' (Nitz and Low Choy 2004), 'limited ankle joint dorsiflexion', 'ankle equinus' and other analogous terms referring solely to ankle dorsiflexion.

The Degrees of Freedom (DOF) of the ankle joint has been debated for some time (Franci et al. 2009). Using 8 cadaveric feet in a jig with markers attached directly to the bones, it has been shown that there is approximately 5^{o} of movement between the talus and calcaneum during the first 25% of the stance phase of gait (Hamel et al. 2004). During late stance, these two bones rotate together and function as one unit. Leardini and colleagues have conducted extensive studies on ankle joint modelling using a number of dissected limbs. Their conclusions indicate that, during passive dorsiflexion, the ankle joint complex behaves as a single DOF system with large sagittal motions occurring mostly at the tibiotalar joint, with very little sagittal plane motion occurring at the subtalar joint (Leardini et al. 1999b; Leardini et al. 2001).

Work by Franci et al (2009) and Leardini et al. (1999a) supports further modelling of the human ankle joint as a one-DOF spatial mechanism. Some of the acknowledged limitations of their model were due to discrepancies caused by oversimplification of the articular surfaces and modelling constraints (Franci et al. 2009).

Tuijthof et al. (2009b) analyzed the range of motion of the ankle using computed tomography. Their findings also confirmed that nearly all dorsiflexion and plantarflexion occurs in the talocrural joint, with increased inversion and axial rotation at this joint being prevalent only in pathologic ankles. It was thus concluded that "Dorsiflexion/Plantarflexion is restricted to the talocrural joint."

One must, however, take into consideration that most of the above studies utilised a small number of amputated limbs, with the limitations that result from these procedures. Leardini et al.

(1999b) (1999) and Leardini et al. (2001) utilised 7 dissected limbs, while Franci et al. (2009) made use of "four skeleton-ligamentous lower leg preparations from lower limb amputation from four different subjects." These small sample sizes make it quite difficult to infer to larger populations. Nonetheless, most work by this Italian group appears to strengthen the single DOF hypothesis. Tuijthof et al (2009), on the other hand using in vivo techniques, used a larger sample size of 10 males and 10 females, perhaps because of the relatively non-invasive techniques employed. This group arrived more or less at the same conclusion as the Italian group using different methodology.

It is important to differentiate between the Ankle Joint and hindfoot; the latter includes both ankle and subtalar joint movements. Thus a 2-DOF model would include a hinge for each of the two joints.

Although there is ample data to support the single DOF hypothesis, there is consensus that one DOF kinematic models are inadequate for capturing the motion of the healthy hindfoot. It is believed that 3 DOF or 2 DOF represent adequately the kinematics of the normal hindfoot during walking (Liu et al. 1997). Van den Bogert et al. (1994) stress, however, that a 3DOF model underestimates the loading of the tibia and fibula and overestimates the forces in the muscles.

On the other hand, besides ankle joint complex movement, Lundgren et al. (2008) have demonstrated that, *during gait*, the medial column may actually produce more movement than the ankle joint itself. In this study, which involved insertion of bone pins for more accurate kinematic analysis utilising a 3D motion capture system, up to 17.6^{o} of sagittal movement was obtained in the medial column, as compared to ankle joint movement which was just 15.3^{o} (Lundgren et al. 2008). In an earlier study, although the talocrural joint was found to account for most of the rotation around its axis occurring from 30^{o} of plantar flexion to 30^{o} of dorsiflexion, there was a substantial contribution from the joints of the arch (Lundberg et al. 1989a).

Kitaoka et al. (1999) also obtained different results for the various foot segments. Maximum normal calcaneal-tibial sagittal plane motion achieved was 19.3^{o} ±1.6^{o}, maximum normal metatarsal-tibial sagittal plane motion 35.2 ^{o} ±4.5^{o}, while maximum normal metatarsal-calcaneal sagittal motion was 19.5^{o} ±3.6^{o} degrees. Others have reported significant sagittal range of movement of various medial structures, including the 1st ray, talo-navicular joint, medial cuneiform-navicular joint and first metatarsal-medial cuneiform joint. This latter accounted to as much as 41% of total dorsiflexion of the foot (Roling et al. 2002).

Thus, because of the highly-segmented nature of the foot, which allows inter-segmental movement, three models may thus explain dorsiflexion movement in the foot:

1. **Pure ankle joint** movement would mean the rotation of the talus within the ankle mortise, with unresisted mobility being obtained by the sliding of the articular surfaces upon each other (Leardini et al. 1998). Referred to as tibio-talar motion, this can be measured in vivo using radiographic techniques or, as Leardini and co-workers have done, through dissection of cadaveric feet. The talus rotates mostly in plantarflexion/dorsiflexion about the talocrural joint, with an average range of $18^{\circ} \pm 4.7^{\circ}$ (Hamel et al. 2004).

Radiographic techniques have the advantage that measurements can be done accurately and subjects can be obtained more easily than amputated limbs. However, for routine clinical assessment, exposure to X Rays makes this modality inappropriate except for very specific cases.

2. **Hindfoot** movement implies the combined movement of the ankle and subtalar joints. This latter joint has a triplanar axis; consequently its movement must also be triplanar, i.e. in the sagittal, transverse and frontal planes (Liu et al. 1997). The sagittal component of movement, i.e. dorsiflexion/plantarflexion, would be combined with pure ankle joint dorsiflexion, resulting in *ankle joint complex dorsiflexion*. This theory is rebutted by some authors, who concluded that the ankle joint complex works as a single Degree of Freedom unit, thus meaning that subtalar joint motion in the sagittal plane is almost negligible (Leardini et al. 1999; Leardini et al. 2001; Franci et al. 2009; Tuijthof et al., 2009).

On the other hand, using 8 cadaveric feet in a jig with markers attached directly to the bones, Hamel et al (2004) have shown that there is approximately 5^{o} of movement between the talus and calcaneus up to 25% of the stance phase of gait. During late stance, these two bones rotate together and function as one unit.

3. **Whole Foot Movement**: The foot is made up of 26 bones with a synovial joint in between each bone. The function of these joints is to facilitate adaptation to uneven terrain. Along the medial column, besides the subtalar joint which is already mentioned above, there are the first metatarso-cuneiform, the navicular-cuneiform and the talo-navicular joints, referred to as the "Medial Pillar" (Roukis and Landsman 2003). Thus if just a little movement is allowed in each of these joints, it is quite likely that their summation would be significant.

Among numerous studies that have published results regarding movement of the medial column, Roling et al. (2002) have reported the following:

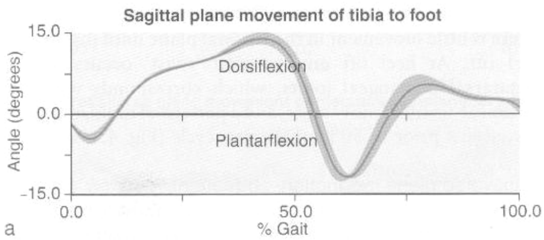
Sagittal 1st ray ROM: 6.4° (0.5°)
Sagittal talo-navicular joint ROM: 0.5°- 0.3° (9%);
Sagittal medial cuneiform-navicular joint ROM: 3.2°-1.2° (50%)
Sagittal first metatarsal-medial cuneiform joint ROM: 2.6°- 0.9° (41%)

As can be seen from these results, the movement of the Medial Pillar may be quite substantial.

More recently, Lundgren et al (2008) have demonstrated that the medial column may produce more movement than the ankle joint itself. In this study, which involved insertion of bone pins for more accurate kinematic analysis, up to 17.6^{o} of movement was obtained in the medial column, as compared to ankle joint movement which was just 15.3^{o}. This supports an earlier study in which, although the talocrural joint was found to account for most of the rotation around its axis occurring from 30^{o} of plantar flexion to 30^{o} of dorsiflexion, there was a substantial contribution from the joints of the arch (Lundberg et al. 1989a). It is important to state that in these two studies, subjects were not controlled for hypermobility of the midtarsal joint, which is a very frequent finding in flat feet.

Thus it is evident that **foot dorsiflexion** may consist of ankle (tibio-talar), subtalar (talo-calcaneal [if the motion at this joint is significant at all]) together with the summation of all the dorsiflexing movements of the joints distal to the tarsus, including the midtarsal joint, which is composed of the talo-navicular and calcaneocuboid joints.

Sagittal plane foot-to-tibia movement (i.e. when the foot is described as a single segment) uses a combination of calcaneal and metatarsal segments (Figure 2.11a). When analyzing Calcaneus-to-tibia movement, the distal segment has been removed. The difference is notably in the amount of plantarflexion; with whole foot movement there is more plantarflexion, implying movement in the distal part of the foot (Figure 2.11b) (Richards and Thewlis, 2008).



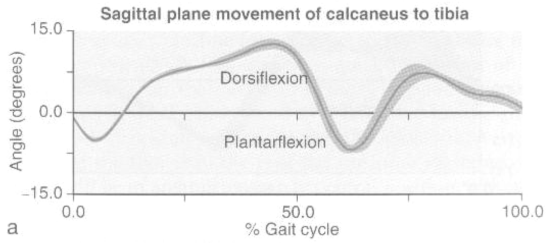


Figure 2.10: A) Sagittal plane movement of tibia to foot. B) Sagittal plane movement of calcaneus to tibia (adapted from Richards and Thewlis, 2008)

Here one should note the significant work done by (Tiberio et al. 1989) and (Woodburn 1991) who have demonstrated that ankle joint dorsiflexion measurement results vary significantly between the various foot postures; in pronated feet an additional 10^o are available during dorsiflexion. These 10^o cannot be accounted for as movement in the ankle joint; hence the joints distal to the tarsus possibly account for this movement. Certainly, during measure ement procedures, these 10^o are likely to confound the issue. Placing the foot in neutral appears to reduce these movements extraneous to the ankle joint complex, thus reducing this confounding element and also supporting the podiatric theory that the midtarsal joint can be ‘locked’ and ‘unlocked’ by changing foot posture (Root et al. 1977).

In summary, it may be important to differentiate the 3 types of movements:

1. Ankle Joint Dorsiflexion
2. Ankle Joint Complex Dorsiflexion
3. Foot Dorsiflexion

This issue of ankle joint/foot dorsiflexion may actually be more complicated than this.

It is highly probable that the ankle joint behaves differently during non-weight bearing and weight bearing activities. Using oblique lateral fluoroscopic images of non-weightbearing and weightbearing dorsiflexion-plantarflexion activities, Yamaguchi et al. (2009) found that the ankle joint was significantly more plantarflexed and adducted during the weightbearing activity than the non-weightbearing activity. The ankle-subtalar joint complex was significantly more everted, and the calcaneus showed significantly greater posterior position than the non-weightbearing activity.

Thus, during the clinical measurement of ankle dorsiflexion, it is often unclear as to which of the above 3 types of dorsiflexion is actually being measured.

At this stage, the act of measuring has not been assessed kinematically and thus during this procedure what is actually being measured is not known and can only be assumed.

2.2.1 Conclusions

- One should differentiate what kind of ankle dorsiflexion is under examination; whether passive or weight-bearing dorsiflexion.

- The type of ankle joint dorsiflexion appears to vary depending on function; in passive motion, the ankle joint is reported to act as a single DOF joint, with very minimal sagittal plane movement at the subtalar joint (Leardini, O'Connor, Catani, Giannini, 1999; Leardini, Stagni, O'Connor, 2001; Franci, Parenti-Caselli, Belvedere and Leardini,2009; Tuijthof et al., 2009).

- important to differentiate the 3 types of movements:

    - Ankle Joint Dorsiflexion
    - Ankle Joint Complex Dorsiflexion
    - Foot Dorsiflexion

- Assessment of ankle joint dorsiflexion involves a different activity to dynamic motions since it involves applying a force to a passive foot.

- This procedure needs to be investigated further utilising kinematic analysis of foot segment movement in order to determine exactly what is being measured.

2.3 Ankle Equinus

Definition:

Main Entry: **talipes equi·nus**[1]
Pronunciation: -ˈek-wi-nəs

Function: *noun***:** a congenital deformity of the foot in which the sole is permanently flexed so that walking is done on the toes without touching the heel to the ground.

Ankle Equinus

Definition: Ankle equinus is a sagittal plane deformity in which there is less than 10° of available dorsiflexion at the ankle joint, when the subtalar joint is in its neutral position and the midtarsal joint is fully locked.[2]

2.3.1 Ankle dorsiflexion necessary for normal walking

It is claimed that during normal locomotion, 10^{o} of ankle dorsiflexion is required for the forward translation of the centre of gravity of the body to occur during single limb support (Root et al. 1977). At this time, during the stance phase of gait, the body passes over the weight bearing foot. This forward translation occurs in the sagittal plane, which is said to occur using a 3 rocker system to permit advancement (Perry 1992). This sagittal plane movement at the ankle occurs during the 2nd rocker (Dananberg 2004).

According to Tiberio (1987), between 5^{o} and 15^{o} are necessary for walking. Sullivan (1997) emphasizes that 15^{o} are necessary, with anything less producing compensations and foot adaptations leading to pain and deformity. A trial investigating kinematics of ankle dorsiflexion

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[1] Merriam-Webster Medical Dictionary

[2] Root et al. 1977

during gait produced results between 12° and 22° (Weir and Chockalingam 2007). The authors concluded that, during gait, ankle joint dorsiflexion in normal subjects is greater than the value traditionally reported.

In an attempt to establish a normal range of ankle joint dorsiflexion, Baggett and Young (1993) measured ankle dorsiflexion in the non-weight bearing and weight bearing positions; the former using the normal goniometer and the latter utilising the Lunge Test, which involves the subject leaning against a wall with the trailing foot held against the ground and the ankle angle (from the ground to the tibia) measured with a goniometer. The normal ranges obtained were established as 0° to 16.5° non-weight bearing and 7.1° to 24.7° weight bearing. This study shows poor correlation between the two measurements and the authors questioned the clinical relevance of the standard non-weight bearing measurement. However, one should note that the Lunge Test may not be representative of normal gait as the subject is leaning too far forward. The authors did, however, conclude that, because of the population's variability, instead of a single number of required degrees, a range of normal should be considered.

Saxena and Kim (2003) studied a group of 40 adolescent athletes (16 girls and 24 boys) with a mean age of 14.8 yrs +/- 0.8years. "0°" was defined as a 90° relationship between the lateral border of the foot and the long axis of the leg. Ankle dorsiflexion was measured at subtalar joint neutral position, using a goniometer aligned with the lateral border of the foot and the long axis of the leg, with the subjects lying supine, first with the knees extended, then flexed. Dorsiflexion of the right ankle was 0.35° ± 2.2° with the knee extended and 4.88° ± 3.23° with the knee flexed. The values for the left ankle were –0.6° ± 2.09° and 4.68° ± 3.33°. There were no statistically significant differences between the sexes. Conclusion was that average ankle dorsiflexion in asymptomatic athletes was 0° with the knees extended and 5° with the knees flexed. They concluded that some degree of equinus is "normal" in adolescent athletes. These results show an influence of the gastrocnaemius since knee position affected the results; perhaps, being athletes, their gastrocnaemius was more developed than the average.

In a study of 82 children with injured ankles, Tabrizi et al (2000) reported mean dorsiflexion values of 5.7° with the knee extended and 11.2° with the knee flexed. In 85 controls, dorsiflexion was 12.8° and 21.5°. However, to what extent the ankle injuries could have limited the amount of dorsiflexion is unclear.

Using a flexible electrogoniometer, Moriguchi et al. (2007) obtained mean dorsiflexion angles of 24^{o} for the left and 19^{o} for the right foot during Toe-Off. The main difference between this and the trials described above is that the former was taken dynamically, while the other trials reported static, passive, non-weightbearing results.

Studying a population with an average age of 25 years, in which ankle dorsiflexion was measured with the foot supinated, Grady and Saxena (1991), found values of 3° with the knee extended and 9° with the knee flexed. This differs from the later study by Saxena and Kim (2003); in the latter the foot was not kept in any specific position so other joints could have dorsiflexed as well (Lundgren et al. 2008), making comparison difficult. Notwithstanding this, the value of 3° and 9° compare quite well with that of 0° and 5° with knees extended, then flexed respectively. The authors themselves admit that one of the limitations of the study was the goniometric assessment, which is very subject to evaluator variability and thus raises questions as to the validity of the measurement (Saxena and Kim 2003).

2.3.2 Ankle Equinus

If 10^{o} of dorsiflexion are not available, *Equinus* is said to be present. This condition has also been referred to as *limited ankle dorsiflexion*, *gastrocnaemius equinus*, *equinus contracture*, *functional equinus* and *ankle equinus*. Although there appears to be no clear definition of equinus, with opinions ranging from 0^{o} (Lavery et al. 2002), $< 5^{o}$ of dorsiflexion (Johnson and Christensen 2005), $<10^{o}$ (Rome 1996) and even $<20^{o}$ (Brantingham et al. 2006), there is universal consensus that it is a reduction in the range of dorsiflexion movement of the ankle joint (Charles et al. 2010; Digiovanni et al. 2001; Johnson and Christensen 2005). It is clear that there is a lack of established baseline values in literature (Saxena and Kim 2003) and thus a need for consensus regarding criteria for definition and diagnosis. This is further complicated by an absence of a standardized method for measuring dorsiflexion range of motion at the ankle (Charles et al. 2010).

DiGiovanni et al (2002) defined *Equinus* as <5° of ankle dorsiflexion with the knee extended or <10° with the knee flexed and used the term ‘gastrocnaemius tightness’. Adhering to this definition would mean that all the subjects in Tabrizi et al (2000), Grady and Saxena (1991), and Saxena and Kim (2003), had *Equinus*. However, all subjects in the latter study were asymptomatic young, health athletes.

Charles et al. (2010) argue that without any prospective studies to determine the effects of different levels of restriction of dorsiflexion, it is difficult to define a particular range of motion below which a definition of equinus can be justified. If a valid and reliable tool, which is essential for diagnosis, is available, Charles et al. (2010) propose a two-stage definition:

> Stage 1: $<10^{o}$ of dorsiflexion, indicating minor compensation and minor increased forefoot pressure
>
> Stage 2: $<5^{o}$ of dorsiflexion, indicating major compensation and major increased forefoot pressure

Immediate shortcomings of these definitions become apparent: there is no scientific backing for this definition and increased forefoot pressure may not necessarily result solely from ankle equinus; for example, the forward migration of the fibro-fatty tissue underneath the metatarsophalangeal joints could also account for such an increase in forefoot pressure. This also implies that to arrive at a diagnosis of equinus, foot pressure mapping apparatus would have to be available.

2.3.3 Causes of Equinus

The commonest cause of Equinus is tightening or shortening of the gastrocnaemius/soleus/Achilles tendon group (the *triceps surae*), causing premature activity of ankle plantarflexors (Perry 1992). In fact, the term *muscular* ankle equinus (Hill 1995) has been coined. This is thought to result from modern lifestyle factors in the daily environment, which put patients at risk of developing this condition. These factors include sleeping with the feet in a plantarflexed position for 6-10 hours daily, sitting for long hours at desks with the knees flexed and the feet in an equinus position and overtraining of muscles at the gym (Hill 1995). Even during standing, the gastrocnaemius is being used to maintain the centre of gravity anterior to the ankle joint axis (Kirby 2000; Kirtley 2006) and to oppose the dorsiflexing moment imposed on the foot (Kirtley 2006).

Equinus may also be caused by a bony blockage of the trochlear surface of the talus as its widened anterior part is trapped between the ankle mortise formed by the tibia and fibula. This can be caused by osseous deformity or lack of widening of the mortise that receives the dorsiflexing talus secondary to failure of translation of the fibula (Dananberg et al. 2000).

Equinus may be the result of neurophysiological impairments which result in clonus (which is an abnormal pattern of neuromuscular activity, characterized by rapidly alternating involuntary contraction and relaxation of skeletal muscle[3]) and hyperreflexia (increased reflex reactions[1]) of the musculature crossing the ankle (Maurer et al. 1995). It is the commonest deformity in cerebral palsy (Borton et al. 2001) and also commonly found in stroke (Fuller 1998).

The passive or active properties of the tissues that contribute to the moment around the ankle provide the aetiological origins of this condition. The active components are clinically manifested by voluntary movement, dynamic spasticity and/or hypertonicity, while the passive components arise from the passive properties of soft tissues crossing the ankle joint, contracture, or joint exostosis (Maurer et al. 1995).

2.3.4 Diagnosis of Ankle Equinus

Diagnostic criteria for ankle equinus are based on a non-functional static examination where the foot is manipulated passively (Maurer et al. 1995). As initially outlined by Root et al. (1977), the foot is placed at subtalar joint neutral position and the stable arm of a clinical goniometer is aligned along a bisection of the lower lateral aspect of the leg. The other arm is placed along the lateral border of the foot and a dorsiflexing force is applied to the forefoot until the foot is maximally dorsiflexed.

This measurement is performed initially with the knees extended. If insufficient foot dorsiflexion results, an adaptation of the original Silvferskiold (1924) technique is employed. The

[3] Mosby's Medical Dictionary, 8th edition. 2009. Elsevier.

[1] Merriam-Webster Medical Dictionary

measurement is repeated with the knees flexed in order to determine the muscular cause of the condition, i.e. whether it is caused by gastrocnaemius or soleus tightening. Since the gastrocnaemius inserts proximal to the knee joint, its effect on foot dorsiflexion is most when the knee is extended and hence the muscle becomes tight. Flexion of the knee reduced this tightness and thus the influence of the gastrocnaemius on foot dorsiflexion.

From literature, it emerges, that this method of assessment is highly unreliable as it introduces a variety of potential sources of error (Charles et al. 2010). (Ref to Section 2.4.2: Un/Reliability of Goniometric Measurements)

2.3.5 Incidence of equinus

It is difficult to estimate the true prevalence of ankle equinus (Charles et al. 2010; Digiovanni et al. 2001) since there is no universally-accepted definition of this condition and no standardized test for establishing the range of ankle joint dorsiflexion (Charles et al. 2010).

Most research concentrates on neurologically-induced equinus. However, the greatest incidence appears to be that of mild equinus which appears to affect a large percentage of the population (Hill 1995). There is very little literature on the impact of isolated gastrocnaemius contracture in 'normal' otherwise unaffected patients, which may be more subtle to detect (Digiovanni et al. 2002). 176 of 209 consecutive new patients were examined for the presence or absence of equinus deformity over a 6 week period by Hill (1995). 96.5% exhibited restricted ankle dorsiflexion requiring compensation during gait. Thus the effect of 'mild' equinus is not being given the interest it deserves. Possibly being present in a large population, it may actually be the most harmful form of the condition overall if numbers are taken into account, causing a significant burden on patient health.

2.3.6 Effects of Equinus

Lack of ankle dorsiflexion is compensated for by altering gait, including early heel-off in mild cases (bouncy gait) or even a total lack of heel strike in severe cases (such as in cerebral palsy) (Maurer et al. 1995); triplanar rearfoot motion (pronation) and an adducted gait pattern (Harris and Beath 1948; Root et al. 1977). Equinus can be uncompensated, with the patient walking on the toes, or compensated by various methods, including foot abduction, significant pronation of the mid foot and rearfoot, resulting in the loss of the medial longitudinal arch and abduction of the forefoot (Sullivan, 1997).

Once the ankle is restricted, the midtarsal joint is the next joint through which dorsiflexion may occur. This is achieved by excessive pronation of the foot (Dananberg, 2004), which turns it into a mobile adaptor to facilitate dorsiflexion at this joint. Forces on the midtarsal joint may eventually lead to the midfoot break and significant structural foot problems (Harrison, Carmont and Walsh, 2001).

Slight-to-moderate limitation of ankle passive dorsiflexion range of motion has been reported to significantly alter the timing, but not the magnitude, of frontal plane rearfoot motion during walking (Cornwall and McPoil, 1999).

Equinus, which is a type of sagittal plane blockage, has been claimed as being a significant causative factor of a variety of lower extremity conditions (Root et al. 1977). The deleterious effect of equinus has been recognized throughout the years, with several old trials, cited by Allinger and Engsberg (1993), implicating limited ankle joint complex motion as a possible cause for injury.

Several overuse injuries of the lower extremities associated with limited ankle dorsiflexion include:

- low back pain,
- hyperextended knees (and consequently various knee problems such as arthritis),
- hallux rigidus,
- calcaneal spurs (Wrobel et al. 2004)
- foot nerve entrapment (Barrett and Jarvis 2005)
- Achilles tendinopathy (Kaufman et al. 1999)
- Patellofemoral pain syndrome (Lun et al. 2004)
- Posterior Tibial Tendon Dysfunction (Hill 1995)
- plantar fasciitis (Riddle et al. 2003)
- metatarsalgia due to forefoot loading (Bardelli et al. 2003; Subotnick 1971)

- forefoot callus (Sgarlato et al. 1975b).

In a study of 1666 consecutive people with diabetes, Lavery et al (2002) found that those with equinus had significantly higher peak plantar pressures than those without. Elevated plantar pressure is considered a significant risk factor in the development of diabetic foot wounds (Pham et al, 2000; Lavery et al. 1998). They defined equinus as 0^{o} dorsiflexion or less. Had they used the 10^{o} criteria, they claim that they would certainly have found a higher percentage of affected patients. Equinus is a significant condition in Type 2 diabetes, resulting from increased glycation of proteins which may contribute to reduced range of motion (Muellenbach et al. 2008).

Although highly evident equinus may be a presentation of neurological conditions, including toe walking (Sobel et al. 1997) and cerebral palsy (Allington et al. 2002) the milder form of equinus is not normally evident except through a thorough lower limb examination. This form of equinus can affect anyone, from diabetics (Pham et al, 2000), adolescent athletes (Saxena and Kim 2003) to children (Evans and Scutter 2006).

Balance and gait is affected in neurological conditions (Borton et al. 2001).

2.3.7 Treatment of Equinus

Muscular ankle equinus (i.e. where posterior muscle group tightening is present) may be managed by the use of stretching of the posterior group of muscles, surgical lengthening of the Achilles tendon and release of the gastrocnaemius aponeurosis endoscopically (Downey and Banks 1989; Saxena 2002). Botox A has been used successfully in the management of equinus in Cerebral Palsy.

Gastrocnaemius stretching has been demonstrated to be quite effective in increasing ankle dorsiflexion. Stretching exercises, casting and night bracing have been utilised to this effect. Stretching has been shown to be safe in diabetic patients by the use of foot pressure measurement, since the act of stretching itself may increase foot pressure and hence an increase in the likelihood of developing diabetic ulceration. Meanwhile, Radford et al. (2006), in a meta-analysis, showed that calf muscle stretching provides a small and statistically significant increase in ankle dorsiflexion. However, it was unclear whether the change is clinically important or not.

Manipulation methods have been used to gain an increase in ankle dorsiflexion (Dananberg 2004; Dananberg et al. 2000). Although criticized by Menz (2001), Dananberg claims that this increase in ankle dorsiflexion is instantaneous. The duration of this effect, however, is unknown, with the likelihood that this manipulation method has to be repeated often.

Once there is failure of conservative treatment, which includes physiotherapy, ankle foot orthoses, casting and Botulinum Toxin A, surgical intervention is indicated (Borton et al. 2001). Tendo Achilles Lengthening (TAL) has been shown to be effective in the management of forefoot ulceration in diabetic patients with an equinus deformity that failed to heal with total contact casting alone. It reported the successful healing of the primary ulcer, a 19^{o} increase in ankle dorsiflexion and no recurrences (Lin et al. 1996). Another trial suggests that TAL causes a temporary reduction in forefoot pressure primarily by reducing PF power during gait (Maluf et al. 2004).

2.3.8 Conclusions

- Definitions of 'Equinus' are rather conflicting.
- The traditional 'orthopaedic definition' is of a plantarflexed foot with the patient walking on the forefoot and the heel off the ground.
- 'Other' definitions of 0^{o}, $<5^{o}$, $<10^{o}$ and $<20^{o}$ have been made by various authors, however with no clear consensus being reached
- Standardization on the use of the term *equinus* is being proposed: the term equinus should indicate the condition with the 'orthopaedic definition', while 'limited ankle dorsiflexion' should reflect the 'other definitions' in milder conditions.
- Reliability of current accepted clinical methods to measure ankle dorsiflexion is quite poor, thus making diagnosis difficult.
- This condition is quite important clinically, affecting a spectrum of pathologies
- Equinus may go unnoticed by a number of practitioners.

- Prevalence of the condition may be quite significant, however in the absence of reliable measuring devices, this cannot be known.
- It is this author's contention that the term 'equinus' should be reserved for the foot that does not reach 0^o of dorsiflexion, i.e. it is in a plantarflexed position. There do not appear to be any issues regarding this terminology in orthopaedic literature and the dictionary definition is quite explicit in that in equinus "the sole is permanently flexed". The term 'limited ankle dorsiflexion' may be more appropriate when there is $<10^o$ of dorsiflexion. This does not imply neurological disease and the condition is most often structural, or biomechanical, in origin.
- Thus, during this dissertation, the term 'equinus' or 'limited ankle dorsiflexion' will imply the non-neurologically induced variety of this condition, referred to as ankle equinus, functional equinus or limited ankle dorsiflexion, in which there is $<10^o$ of foot dorsiflexion.

2.4 Clinical Examination for ankle dorsiflexion

Ankle joint movement examination may be performed using various methods. The procedures mostly used in clinics and research include goniometry (Gastwirth 1996) and visual estimation (Digiovanni et al. 2001). This may be because goniometers can be found easily in clinics and are relatively inexpensive.

2.4.1 Goniometric Procedure of Ankle Dorsiflexion Measurement

During goniometric examination of ankle joint movement, one arm of the goniometer is placed along a bisection of the lateral aspect of the lower leg, and the other arm along the lateral margin of the foot (Gastwirth 1996; Root et al. 1977). The subtalar joint is held in neutral position, with the midtarsal joint locked by application of force on the 4^{th} and 5^{th} metatarsophalangeal joints in order to pronate the midtarsal joint. It is assumed that once the midtarsal joint is locked, the remaining movement is only at the ankle joint (Root et al. 1977). An upward force is applied until the maximum ankle joint range of motion is reached. This examination is initially done with the knee extended and then with the knee flexed in order to differentiate between gastrocnaemius (the former) and soleus tightening (Valmassy 1996).

This method of ankle range of motion assessment is generally accepted, so much so that there are various textbooks outlining this procedure, and various research (including published papers) has been carried out utilising this methodology (Johanson et al. 2006a; Johanson et al. 2006b; Wessling et al. 1987). However, there is ample evidence in literature nowadays that goniometry is not reliable as this method introduces a variety of potential sources of error which, according to Charles et al. (2010) include:

- Positioning of the knee affecting the range of motion of the ankle
- Range of Motion affected by tension in the soleus muscle, bony limit or the end of range of the ligaments
- Patient position: whether the patient is sitting or lying down (Thoms and Rome 1997)
- Subtalar joint position (Tiberio et al. 1989; Woodburn 1991)
- Movement of the midfoot or rearfoot compromise measurements (Digiovanni et al. 2001)

There is a need for devices that produce reliable (i.e. reproducible) results (Charles et al. 2010). Thus the need for various alternative methods has been felt, with specialized devices being designed and manufactured specifically in order to measure ankle joint dorsiflexion. Such devices include the Biplane Goniometer (Donnery and Spencer 1988), the Equinometer (Weaver et al. 2001), and the Mechanical Equinometer (Meyer et al. 2006) among many others. (Chapters 3 and 4).

2.4.2 Un/Reliability of Goniometric Measurements

Although goniometric measurements by health care professionals have become common practice, literature has challenged the reliability of these measurements for quite some time. Even though the hand-held goniometer has introduced quantification (Woodburn et al. 2002) it has major drawbacks in measuring ROM; goniometric reliability is unproven with reliability studies often having major flaws in design or analysis (Jordan et al. 2001). In fact, goniometry has also been shown to be unreliable for rearfoot assessment (Ball and Johnson 1993; Buckley and Hunt 1997).

Nowadays there still exists confusion as to the correct maximal dorsiflexion values, resulting in a lack of determination for the reliability of clinical examination for correctly identifying this condition (Digiovanni et al. 2002). With ankle joint dorsiflexion being such an important issue for both the clinician and researcher, a few studies aimed at investigating reliability issues with these measurements have been published.

Digiovanni et al. (2001) have found that practitioners' ability to diagnose ankle equinus depended on whether equinus was defined as <5 degrees (75%) or <10 degrees (100%) in equinus patients, while in non-equinus patients these values increased from 75% to 93.8% in <5 degrees, and decreased to 50% in <10 degrees. Thus reliability not only changed from how much equinus was defined, but also varied depending whether equinus was actually present or not.

On the other hand, on the basis of a literature review, Martin and McPoil (2005) concluded that the responsiveness of ankle range of motion measurements is uncertain and further studies using actual patient populations are required.

There are no doubts that there are important questions that need to be raised regarding these measurements. An obvious conclusion appears to be that reliability increases with training and experience (Pierrynowsky et al. 1996), yet apparently no amount of training can make this measurement accurate enough to warrant Van Gheluwe et al. (2002) to recommend it to be used for clinical practice. In fact, they conclude that the differences between examiners (i.e. inter rater reliability) "may be clinically unacceptable". In fact, Kim et al. (2011) have researched the relationship between experience and reliability and, in contrast with Pierrynowsky et al., surprisingly concluded that rater experience does not increase reliability.

In order to try to solve this reliability problem, using a modified Lidcombe Template, Scharfbillig and Scutter (2004) claimed excellent reliability for both intrarater and interrater reliability using Intraclass Correlation Coefficient (ICC) model (1,1) and Standard Error of Measurement (SEM) calculations from their subject population.

As with any other clinical examination, it is clear that accuracy and reliability of ankle joint dorsiflexion measurement is of paramount importance. This state of unreliability is unfortunate for the researcher and clinician. Hence it could be possible that some patients may be treated for a non-existent condition, or else not treated for this condition if the measurement error is too large. Not only that, but apparent improvement in a treatment regime might not be anything more than errors in measurement.

Goniometric reliability is also compromised by placement of the goniometer. The main anatomical sites appear to be the lateral head of the fibula and the lateral malleolus for the stable arm and the plantar aspect of the foot to the 5th metatarsophalangeal joint for the other arm. It is very easy for any of the two arms to move when the foot is being placed at subtalar joint neutral and a dorsiflexing force is applied, thus altering the result.

Another issue is the documental unreliability of obtaining subtalar joint neutral itself (Elveru et al. 1988). This appears to be critical since Tiberio et al. (1989) and Woodburn (1991) have shown that measuring ankle dorsiflexion with the subtalar joint in a pronated position increases total dorsiflexion by as much as 10 degrees – enough to classify anyone with equinus as not having this condition, and vice versa.

Besides establishing subtalar joint neutral position, patient position also appears to be an important factor. Since ankle dorsiflexion may potentially be assessed by a number of different researchers, the patient position may reflect on the resultant ankle dorsiflexion. This was confirmed by Thoms and Rome (1997), whose paper demonstrates that, while a prone or supine patient position does not affect the result, sitting does.

An significant factor for obtaining reliable ankle measurement appears to be the amount of dorsiflexing force that is applied by the examiner. According to Assal et al. (2003) and Charles et al. (2010), applying the correct torque is essential since the resultant angle is dependent on this. The torque applied to the ankle joint complex might vary between one examiner and another, or between one examination and another, thus exerting unequal forces on the gastrocnaemius. The stretching characteristics of the triceps surae themselves may vary depending on other intrinsic or extrinsic factors, such as heat (Knight et al., 2001).

It is clear that there are various things that can go wrong during ankle joint complex dorsiflexion measurement, so much so that research in this area has criticized this measurement, claiming that it is *unreliable* and *clinically unacceptable* (Van Gheluwe et al. 2002).

According to Maurer et al. (1995), it is unfortunate that diagnosis is based on a non-functional static examination where the foot is manipulated passively. This emerges as clearly the foot is a functional mechanism that needs to be assessed during gait, i.e. when it is functioning. Clinically, it is often difficult to assess (Maurer et al. 1995) thus it is clear that this issue needs to be tackled, for example by developing and validating a tool to confirm/disprove the clinician's physical assessment, which to date only includes goniometric measurements.

2.4.3 Conclusions

It becomes apparent, from the above literature on reliability, that

- an alternative to goniometric measurement is necessary in order to increase reliability of the examination of ankle dorsiflexion.

- Although it has been pointed out that ideally ankle dorsiflexion should be measured dynamically, the need for a clinical assessment will always be present, mainly because it is impractical to examine each and every patient using expensive and time-consuming gait analysis techniques.

2.5 Kinematic Analysis

Kinematics, which is the study of bodies in motion, is concerned with describing and quantifying both the linear and angular positions of bodies and their time derivatives. Commonly, collecting kinematic data involves the use of imaging or motion-capture systems that record the motion of markers affixed to a moving body or segment. The position of these images are then digitized to obtain the 3D coordinate (i.e. in X, Y and Z planes) of each marker. A mathematical model and a graphical representation of the body under study would then be constructed using specialized software and the output data used for various applications, such as measuring joint angles.

A variety of markers are available and their use is dependent on the system being utilised. Such markers include passive reflective markers used by Vicon, APAS, Simi and active Infrared Emitting markers such as used by Optotrak (Robertson and Caldwell, 2004). All systems have their own advantages and disadvantages, with cost being a major consideration when deciding which system to use.

Traditionally, kinematic analysis of the foot involved a single DOF model which represented the foot as a rigid lever (Liu, Siegler, Hillstrom and Whitney, 1997; Davis, Ounpuu, Tyburski and Gage, 1991). This has been generally accepted as being insufficient to capture 3D foot motion and it is believed that 3 DOF or 2 DOF represent adequately the kinematics of the normal hindfoot during walking (Liu et al. 1997).

The difficulty was due to problems with tracking small, closely clustered markers. Dynamic in vivo measurement is quite difficult to achieve because of the foot's complex structure (Carson, Harrington, Thompson, O'Connor and Theologis, 2001).

A number of foot models were developed in order to understand foot function better during gait. One such model was an anatomically based, five-segment shank-foot model which consisted of 5 rigidly-assumed segments that included the shank (tibia and fibula), the calcaneus, mid-foot (navicular, lateral, middle and medial cuneiforms and the cuboid), 1st metatarsal and the proximal phalanx of the hallux (Leardini et al. 1999).

Another foot model was the Oxford Foot Model (Carsonet al. 2001) which divides the foot into tibial, hindfoot, forefoot and hallux segments. This is dealt with in more detail in Chapter 5 as it has been utilized for research throughout this thesis.

The Heidelberg Foot Model is another foot model which was also developed to provide a kinematic measurement method for the foot that could be applied clinically. This model did not rely solely on rigid segment modeling, but described the angular orientations of anatomical landmarks that sometimes spanned more than one anatomical joint (Simon et al. 2006).

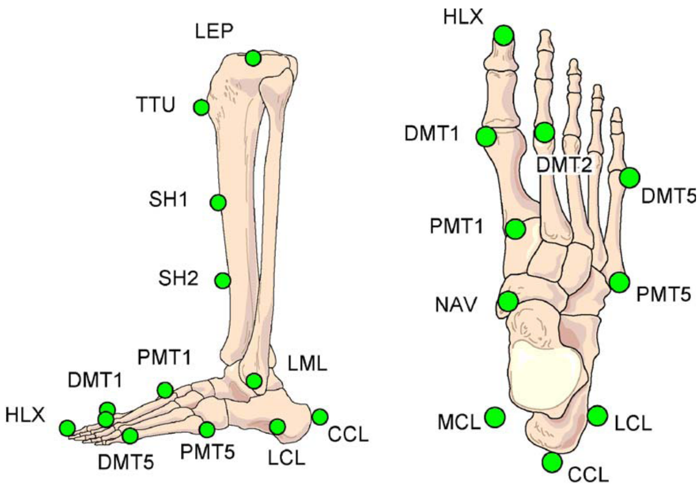


Figure 2.11: Marker placement for the Heidelberg Foot Model (Adapted from Simon et al, 2006)

Mosely et al. (1996) used a much simpler approach. Utilising just 8, 1cm-diameter markers, they modelled the rearfoot and leg as two rigid segments (Figure 2.14)

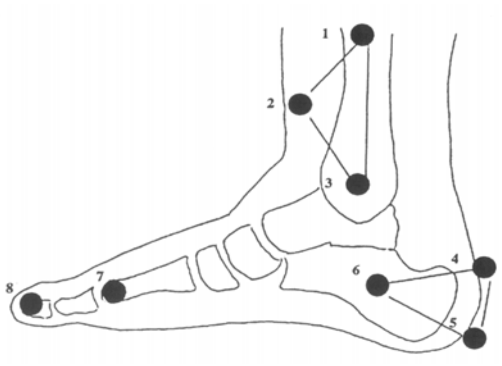


Figure 2.12: marker placement used to define the rearfoot and leg segments (Adapted from Moseley et al, 1996)

Liu et al. (1997) defined Neutral position of the ankle for plantarflexion/dorsiflexion as 90^o between the plantar aspect of the foot and the long axis of the fibula.

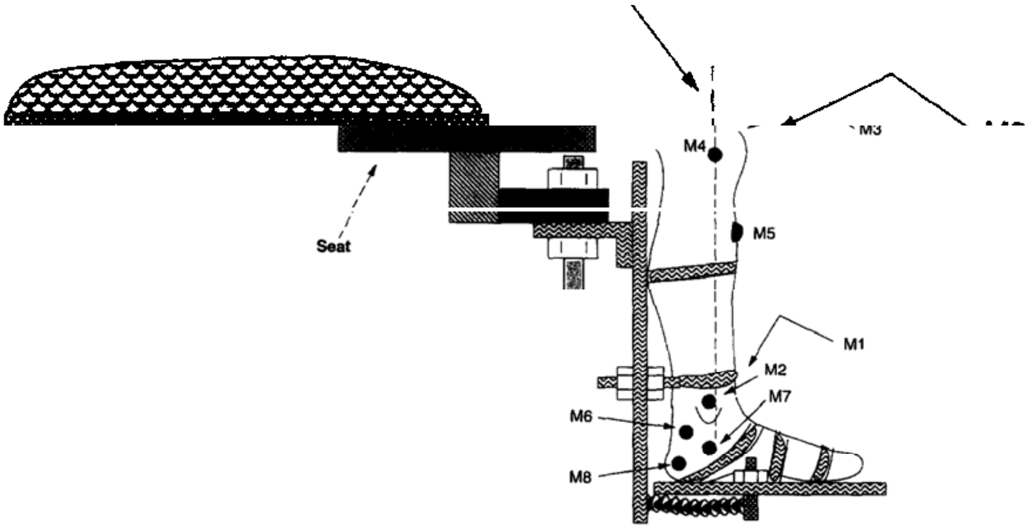


Figure 2.13: Setup used to position hindfoot in neutral position (Adapted from Liu et al, 1997)

When waveforms from different subjects were compared, only dorsiflexion/plantarflexion showed a coefficient value above 0.7, indicating that in this direction the waveform has similar trends between subjects (Liu et al. 1997)

2.5.1 Kinematic analysis of the Ankle Joint complex

The motion of the Ankle Joint Complex (AJC) occurs at both the talocrural and talocalcaneal joints. Their combined motion has components in all three planes (Liu et al. 1997; Moseley et al. 1996). However, the general hypothesis is that the talo-crural joint contributes very little to calcaneal inversion and eversion (Siegler et al. 1988). Assumptions are made that sagittal plane movements, i.e plantarflexion/dorsiflexion occur largely through the talo-tibial joint (Woodburn et al. 2002). These assumptions have been largely validated through the work of Leardini et al. (1999b), Leardini et al. (2001) and Franci et al. (2009) who modelled the ankle joint as a one Degree of Function mechanism.

The main problem associated with modelling the Ankle Joint Complex, i.e. the ankle and subtalar joint, is the difficulty of measuring directly the motion of the joints separately because bony landmarks are deep to other tissues and the complexity of the triplanar movements in these joints (Moseley et al. 1996; Youberg et al. 2005). The rearfoot is considered to be composed of a single articulation because of the absence of a specific landmark on the talus (Scott and Winter 1991)). Using conventional movement analysis techniques, it is difficult to distinguish movement at the two articulations (Moseley et al. 1996).

Using separate segments to model a foot, it is assumed that the individual bones within that segment do not move relative to each other, which appears to be unlikely (Nester et al. 2007). This could result in incomplete description of foot kinematics because certain foot bones are excluded during the measurements. Of particular interest is the talus which is not accessible except through an invasive approach (Lundgren et al. 2008).

Further issues continue to complicate the matter. These involve skin movement artefacts which possibly may reduce the validity of kinematic data (Cappozzo et al. 1996; Reinschmidt et al. 1997). To overcome this problem, bone markers are sometimes used. These are inserted directly into the bones under local anaesthesia so that they reflect purely skeletal movement and eliminate any skin movement (Lundgren et al. 2008). However, this would naturally raise significant ethical issues in many European countries. Furthermore, the use of an invasive approach for kinematic analysis for clinical reasons would be highly debatable. In order to overcome this problem, cadaveric feet are sometimes used in ‘gait simulators’ (Figure 2.16). This allows direct mounting of markers to the bones; however there may be limitations when using cadaveric feet.

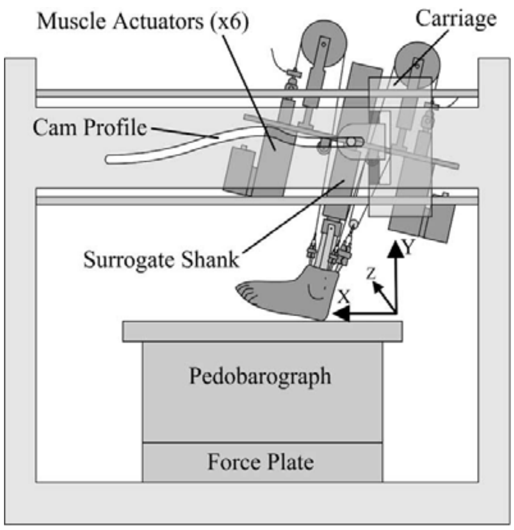


Figure 2.14: Recreating the stance phase of walking in cadaveric feet (Adapted from Hamel et al, 2004)

Chapter 3

A Systematic Review of Ankle Joint Dorsiflexion Measurement Techniques in the Non-neurological patient

Aspects of this chapter have been published:

Gatt A, Chockalingam N. 2011. Clinical assessment of ankle joint dorsiflexion: A review of measurement techniques. *Journal of the American Podiatric Medical Association.* 101(1): 59-69

3.0 Introduction

This chapter will present the methodology and findings of a systematic review on ankle joint measurement techniques. This was an essential primary requirement aimed at acquiring a deeper understanding of these techniques, finding common grounds and identifying issues that govern the subject matter.

Diagnosis of Ankle Equinus is based solely on measurement, which is often made by goniometric examination of the ankle range of motion (Gastwirth 1996; Root et al. 1977). It thus becomes immediately obvious that accuracy and reliability of ankle joint dorsiflexion measurement is of paramount importance. Unfortunately for the researcher and clinician, the unreliability of these goniometric measurements has been established by various authors (Martin and Mcpoil 2005; Rome 1996; Van Gheluwe et al. 2002). As a consequence of possible mis-diagnosis through unreliable goniometric techniques, some patients may be treated for a non-existent condition, or else not treated for this condition if the measurement error is too large. Apparent improvement in a treatment regime might not be anything more than errors in measurement.

This unreliability may arise due to several factors mostly based on wrong techniques, as discussed in section 2.4.1.

Since there is a plethora of studies utilising ankle dorsiflexion assessment as an outcome measure, it is extremely important to establish to what extent factors affecting reliability also influence available results. It is evident that these issues are central to good research and clinical practices.

Prior to embarking on a comprehensive research programme, it is essential that available information is collated in order to bring the investigators up to date with research carried out in the field. As one of the principal aims of this project was to produce a valid and reliable Ankle Goniometer, similar devices had to be investigated in order to assess their strengths and weaknesses, thus determining whether such an alternative apparatus is in fact necessary. It is currently known that besides the goniometer technique, there are other techniques to measure ankle dorsiflexion, such as the equinometer (Assal et al. 2003; Digiovanni et al. 2001; Weaver et al. 2001) and various variations of the Lunge Test (Bennell et al. 1998; Menz et al. 2003).

In view of this, a systematic review was performed in October 2008 to, mainly, establish the various ankle dorsiflexion techniques in existence to date.

3.1 Systematic Reviews

Systematic reviews are increasingly being used to summarize research evidence. As opposed to narrative reviews, which are known to suffer from a lack of rigor in their creation (Hemingway and Breretron 2009), systematic reviews are performed through a comprehensive search for primary studies with a well-defined clinical question. This method of reviewing has a reproducible protocol, with an established process for searching studies, their critical appraisal for quality and the production of results (Pai et al. 2004). Statistical methods (meta-analysis) then may or may not be used to analyze and summarize the results of the included studies (Torgerson 2003).

With the increased shift towards Evidence Based Medicine, systematic reviews provide the highest level of evidence for medical decision making (Editors 2007) (PLOS medicine editors, 2007), making them a cornerstone for Evidence Based Medicine (Whiting et al. 2003). An increased need for wide-ranging information by the various health professionals causes a resultant need for good quality information on the effectiveness, meaningfulness, feasibility and appropriateness of a large number of interventions (Hemingway and Breretron 2009).

Since the production of a systematic review is a research project in itself (Wieseler and Mcgauran 2010), there appears to be a consensus about the various steps necessary to produce consistent results (Pai et al. 2004; Wieseler and Mcgauran 2010).

These include:

1. Formulate the research question and develop the protocol. Protocol should specify (PICOS):

    - Patient population
    - Intervention being evaluated
    - Comparison intervention (if applicable)
    - Outcome (Pai et al. 2004)
    - Search for evidence.

Electronic databases are the most efficient method of retrieval (Dissemination 2002) but they are by no means the only sources available. The search might include:

    - General databases, such as PubMed
    - subject-specific databases
    - Screening of bibliographies of included studies
    - Search of relevant journals (Dissemination 2002)
    - Hand-searching of relevant journals

2. Select the studies. Selection of studies should conform with the inclusion/exclusion criteria determined during the design of the protocol.

3. Extract the data and other information. Once studies are selected, relevant data should be extracted onto a standardized form (Torgerson 2003).

4. Appraise the risk of bias in individual studies and cross studies

5. Analyze and present the data

6. Interpret the findings (Pai et al. 2004; Wieseler and Mcgauran 2010)

Table 3.1: Systematic review process according to (Khan et al. 2005)

Step 1 Framing Questions
Step 2 Identifying relevant literature
Step 3 Assessing Quality of the literature
Step 4 Summarizing the evidence
Step 5 Interpreting the findings

3.2 Quality Assessment

As individual studies may be biased, the quality analysis of systematic reviews could also be compromised and thus studies should be scrutinized for potential for bias, lack of applicability and the quality of reporting (Whiting et al. 2003). Lack of quality would undermine the work produced, making quality assessment a very important aspect of the whole research process.

Reasons for study quality assessment in reviews include:

- To determine a minimum quality threshold (study design threshold) for the selection of primary studies
- To explore quality differences as an explanation for heterogeneity in study results
- To weight the study results in proportion to quality in meta-analysis
- To guide the interpretation of findings and to aid in determining the strength of inferences (Khan et al. 2005)

Quality assessment should be done by two independent reviewers (Pai et al. 2004). Quality refers to various issues, including lack of bias (internal validity), randomization and blinding of both raters and subjects. Although appraisal of the methodological quality of primary studies is essential in systematic reviews, no consensus exists on the ideal checklist and scale for assessing methodological quality (Moja et al. 2005). In fact, the methodological quality of reviews assessing diagnostic tests is generally poor (Reid et al. 1995). Furthermore, quality assessment for diagnostic test evaluations differ from those needed to assess evaluations of therapeutic interventions as they have unique design features (Deeks 2001). These unique features include referencing the test to a 'reference standard'. The test, also known as the "index test" has been defined as "any procedure used to gather information on the health status of an individual… including laboratory tests, questionnaires and pathology" (Whiting et al. 2003). On the other hand, the reference standard should be the best available method to determine whether the patient has the condition being studied.

A quality assessment tool - QUADAS - was designed, keeping with the above criteria (Whiting et al. 2003).

Table 3.2: The Quadas Tool from Whiting et al., 2003

		Yes	**No**	**Unclear**
1	Was the spectrum of patients representative of the patients who will receive the test in practice?			
2	Were selection criteria clearly described?			
3	Is the reference standard likely to correctly classify the target condition?			
4	Is the time period between reference standard and index test short enough to be reasonably sure that the target condition did not change between the two tests?			
5	Did the whole sample or a random selection of the sample, receive verification using a reference standard of diagnosis?			
6	Did patients receive the same reference standard regardless of the index test result?			
7	Was the reference standard independent of the index test (i.e. the index test did not form part of the reference standard)?			
8	Was the execution of the index test described in sufficient detail to permit replication of the test?			
9	Was the execution of the reference standard described in sufficient detail to permit its replication?			
10	Were the index test results interpreted without knowledge of the results of the reference standard?			
11	Were the reference standard results interpreted without knowledge of the results of the index test?			
12	Were the same clinical data available when test results were interpreted as would be available when the test is used in practice?			
13	Were uninterpretable/ intermediate test results reported?			
14	Were withdrawals from the study explained?			

3.3 A Systematic Review of Ankle Dorsiflexion Measurement

In view of the various methodologies available to measure ankle dorsiflexion and the various queries that arise thereof, a systematic review was held during October 2008; this was, however, kept updated during the process of this thesis. As can be seen from the above section, the validity of the review findings depended on various factors, including how comprehensive the search was (Glanville, n.d.), proper data extraction, quality assessment of studies found and the accurate synthesis of results and their reporting.

3.3.1 Aims and Objectives

Aims:

1. To identify the various measurement techniques used in research and clinical practice to measure ankle joint complex dorsiflexion in the non-neurological patient.

2. To explore the various issues related to these methods, possibly finding common grounds that have been standardized, with a view of applying these to an Ankle Goniometer design.

Objectives:

1. To perform a rigorous scientific search to identify studies that utilised ankle joint complex dorsiflexion measurements as one of the outcomes

2. To obtain information from the various studies that would enable standardization between various factors, including:

   - Apparatus/techniques used
   - Anatomical Landmarks used
   - Amount of force/torque applied

3. To apply methodological quality assessment so as to determine the reliability and validity assessment methods of the various techniques identified.

3.3.2 Methodology:

Search Strategy

An electronic search of Pubmed, EDBSCO HOST, which includes CINAHL, SPORTSdiscus, DynaMed and Academic Search Complete, was performed. However, this alone was not deemed to be sufficient and further searches were performed on the internet and other electronic bibliographic databases (Glanville). In particular, the *Journal of the American Podiatric Medical Association* was searched individually to ensure that no studies may have been overlooked. Furthermore, hand searching reference lists of studies found was also another source of references.

The search was limited to:

- Clinical trials
- Meta-analysis
- Randomized Controlled Trials
- Reviews
- Editorials
- Humans

Inclusion Criteria

- Published journal articles/studies that dealt mainly with the diagnosis of ankle equinus in non-neurological subjects.
- Studies that evaluated ankle equinus using any means
- Studies that evaluated reliability of diagnostic measures relative to this condition
- Studies that included a definition of equinus

Exclusion Criteria

Studies were excluded if they dealt with:

- neurologically-induced equinus, such as in cerebral palsy and stroke.
- trials involving Diabetes (issues with neuropathy) if the technique was not also used on non-diabetic subjects as controls.
- editorials and reviews. These were only included in the search as a source of further references and not included in the final article selection.

Equinus OR (ankle AND dorsiflexion) Not cerebral Not palsy NOT stroke

On Pubmed, this produced the search string:

equinus[All Fields] OR (("ankle"[MeSH Terms] OR "ankle"[All Fields]) AND dorsiflexion[All Fields]) NOT ("cerebrum"[MeSH Terms] OR "cerebrum"[All Fields] OR "cerebral"[All Fields]) NOT ("paralysis"[MeSH Terms] OR "paralysis"[All Fields] OR "palsy"[All Fields]) NOT ("stroke"[MeSH Terms] OR "stroke"[All Fields]) AND ("humans"[MeSH Terms] AND English[lang] AND (Clinical Trial[ptyp] OR Editorial[ptyp] OR Meta-Analysis[ptyp] OR Practice Guideline[ptyp] OR Randomized Controlled Trial[ptyp] OR Review[ptyp]))

3.3.3 Data Extraction

755 trials were identified, including 23 papers from hand searched articles. All abstracts were scrutinized to determine whether the studies were appropriate for the review. As determined by the inclusion/exclusion criteria, studies were excluded if they dealt with neurologically-induced equinus, such as in cerebral palsy and stroke. Kinematics were excluded as this method of assessment was felt to be beyond the reach of the majority of clinicians. Radiological methods were included because it was felt that their reliability was great; however caution was kept in mind because these methods are not used in routine clinical evaluation and only utilised when further special investigations are required.

Studies were included if they utilised ankle dorsiflexion measurement as one of their main outcome measures. From some of these papers, innovative methods were identified (Table 3.4) and the validating studies also determined; for example although the Lunge Test was used in various papers, the original validating study was by Bennell et al. (1998).

It was clear that at this stage, studies had to be divided into two groups:

Primary Studies: Those that dealt mainly with the evaluation of a particular measurement technique or device; e.g. in the case of the Lunge Test, Bennell et al. (1998), and Meyer et al. (2006) for the Mechanical Equinometer

Secondary Studies: Those that used ankle dorsiflexion measurement as an outcome measure. Secondary studies were important because they were the means of identifying the Primary Studies.

3.3.4 Quality Assessment

A ten-item quality assessment tool (Table 3.3) was derived from QUADAS (Whiting et al. 2003) and (Jull 2002). Two experienced podiatrists, both of whom were university lecturers with over 10 years' clinical experience, evaluated the studies on their own to ensure blinding and the presented results are the agreed-on scores (Table 3.6).

Table 3.3: A Quality Assessment Tool derived from Quadas and Jull (2008)

		Yes	No	Unclear
1	Were subjects actual patients?			
2	Was the number of subjects sufficiently high to be statistically significant?			
3	Were selection criteria clearly described?			
4	Were subjects randomly selected?			
5	Has the test been compared with a reference standard?			
6	Is the period between consecutive tests short enough to ensure that subject characteristics have not changed?			
7	Were subjects blinded			
8	Were examiners blinded effectively?			
9	Was statistical analysis sound and clearly explained?			
10	Was the execution of the test described in sufficient detail to permit replication of the test?			
Total				

3.3.5 Results

Primary Studies

12 Primary Studies were identified (Table 3.4). Data extraction was performed using the assessment tool (Table 3.3).

Table 3.4: Various ankle dorsiflexion tools/techniques identified

	Device	Reliability Study	Moment applied (Nm)	Subject Posn?	Neutral posn?
1	Goniometer	Elveru et al, 1988	NA	As determined by therapist	Yes
2	Dynamometer with foot attachment				
3	Visual	DiGiovanni et al, 2001	10	Seated	Yes
4	Lunge Test/ Inclinometer Testing Modified Lunge Test	Bennell et al, 1998 Menz et al, 2003	NA	Leaning against wall	No
5	Torque Range of Motion Device	Hume et al, 2000	NA	NA	NA
6	Biplane Goniometer	Donnery and Spencer, 1988	Unclear	Supine	Yes
7	Modified Lidcombe Template	Scharfbillig and Scutter, 2004	16.1 (8.2 kg)	Seated, knees extended	Yes
8	A Manually controlled instrumented footplate	Moseley et al, 2001	12	Supine, knees extended	no
9	Equinometer	Weaver et al 2001	10Nm	Sitting with knees fully extended	Yes
10	A Mechanical Equinometer	Assal et al, from Meyer et al, 2006	10Nm applied;	Supine with knees bent; prone with knees straight	Forefoot in neutral rotation/neutral pronation and supination
11	Iowa Ankle Device	Wilken et al, 2004	10,15,20, 25	Unclear	No
12	Device to assess Gastrocnemus Contracture	Greisberg et, 2002	20Nm	Knees flexed and extended	Hindfoot neutral

3.3.6 Data Extraction

Techniques for measuring ankle joint complex dorsiflexion have been categorized into 3 broad categories:

1. 'Conventional' methods which include the Goniometer, Lunge Test and Visual Estimation. These do not require any specialized instruments designed specifically for this purpose.

   The Lunge Test has 5 variations:

   - with inclinometer attached to tibia (Bennell et al. 1998)
   - with Gravity Goniometer (Nitz and Low Choy 2004)
   - measuring distance from wall to the big toe (Bennell et al. 1998)
   - with Goniometer (Bagget and Young 1993)
   - with a transparent scale on the lateral side of the leg (Menz et al. 2003)

2. More sophisticated methods utilising readily-available equipment, which include

   - the Electrogoniometer and Potentiometer (Tesio et al. 1995),
   - Inclinometer/Gravity Goniometer (Nyanzi et al. 1999),
   - lateral radiographs (Backer and Kofoed 1989),
   - 2D Video (Woodburn 1991)
   - photography (Moseley 1997) .

3. Specifically designed apparatus and methods. There is a surprisingly large number of apparatus designed specifically for measuring ankle joint complex dorsiflexion. These include:

   - Dynamometer with foot attachment (Muir et al. 1999)
   - Torque Range of Motion Device (Hume et al. 2000)
   - Lidcombe Template (Moseley and Adams, 1991)/Modified Lidcombe Template (Scharfbillig and Scutter 2004)
   - Biplane Goniometer (Donnery and Spencer 1988)

- A Manually Controlled Instrumented Footplate (Moseley et al. 2001)
- Equinometer (Weaver et al. 2001; Assal et al. 2003)
- Mechanical Equinometer (Meyer et al. 2006)
- Iowa Ankle Device (Wilken et al. 2004)
- Device to Assess Gastrocnaemius Contracture (Greisberg et al. 2002)
- A custom apparatus fixed to the leg and foot for measuring the isometric force of ankle dorsiflexion at ankle angles (Bobet et al. 2005)

Some common features found in these designs include:

a. Composed, or a variation, of a vertical arm and a plate for the sole of the foot (Scharfbillig and Scutter 2004; Donnery and Spencer 1998; Moseley et al. 2001; Weaver et al. 2001; Wilken et al. 2004; Greisberg et al. 2002)

b. The head of the fibula and the midline of the lateral malleolus appear to be accepted markings for lateral alignment (Menz et al. 2003; Moseley et al. 2001; Assal et al. 2003; Weaver et al. 2001; Wilken et al. 2004). Exceptions are the Mechanical Equinometer, which uses the anterior aspect of the tibia for alignment purposes (Meyer et al, 2006), the Lidcombe Template, which uses the posterior aspect of the lower leg for this purpose (Scharfbillig and Scutter 2004) and the Device to Assess Gastrocnaemius Contracture uses the axis of the second Ray instead of the plate (Greisberg et al. 2002)

c. Axis of device is oriented to the axis of the ankle joint in the transverse plane (Moseley et al. 2001; Wilken et al. 2004).

d. Axis may be in line with ankle axis (Moseley et al. 2001; Assal et al. 2003; Weaver et al. 2001; Wilken et al. 2004) However, axis below the lateral malleolus as per Rootian model was not utilised in any of these specially designed apparatus, except for the Biplane Goniometer (Donnery and Spencer, 1988). The Lidcombe Template axis approximates this by being placed at the rearmost part of the base board and foot plate "to simulate attachment of the Achilles tendon to the calcaneum and to provide a constant axis from which the force of the foot was applied" (Scharfbillig and Scutter 2004).

e. An average reading is taken from a number of measurements (DiGiovanni et al. 2001; Greisberg et al. 2002)

Secondary Studies:

85 trials that somehow assessed ankle joint complex dorsiflexion were identified. Consequently, these revealed a variety of methods that have been utilised for ankle joint dorsiflexion research.

The most common technique used was that of the traditional Goniometer. The angle readings were taken both at subtalar neutral and not. A number of authors did not define the foot posture at which readings were made. Position also varied, with the subjects lying prone, supine or seated.

Various dynamometers with ankle attachments were also used, with Biodex and Cin-com being the most common. These accounted for 20 out of the 85 studies, which makes this the next commonest technique used. No primary studies, i.e. validating this technique, were found. Also there was no mentioning of placing the foot at subtalar neutral and subjects appear to be seated.

The Lunge Test (9/85) had 5 variations: the test performed with an inclinometer attached to the tibia, which appears to be the commonest variant; the test with a gravity Goniometer, which more or less would be similar to the previous variant; the test measuring the distance from the wall to the big toe, the test with a large transparent scale on the side of the foot and the test with the angle between the lateral fibula and the ground measured by a Goniometer. In this last variant, a wedge was placed under the first metatarsophalangeal joint to stop the foot from pronating.

An inclinometer was also used in 3 studies. Other minor studies include 2d video, photographs, lateral XRays. Electrogoniometers and potentiometers played a surprisingly minor role in the studies that were found.

Table 3.5: The utilization of the various techniques used to measure Ankle Joint Complex Dorsiflexion in Scientific Literature

Device used	No of Studies
Conventional goniometer	23
Dynamometer, various	20
Unsure	12
Lunge Test with inclinometer attached to tibia Lunge test with gravity Goniometer Lunge test, measuring distance from wall to big toe Lunge test, with transparent scale on the side Lunge test, with goniometer	4 1 1 1 2
Inclinometer/Fluid filled goniometer	3
2d video	3
Electrogoniometer	2
Potentiometer	2
Lateral Radiographs	1
Biplane Goniometer	1
Protractor like scale set on the side of the foot resting on a plate	1
Foot plate with axis of rotation of ankle aligned with shaft	1
Olerund and Molander functional scale	1
TROM Torque range of motion device – uses potentiometer	1
Specifically designed 6 degree of freedom fixture	1
Photograph	1
Spasticity measurement system (SMS)	1
Equinometer	1
Lidcombe Template	1
Iowa Ankle Device	1

3.3.7 Data extraction form

The trials of interest were assessed by the use of an ad hoc data extraction form. This form was developed by taking into account published reports on the quality assessment of trials included in systematic reviews.

From the selected studies, various issues were identified. These include:

3.3.7.1 Subject Positioning

Because ankle dorsiflexion may be assessed in a variety of different clinical situations, patient position may affect the resultant ankle dorsiflexion angle. A patient may be assessed lying down in a supine (Moseley et al. 2001) or prone position or in the more conventional clinical position of sitting. Patients may also be assessed with knees extended and/or flexed. Subject position is known to affect the resultant amount of ankle joint dorsiflexion. Thoms and Rome (1997) confirmed that although a prone or supine patient position does not affect this result, sitting does influence this.

3.3.7.2. Foot Position

Whether the foot is held at subtalar joint neutral or not seems to be quite an important issue which, however, is not addressed by a large number of retrieved trials. Rootian theory suggests that a pronated foot allows increased sagittal plane motion, making this an unwanted situation if only ankle joint complex dorsiflexion measurement is desired. In fact, Tiberio et al (1989) have shown a variation of 10^{o} between pronated and non-pronated feet. This is in accord with Woodburn (1991) who has demonstrated a marked difference between the pronated, neutral and supinated foot types. This consequently implies that in order to standardize measurements, it must be decided which foot position to use, the pronated, neutral or supinated posture? A 10^{o} error is certainly unacceptable. It is hypothesised that holding the subtalar joint at neutral position prevents dorsiflexion through the midfoot (Mueller et al. 1989; Woodburn, 1991). A pronated foot may hide a true diagnosis of limited ankle dorsiflexion, while a supinated foot may produce a result of equinus with resultant important clinical consequences (Woodburn 1991)

Naturally, issues of subtalar joint neutral position reliability would arise at this time (Weaver et al. 2001) – it is well known that untrained therapists do not consistently find subtalar joint neutral (Elveru et al. 1988; Pierrynowsky, 1996) however, it is claimed that training increases reliability (Diamond et al. 1989) although there is room for improvement (Pierrynowsky et al.

1996). On the other hand, this is totally refuted by Kim et al (2011) who demonstrated that experience does not increase reliability when measuring ankle dorsiflexion.

Trials that performed the measurement at subtalar joint neutral include DiGiovanni et al. (2001), Scharfbillig and Scutter (2004), Donnery and Spencer (1989), Assal et al. (2003); and Weaver et al. (2001).

3.3.7.3 Force Applied

According to (Assal et al. 2003), when the amount of dorsiflexing force that is applied by the examiner varies, the resultant angle will also vary. The product of the applied force and the distance between the axis of movement, i.e. ankle axis, and the point of application of the force, gives the moment, which is synonymous with *torque*. Using moment measurement as well as angular displacement, passive versus angular displacement curves can be produced as opposed to simpler systems where only a single point is recorded (Moseley et al. 2001). The moment applied to the ankle joint complex might fluctuate between one examiner and another, or between one examination and another, thus exerting unequal forces on the gastrocnaemius. The stretching characteristics of the triceps surae themselves may vary depending on other intrinsic or extrinsic factors, such as temperature (Knight et al. 2001; Robertson et al. 2005). The amount of force, or moment, applied to the ankle joint, normally to the metatarsophalangeal joint area, was reported in 75% of assessed studies. This was not applicable to those studies that assessed a type of lunge test, e.g. Bennell et al. (1998) and Menz et al. (2003). The moment applied varied: 10Nm (DiGiovanni et al. 2001; Weaver et al. 2001; Meyer et al. 2006), 12Nm, (Moseley et al. 2001), 15Nm, (Assal et al. 2003), 16.1Nm (Scharfbillig and Scutter, 2004) and 20Nm (Greisberg et al. 2002). Wilken et al. (2004) assessed angular displacement over a range of forces at 10, 15, 20 and 25Nm. Different amounts of force appear to have been arbitrary, except for DiGiovanni et al. (2001) who justified their 10Nm moment as having been chosen following previous work.

Applying the same amount of force to all subjects reduces the variability of subsequent readings between the same patients, making the test appear more reliable than if the force were not controlled. This is because the magnitude of force applied determines the applied torque, directly influencing the ankle dorsiflexion angle (Assal et al. 2003). If a known torque is applied to dorsiflex the ankle, reliability is thus increased (Moseley and Adams 1991).

This may be one way of standardizing one of the variables (Weaver et al. 2001) thus increasing the possibility of comparing results between trials. Additional apparatus may be required to do this, although a simple spring balance has been used to good effect to attain this goal (Moseley and Adams, 1991).

3.3.8 Methodological Quality Assessment

Appraisal of the methodological quality of primary studies is essential in systematic reviews. However, no consensus exists on the ideal checklist and scale for assessing methodological quality (Moja et al, 2005). Quality assessment was felt to be important because of the quoted poor reporting of tests carried out (Reid et al. 1995).

As mentioned earlier, two experienced clinicians evaluated each Primary Study and filled out the Quality Assessment forms. These were then compared and the presented data are the agreed results.

Table 3.6. Quality Assessment Scores.

	Question										
Study	1	2	3	4	5	6	7	8	9	10	%
Digiovanni et al, 2001	Y	Y	Y	Un	Y	Un	N	N	Y	Y	60
Bennell et al,1998	N	N	Y	N	N	Y	Y	N[a]	Y	Y	50
Menz et al, 2003	Y	Y	Un	Un	N	Y	Un	Y	Y	Y	60
Hume et al[b] 2000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Donnery and Spencer, 1988	Un	N	N	Un	Y	Y	Un	Un	Y	Un	30
Scharfbillig and Scutter, 2004	N	N	N	N	Un	Y	Y	Y	Y	Y	50
Moseley et al, 2000	N	Y	Y	Un	Y	Y	Un	Un	Y	Y	60
Assal et al, 2003	N	N	Y	Un	N	Y	Un	Un	Y	Y	40
Weaver et al, 2001	N	N	N	Un	N	Y	Un	Un	Y	Y	30
Meyer et al, 2006	N	N	N	Un	Y	Y	Un	Y	Y	Y	50
Wilken et al 2004	Un	N	N	Un	Y	Y	Un	Un	Y	0	30
Greisberg et al, 2002	Un	N	N	Un	N	Y	Un	Un	Y	Y	30

Horizontally, the numbers indicate the number of the question
Abbreviations: Y, yes; N,no; NA, not available; Un, unclear
Note: The higher the score, the higher the quality of the trial

[a]Although each rater was unaware of other raters' results, they were aware of their own, so they were not blinded effectively.
[b]Abstract available only; thus quality assessment could not be conducted

Table 3.7: Quality assessment Score Totals per study

Trial	Technique	Quality Score
Digiovanni, Holt, Czerniecki, Ledoux, Sangeorzan. 2001	Visual estimation of dorsiflexing angle	60%
Bennell, Talbot, wajswelner et al. 1998	Lunge Test	50%
Menz, Tiedemann, Mun-San Kwan, Latt, Sherrington, Lord. 2003	Modified Lunge Test	60%
Hume, Nakamura, Buford, Trevino, Patterson. 2000	Torque Range of Motion Device	NA
Donnery and Spencer 1988	Biplane Goniometer	30%
Scharfbillig and Scutter. 2004	Modified Lidcombe Template	50%
Moseley, Crosbie and Adams. 2000	A Manually controlled instrumented footplate	60%
Assal, Shofer, Rohr, Price, Czerniecki, Sangeorzan. 2003	Equinometer	40%
Weaver, Price, Czerniecki, Sangeorzan. 2001	Equinometer	30%
Meyer, Werner, Wyss, Vienne. 2006	A Mechanical Equinometer	50%
Wilken, Saltzam, Yack. 2004	Iowa Ankle Device	30%*
Greisberg, Drake, Crisco, DiGiovanni. 2002	Device to assess Gastrocnaemius Contracture	30%

*Note: Since this Systematic Review was published in the January-February edition of JAPMA, 2011, Wilken et al have published a detailed validation/reliability paper which, if included in the systematic review, would have scored highly (Wilken et al. 2011).

Although 12 papers that reported reliability were identified for quality assessment full text of two papers (Hume et al. 2000; Bobet et al. 2005) could not be obtained at the time of writing, which reduced the list to 10.

3.3.8.1 Participants in Ankle dorsiflexion Reliability Assessment

The majority of assessed studies used small, convenience samples of healthy volunteers (Table 3.6). Only 3 of the trials utilised real patients (Digiovanni et al. 2001; Menz et al. 2003; Wilken et al. 2004). “Evaluations of new tests often omit the essential developmental stage of evaluation in a real clinical population” (Jull 2002). The use of a suitable spectrum of patients is required when evaluating the validity and reliability of new diagnostic tests, otherwise *spectrum bias* may occur. This is because differences in clinical features between patients may produce considerable variations in results (Whiting et al. 2003).

As regards sample size, only DiGiovanni et al (2001), Menz et al. (2003) and Moseley et al. (2001) had a significant number of subjects. The ability to infer to larger populations in all the other cases is consequently debatable.

3.3.8.2 Randomization

Selection bias can be present when subject selection is not random (Lijmer 1999). Although only 3 trials selected actual patients (DiGiovanni et al. 2001; Menz et al. 2003; Wilken et al. 2004) the reporting of whether they were randomly selected is not clear.

3.3.8.3 Comparison to a Reference Standard

“Was there an independent blind comparison with a reference (gold) standard of diagnosis?” is an important question which should be asked to assess diagnostic tests (Jull 2002).

This mostly refers to the validity of the instrument. In simple words, are the reported results actual results, or is there the possibility of any confounding elements present? If a measure is reporting 0^o of ankle joint complex dorsiflexion, is it actually 0^o? Is there only ankle joint complex dorsiflexion, or does the result incorporate midtarsal joint dorsiflexion as well? This can only be ascertained by cross-checking this result with another measure that is known to produce good results. In this context, this may be quite difficult to achieve, because it is already known that there is a problem with achieving true dorsiflexion angles.

5 studies validated their results by cross-referencing with a known measurement technique:

DiGiovanni et al (2001) checked visual estimation of ankle dorsiflexion with an equinometer, although, as the authors themselves point out, there is a lack of a "gold standard" test. While Moseley et al. (2001) referenced their results with photography, Donnery and Spencer (1988) and Meyer et al. (2006) compared their results with a Goniometer, even when this method is known to have high reliability problems. Wilken et al. (2004 and 2011) assessed their dorsiflexion results with an Optotrak motion analysis system.

When measuring ankle dorsiflexion, true tibio-talar motion can be measured accurately using radiographic techniques. The vertical midline of the fibula can be compared to a line dividing the talar trochlea (Backer and Kofoed 1989). Thus this type of modality may be indicated as a true Reference Standard when comparing new techniques/equipment. Notwithstanding this, it is clear that some authors may run into ethical difficulties when proposing this modality because of radiation issues.

3.3.8.4 Statistical Analysis

Test-retest designs appear to be the preferred method of assessment, with Intraclass Correlation being the statistical test of choice (Bennell et al. 1998; Menz et al. 2003; Scharfbillig and Scutter 2004; Moseley et al. 2001; Weaver et al. 2001; Meyer et al. 2006; Wilken et al. 2004; Greisberg et al. 2002). They follow a trend in reliability trials. "The consistency or the repeatability of the ROM measurement - whether the application of the instrument and the procedures produce the same measurements consistently under the same conditions" (Gajdosik and Bohannon 1987).

Currier (1984), cited by Gajdosik and Bohannon (1987), continues to add that the validity of a measurement "constitutes the degree to which an instrument measures what it is purported to measure; the extent to which it fulfils its purposes." Measures of validity tell us whether an item measures what it is supposed to—that is, whether a measurement is true.

3.3.9 Discussion

When embarking on new research projects, it is normal practice to assess the validity and reliability of any outcome measures used. Thus it is perplexing why, with the current evidence regarding the unreliability of goniometric measurements, so many trials utilised this type of assessment as their main outcome measure. This not only raises questions as to the reliability and validity of their results, but also as to their clinical value.

It is evident that researchers always felt unhappy with goniometric measurements. The number of systematic reviews regarding this issue, and the number of different apparatuses that have been developed in order to improve on ankle dorsiflexion measurement techniques attest to this. A great number of these specifically designed apparatuses mainly aim to reduce errors of placement by securing the vertical arm to the leg. The accepted method of alignment appears to be from the lateral head of the fibula to the middle of the lateral malleolus for the vertical arm, and a plate to cover the plantar aspect of the foot for the other arm. For the former, a number of researchers have drawn a vertical line from the lateral head of the fibula to the malleolus to maintain alignment; if this practice is not maintained during clinical goniometric measurements, this may provide a significant error of placement which can be reduced by having the vertical, stable arm, long enough to reach up to the head of the fibula.

It is acceptable that, as the forefoot is pushed upwards to dorsiflex, kinematic changes occur in all the joints distal to the ankle joint. Although the study by Lundgren et al. (2008) was limited to just 6 subjects, who apparently were not controlled for hypermobility (i.e. whether there was an excessive amount of rotation around the axes) of the midtarsal joint, it confirms that motion of the foot is not solely at the ankle joint complex and the other foot joints contribute a significant amount of dorsiflexion.

At this stage, pending further analysis, it appears that, after all, Root et al (1977) may have had a very valid point in proposing that the ankle dorsiflexion angle be measured at subtalar joint neutral position. Woodburn (1991) and Tiberio et al.(1989) observed a very significant difference between pronated and non-pronated feet. In view of this, it is surprising why

Lundgren et al. (2008) did not control for subtalar joint position, which could have affected results.

This means that those trials which compared ankle dorsiflexion measurements taken at subtalar joint neutral and those which did not maintain this position, cannot be compared directly, because in the latter there may be the possibility of having increased angles due to joint motion extraneous to the ankle. With this regard, it follows that subjects with pronated, or flat, feet would exhibit increased ankle dorsiflexion measurements derived from additional midtarsal joint motion. In such cases the presence, or otherwise, of ankle equinus would be masked by false results, since these would include both ankle and midtarsal joint motion.

Whether subtalar joint neutral position can be consistently established by clinicians is debatable; Diamond et al. (1989) believe that reliability may be increased by training. However, its use may in fact increase measurement error (Lundgren et al. 2008). Currently there is a paucity of information that compares pronated and non-pronated feet dorsiflexion values to those of supinated feet (Woodburn 1991). Finding a way around the subtalar joint neutral position issue would eliminate one important factor that significantly affects this type of measurement (Meyer et al. 2006).

With reference to subject positioning, from the Thoms and Rome trial (1997), it can be concluded that this should be either prone or supine. Subject positioning is one of the factors that should be standardized in order to obtain consistent results in ankle joint measurement trials. However, even here, more research is required since the Thoms and Rome trial only assessed prone and supine positions with knee extended and sitting position with knee flexed. This could be because it is known that there is poor correlation between knees extended and knees flexed (Meyer et al. 2006). It is still puzzling, however, why sitting position with knees extended were not included in this trial.

While most of the papers reviewed used the term “torque” (DiGiovanni et al. 2001; Scharfbillig and Scutter 2004; Moseley et al. 2001; Assal et al. 2003; Weaver et al. 2001; Meyer et al. 2006; Wilken et al. 2004; Greisberg et al. 2002). “Moment” may be more appropriate and is accepted terminology within the biomechanics community. As to the *amount* of force applied, it emerges that consistency can only be attained by applying the same moment, which directly influences the ankle dorsiflexion angle (Assal et al. 2003). This may be one way of standardizing one of the variables, thus increasing the possibility of comparing results between trials. Additional apparatus may be required to do this, although a simple spring balance has been used to good effect to attain this goal (Moseley et al. 1991). Another interesting point to note is that the amount of force being quoted (DiGiovanni et al 2001; Scharfbillig and Scutter 2004; Moseley et al. 2001; Assal et al. 2003; Weaver et al. 2001; Meyer et al. 2006; Wilken et al. 2004; Greisberg et al. 2002) is generally a small percentage of the actual forces being applied to the foot during locomotion.

Although all studies report high Intraclass Correlation Coefficient (ICC) values for reliability, methodologies used to assess the various tools appear to be weak. It has been pointed out that although the number of diagnostic test evaluations is increasing, their methodological quality is on average poor (Lijmer et al 1999). Very few studies utilise actual patient populations. Most lack reference to a 'reference standard', such as X-Rays. Consequently one cannot discern if the reported angles are, in fact, the true angles of foot dorsiflexion.

It is also clear that the term 'reliability' and 'repeatability' are being used interchangeably. According to Gajdosick and Bohannon (1987) *"Reliability in goniometry simply means the consistency or the repeatability of the ROM measurements, that is, whether the application of the instrument and the procedures produce the same measurements consistently under the same conditions."* This definition, however, does not take into consideration validity, i.e. is the instrument *actually* measuring the correct angle? This is one of the main reasons why any such procedure must be compared to the Reference Standard. In the case of ankle joint complex measurement, following Tiberio et al. (1989) revelation that in a pronated foot there are 10^{o} degrees more dorsiflexion, the instrument under review might actually be measuring both ankle joint complex and midtarsal joint complex dorsiflexion. To complicate this further, it might be actually measuring also the summation of all dorsiflexion movements of joints distal to the ankle (Lundgren et al. 2008). Thus this Reference Standard may be Radiological, where the movement between the actual bones themselves may be measured more accurately.

Finally, in view of the evidence regarding goniometric unreliability, serious doubts arise as to the value of all research done utilising this method. A method/technique of assessing pure ankle joint complex dorsiflexion needs to be validated fully and, possibly, most of the research mentioned above repeated using this method to ensure that all the results are, in fact, true foot dorsiflexion results.

3.3.10 Conclusions

From this review, it can thus be deduced that:

- The majority of devised instruments consistently produced the same results in healthy populations. Utilization of a patient population is lacking in these studies.

- Most of the studies are characterized by small sample sizes.

- There is still no total agreement as to how the foot dorsiflexion angle can be measured. At the moment, the various techniques are inconsistent, thus causing a deficit in this particular area of research.

- Lack of standardization makes direct comparisons between trials impossible.

- It is not clear what is being measured, whether it is tibio-talar joint motion, ankle joint complex motion or the summation of all the movement of the joints of the foot. It appears that the latter may be the most likely, thus the term *foot dorsiflexion* may be more appropriate.

It is being proposed that the following be standardized:

- Placement of the vertical arm
- Should the other arm take the form of a plate?
- The amount of force applied to dorsiflex the foot (currently between 10Nm to 20Nm)
- Further research is required into the following aspects of this field:

- Subject position: does it influence the final result?
- Foot position: can subtalar joint neutral be consistently applied? If not, can a way around this problem be found?
- Placement of the axis, whether in line with the ankle joint axis, or below the lateral malleolus as described by Root et al.
- What is the amount of force needed to be applied to the plantar forefoot. Should it try to simulate normal kinetics during gait?

Unless true standardization of measurement is achieved, the accuracy of communication between clinicians, the act of measuring ankle joint dorsiflexion and the accuracy of the measurement itself, which is so important in determining therapeutic options, will be sorely lacking. Furthermore, the research that is going on cannot be responsibly utilised.

It appears that, even at this day and age, ankle joint complex dorsiflexion measurement is still a grey area.

3.3.11 Recommendations

Investigate what is actually happening during passive ankle joint dorsiflexion. Is it true that only tibio-talar movement occurs when the foot is placed in neutral position and the midtarsal joint locked?

Does the above also apply to children? Since children's feet are more flexible, if there is movement extraneous to the ankle joint, this is bound to be more pronounced than in adults. Hence it is essential to investigate paediatric foot segment movements since error of measurement may actually be larger than in adult feet.

Chapter 4

Ankle Joint Dorsiflexion Measurement Techniques

4.0 Introduction

This chapter will present the various methods/apparatuses for measuring ankle joint dorsiflexion presented in the systematic review, highlighting important unique feature of each device and identifying their strong and/or weak points in order to assemble design criteria for a possible ankle goniometer device that amalgamates and, possibly, improves on their weak points. A critical analysis of these devices will be carried out.

4.1 Traditional methods of measuring ankle joint complex dorsiflexion

Goniometry

The Root method is the most common method of goniometric measurement. In actual fact, this is derived from the *Silverskiold* method with the knees flexed and the knees extended to diagnose whether contracture is due to gastrocnaemius or soleus (Silverskiold 1924).

In this method the flexible arm of the Goniometer is aligned with the lateral head of the fibula and the lateral malleolus, while the other arm parallels the lateral aspect of the foot to the 5th metatarsophalangeal joint. The foot is held in neutral position and a dorsiflexing force is applied to the forefoot (Gastwirth 1996; Root et al. 1977).

The reliability of this method has been often criticized, with various authors having published various trials (Kim et al. 2011; Martin and Mcpoil 2005; Rome 1996; Van Gheluwe et al. 2002).

Visual Testing:

The ability to visually measure ankle joint dorsiflexion was investigated by DiGiovanni et al (Digiovanni et al. 2001). 68 people were examined first visually then by an equinometer to determine if the two methods correlated. An orthopaedic surgeon performed the clinical evaluation of each subject, who was sitting with the knees extended. The talonavicular joint was held in neutral position and a dorsiflexing torque was applied until there was no more movement. The angle was then estimated visually.

Strong Points	Weak Points
Cheap and readily available	Very subjective, depending on practitioner's eye judgment
No apparatus necessary	No objective measurement; thus it is very hard to replicate and/or prove result

The Lunge Test:

Most studies utilising the Lunge Test refer to Bennell et al. (1998) for validation purposes.

Figure 4.1: The Lunge Test

Modifications of the Lunge Test

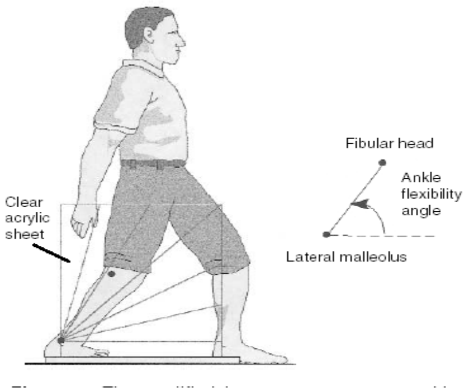


Figure 4.2: Modified Lunge Test (from Menz et al., 2003)

Figure 4.3: Another modified Lunge Test; measurement form wall to great toe (from Dennis et al, 2008)

Design features:

Most Lunge tests use simple, readily available accessory equipment, such as an inch tape to measure the distance from the wall to the great toe, or a goniometer or an inclinometer to measure the leg angle to the ground.

Design criticism:

This method is not suitable for patients who cannot bear weight due to contracture, recent surgery or other impairments (Moseley 1997).

4.2 Devices specifically designed to measure Ankle Dorsiflexion

A number of devices made specifically for measuring ankle dorsiflexion have been identified. Although they have been assessed as Primary Studies, there were other studies that utilised these apparatus.

These devices include:

The Biplane Goniometer

Figure 4.4: The Biplane Goniometer. (Donnery and Spencer 1988)

The Biplane goniometer, as opposed to a normal goniometer which has two moving arms, appears to be the first of its kind to include a footplate instead of the moving arm. Although this idea was innovative at its time, now it appears that there are various issues with this design.

Device design features:

- Vertical transparent arm aligned with lateral aspect of leg
- Footplate replaces the traditional moving arm of the goniometer.
- Flexibility of vertical arm allows the user to invert/evert the heel in order to place the foot at subtalar neutral position

Design criticism:

- Vertical arm is not held in place, thus operator must keep it aligned during the dorsiflexing process
- Foot position must be controlled and held by the operator
- The use of a foot plate raises issues as it has been shown that forefoot movement also accompanies hindfoot movement during passive dorsiflexion when a force is applied on the forefoot (Ref to Chapter 6).
- Axis of rotation does not approximate axis of rotation of the ankle joint; hence although it is closest to the Rootian method of measurement, one does not really know what is actually being measured. Certainly not ankle dorsiflexion by itself

The Lidcombe Template

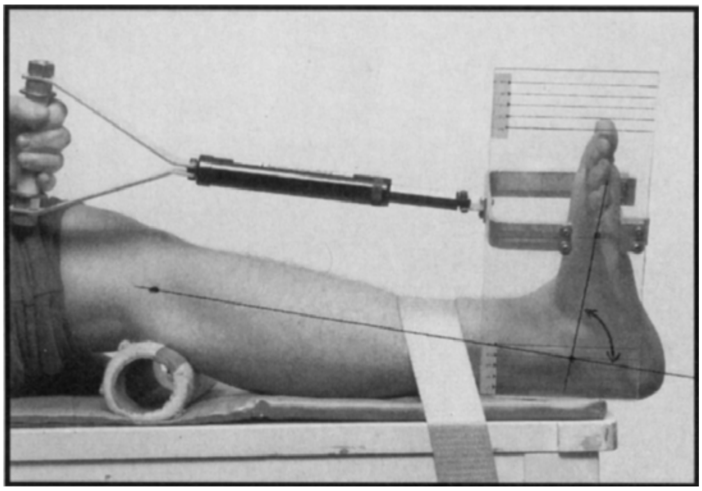


Figure 4.5: The Original Lidcombe Template (from Moseley, 1997)

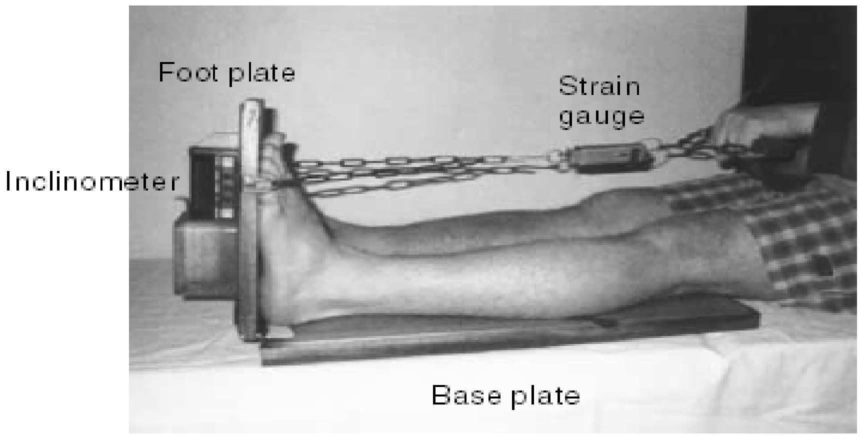


Figure 4.6: The modified Lidcombe Template (from Scharfbillig and Scutter, 2004)

Device design features:

- Easily applied torque by the use of a simple strain gauge. Very straightforward
- Simple design

Design criticism:

- Hinge lies behind the foot itself, which raises queries as to what is actually being measured. Certainly not ankle joint rotation
- Gastrocnaemius on base plate will move whole lower limb up and down with contraction and relaxation of the muscle.
- Utilization of non-standard anatomical references for alignment; uses horizontal position of the leg as the rigid lever

Torque Range of Motion Device

This is a single hinged device with a potentiometer to measure ankle angle and a strain gauge to measure ankle torque.

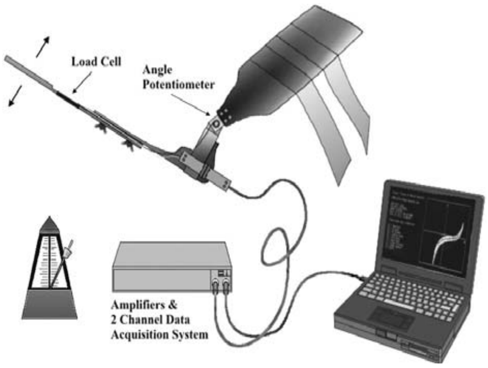


Figure 4.7: TROM in use (Trevino et al. 2004)

Device design features:

- Two-piece lower-leg splint for the foot and ankle, constructed of a flexible but resilient plastic.
- The two pieces of the splint hinged with a half-inch diameter, single-turn precision potentiometer at the ankle to allow passive plantarflexion and dorsiflexion.
- The foot part of the mold reinforced with a steel bar extending the full length of the cast to make it rigid.
- At a designated point on this bar, a cantilever beam load cell was mounted in the aluminium handle.
- The device was a single-degree-of-freedom hinge connected to molded thermoplastic splints strapped to the calf and foot

- Two amplifiers designed to condition the potentiometer angle signal and to amplify the load cell torque signal, which fed into a two-channel data acquisition system. The output from the data acquisition system was transmitted to a portable PC running custom designed software to acquire and display the TROM data in real-time.
- The centre of motion was adjusted to align with the tibio-talar joint axis just below the malleoli. The instrument was calibrated
- Patient sitting with knee flexed 20^{o}.

Design criticism:

- No control for foot posture
- Use of a plate under the foot raises issues as to what is actually being measured
- Use of wires from device to personal computer

The Equinometer

Developed by Weaver et al. (2001), this device consists of a potentiometer to measure ankle angles and a load cell to control the amount of torque applied to the foot. At initial examinations, this appears to be one of the most valid devices as it has a number of strong points:

- Fibula serves as a very reproducible anatomical landmark
- Tip of lateral malleolus approximates the centre of rotation of the ankle joint
- Footplate with stiff plastic heel designed to eliminate hindfoot movement and holds the foot at neutral position since hindfoot position can be influenced by subtalar joint axis (Weaver et al. 2001)
- Electromyograph (EMG) is used to ensure that patient is relaxed
- Connection to a computer calculates torque and gives and audible indication when the required torque is reached and when the test is over
- Velcro straps hold the device in place

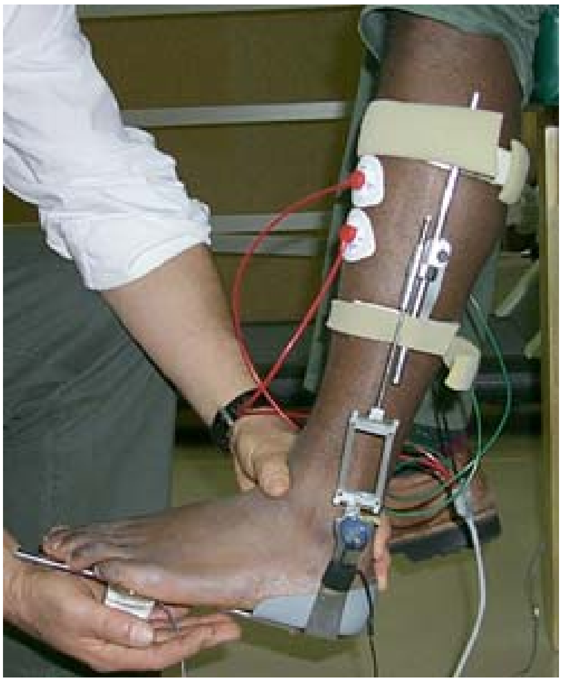


Figure 4.8: The Equinometer (from Digiovanni et al, 2001)

However, after carefully noting the text of the various studies found (Assal et al. 2003; Digiovanni et al. 2002; Weaver et al. 2001) it should be noted that:

- It is not clear how the heel cup holds the hindfoot in neutral position; it appears to be simply fixed to the footplate. Thus probably it is the operator that has to hold the whole assembly in the required position.

- Width and size of hindfeet will obviously vary. There appear to be no facility to adjust the heel cup to the width of the patient's heel. Thus if the heel is actually smaller than the heel cup, it cannot be held so securely and heel rotation inside the cup can occur.

- A whole foot plate may invalidate the reading, since during passive dorsiflexion, by the application of a force on the forefoot, it has been established that forefoot movement occurs as well (refer to Chapter 6). This movement cannot be completely eliminated, as previously advocated by the Rootian method (Root et al. 1977).

- There appear to be a lot of wires going to and from the device to the personal computer. These include a power supply and signal conditioner unit that powers and amplifies the potentiometer and load cell, together with a wire for the two channel EMG (Weaver et al. 2001) (pp 472) and another wire running from the load cell to the bundle of wires at the lateral side of the device. From this investigator's previous experience, wires running from the device can make it more cumbersome and can increase unreliability.

The Mechanical Equinometer

This device was developed for standardized and reproducible measurement of ankle dorsiflexion and allows control of foot position with application of a controlled torque to the foot (Meyer et al. 2006). It is composed of two mobile parallelograms connected with a hinge and angular scale.

- Attached anteriorly to the tibia using two slings
- Plantar surface of the foot attached to a plate and sandal
- Design is entirely independent of instantaneous centre of rotation
- Measures angle between anterior tibia and sole of foot
- Clinical measurements done by stabilizing the forefoot in neutral position and neutral pronation-supination

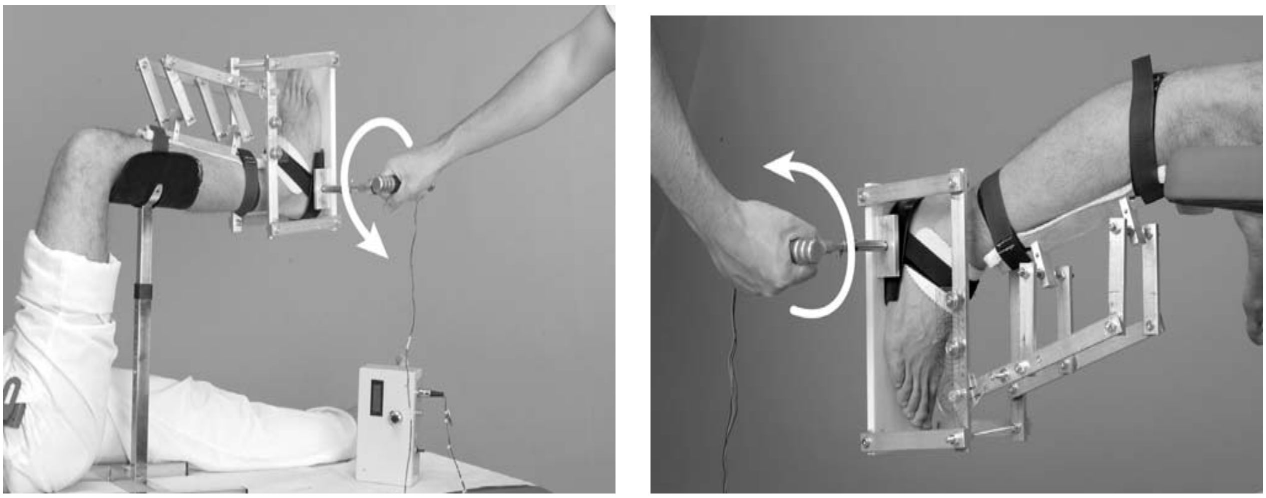


Figure 4.9 a,b. The Mechanical Equinometer

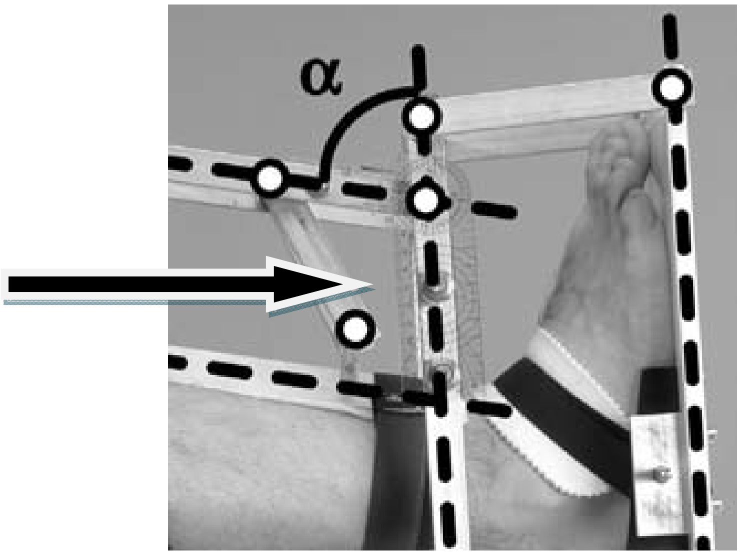


Figure 4.9c: The mechanical equinometer (from Meyer et al, 2006). Note plastic goniometer used to measure angle

- The only device using the anterior aspect of tibia; non-standardized alignment
- Plastic goniometer may be difficult to assess (small scale, with graduations very near to each other)
- Quite bulky
- How subtalar neutral was achieved is not very clear as what mechanism there is incorporated in the device for allowing this are not discernable from the text or photographs (operator appears to be only turning handle without holding the foot at neutral position)
- The use of a whole foot plate may invalidate the reading, since during passive dorsiflexion, by the application of a force on the forefoot, it has been established that forefoot movement occurs as well (refer to Chapter 6). This movement cannot be completely eliminated, as previously advocated by the Rootian method (Root et al. 1977).
- As this device measures angle of front of tibia to sole of foot, it cannot be said to be measuring ankle dorsiflexion, but foot dorsiflexion incorporating a potentially substantial amount of forefoot dorsiflexion.

The Iowa Ankle Device

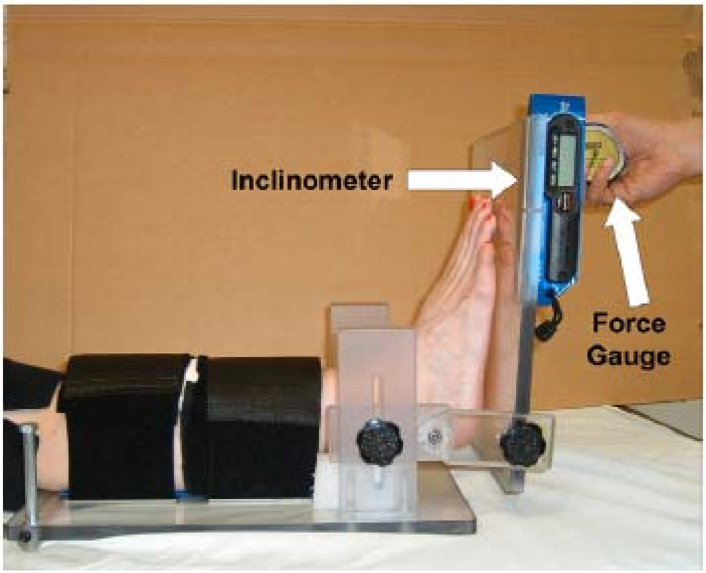


Figure 4.10: The Iowa Ankle Device (Rao et al. 2006).Validated by Wilken et al. (2004).

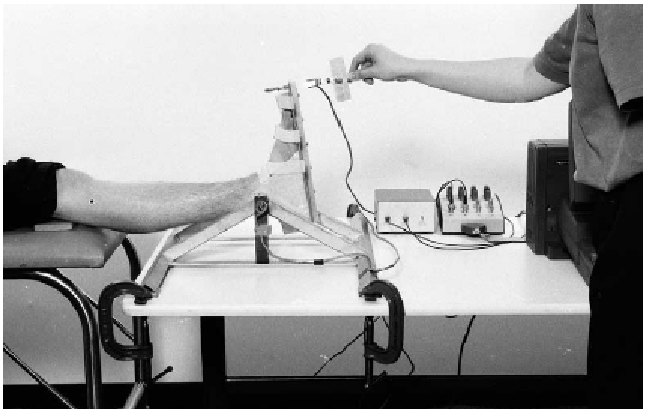
Device Design Features:

- Patients supine with knee extended, then flexed
- Long axis of foot aligned with clear acrylic footplate and tibia secured to the base plate by Velcro straps
- Device axis of rotation approximates ankle axis of rotation
- Angular measurement with a digital inclinometer which was referenced to the tibial crest and then mounted on the foot plate which was parallel to the sole of the foot.
- Torque controlled with hand-held force gauge

Design criticism:

- Device does not take into consideration foot position (neutral, supinated, pronated) and hence possible alteration in ankle/foot dorsiflexion
- The use of a plate across the sole of the foot makes this device a "foot dorsiflexion" measurement device, not an ankle device.
- From this investigator's experience during the design of an ankle goniometer, the bulk of the gastrocnaemius muscle changes with dorsiflexion/plantarflexion, thus changing the alignment of the hinge at the lateral malleolus level.

A Manually controlled instrumented footplate



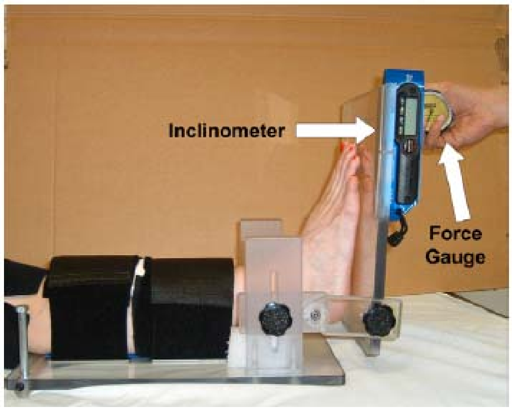


Figure 4.11: Demonstrating similarities between a) Instrumented footplate (Moseley et al. 2001) and b) The Iowa Ankle Device (Rao et al. 2006), validated by Wilken et al. (2004). The use of a pyramid shape in Moseley et al. has eliminated the possible interference by contraction of gastrocnaemius, however pressure on the Achilles Tendon may be painful in instances of Achilles Tendinitis

- Subjects supine with knees extended
- Shank placed horizontal
- Use of a footplate
- Lateral malleolus aligned with axis of rotation of footplate
- Footplate mounted on pylons using nylon sleeves
- Torque measured using a 250N load cell located 0.22m from axis of rotation of footplate
- Rotary displacement measured with a potentiometer mounted on the axis

Design criticism:

- No provision for controlling foot posture
- Use of footplate raises issues as discussed previously

A Device Designed To Assess Gastrocnemius Contracture

This device uses "Flock of Birds", which is a pulsed DC magnetic tracking device for motion analysis by Ascension Technology Corporation (2010).

- Tracking sensor on long axis of the leg, with another on the sole of the foot along the axis of the second ray. Centre of head of fibula and centre of lateral malleolus were marked, and a line drawn between markings to delineate the long axis of the leg.
- Leg sensor strapped to leg aligned with long axis
- Foot component placed orthogonally to the leg piece and device is zeroed
- The angle formed by the projections of the two sensors in a two dimensional plane defined by these sensors is the measured angle of dorsiflexion.
- Software measures sagittal plane dorsiflexion
- Software measures coronal plane motion (hindfoot eversion) so that the foot can be placed in a consistently neutral position for measurements to prevent inversion or eversion at the hindfoot from contributing to the measurement of ankle dorsiflexion (Greisberg et al. 2002)
- Subjects with knees flexed and extended
- Foot component separate from leg component to allow ankle and hindfoot to move through their normal axes.
- Foot component consists of a heel cup and a forefoot pad connected on a sliding rail in order to accommodate various foot sizes
- Examiner holds heel in the heel cup and other hand controls the forefoot

Design Criticism:

- 3-Dimensional tracking technology, while acceptable for laboratory research purposes, is possibly at present too expensive for everyday clinical use.
- Although variation in foot length is addressed by a sliding rail, the size of heel cup does not appear to make allowances for variability in heel girth.
- Like with the use of a plantar plate, the sliding rail from the heel to the forefoot raises issues with hindfoot to forefoot angles as discussed elsewhere (Chapter 6).

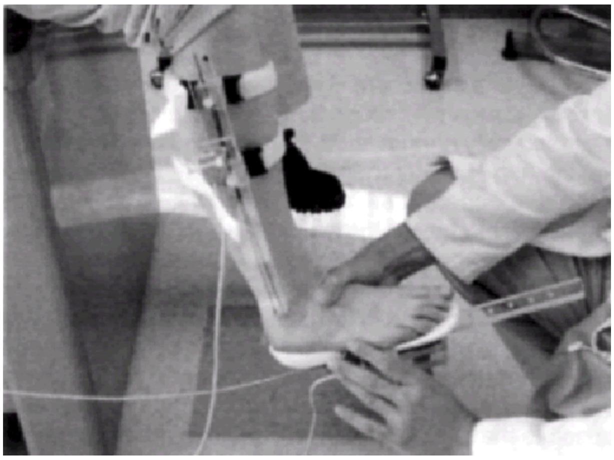


Figure 4.12. A device designed to assess Gastrocnemius Contracture. From Greisberg et al. (2002)

From the above, there is clear evidence of a number of methods and apparatuses designed specifically to measure ankle joint dorsiflexion. They all have their weak and strong points. Thus the question that arises naturally is, why is there a need for another Ankle Goniometer?

It is this investigator's belief that a goniometer that truly measures ankle joint complex dorsiflexion is still not available to the clinician as all the above devices differ in significant ways.

Data that can be extracted from the preceding investigation include:

Pivot Point: Most devices include a pivot point near the lateral malleolus to approximate the ankle joint axis. Other methods, such as the Lidcomb Template, the traditional goniometer and the Lunge Method do not truly measure ankle joint movement, but perhaps foot dorsiflexion. This could be significantly different from ankle joint movement because of the possible movement at other joints of the foot, mainly the mid-tarsal joint (calcaneo-cuboid and talo-navicular).

Anatomical reference: It arises that a line drawn from the lateral head of the fibula to the malleolus appears to be one of the main criteria about which there is agreement between the various authors, as this represents the vertical axis of the leg. A sole exception for this is Meyer et al. (2006) who use the front of the tibia as the reference for the placement of the vertical arm.

Notwithstanding this, this choice of an anatomical region represents a very solid anchor point to any device since there is very little soft tissue between the frontal edge of the tibia and the skin.

Footplate: The use of a footplate appears to be a standard procedure between the majority of devices. At initial glance, this would appear to be a very good choice since the force being applied on the forefoot can be applied through this plate and since such a design feature would eliminate many errors arising from the use of a narrow goniometer arm by preventing this arm from moving upwards, thus causing mis-alignment between the moving arm and the sole of the foot. In fact, in concluding the Systematic Review, it was in fact concluded that a footplate should be one of the standardization criteria for measuring ankle dorsiflexion since it is used by a majority of authors. However, although Rootian theory suggests that the midtarsal joint locking mechanism eliminates any forefoot movement when the subtalar joint is placed in neutral position, this has not been proven anywhere in literature and indeed there are doubts cast on this theory which requires to be investigated during this dissertation.

Because of the flexible nature inherent in the foot originating from its multi-jointed structure, it seems quite unlikely that this is so. Thus further research into segmental foot motion is surely warranted. One year after the writing of this piece of research, this investigator now has doubts as to how beneficial the use of a footplate would be.

Foot Posture: Some devices allow the examiner to place the foot into neutral position in order for this examination to be carried out at this position, to be congruent with Rootian Theory. However, they do not actually aid the examiner to maintain this position, which could be critical as it is well known that in a pronated foot there are 10^{o} of dorsiflexion available (Tiberio et al. 1989; Woodburn 1991). Where these 10^{o} are coming from has not yet been explained, however one suspects that this could be movement arising from the midtarsal joint.

Torque Applied: Various devices depend on a known application of torque in order to increase their reliability. This is because the amount of ankle movement is proportional to the Torque applied. However, the clinical use of dorsiflexion measurement warrants a simpler system (Moseley and Adams 1991). Torque is applied when a measure of ankle stiffness is required

(Moseley et al. 2001), which is more often the case in neurological patients with gastrocnaemius spasms.

Thus, it is clear that there are standard conclusions, but also questions that arise from the above investigation. These include:

Axis of Rotation: This axis should approximate the ankle joint axis when one is measuring ankle joint dorsiflexion as compared to foot dorsiflexion

Line of reference: Lateral head of fibula to lateral malleolus

Footplate: Does the use of a footplate in fact cause errors in measurement by also introducing forefoot movement into the equation?

Foot Position: Which is the optimum foot posture to use; the pronated, neutral or supinated postures?

Torque Applied: Should one control for torque when analyzing the ankle dorsiflexion angle? Or should torque be reserved for research purposes?

In order to start answering some of these questions, a study to investigate segmental movement of the foot in the various foot postures was devised, utilising the best and most accurate and reliable method known to-date, i.e. kinematics.

Chapter 5

General Experimental Methodology

5.0 Background

This chapter outlines the methodology employed during the various trials in order to illustrate the various equipment, reference systems and the kinematic foot model. All subsequent experimental chapters will consequently refer to this section.

5.1 Motion Capture

Motion capture and analyses carried out throughout this thesis involved the use of a VICON MX Motion Analysis System (Vicon, OMG, Oxford, UK) employing 8 MX6 cameras at the Staffordshire University Gait Laboratory and a similar 6 camera system at the Faculty of Engineering, University of Malta. Since these two systems were directly compatible, including the same software version and laboratory layout, this allowed the research to be performed at the two Labs, utilising the same software and computer hardware.

Figure 5.1 : Biomechanics Lab layout showing camera Vicon placement and couch for participants

Nexus, a proprietary software by Vicon, was employed for motion capture while the data was analyzed using Polygon. The Oxford Foot Model has been chosen to model foot segment motion of both adult and adolescent participants since this model has been previously validated by Carson et al (2001) in adults and by Stebbins et al (2006) in children. It has been implemented in Vicon Nexus software utilising BodyBuilder Software as a standard plug-in, enabling it to be used by Vicon users in a standardized format. Thus since the marker set has been applied consistently by the same researcher and both equipment and software are the same, repeatability of the model is not affected and the results obtained by the two Labs are consistent. Furthermore, since this is a standard model, the same Joint Co-ordinate System was employed, otherwise the model would not run. This model is very well described by Stebbins et al (2006), including anatomical, technical and marker definitions which were adhered to during the implementation of this model for this research.

The Oxford Foot Model divides the foot into various segments (Figure 5.2) and analyzes:

- the Tibia with respect to the floor
- hindfoot with respect to the tibia
- forefoot with respect to the hindfoot
- hallux with respect to the forefoot

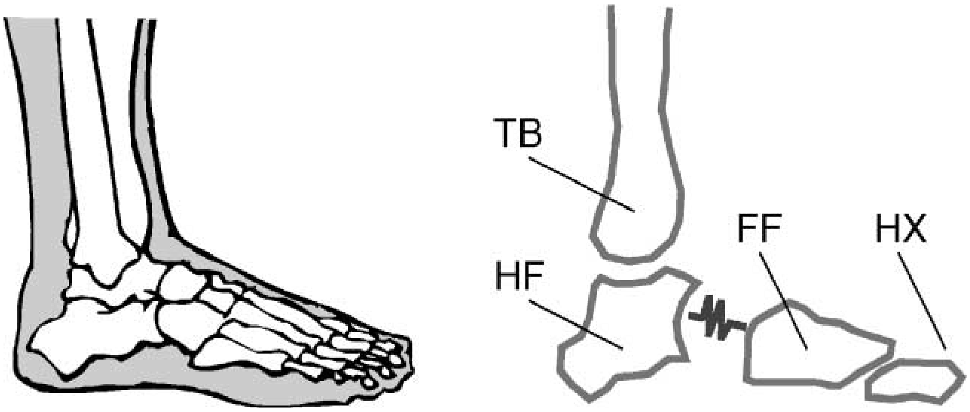


Figure 5.2: Schematic of the three segment foot model with tibia: TBTibial segment (tibia and fibula), HF-Hindfoot (calcaneus and talus), FF-Forefoot (five metatarsals), HX-Hallux (hallux proximal phalanx). (Adapted from Carson et al, 2001)

Table 5.1: Names and positions of markers used in the Oxford foot model (from Stebbins et al, 2006)

Marker name	Position	Segment
KNE	Femoral condyle	Femur
TTUB	Tibial tuberosity	Tibia
HFIB	Head of fibular	Tibia
LMAL	Lateral malleolus	Tibia
MMAL	*Medial malleolus*	Tibia
SHN1	Anterior aspect of shin	Tibia
CAL1	Posterior distal aspect of heel	Hindfoot
CAL2	*Posterior medial aspect of heel*	Hindfoot
CPEG	Wand marker on posterior calcaneus aligned with transverse orientation	Hindfoot
LCAL	Lateral calcaneus	Hindfoot
STAL	Sustentaculum tali	Hindfoot
P1MT	Base of first metatarsal	Forefoot
P5MT	Base of fifth metatarsal	Forefoot
D1MT	*Head of first metatarsal*	Forefoot
D5MT	Head of fifth metatarsal	Forefoot
TOE HLX	Between second and third metatarsal heads	Forefoot
	Base of hallux	Hallux

Names in italics are used in the static trial only and are removed for dynamic trials.

Figure 5.3 a-d: Marker placement for the Oxford Foot Model

Table 5.1 and Figures 5.3 a-d illustrate markers used in the Oxford Foot Model.

Reproduced from Stebbins et al (2006), segments are defined as follows:

Tibia Segment: assumed to be a rigid body composed of the tibia and fibula. Segment is based on the plane defined by the line from the knee joint centre to the ankle joint centre and the trans-malleolar axis. Longitudinal axis is from the ankle joint centre to the knee joint centre. Anterior axis is perpendicular to the plane defined by the longitudinal axis and the trans-malleolar axis. Transverse axis is mutually perpendicular.

Hindfoot Segment: The calcaneus defines the hindfoot. Motion at the talocrural and sub-talar joints are considered to contribute jointly to motion of the hindfoot relative to the tibia. Segment is based on orientation of the mid-sagittal plane of the calcaneus in standing posture (defined by the line which passes along posterior surface of the calcaneus, which is equidistant from both lateral and medial borders of this surface, and the point mid-way between the sustentaculum tali and the lateral border of the calcaneus). Anterior axis from the most posterior aspect of the calcaneal tuberosity, in the plane defined above and parallel to the plantar surface of the hindfoot. Lateral axis perpendicular to this plane.

Forefoot Segment: Comprised of the five metatarsals, and assumed to move as a single rigid body. Segment is based on the plane defined by the centre of distal heads of the first and fifth metatarsals and the proximal head of the fifth metatarsal. Superior axis is perpendicular to this plane.

Hallux Segment: Comprised of the proximal phalanx of the hallux. Based on a longitudinal line along the proximal phalanx.

Dorsiflexion/Plantarflexion of segments:

For the hindfoot relative to the tibia (HINDFOOT/TIBIA): Plantar/dorsiflexion: about the transverse axis of the tibia.

For the forefoot relative to the hindfoot (FOREFOOT/HINDFOOT): Plantar/dorsiflexion: about the transverse axis of the hindfoot.

Rotations of the forefoot relative to the tibia (FOREFOOT/TIBIA): Plantar/dorsiflexion: about the transverse axis of the tibia.

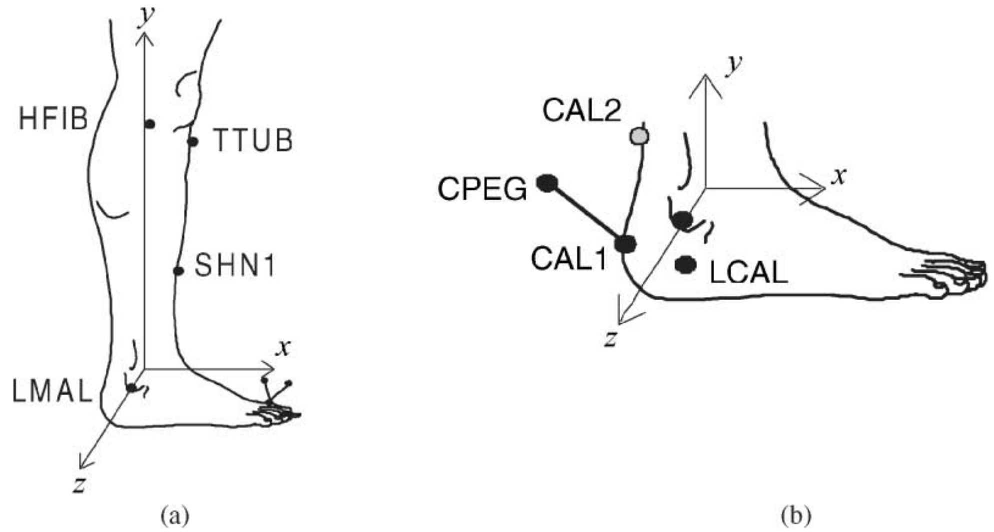


Figure 5.4: FF/HF: Plantar/dorsiflexion about the mediolateral axis of the hindfoot, z, in b (adapted from Carson et al, 2001)

5.2 Hindfoot Model

For validation of the Ankle Goniometer, it was necessary to synchronize the goniometer with a hindfoot model. This model, which had been in use at the Staffordshsire Gait Lab, is based on the Oxford Foot Model and was constructed using Visual 3D (C-Motion, Germantown, USA). (http://www.c-motion.com/v3dwiki/index.php?title=Oxford_Foot_ Model). This model was built in reference to Carson (2001) and Stebbins (2006) who provide very detailed information about the model.

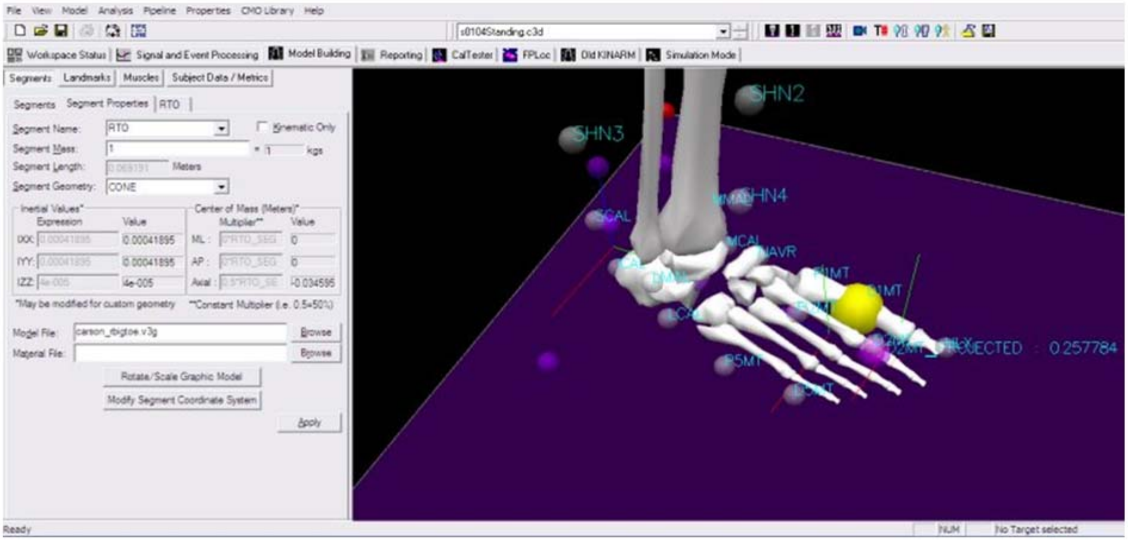


Figure 5.5: Oxford foot model implementation in Visual 3D (https://www.c-motion.com/v3dwiki/index.php?title=Tutorial:_Oxford_Foot_Model#Part_2._Defining_the_tibia_segment)

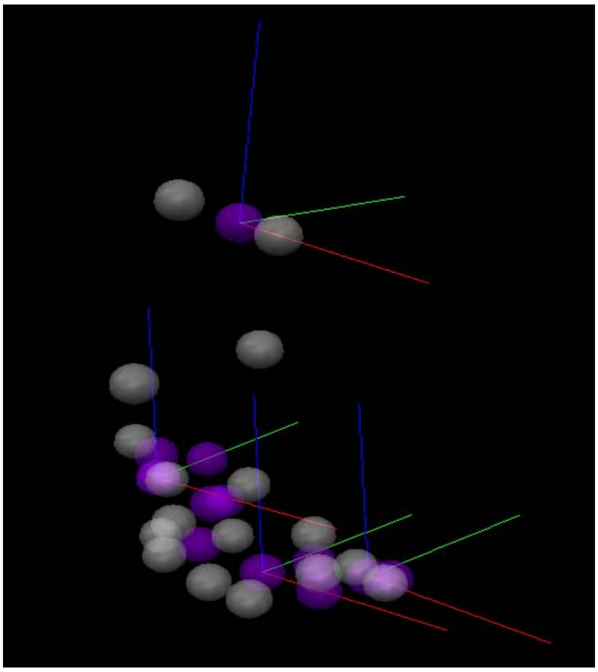


Figure 5.6 : screenshot which highlights the local coordinate system for the tibia, hindfoot, forefoot and hallux.

Laboratory coordinate system

Anterior/posterior Axis – X (Red)

Medial/lateral Axis – Y (Green)

Vertical Axis – Z (Blue)

Cardan sequence

Y (Sagittal), X (Frontal), Z (Transverse)

Filter

Butterworth filter with a low-pass cutoff frequency of 6Hz

5.3 Analysis

The data generated by the Vicon Nexus software was consequently analyzed in Vicon Polygon, which is the Vicon proprietary software for reporting. This has the Oxford Foot Model implemented as a plugin, which means that the model can be run seamlessly within this software.

A report was created for each participant, where the required angles were graphed and the angles measured for:

- Maximum Ankle Angle (MaxAnkleAngle)
- Maximum Hindfoot to Tibia Angle (MaxHFTBA)
- Maximum Forefoot to Tibia Angle (MaxFFTBA)
- Hindfoot to Forefoot Angle Range (HFFFA)

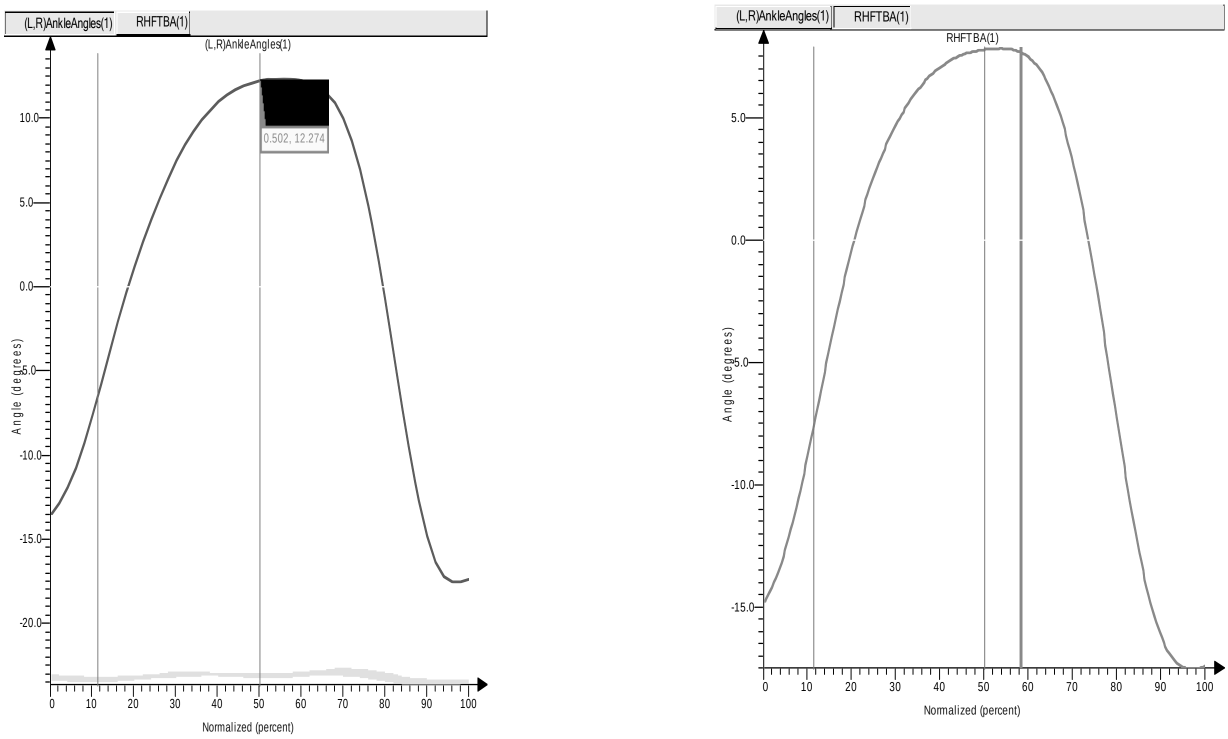


Figure 5.7: An example of Ankle Angle (on the left) and Hindfoot to Tibia Angle (on the right) output by Polygon Software, for the same trial. "Dorsiflexion" in both instances is the angle above 0^o, whilst Maximum Angle was determined by the maximum height of the graph. This was performed in the neutral, pronated and supinated postures

In the hindfoot model and electrognoniometer experiment as described in Chapter 10, results of the synchronized angles were exported to MS Excel as ASCII, for further analysis. Values were consequently plotted for both the ankle dorsiflexion angles ouput by the Ankle Goniometer and the Vicon software (Figure 10.5).

5.4 Dorsiflexion Terminology:

According to Siegler et al (2002), definitions of the hindfoot include:

- The **ankle** (talocrural) joint: The articulation formed between the talus and the tibia/fibula.

- The **subtalar** (talocalcaneal) joint: The articulation between the talus and the calcaneus.
- The **ankle joint complex**: The structure composed of the ankle and the subtalar joints.

As regards "foot dorsiflexion", there is an increase in complexity as the other foot joints must be taken in consideration, keeping in mind that the foot is multi-segmental and often with large ranges of motion at these joints, e.g. the midtarsal joint.

Thus it is important to maintain a standardized definition of the various dorsiflexion movements available at the foot and ankle since there are distinct differences in the various forms of this sagittal plane motion. As outlined in Section 2.2, three types of dorsiflexion movements are referred to throughout this thesis. These include:

Foot Dorsiflexion: Sagittal plane movement of the whole foot with the dorsum of the foot raised towards the lower leg. This implies that this upward movement can occur at all the joints capable of allowing this type of movement, which include the ankle, subtalar and midtarsal joints. Thus this movement is a summation of all the dorsiflexion movement, as represented in traditional Kinematic analysis using a single segment model of the foot.

Ankle Dorsiflexion: Sagittal plane movement of the whole foot with the dorsum of the foot raised towards the lower leg occurring only at the ankle joint. This type of motion, according to the Rootian Theory, is said to occur when the subtalar joint is placed at neutral position, the midtarsal joint is 'locked' and a dorsiflexing moment applied to the ball of the foot.

Hindfoot dorsiflexion: Ankle joint complex dorsiflexion, which includes dorsiflexion at the ankle (talo-crural) and subtalar joint.

Hence, this convention will be adhered to throughout this thesis. The term “Maximum Foot Dorsiflexion” refers to the upward, sagittal plane movement of the whole foot, which includes movement in all available foot joints, until the end of available motion. This can also be termed ‘Tibia to Foot’ angle, with an example output of ‘Tibia to foot angle’ being shown in Figure 2.10.

The term “Maximum Ankle Dorsiflexion” refers to the upward, sagittal plane movement of the ankle joint until the end of available motion. In the Oxford Foot Model, this is calculated by the angle formed between the ‘tibia and hindfoot’ segment; an example of this movement is demonstrated in Figure 2.10.

Chapter 6

A repeated measures study to explore the effect of foot posture on Sagittal Plane Kinematics of the Foot during Passive Ankle Dorsiflexion in Healthy Adults

Aspects of this chapter have been published:

Gatt A, Chockalingam N, Chevalier TL. 2011. Sagittal plane kinematics of the foot during passive ankle dorsiflexion. *Prosthetics and Orthotics International*. 35(4). pp. 431 - 437.

6. 0 Introduction

Examination of the range of motion of the ankle joint is a routine clinical procedure for the static diagnosis of ankle equinus (Rome 1996) and to assess the influence of disease and joint surgery (Backer and Kofoed 1989). This examination involves the dorsiflexion of the foot through the application of force at the metatarsophalangeal joint area. As has already been established, the maximum ankle dorsiflexion angle may be assessed through a variety of techniques, such as visual estimation (Digiovanni et al. 2001), goniometry (Gajdosik and Bohannon 1987; Gastwirth 1996; Root et al. 1977) or with the use of one of the various ankle measuring devices (Assal et al. 2003; Donnery and Spencer 1988; Hume et al. 2000; Wilken et al. 2004). The goniometric measurement of maximum dorsiflexion is a clinical procedure during which the stable arm of the goniometer is aligned between the lateral head of the fibula and the lateral malleolus, while the moving arm is held along the lateral border of the foot up to the 5th metatarsal head. The subtalar joint is placed in neutral position and a dorsiflexing force is applied to the fourth and fifth metatarsophalangeal joints (Gastwirth 1996; Root et al. 1977). Reliability of this technique, however, has been criticized by various authors (Martin and Mcpoil 2005; Rome 1996; Van Gheluwe et al. 2002; Wrobel and Armstrong 2008), which casts serious doubts as to whether this technique should be used at all. Moreover, even in research, this technique is also used routinely (Kilgour et al. 2003; Mecagni et al. 2000).

While ankle and foot dorsiflexion during gait has been studied extensively, there is little information regarding passive dorsiflexion, such as manual dorsiflexion of the foot. This manual dorsiflexion forms an important part of any clinical assessment related to foot pathologies. Furthermore, the resultant angle determines diagnosis of equinus-related conditions and it may influence treatment given to the patient. Thus it is essential to understand foot mechanics when force is applied to the forefoot and the foot is dorsiflexed.

An important aspect of clinical ankle dorsiflexion measurement is foot posture, i.e. the effect of pronation and supination on the maximum foot dorsiflexion angle. In one study, in which maximum ankle dorsiflexion was measured on a projection of a 35mm slide, a significant difference between the neutral position and the pronated position was found (Tiberio et al. 1989). Two-dimensional video analysis was also used to measure ankle dorsiflexion in 30 healthy females. In this study, an increase of 10^{o} of dorsiflexion was noted in pronated feet (Woodburn 1991). Both studies concluded that the measurement of ankle dorsiflexion should be performed with the subtalar joint at neutral position.

The procedure behind clinical examination of ankle dorsiflexion has an important assumption that has never been clinically proven: that when the foot is placed in neutral position and the foot is dorsiflexed by applying a force on the metatarsophalangeal joints, movement occurs only at the ankle joint (Root et al. 1977). However, the foot is composed of several segments, with movement occurring between the various joints. Research has shown that the movement between these foot joints may be quite extensive during gait. Hypermobility of the forefoot, for example, is a very common finding during clinical examination. This forefoot movement may, in fact, be providing false results; ankle equinus may not be diagnosed because the foot has bypassed the 0^{o} mark or, according to some clinical theories, has exceeded 10^{o} of dorsiflexion. These 10^{o} may, in fact, be mostly attained by the upward movement of the forefoot at the midtarsal joint, and not at the ankle joint itself. This would be a clear case of misdiagnosis and a patient with ankle equinus may not get the required treatment because of an apparent 'normal' amount of dorsiflexion. This may result in a midtarsal joint break, which is noted as a characteristic of equinus feet.

While hypothesizing that foot postures alter sagittal foot and foot segment motion, this study aimed to investigate ankle dorsiflexion in various foot postures. Furthermore, this study examined the intrinsic sagittal foot segment motion during passive ankle joint dorsiflexion, as would happen during normal clinical examination of ankle range of motion through goniometry as outlined by Root et al (Gajdosik and Bohannon 1987; Gastwirth 1996; Root et al. 1977).

Aim:

- To investigate the effect of foot posture on sagittal plane foot segment kinematics during the clinical assessment of passive maximum ankle joint dorsiflexion and maximum foot dorsiflexion.

Objectives:

- To kinematically quantify maximum foot and ankle joint dorsiflexion angles at the pronated, neutral and supinated postures.
- To determine whether the Forefoot to Rearfoot Angle remains constant during passive dorsiflexion as force is applied to the forefoot
- To assess whether the hindfoot to tibia angle is proportional to the forefoot and tibia angle

6.1 Method

16 healthy subjects (4 females, 12 males) with a mean age of 35.5 yrs (range 20-56yrs) were invited to participate in this study. Ethical approval was sought from and granted by Staffordshire University Ethics Committee. The experimental process was explained both verbally and through the use of an information sheet (Appendix 1) to all participants, who signed informed consent._Exclusion criteria included neurological disease, history of foot surgery and obvious foot deformity.

Height and weight, leg length, knee and ankle width was recorded for each subject to create their corresponding lower-limb kinematic model. An 8-camera optoelectronic system (Vicon, OMG, Oxford, UK) was employed to collect the kinematic data at 100Hz (Ref to Chapter 5). Reflective markers were placed by the primary researcher (a clinician), using the Oxford Foot Model marker set, then cross-checked by an experienced researcher. After a standing static calibration, the markers were checked again and another static calibration was carried out with the subject sitting on the couch. This position was necessary so that the Posterior Superior Iliac Spine markers were visible to the rearmost cameras.

Each subject's right foot was held in one of the 3 possible postures by the primary researcher (i.e. maximally pronated, subtalar neutral or maximally supinated), using the talonavicular congruency method (Root et al. 1977). The sequence of these foot postures was determined randomly by the other researcher to avoid any bias that could affect the results. The foot was dorsiflexed slightly to minimum resistance, then to its limit by the application of a force on the forefoot, at the metatarsophalangeal joint area. It was held in that position for three seconds before being released.

The primary focus of the methodology was to keep in line with normal clinical assessment. To ensure neutral subtalar joint position, the talar head was palpated until it was felt equally on the lateral and medial aspects, then maintained while the foot was dorsiflexed. The pronated position was maintained by directing the force laterally and ensuring that only the medial head of talus was palpable, while the supinated position was maintained by palpation of the talar head on the lateral side. Ten repetitions for each posture were done, for a total of 30 trials per subject. The following variables were recorded in three different foot positions (supinated, neutral and pronated):

Table 6.1: Variables used to denote dorsiflexion terminology throughout the thesis

Symbol	Variable Name	Explanation
$\alpha_{dorsi,\ max}$	Maximum Foot dorsiflexion	Maximal passive dorsiflexion measured in the sagittal plane
$\Delta\beta_{hindfoot,\ ROM}$	Hindfoot range of movement	Range of movement of the hindfoot with regards to the tibia
$\Delta\beta_{forefoot,\ ROM}$	Forefoot range of movement	Range of movement of the forefoot with regards to the tibia
$\Delta\lambda_{forefoot}$	Forefoot movement	Forefoot movement with regards to the hindfoot

Each subject's data were normalized and then averaged for each condition. Further statistical analyses were performed using SPSS 17.0, with the level of significance set at p=<0.005 throughout all statistical analysis. Data were analyzed with the Kolmogrov-Smirnov test, which returned a non-significant p-value of 0.200 for all three postures, thus demonstrating a normal distribution.

6.2 Results

The first 5 correct trial results out of 10 were recorded for each posture for each participant. Thus each participant yielded a total of 15 trials.

6.2.1 Maximum Foot Dorsiflexion Angle

Maximum dorsiflexion angles in the pronated, neutral and supinated postures for each of the 16 participants is shown in Table 1 (Appendix 2) and Figure 6.1 which demonstrate the relationship between foot posture and the maximum foot dorsiflexion angle.

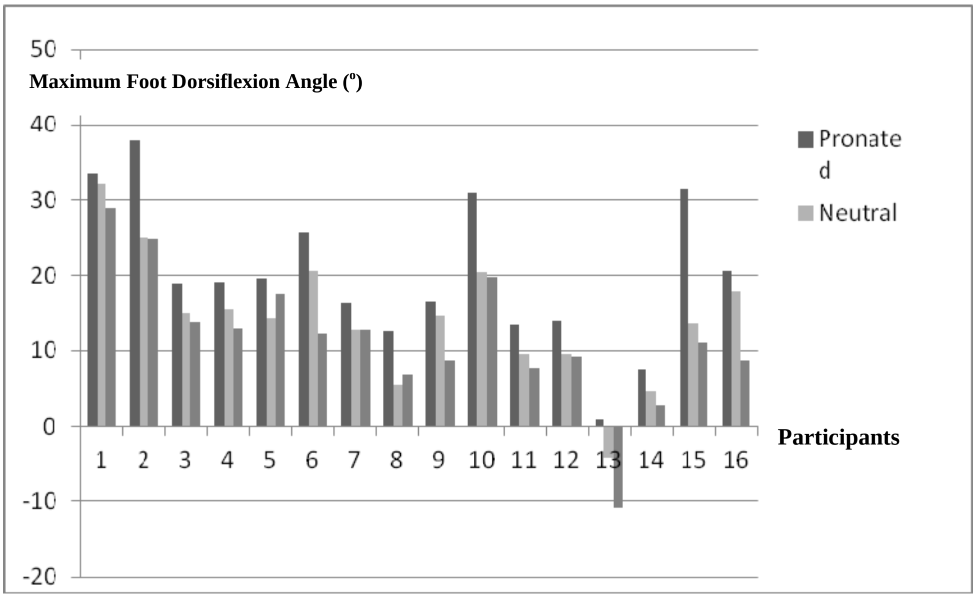


Figure 6.1: Maximum Foot Dorsiflexion vs Foot Posture. Maximum angle in the pronated position is greatest in all 16 subjects. Supinated position returns the least position also in 14 subjects. Neutral position lies "in between" in 14 out of the 16 subjects.

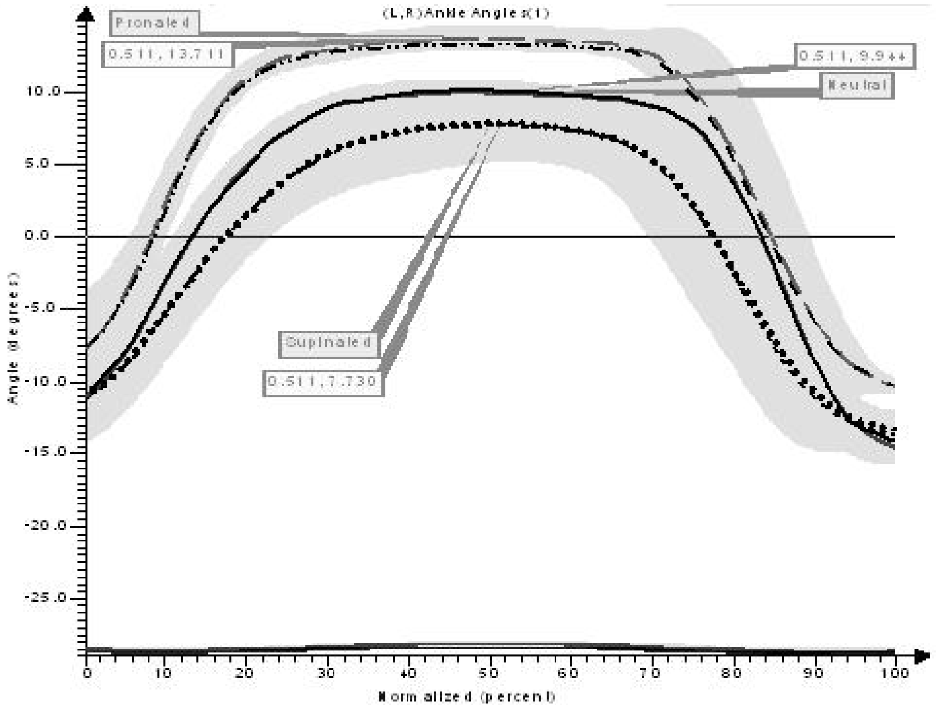


Figure 6.2: Example of Foot Dorsiflexion Graph in the pronated, neutral and supinated positions as output by Polygon software (Vicon)

6.2.2 Hindfoot and Forefoot Movement

Table 2 (Appendix 2) shows the forefoot to hindfoot angle range of movement in the pronated, neutral and supinated postures.

6.3 Statistical Analysis

6.3.1 Maximum Foot Dorsiflexion Angle

A One way repeated measures Analysis of Variance (Anova) was conducted to compare the mean Maximum Foot Dorsiflexion Angle between the 3 foot postures, which indicated a significant difference between groups (p=0.000) (Table 4, Appendix 2). As shown in Table 5 (Appendix 2), the mean maximum foot dorsiflexion angle is significantly different in both the pronated to neutral postures and pronated to supinated postures (p=0.000). Likewise, there is also a significant difference in maximum foot dorsiflexion between the neutral and supinated postures (p=0.032).

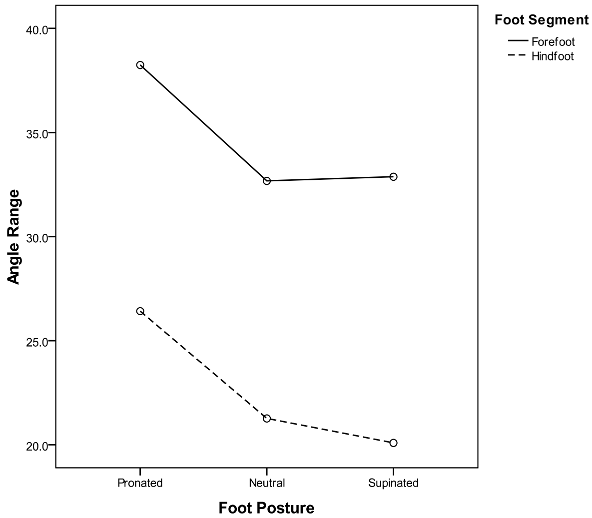


Figure 6.3a: Foot segment vs Foot Posture

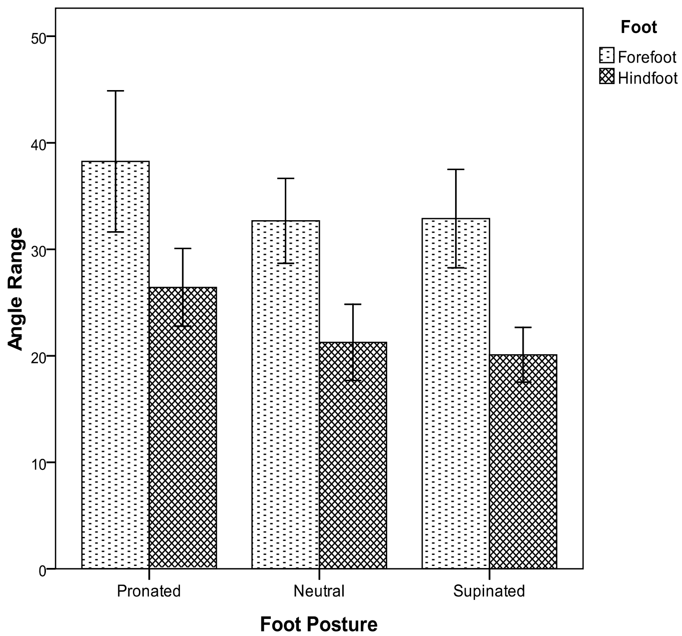


Figure 6.3b: Foot segment Ankle Range of Motion vs Foot Posture

Figures 6.3 a and b demonstrate increased forefoot movement relative to hindfoot movement in the pronated, neutral and supinated postures.

The difference between the mean maximum foot dorsiflexion angle between pronated and neutral is 5.78°; between pronated and supinated is 8.27°, while between supinated and neutral it is only 2.49° (Table 3, Appendix 2).

As shown in Figure 6.3, the mean Maximum Foot Dorsiflexion Angle in the Pronated posture is higher than the corresponding mean angles in the Neutral and the Supinated positions for all participants. The general trend indicates that the maximum foot dorsiflexion angle is reached in the pronated posture, reduced in the neutral posture, further reduced in the supinated posture. This is true in 14 out of the 16 participants: 87.5% of subjects. A typical subject results are illustrated in Figure 6.2.

6.3.2 Hindfoot and Forefoot Movement

A two-way Anova was used to compare the Mean Angle Range of Movement of the hindfoot and forefoot at each of the Foot Postures.

The mean dorsiflexion range of motion differ significantly between the 3 foot types for both hindfoot and forefoot (p=0.008). As indicated in Figures 6.3a and b, the mean angle range for the pronated foot posture is significantly higher than the other foot postures both for the forefoot and hindfoot segments (Mean angles recorded for forefoot and hindfoot in Pronated, Neutral and Supinated foot types were, 38.24(SD 12.44) and 26.42 (SD 6.83), 32.67(SD7.47) and 21.26 (6.71) and 32.875(SD8.66) and 20.08 (SD4.83) respectively) (Table 6, Appendix 2).

Pronated to Neutral Posture returns a p-value of 0.027, while Pronated to Supinated Posture is also significant, with a p-value of 0.014. On the other hand, there is no significant difference between the Neutral and Supinated Postures, with a p-value of 0.969 (Table 7, Appendix 2).

The p-value for the Interaction Term (p=0.942) exceeds the 0.05 level of significance, indicating that the line graphs for the forefoot and hindfoot are fairly parallel, i.e. what is happening in the forefoot is also happening in the hindfoot. However forefoot scores are significantly higher (Figure 6.3). Thus the forefoot range of motion is greater than the hindfoot range of motion throughout the three foot postures: there is always more forefoot range of motion than the hindfoot in all foot postures.

6.3.3 Forefoot to Hindfoot Angle

According to the way that the Oxford Foot Model estimates the forefoot to hindfoot angle, if there is only hindfoot movement with no forefoot movement relative to the hindfoot, during ankle dorsiflexion, this angle would remain constant during the dorsiflexing procedure. However, as shown in Figure 6.4, with the application of force during dorsiflexion, the angle increased, then remained at the same position during the period of time when the foot was held at a dorsiflexed position. This then decreased again as the foot was released.

One way repeated measures Anova indicated a significant difference for the forefoot to hindfoot ankle range of motion (p=0.007). Pairwise comparisons demonstrated a non-significant difference between the pronated and supinated postures (p=0.139) and neutral and supinated (p=0.147) but a significant difference between pronated and supinated postures (p=0.005) (Table 8, Appendix 2).

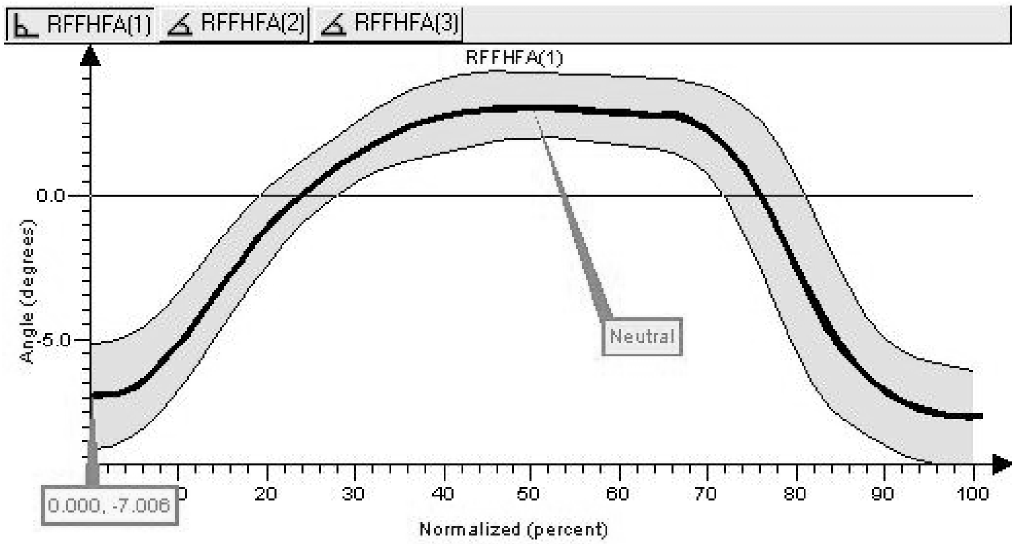


Figure 6.4: Example of Forefoot to Hindfoot movement graph. 1st sector is the dorsiflexing part; 2nd sector is the foot being held in the dorsiflexed position; 3rd sector is release of the foot back to its original position

6.4 Discussion

Little is known about what actually happens to the various foot segments when a dorsiflexing force is applied to the forefoot during the clinical examination for ankle dorsiflexion. Thus this research was carried out to investigate sagittal plane kinematics of passive ankle joint dorsiflexion, such as would occur during the measurement of the maximum ankle dorsiflexion angle, using a 3D motion capture system. As the foot is multi-segmental, it is important to determine whether there is pure ankle joint movement or whether there is forefoot movement as well during this process. Root Theory advocates the use of subtalar joint neutral position in order to lock forefoot movement at the midtarsal joint. Issues regarding both the neutral position (Elveru et al. 1988) and the midtarsal joint locking mechanism have been amply discussed elsewhere.

This procedure has thus never been investigated using a structured method such as the Oxford Foot Model. Whereas in traditional 3D motion capture systems the foot is treated as a single rigid lever, this model can measure segmental motion within the foot.

Two previous studies (Tiberio et al. 1989; Woodburn 1991), using measurements obtained from projections of 35mm slides (Tiberio et al. 1989) and video (Woodburn 1991) that investigated the effect of foot posture on maximum ankle dorsiflexion, both concluded that the pronated foot posture produces significantly more dorsiflexion than the other postures. Although these studies also concluded that ideally ankle angle assessment should be carried out at subtalar joint neutral, Woodburn advocated reverting to a 'slightly supinated position' when there is uncertainty in establishing a neutral position, a conclusion confirmed by the results of this trial. Furthermore, the study by Woodburn established a difference of 3.5 ^{o} between the neutral and supinated posture, which is also supported by this trial since the difference amounted to 2.49^{o}

Not only is the effect of foot posture on maximum foot dorsiflexion important because of issues of unreliability in placing the subtalar joint at neutral position (Elveru et al. 1988) but movement within the foot itself must be investigated to verify whether, after "locking" the midtarsal joint, by placing the foot at neutral, the only movement left during manual dorsiflexion of the foot is indeed pure ankle joint movement (Root et al. 1977).

The results obtained confirm the conclusion by the two previous studies; i.e. that in the pronated position, there is significantly more dorsiflexion of the foot. This would appear to point out that, if one is measuring ankle dorsiflexion, the pronated position needs to be avoided because it would give larger, possibly false results which are significantly different to both the neutral and supinated positions.

There is a statistically significant difference between maximum foot dorsiflexion angle between all three postures. These differences between the pronated and neutral postures and pronated and supinated postures are quite significant, both statistically (p=0.000) and clinically (5.78^{o} and 8.27^{o} respectively).

Although there is a statistically significant difference between the neutral and supinated posture, the clinical significance is debateable since this amounts to just 2.49^{o}. It is unlikely that this difference will be detected using normal clinical methods which are not as accurate as an eight-camera optoelectronic system. Even so, the clinical relevance of such a difference is questionable and unlikely to affect clinical decisions.

Unlike the previous two studies, it appears that the neutral position does not provide consistent results; neutral angle range lies between the pronated and supinated postures in 87.5% of subjects. This could perhaps be due to problems with consistent placement of the subtalar joint at neutral. If consistency in placement by an experienced clinician under controlled experimental conditions was an issue, the implications for uncontrolled clinical examination must be borne in mind.

Another important consideration is that the forefoot appears to move through a greater range than the hindfoot in all 3 foot postures (Figure 6.3); i.e. forefoot movement cannot be eliminated by putting the foot in any particular posture. Thus it is clear that, when applied to clinical measurement of ankle dorsiflexion, both ankle and forefoot movement is being measured irrespective of the position the foot is put in. Thus the term ‘foot dorsiflexion’ would be more appropriate than ‘ankle dorsiflexion’ in this case. This may be of significant importance as sometimes there can actually be more movement at the forefoot than at the ankle, as also pointed out by Woodburn who concluded that ‘with a pronated subtalar joint we may miss a diagnosis of true limitation'. On the other hand, our results show that there is little clinical difference between the neutral and maximally supinated postures, which is not in agreement with the statement that 'with a supinated subtalar joint we falsely diagnose ankle equinus'.

Using a different, yet clinically relevant methodology to previously published papers, the current study has obtained different results for hindfoot movement. Surprisingly, hindfoot movement is not constant as reported elsewhere and appears to vary with posture as well. As the amount of movement at the ankle joint should not be affected by changing foot posture, this can only happen at the subtalar joint; namely the sagittal plane component of movement of this articulation. This is in total disagreement with other studies which had concluded that there is no sagittal plane movement at this joint in a non-weightbearing situation (Leardini et al. 1999b; Leardini et al. 2001).

6.5 Limitations

There were some limitations to this study, including the small sample size, which consequently points to a need for another similar study on a larger scale. Time constraints, together with the fact that the trial week coincided with the first week of semester, prevented us from finding more subjects in the week's time that was available.

The exclusion of subjects with specific foot conditions, and patient populations, imply that the results of this study cannot be inferred to actual patients, but only to healthy subjects. Children would also have possibly produced a different outcome due to their increased foot flexibility. Subject 13 had an obvious limitation of dorsiflexion and perhaps should have been excluded from the study in order to obtain a more homogenous result.

The fact that we opted not to control for force applied to the forefoot, as some other studies, could be an important limitation of the study. However, we were mostly interested in the clinical application of this technique and clinicians do not normally apply a known force, but dorsiflex to the end of the range of motion.

Foot starting position could also be another important limitation. However, whatever the starting position, the tibia to hindfoot and tibia to forefoot angles would still have travelled through the same angle should dorsiflexion have occurred only at the ankle joint.

6.6 Conclusions

1. The amount of sagittal foot movement, including the range of forefoot and hindfoot movement, varies depending on foot posture.

2. Foot dorsiflexion was maximum at the pronated posture in all participants; it was least in the supinated posture in 87.5% of subjects. Changing posture does not totally eliminate forefoot movement.

3. When dorsiflexing the foot using a manual force on the plantar metatarsophalangeal joint area, the forefoot moved through a greater angle than the hindfoot in all the investigated foot postures. This was also confirmed by the forefoot to hindfoot angle, which increased with the application of force during dorsiflexion. This implies that the mid-tarsal joint locking mechanism does not function at neutral position, that pure ankle dorsiflexion cannot be obtained in this manner and thus any apparatus, such as the traditional goniometric method, that measures foot dorsiflexion across the forefoot and hindfoot may actually be measuring the summation of the movement of both foot segments.

4. Thus foot posture is an important element that must be borne in mind when conducting foot dorsiflexion measurements.

Chapter 7

A repeated measures study to explore the effect

of foot posture on Sagittal Plane Kinematics

Of passive dorsiflexion of the foot

In Adolescents

Aspects of this work have been accepted for publication:

Gatt A, Chockalingam N. 2012. Sagittal Plane kinematics of passive dorsiflexion of the foot in adolescent athletes. *Journal of the American Podiatric Medical Association* (In Press).

7.0 Introduction

Although assessment of the passive maximum foot dorsiflexion angle is performed routinely, there is a paucity of information regarding adolescents' foot and foot segment motion during this procedure. There are currently no trials investigating kinematics of the adolescent foot during passive foot dorsiflexion to determine what occurs during this clinical manoeuvre. Hence this chapter will investigate the effect of foot posture on maximum foot dorsiflexion and segmental motion during passive dorsiflexion in adolescents in order to inform the prospective clinician/researcher as to foot and foot segment movement of adolescent feet during this procedure.

7.1 Background

Various authors have proposed different normative angular values for ankle dorsiflexion during gait. Unfortunately it is not always differentiated whether "ankle" or "foot" dorsiflexion is being reported in a paper; as already pointed out throughout this thesis, there is a significant difference between the two terms. It is claimed that during normal locomotion, 10^{o} of ankle dorsiflexion is required for the forward translation of the centre of gravity of the body to occur during single limb support (Root et al. 1977). According to Tiberio (1987), between 5^{o} and 15^{o} is necessary for walking. However, Sullivan (1997) emphasizes that 15^{o} are necessary, with anything less producing compensations and foot adaptations leading to pain and deformity. Another trial investigating kinematics of ankle dorsiflexion during gait reported results between 12^{o} and 22^{o} (Weir and Chockalingam 2007). The authors concluded that, during gait, ankle joint dorsiflexion in normal subjects is greater than the value traditionally reported.

7.1.1 Foot Dorsiflexion in Children

While this applies to adult foot dorsiflexion, there is certainly a paucity of scientific information regarding passive dorsiflexion in children. The majority of scientific literature appears to concentrate on the effect of neurological disorders on ankle dorsiflexion, with little attention being given to normative data in healthy children.

Saxena and Kim (2003) studied a group of 40 adolescent athletes (16 girls and 24 boys) with a mean age of 14.8 yrs +/- 0.8years. "0°" was defined as a 90° relationship between the lateral border of the foot and the long axis of the leg. Ankle dorsiflexion was measured at subtalar joint neutral position, using a goniometer aligned with the lateral border of the foot and the long axis of the leg, with the subjects lying supine, first with the knees extended, then flexed. Dorsiflexion of the right ankle was 0.35° ± 2.2° with the knee extended and 4.88° ± 3.23° with the knee flexed. The values for the left ankle were –0.6° ± 2.09° and 4.68° ± 3.33°. There were no statistically significant differences between the sexes. The authors concluded that the average ankle dorsiflexion in asymptomatic athletes was 0^{o} with the knees extended and 5^{o} with the knees flexed. They also concluded that some degree of equinus is "normal" in adolescent athletes. These results show an influence of the gastrocnaemius since knee position affected the results; perhaps, being athletes, their gastrocnaemius was more developed than the average. However, the overwhelming evidence of unreliability of goniometric measurement (Elveru et al. 1988; Kim et al. 2011; Martin and Mcpoil 2005; Rome 1996; Wrobel and Armstrong 2008) casts doubt as to the validity of these results.

In a study of 82 children with injured ankles, Tabrizi et al (2000) found mean dorsiflexion values of 5.7° with the knee extended and 11.2° with the knee flexed. In 85 controls, dorsiflexion was 12.8° and 21.5° respectively. However, to what extent the ankle injuries could have limited the amount of dorsiflexion is unclear.

Studying a population with an average age of 25 years, in which ankle dorsiflexion was measured with a supinated foot, Grady and Saxena (1991), found values of 3° with the knee extended and 9° with the knee flexed. This differs from other later studies by the same authors (2003) where the foot was not kept in any specific position, so other joints could have dorsiflexed as well (Lundgren et al. 2008), making comparison difficult. Notwithstanding this, the value of 3° and 9° compare quite well with that of 0° and 5° with knees extended, then flexed respectively. The authors themselves admit that one of the limitations of the study was the goniometric assessment, which is subject to evaluator variability and thus raises questions as to the validity of the measurement (Saxena and Kim 2003).

The study of intrinsic foot movement is nowadays possible with the use of kinematic foot models, such as the Oxford Foot Model. This model, which has been shown to be reliable both in adults and children (Carson et al. 2001; Stebbins et al. 2006; Wright et al. 2011), divides the foot into tibia, hindfoot, forefoot and hallux segments. It has been employed in the previous trial investigating foot segment analysis of passive foot dorsiflexion in adults (Chapter 5).

7.1.2 Need for this study

Since children's feet are inherently more flexible than adult feet, it is being postulated that these will function differently during passive ankle dorsiflexion. Hence it was hypothesised that foot posture would affect the maximum ankle angle and the range of movement of the tibia to hindfoot and tibia to forefoot angles, with adolescent feet acting in a different manner to adult feet

Aim:

- To investigate the effect of foot posture on maximum foot dorsiflexion in adolescents during passive foot dorsiflexion.

Objectives:

- To measure passive maximum foot dorsiflexion utilising an optoelectronic motion capture system in the pronated, neutral and supinated foot postures.
- To measure forefoot to rearfoot angle in the sagittal plane within the 3 foot postures.
- To determine the effect of foot posture in adolescents along with inter-segmental kinematics of the foot in adolescents.

7.2 Method

Ethical permission was sought from and granted by the Faculty of Health Sciences Ethics Board and consequently by the University of Malta Research Ethics Committee. As all participants were minors, informed consent was obtained both from parents and participants following an explanation of the research process both verbally and through an information sheet. Relevant application form together with approval, information sheets and consent sheets may be found in Appendix 1. Although an attempt was made to recruit mixed-gender participants, only a number of females attended on the day of data collection. Unfortunately, due to Lab utilization, it was not possible to replicate the exact equipment and laboratory setup on another day so that a number of male participants could be enrolled, hence the available participants had to suffice. As it turned out, all respondents attended a gymnastics club which, in retrospect, enabled this trial to compare adolescent athletes' dorsiflexion with the values obtained by Saxena and Kim (2003), but utilising a much more accurate and validated method. It was thought that, since all participants trained in gymnastics on an amateur basis, they would also be representative of other adolescents as many such-aged children would still be engaged in active physical activities.

A convenience sample of 8 females with a mean age of 13.2years (range 11-16 (SD 1.7)) and a mean height of 1.53m (SD 0.09m) were recruited from a local gymnastics club. Participants trained in this sport on an amateur basis, attending two to three, 3 hour sessions per week. Exclusion criteria included any recent foot injury, pain, presence of neurological or systemic conditions and musculoskeletal deformities. Data collection took place at the Gait Laboratory at the Faculty of Engineering, University of Malta.

Markers, as required by the Oxford Foot Model protocol (Fig 7.1), were applied to each participant's lower extremities, with the full marker set on the right foot. A 6-camera optoelectronic system (Vicon, OMG, Oxford, UK), sampling at 100Hz, was employed to capture motion. Each participant was seated on a flat examination couch, with the arms gripping the sides of the couch for support, to ensure that all markers, especially the right and left posterior superior iliac spine markers (LPSI and RPSI) were visible to at least 2 cameras. Camera placement is shown in Figure 7.2. Although 6 cameras provided a challenge for data collection, the fact that only passive foot movement was collected enabled this process to be performed quite consistently.

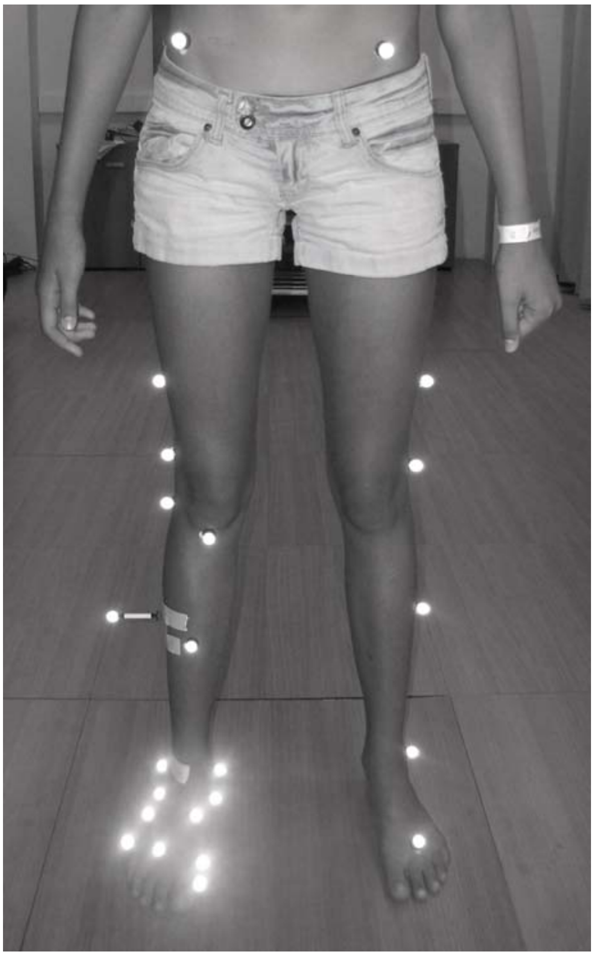


Figure 7.1: Oxford Foot Model Marker Set

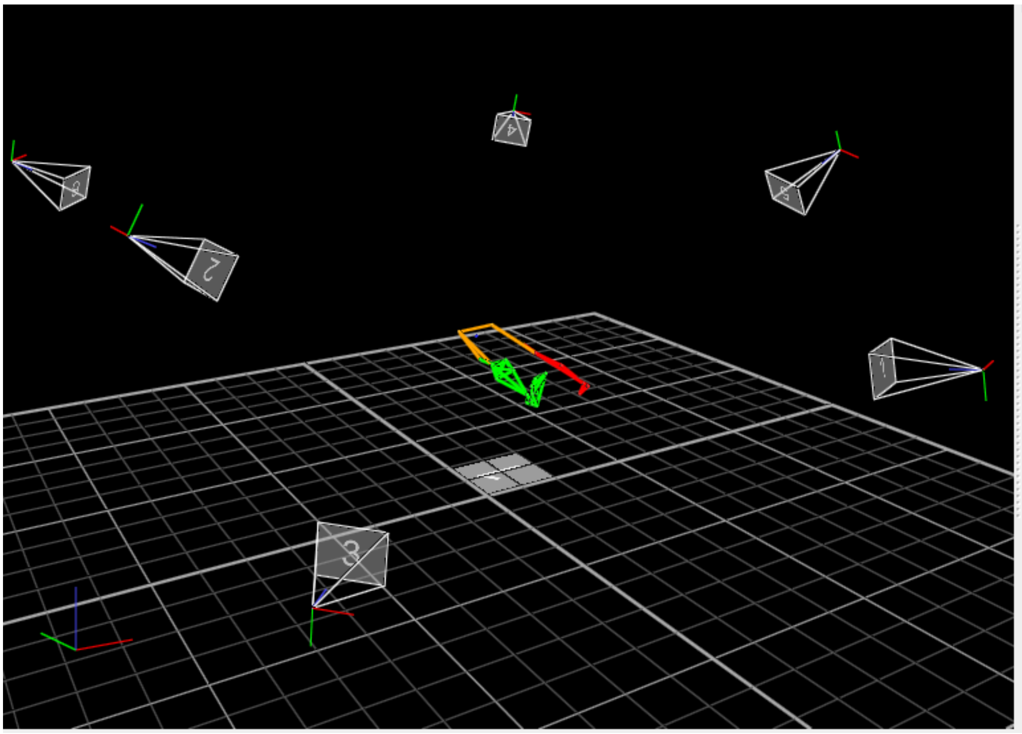


Figure 7.2: Camera placement in relation to subject position

The principal investigator (AG), who has over 20 years' of clinical experience in finding subtalar joint neutral position, was responsible for maintaining the foot in the 3 required postures: i.e. pronated, neutral and supinated. Each posture was determined randomly by the biomedical engineer responsible for the gait laboratory, who was also responsible for data capture. Foot posture was determined by the talo-navicular congruency method: neutral position was determined by equally palpating the head of talus on the medial and lateral aspect; the pronated position was determined when the head of talus was only palpable on the medial aspect, while the supinated position was determined when the head of talus was only palpable on the lateral aspect. Although finding subtalar joint neutral has been shown to be notoriously difficult for less-experienced raters (Elveru et al. 1988; Pierrynowsky et al. 1996), an Intraclass Correlation Coefficient of 0.88 has been demonstrated in experienced clincians (Elveru et al. 1988) who are claimed to be within +/- 3^{o} of subtalar neutral position 90% of the time (Pierrynowsky et al. 1996).

The foot was dorsiflexed maximally to the end of motion by the application of a force to the metatarsophalangeal joint area and maintained in the determined posture, where it was held for 3 seconds before being released. 10 trials were captured and recorded for each posture to ensure that enough data was collected.

Each participant's data were normalized and then averaged for each posture prior to further statistical analysis with SPSS 19. Reference for the minimum foot dorsiflexion angle was the "0" degree mark; i.e. dorsiflexion range was considered to be from 0^o up to Maximum Foot Dorsiflexion Angle. The level of significance was set at p=<0.005 throughout all statistical analysis.

7.3 Results and statistical analysis

Table 7.1: participant demographics

Participant	**Height (cm)**	**Age (years)**
1	160	16
2	142	11
3	154	14
4	161	14
5	162	13
6	168	14
7	155	13
8	144	11
Average	**155.7**	**13.2**
Standard deviation	**8.9**	**1.67**

7.3.1 Maximum Foot Dorsiflexion Angle

The mean maximum foot dorsiflexion angles in the pronated, neutral and supinated postures for each participant are illustrated in Fig 7.2. The Mean Maximum foot dorsiflexion angles for all participants were 36.3^{o} (SD 7.2 ^{o}) for pronated, 36.9^{o} (SD 4.0^{o}) for neutral and 33^{o} (SD 4.9 ^{o}) for supinated posture (Table 9, Appendix 2).

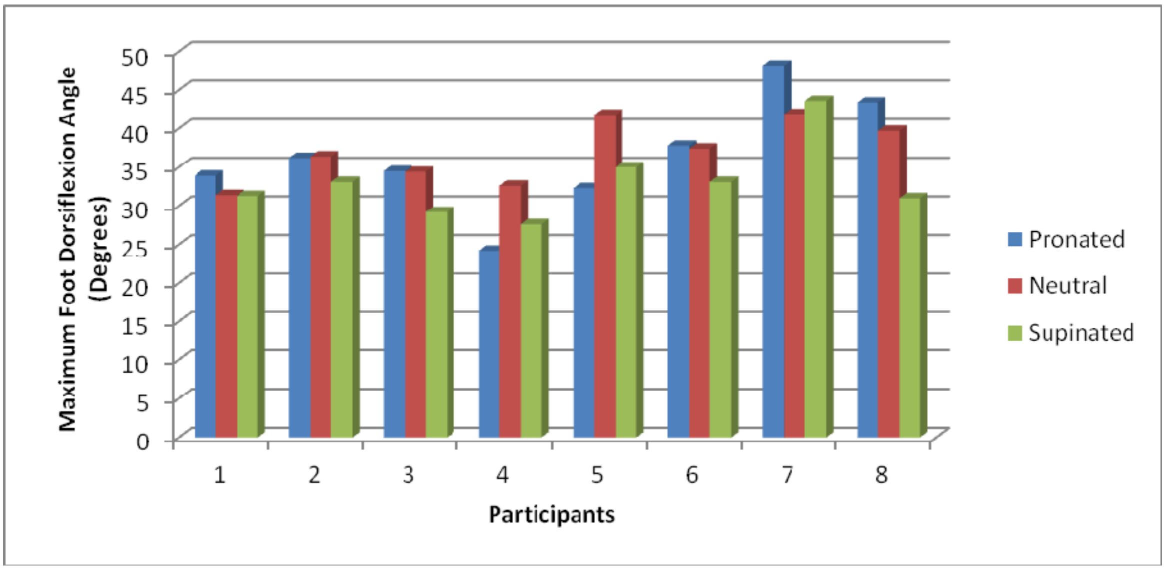


Figure 7.3: Maximum Foot Dorsiflexion Angles in the 3 postures. When compared to the similar graph in adults (Figure 5.3), it may be seen that the pronated posture did was not greatest in all participants.

One-way repeated measures ANOVA was employed for statistical analysis of the Maximum Foot Dorsiflexion Angle. There was no significant difference between this angle in the pronated, neutral and supinated postures (p=0.70) (Table 10, Appendix 2). Post hoc analysis also revealed similar results when comparing one posture to the other, with pronated to neutral (p=1.00), pronated to supinated (p=0.299) and neutral to supinated (p= 0.039) (Table 11, Appendix 2).

7.3.2 Forefoot to Hindfoot Angle (FFHFA)

The ranges of variation in the Forefoot to Hindfoot Angle, taken from 0^{o} of foot dorsiflexion to the maximum dorsiflexion angle, are presented in Table 12 (Appendix 2), from which it may be seen that the FFHFA variation was positive in all participants; i.e. the FFHFA increased with the application of force when compared to the starting position at 0^{o} dorsiflexion of the foot. However, a one-way repeated measures ANOVA indicated a non-significant difference for the forefoot to hindfoot angle variation between groups (p=0.346). Pairwise comparisons demonstrated a non-significant difference between pronated and neutral (p=0.46) and both neutral and supinated and pronated and supinated postures (p=1.0).

7.3.3 Hindfoot and Forefoot Movement

The mean Forefoot to Tibia Angle (FFTBA) and Hindfoot to Tibia Angle (HFTBA) are presented in Figure 7.4. Both angles returned non-statistically significant results. Repeated measures Anova shows no significant difference between the 3 groups, i.e. between pronated, neutral and supinated postures (p=0.0910 for FFTBA) and 0.188 for HFTBA.

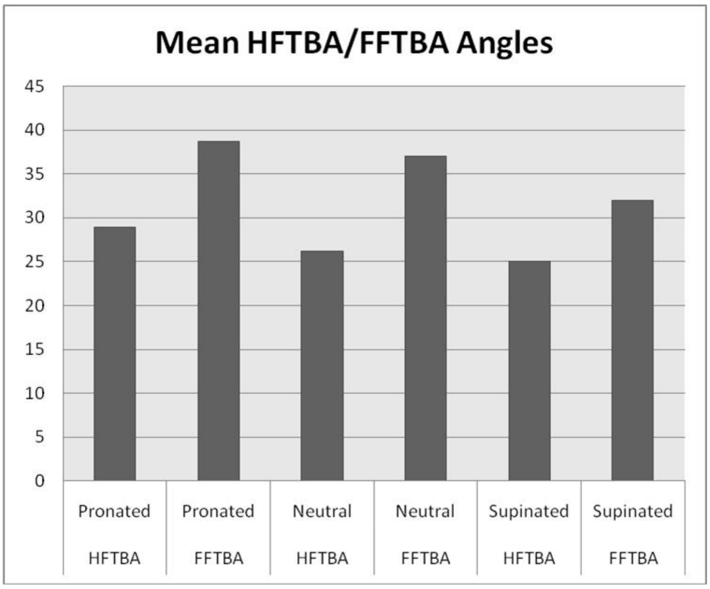


Figure 7.4: Mean HFTA/FFTBA Angles in all 3 postures.

The Forefoot to Tibia Angle is greater than the Hindfoot to Tibia Angle in all 3 postures, signifying that the forefoot travels through a greater range than the hindfoot, even at neutral position when the midtarsal joint is supposedly ‘locked’ according to Rootian theory

7.4 Discussion

Despite the fact that assessment of ankle dorsiflexion is carried out frequently, little is known as to what actually occurs to the foot as a whole and how foot segments behave during this passive procedure. What little information is presented has been acquired using traditional goniometric measurements, which are known for their unreliability (Elveru et al. 1988; Kim et al. 2011; Martin and Mcpoil 2005; Rome 1996; Wrobel and Armstrong 2008). Measurement of foot dorsiflexion is notoriously difficult to perform as the foot has to be held at subtalar joint neutral position; the goniometer has to be aligned with the lateral aspect of the lower leg and the lateral aspect of the foot while at the same time the foot is dorsiflexed to its end of range of motion.

In order to overcome this limitation, this trial employed an optoelectronic motion capture system, with a well tried and tested foot model that can measure foot and foot segment movement much more accurately than a simple goniometer.

Unlike in the adult foot, there is no trend for the maximum foot dorsiflexion angle produced in the pronated posture to be greater than in the supinated posture. All statistical results returned non-significant differences, implying that there is little variation between the maximum foot dorsiflexion angles obtained in any of the 3 postures. This may be due to the increased flexibility in adolescents' feet. In fact angles obtained in this trial were significantly higher than those reported by Saxena and Kim (2003), who studied adolescent athletes and concluded that 0^o of dorsiflexion (i.e. no dorsiflexion) was quite normal for these athletes.

The only comparable result to the similar adult trial presented in Chapter 6 is the behaviour of the FFHFA. This angle clearly increases as a moment is applied to the forefoot, indicating that forefoot movement is greater than hindfoot movement, as also confirmed by the difference between the FFTBA and HFTBA in all 3 postures in Figure 6.3. This implies that putting the subtalar joint at neutral position and "locking the midtarsal joint" does not eliminate forefoot movement as Rootian Theory has been suggesting for the past 30 years and that any measurement of foot dorsiflexion will be different to ankle dorsiflexion due to sagittal plane movement of the midtarsal joint, which can be quite considerable (Lundberg et al. 1989a; Lundgren et al. 2008). Thus, any measurement of ankle dorsiflexion, as differentiated to foot dorsiflexion, must not involve the forefoot, otherwise larger angles may result, possibly giving false results that could give rise to a wrong diagnosis and treatment.

It could be hypothesised that this high flexibility may be due to the nature of the sport itself; this clearly demonstrates that the amount of foot dorsiflexion will have to be investigated in different athletic populations since results cannot be generalized over the whole adolescent population.

An obvious limitation of this trial is the small number of participants. However, trends are quite clear from the several trials of data, although another trial with a much larger participant population could confirm these clinically important results.

7.5 Conclusions

- Results indicate high flexibility in female adolescent gymnasts' feet, unlike results obtained in another study using alternative, less accurate methods (clinical goniometry).

- The measurement of maximum foot dorsiflexion angle in this population may be performed at any posture as the range of this angle will not be affected, contrary to what occurs in adults. This is possibly due to the high flexibility reported.

- During passive foot dorsiflexion, the Forefoot to Hindfoot Angle increases gradually with the application of a moment, disputing earlier Rootian theory of the midtarsal joint locking mechanism.

- Any measurement of ankle dorsiflexion should not involve the forefoot if unrealistically large angles are to be avoided.

Chapter 8

The effect of uncontrolled moment and short-term, repeated passive stretching on Maximum Ankle Joint dorsiflexion angle

Aspects of this chapter have been accepted for publication:

Gatt A, Chockalingam N. 2012. The effect of uncontrolled moment and short-term repeated passive stretching on maximum ankle joint dorsiflexion angle. *The Foot.* (In Press)

8.0 Introduction

This chapter investigates whether it is possible to carry out a passive dorsiflexion analysis without applying a known moment. To-date, a typical scenario in various physical therapy researches is to control the dorsiflexing moment, unlike during podiatric examinations which do not involve the controlled application of force for measuring maximum ankle dorsiflexion (Root et al, 1977; Gastwirth, 1996). It is thought that eliminating the complication of controlling moment is a way of increasing reliability of ankle goniometric devices by making them easier to use. Measurements taken are of end of the range of motion of the joint, i.e. at that point at which there is no more possible movement without incurring damage to the patient. Thus controlling the force applied is deemed superfluous. However this type of investigation has never been conducted before as far as this investigator is aware.

8.1 Background

The clinical measurement of the Maximum ankle dorsiflexion angle is a common and important clinical examination (Gastwirth 1996), routinely performed in order to establish whether there is sufficient ankle movement (Rome 1996; Woodburn 1991) to allow for normal ambulation (Root et al. 1977) and for the diagnosis of various pathological conditions of the foot and ankle (Meyer et al. 2006). This examination is carried out by placing the foot at subtalar joint neutral position, applying a force to the forefoot until there is maximum dorsiflexion at the ankle joint (Root et al. 1977). Then a measurement is taken using one of various methods, such as a goniometer (Gastwirth 1996; Rome 1996) or a specifically-designed device such as the mechanical equinometer (Meyer et al. 2006), the Iowa Ankle Device (Wilken et al. 2004) or the Biplane Goniometer (Donnery and Spencer 1988), among others.

The calf Muscle-Tendon Unit (MTU), which is composed of the Gastrocnaemius, Soleus and Achilles Tendon, originates above the knee (lateral and medial condyles on the posterior aspect of the femur) and inserts in the posterior aspect of the calcaneus. This consequently determines the amount of flexion at the ankle joint (Gajdosik 2001) as it stretches to its extensible limit. Thus the maximal passive dorsiflexion ankle angle is directly related to maximal muscle length (Gajdosik et al. 2004).

During ankle angle measurement, there is stretching of the calf MTU. The point of initial resistance, termed the *initial passive resistance*, is overcome by the application of more force until *maximum passive resistance* is reached, corresponding to *maximum muscle length*. Stretching beyond this could result in damage to the tendino-muscular junction (Gajdosik 2001). As has already been established, two factors that could influence the maximum ankle angle include foot posture and the amount of force, or moment, applied.

A pronated foot posture increases the maximum ankle angle by as much as 10^o (Tiberio et al. 1989; Woodburn 1991). This was confirmed by the study that investigated foot segment movement during passive dorsiflexion (Chapter 6). Root et al (1977) maintain that performing this examination at subtalar joint neutral position "locks" the midtarsal joint and the resultant dorsiflexion occurs only at the ankle joint. This previous trial disproves the theory presented by Root et al., at least during passive dorsiflexion, and results show that there is always more forefoot movement than hindfoot movement irrespective of the posture that the foot is placed in. Results also confirm that there is no significant difference in the maximum ankle angle between the neutral and supinated foot postures (Chapter 6). Evidence hence suggests that the pronated posture should be avoided during passive ankle angle measurement since there is excessive foot segment movement extraneous to the ankle joint.

The amount of moment applied has also been identified as a significant factor when performing this examination. Recommended moments in various studies and clinical trials range between 10Nm (Digiovanni et al. 2001; Meyer et al. 2006; Weaver et al. 2001), 12Nm (Moseley et al. 2001), 15Nm (Assal et al. 2003), 16.1Nm (Scharfbillig and Scutter 2004),20Nm (Greisberg et al. 2002) and 25Nm (Wilken et al. 2011). Although it is claimed that the amount of moment applied influences the ankle angle (Assal et al. 2003), this appears to be anecdotal as no scientific basis to this statement has been presented in literature. Although there is no universally accepted amount of moment recommended to be applied to the foot during this examination procedure, these trials were very careful in applying a moment which was constant in all subjects and the resultant measurement angles were consequently consistent, returning high Intraclass Correlational Coefficient (ICC) results.

As the ankle joint is dorsiflexed to its maximum, the calf MTU reaches its *maximum passive resistance*, and thus its *maximum muscle length*, implying that differing amounts of moment should have no - or minimal - effect on maximal ankle dorsiflexion once this angle is reached, since the amount of moment applied beyond this point would be damaging to the MTU.

The ankle dorsiflexion assessment routine may be required to be performed a number of times (with the calf MTU being repeatedly stretched to its maximal passive resistance limit) since it is normal practice to obtain an average reading. During reliability testing of any ankle measuring device, for example, this may be repeated over and over again (Donnery and Spencer 1988; Meyer et al. 2006). A question that would arise out of this is whether this brief repetitive stretching of the calf MTU could increase its length and thus alter the maximum ankle angle. Thus one could hypothesise that this repetitive stretching could change the result of the measurement itself since muscle length and consequently maximal angle may be increased.

If the calf MTU stretches significantly following the application of a moment to the forefoot, the maximum ankle angle would get progressively bigger. A significant difference between the results would consequently imply a stretching effect, while a non-significant difference would imply that a consistent result was obtained without a known moment being applied.

Thus this study aimed to investigate primarily whether performing this examination procedure without applying the same moment to all subjects would provide reliable and consistent results. If in the positive, the important clinical outcomes of this investigation would imply that there is no need for a force gauge, which is rarely available to the clinician and which would complicate the examination procedure. Furthermore, the effect of short repeated passive stretching on the maximum ankle angle was also investigated.

Aim:

- To establish whether it is possible to obtain consistent maximum foot dorsiflexion angle with the use of uncontrolled moment during passive foot dorsiflexion.

Objectives:

- To kinematically assess the maximum foot dorsiflexion angle when moment is not controlled during passive dorsiflexion..

- To compare homogeneity of the maximum foot dorsiflexion angles; i.e. whether they are the same.

8.2 Method

This investigation uses the same method/data presented in Chapter 6, *A repeated measures study to explore the effect of foot posture on Sagittal Plane Kinematics of passive dorsiflexion in healthy adults.*

8.3 Results and Statistical Analysis

Table 13 (Appendix 2) shows the results from 5 trials, demonstrating successive maximum ankle dorsiflexion angles following the repeated application of a dorsiflexing moment which has not been controlled with a force gauge. Since three previous studies have already established that the pronated foot posture produces significantly larger dorsiflexion angles (Chapter 6 results together with Tiberio et al. 1989; Woodburn 1991), only the results of the neutral and supinated postures are being presented here. Moreover, two of these studies also demonstrated that there is only a minor clinical differences between the neutral and supinated postures, ranging from 2.5^o (Chapter6) to 3.5^o (Woodburn 1991). Data presented are the maximum Ankle Angles as output by the Oxford Foot Model.

As shown in the table, one of the participant's (No 13) data indicates a negative value. This implies that at maximum force, the foot remained plantarflexed and not dorsiflexed (i.e. the participant had reduced range of motion). As the aim of this investigation was to compare consistency (within subject), this participant was not excluded from analysis. Repeated measure ANOVAs were carried out separately on the neutral and supinated posture data to assess the effect of repeated passive stretching on the maximum ankle angle.

The results indicated that there were no differences in the maximum ankle angles both at neutral position, ($F(2.26, 29.4) = 0.555$, $p = 0.601$) (Table 15, Appendix 2), and at supinated position ($F(4, 52) = 0.664$, $p = 0.620$) (Table 17, Appendix 2).

The p-values obtained were dependent on Mauchly’s Test of Sphericity, whose results indicate that at the neutral position sphericity was violated (p=0.002) (Table 14, Appendix 2) while at a supinated position they were not (p=0.121) (Table 16, Appendix 2).

Sphericity relates to the equality of the variances of the differences between levels of the repeated measures factor, which is an assumption of an ANOVA with a repeated measures factor. The null hypothesis for this test is that sphericity holds and a significant result indicates that sphericity cannot be assumed. When this happens, a statistical test that provides for correction of violations of sphericity, such as Greenhouse-Geisser, should be employed, while a ‘Sphericity Assumed’ test should be employed when sphericity has not been violated.

Whilst it was assumed that a stretching effect would exhibit an increase in the angle, only one subject (no 9), exhibited a significant increase in maximum ankle angle by 2.88^{o} with every repetition (at the Neutral Position) and the other didn’t exhibit any significant increase or decrease.

Maximum Ankle Angles:

Regression Analysis, which is used to ascertain the causal effect of one variable upon another, was utilised to determine if the maximum Ankle Angle increased progressively after each test. A stretching effect would exhibit an increase in the angle and a positive gradient in the Max Angle vs Repetition Graph, such as that depicted in Figure 8.1. All resultant angles are presented in Table 18 (Appendix 2). Only one subject, no 9, exhibited a significant increase in maximum ankle angle by 2.88^{o} with every repetition, at the Neutral Position.

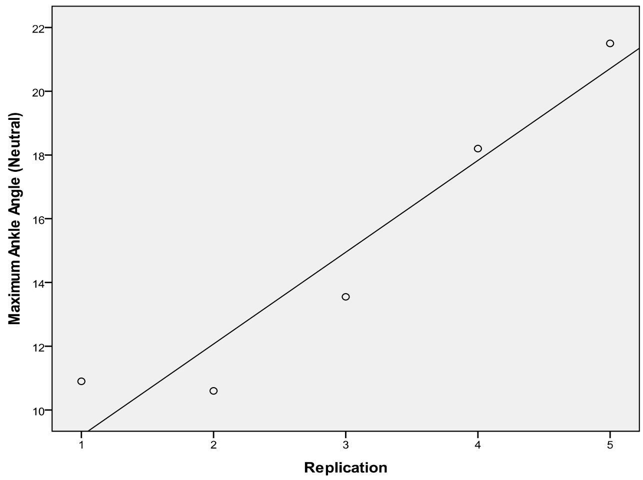


Figure 8.1: Regression analysis of participant no9, showing increase in Maximum Ankle Angle with each repetition of the test performed.

8.4 Discussion

There are various factors affecting the apparently straight forward clinical procedure of measuring ankle dorsiflexion (Rome 1996). These include, amongst others, foot posture and the amount of moment applied (Chapters 3, 6 and 8). However, there is no consensus in literature as to how much this moment should be or indeed whether this should be controlled at all. There appear to be no trials at present that investigate whether or not controlling for torque would in fact affect the results. Thus this study sought to investigate whether it is necessary at all to control the amount of moment since it was hypothesised that the elasticity and stretching limit of the calf MTU itself would serve to limit ankle dorsiflexion. A second important hypothesis was whether brief repetitive stretching would affect the calf MTU itself, thus increasing its length with subsequent dorsiflexions, consequently increasing maximum ankle angles.

These issues need to be investigated if the reliability of clinical measurement of ankle dorsiflexion is to be improved or maintained. One simple fact is that clinically, moment is not usually controlled. Since having a known moment is impractical in a real clinical situation, alternatives need to be found in order to avoid the complication of having to use a force gauge, so that practitioners in different clinical settings can examine patients according to a standardised method of assessment. Inconsistencies with placement of subtalar joint at neutral position that require a high clinical proficiency also contribute to making this procedure a difficult one to master, especially for students. (Elveru et al. 1988; Pierrynowski et al. 1996)

This measurement of the maximum dorsiflexion angle of the ankle joint is not an easy procedure at best (Rome 1996); adding the use of a force gauge to control the moment applied would certainly not make matters any easier. Finding a way of eliminating this problem, yet maintaining reliability, would certainly make matters easier for the clinician.

Although small sample is a limitation, the results from this investigation indicate that there is some homogeneity in both supinated and neutral postures; i.e. results do not vary significantly from each other to the extent that they cannot be reliably considered as being similar if the moment is not controlled. This then implies that there is no need to control the moment when measuring maximum values. Regression analysis also determines that, although there was no significant stretching of the calf MTU in the majority of subjects, it did occur in one subject at the neutral position, which, however, did not occur at the supinated posture as well.

As stated earlier, clinicians do not normally have access to a force gauge when assessing ankle dorsiflexion. However, as indicated in the results, there is no need to control moment when assessing the maximum ankle dorsiflexion angle as the dorsiflexion range of movement is clearly determined by other physical factors, such as length and elasticity of calf MTU and anatomy of the ankle joint itself.

8.5 Conclusions

- In general, results from this study indicate that the Maximum Ankle Dorsiflexion Angle did not increase following brief repetitive stretching of the calf MTU.
- Furthermore, the maximum Ankle Dorsiflexion Angle can be assessed at both Neutral and Supinated positions without moment being controlled provided that the joint is dorsiflexed to its end of motion.

Chapter 9

The Ankle Goniometer: Design and Manufacture

9.0 Introduction

The aims of this chapter are to describe the circumstances leading to the awareness that there is a need for a novel design of an ankle goniometer, to discuss research findings arising from the Systematic Review and the Sagittal Plane movement investigation in adults and children (Chapters 6 and 7) and the Uncontrolled Moment trial (Chapter 8), their implications on the design and the evolution of the design itself following these research findings.

9.1 Background

Initial suspicions that there could be a significant problem with goniometric measurement of ankle dorsiflexion arose during the practical sessions of an Applied Podiatric Biomechanics module that this investigator delivers during the first year of the Podiatry Course at the University of Malta, in which the traditional Rootian method of ankle assessment was taught. Over the years, after many practical sessions and different student cohorts, it became clear that students were struggling with alignment of both arms of the goniometer and, without their realizing it, they were constantly producing incorrect results. This trend continued even during the second and third year of each course, even though emphasis was placed on this technique and these wrong methods were discussed on various occasions. As this investigator feels that ankle equinus is a important foot condition that has significant repercussions both on gait and integrity of the foot itself, leading to various, sometimes major, conditions such as metatarsalgia and diabetic ulceration, this was felt to be an important aspect of biomechanical evaluation that needed further investigation.

Goniometric unreliability was further confirmed following a literature review which identified several papers dealing specifically with this problem (Refer to Section 2.4.2).

Thus initial sources of errors identified were:

- The correct bisection of the lateral aspect of the lower leg
- Holding the stable arm in alignment with the lateral bisection

- Holding the moving arm in alignment with the lateral border of the foot, from the area of the heel to the area of the 5th metatarsophalangeal joint
- Holding the foot in subtalar joint neutral position while it is passively dorsiflexed.
- Reading the goniometric output (normally small scales) which involves leaning to the side whilst holding the foot in the 'correct' position.

Thus the first thought was whether it was possible to produce an ankle goniometer that replicated the traditional goniometer, but possibly eliminated these alignment problems. The first device produced (Figure 8.1) was aimed at:

1. holding the stable arm in place, in a position aligned with the lateral head of the fibula and the lateral malleolus, by the use of velcro straps
2. eliminating alignment errors in the moving arm by the use of a footplate
3. placing the point of rotation below the lateral malleolus to replicate a traditional goniometer.

To note is that at this time, it was thought that there were no issues involving the use of a footplate. In fact, like other investigators, our conclusion was that a footplate would actually aid in maintaining correct alignment. However, following the trial in Chapter 5, it was realized that a goniometer should, ideally, only involve the hindfoot since if the forefoot is involved, the resultant angle could be the summation of both hindfoot and forefoot dorsiflexion.

A. B.

Figure 9.1: First attempt at producing an ankle goniometer. A) Features included an extendible vertical arm, a pivot to duplicate the Rootian method and a foot plate. B) a spring-loaded mechanism held the foot in an everted/inverted position.

Another important aspect that was causing errors was placement of the foot at subtalar joint neutral position. Various methods where tried on this rather crude device, which was later replaced by another device that locked the footplate in an everted or inverted position in order to reduce this function which has to be performed by the practitioner (Figure 8.2).

A. B.

C.

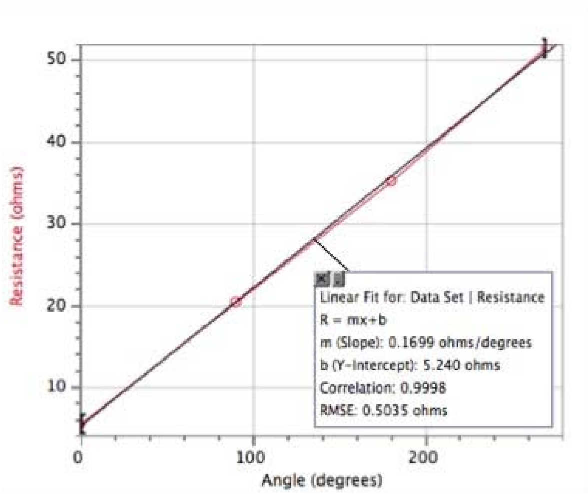
Figure 9.2: A more sophisticated ankle goniometer design, with a large stable arm and a footplate that could be rotated and locked in the sagittal and frontal planes. As yet no actual measuring device was incorporated into the design

At this time, it became also apparent that the small graduations were also a significant source of error as the examiner has to bend to the side to take the reading. Thus it was decided that an output in a digital format was preferable, both for its accuracy and ease of reading. Various types of digital rotational devices were investigated, including the traditional potentiometer and Hall Effect integrated circuits.

The potentiomer (or variable resistor) has in fact been used in previous research. Various types of potentiometers were tried, including the normal linear, wire-wound and high-precision potentiometers.

Figure 9.3: High precision angle finders (potentiometers) aimed at the manufacturing and automotive industry, such as throttle position encoding. (Left)

Designed to convert rotary movement into a proportional voltage, position transducers are also aimed at the automotive industry (Right)



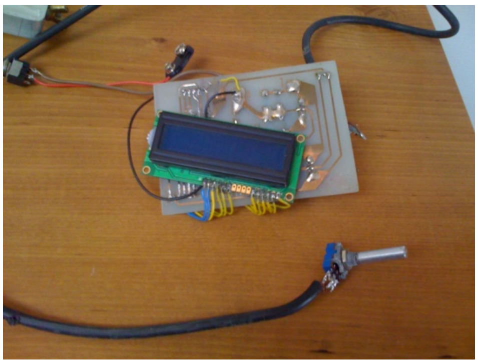
$$\theta = \frac{R - 5.24 \text{ ohms}}{0.17 \text{ ohms/degree}}$$

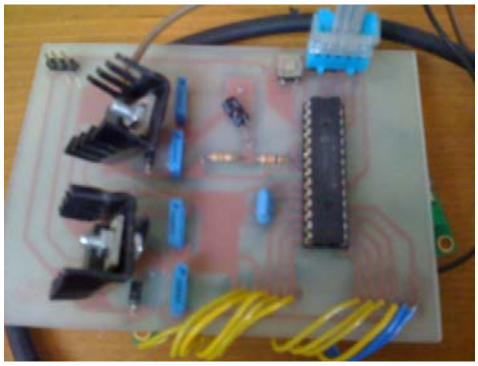
Figure 9.4: An example on the use of a linear potentiometer to find the angle. If resistance R vs Angle (degrees) is mapped, angle can be calculated with the formula on the right.

Using a PIC (Programmable Integrated Circuit) it is possible to divide the rotation available at the potentiometer by the resolution of this circuitry, which in theory produced quite a reasonably accurate device with about 1^{o} of accuracy, which was thought to be more than ample for the required application. The output of this circuitry was fed into an LCD (Liquid Crystal Display) in order to produce a readout of the angle. Circuitry also had a zeroing and maximum value features.

Figure 9.5: This design incorporated a carbon-fibre foot-plate that could be locked into inversion/eversion, a linear potentiometer into the aluminium housing and a joint to enable the stable arm to be lined with the long axis of the foot

Figure 9.6: Same features as above, with a transparent acrylic foot-plate, but housing professionally-built on a lathe. End result, however, was considered too bulky and the wiring to the display unit made the unit (below) uncomfortable to work with





A.

B.

Figure 9.7: Display units, A and B. Both units had zeroing capabilities. Unit below provided the angle in real-time and the maximum ankle angle attained. Could also be calibrated to various potentiometers with different rotation angles

Another type of rotational angle finder tried was the Hall Effect Rotary Encoder. This type of sensors rely on a magnetic field in order to sense motion. The principle is based on the Hall Effect, discovered more than 100 years ago by Edwin Herbert Hall. This effect is the small electrical potential created when a stationary magnetic field is placed perpendicular to a current-carrying conductor.

A Hall Effect sensor consists of an integrated circuit with a small magnet (diametral magnetised - two poles on the working face) rotating above it. The variations in the magnetic field are picked up by the sensor, encoded into an angle by the integrated electronics and displayed in a convenient manner if required.

The AS5040 Rotary Encoder IC, 10-bit Absolute Programmable Magnetic Rotary Encoder with Incremental, SSI, and PWM Output, manufactured by Austrian MicroSystems (http://www.austriamicrosystems.com/eng/Products/Magnetic-Encoders) was identified as a potential source of providing a digital readout. There appeared to be many advantages to using such a system, including:

- Small integrated circuit should have facilitated its integration into the device

- Software for interfacing to a personal computer already available from the manufacturer, thus giving a programmable medium which could be easily visualized on a laptop
- High angular accuracy

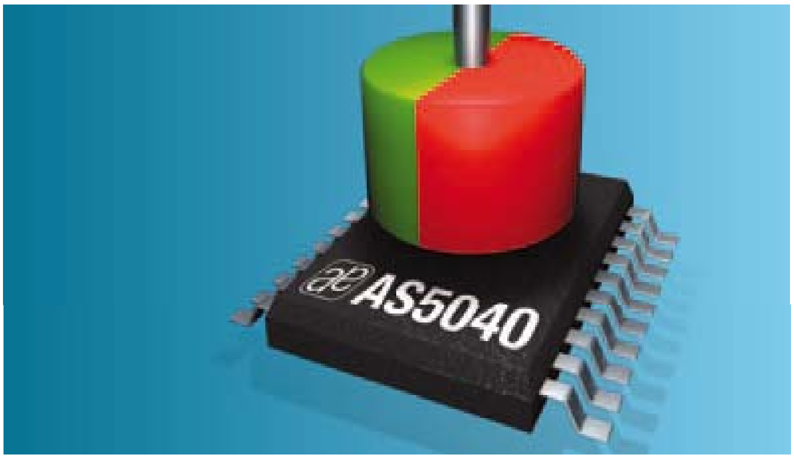


Figure 9.8. The AS5040 Angle Encoder

The AS5040 comes with an evaluation "demoboard" aimed at demonstrating the principle of function of the magnetic rotary encoder without additional hardware and software effort. This kit consisted of a reference magnet with its holder and an LED display. The demoboard can be used in standalone mode through LED display or in combination with the PC software in order to be able to evaluate all the functionalities of the AS5040 magnetic encoder.

However, the demoboard (Figure 8.9) proved to be too bulky to be used in the device itself. For this reason, an "adaptorboard" (Figure 8.9) is also available from the manufacturer, in order to make this easier to implement.

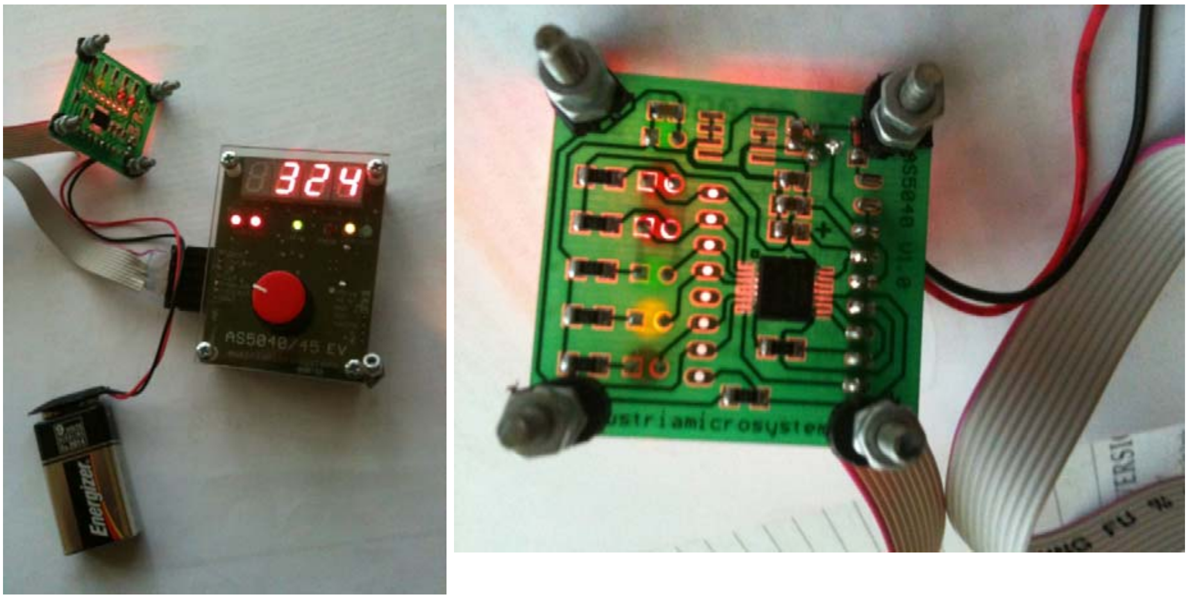


Figure 9.9: The AS5040 adaptorboard (left) and demoboard (right) including power supply but excluding USB lead. The value on the LED is actually a graduation representing the angle of rotation (1024 steps in 360^{o}). The actual rotary sensor is the small integrated circuit on the right of the adaptorboard.

The whole configuration would thus consist of the adaptorboard integrated within the device itself, together with the demoboard to provide the angular readout. This could then be read out by optionally connected to a PC through USB. This latter option was, in actual fact, mandatory as the readout from the demoboard was not an angle itself, but a mathematical representation of the angle; i.e. the 360 degree angle divided into 1024 steps (since Integrated Circuit is 10-bit). The actual final angle in degrees could only be visualized by the software.

Following experimentation with this device, however, various issues arose, including:

- Bulkiness of the whole system
- Use of PC mandatory
- Distance between IC and magnet critical
- Too many wiring and components leading to an inherently complex and unstable system.

Thus this system was finally rejected, even though a huge amount of effort had been invested, both in trying out the system and in designing an appropriate housing and mounting method within the device.

9.2 Alternative methods of measuring angular movement

Various alternative methods of measuring rotational angle movement were investigated. The following list is by no means comprehensive, and only relevant apparatus is presented here. These alternative methods, however, almost all invariably required the involvement of a professional electronics engineer, which was considered a disadvantage by the investigator following experience by two different technicians who designed and manufactured the two different systems using potentiometers. It was consequently decided that a commercially-available device would be preferable. Features sought in these devices were:

- Size
- Ease of availability
- Possibility of use without complex engineering knowhow
- Price

Thus a period of intensive internet searches ensued, with a few stand-alone devices being identified, purchased and evaluated by the investigator. Most of these devices were disappointingly bulky as they were actually designed for the construction industry. These included various types of inclinometers, rotary angle finders and electronic rulers (Figures below).

Figure 9.10: Digital Angle Finder

Figure 9.11: A) Rotating angle finder, complete with display. Initially was very promising, however the mechanism that needed to be attached to the Ankle Goniometer was too bulky. B) Inclinometer, also a very bulky device.

Figure 9.12: Digital inclinometer, which however does not perform rotational angular measurements

9.3 Some Ankle Goniometer Design iterations

Various designs incorporating some of these devices were also done, most of which were actually constructed.

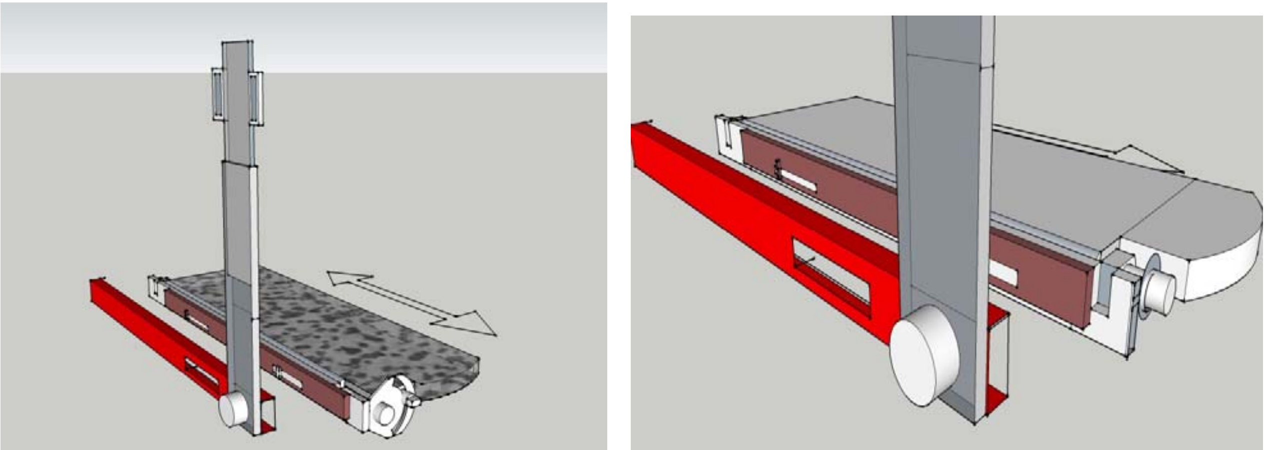


Figure 9.13: A goniometer design incorporating the digital angle finder in Figure 9.10. The hooks in the left diagram are for attaching a velco strap to hold the vertical arm in place. The footplate could hold the foot in an inverted/everted position

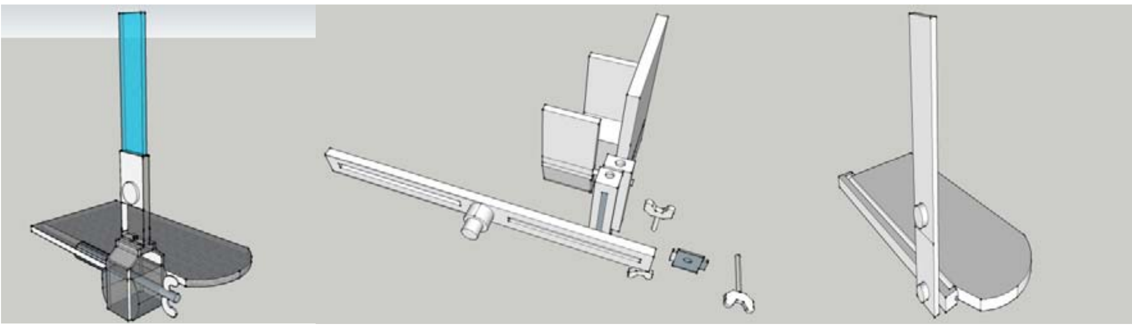


Figure 9.14: 3 iterations of another possible design

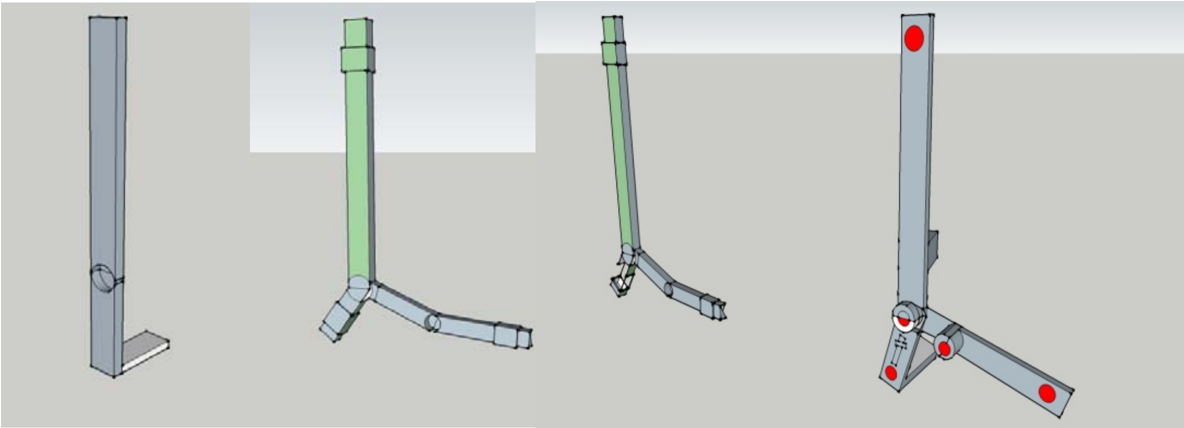


Figure 9.15: Various iterations of a hindfoot design: On the left: a simple design with a heel rest; Other designs: the possibility of incorporating midtarsal joint measurement was contemplated for some time, however in actual practice this proved impractical. Angular measurement was to be by angle finders (Potentiometers). Red circles on the design on the right simulate markers for validation purposes with a 3d motion system. However, design was later discarded.

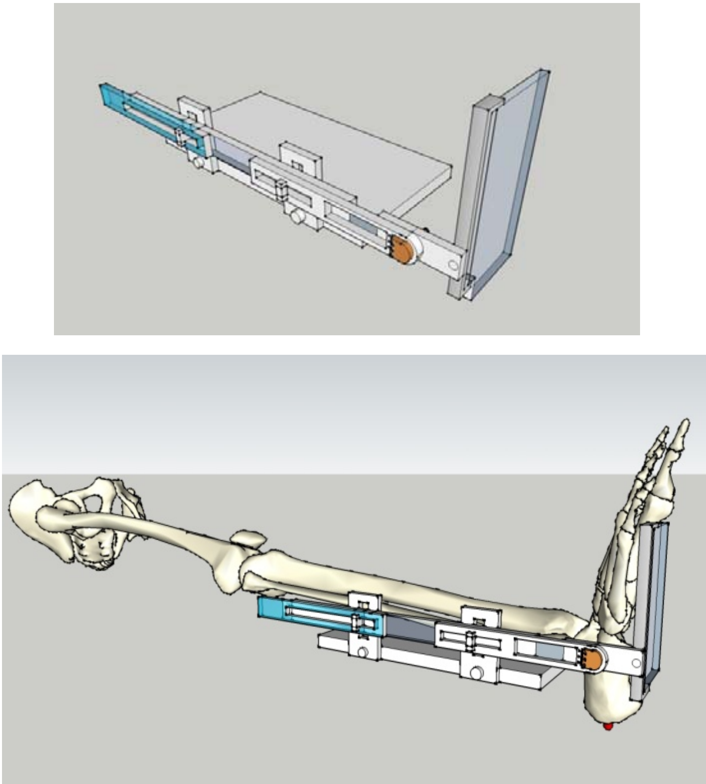


Figure 9.16: Design of an Ankle Goniometer with a rest under the leg in order to stabilize the whole device without the use of Velcro straps

Figure 9.17: From design to fabrication: Actual goniometer from the designs in Figure 8.16, demonstrating various features of the Ankle Goniometer which appeared to be the most promising

At this stage, a design incorporating several features was arrived at. These features included:

- A Footplate
- Alignment of the stable arm on the lateral side (sagittal plane) by individual butterfly screws
- Ability to place pivot where required, i.e. either in line with medial malleolus or further down (to simulate Rootian method) by means of an adjustable arm
- Footplate adjustable up and down (along sagittal plane) to help placement as above

- Ability to place and hold (by means of butterfly screws) the footplate in an inverted/everted position
- The use of a plate underneath the leg stabilized the device without the need for Velcro straps

However, certain factors showed that this design could be further improved, leading to the last design.

1. Contraction of the calf muscles appeared to move the location of the ankle axis (lateral malleolus) in relation to the the pivot arm, throwing it off slightly and causing alignment problems

2. Data from the Kinematic investigation of sagittal plane segmental movement in both adults and children suggests that, upon application of a dorsiflexing force on the metatarsophalangeal joint area, the hindfoot to forefoot angle increases and thus there is forefoot movement at every foot posture. Keeping the foot at subtalar joint neutral position does not appear to stop this movement, as traditionally taught by the Rootian method (Chapters 5 and 6). Thus it was concluded that a footplate would be eliminated because its movement would be the result of summation of all sagittal plane movement of both hindfoot and forefoot.

3. The use of a footplate by itself, even if locked in a particular posture, does not appear to securely hold the hindfoot in that position

4. The display attached by a wire to the device proved to be a constant distraction as the display continued to slide off to a position where it was not highly visible to the rater; the construction of a small stand was attempted but it did not make matters any easier

Thus a few final, but very important changes were done in order to improve the performance of the Ankle Goniometer and to make it easier for the clinician/researcher to use, at the same time increasing its reliability. These changes were the result of:

- various literature research performed
- experience with previous designs whose shortcomings were identified

- critical analysis of devices attesting to perform a similar function
- original research aimed at determining what occurs during passive dorsiflexion

The final design criteria for the Ankle Goniometer were:

1. The entire footplate was shortened to cover just the heel area so that, even though there is forefoot movement upon the dorsiflexing force, forefoot movement would not affect the final angle. This was considered to be a very important criteria, derived from the Sagittal Plane Kinematic analysis of adults and children (Chapters 5 and 6), from which it was concluded that during passive dorsiflexion, there is always an “accessory” movement, i.e. that of the forefoot relative to the hindfoot. It has been shown that this angle increases during the application of force, thus the resultant angle is not purely ankle or rearfoot motion, but is a summation of the hindfoot and forefoot angles. This was noted in all 3 foot postures; thus putting the foot in subtalar joint neutral position does not in reality eliminate midtarsal joint and hence forefoot movement. Thus the term “footplate” has been changed to “heelplate”.

2. Removal of accessory wiring and display. Putting the display onto the display unit into the device itself would make handling much easier.

Figure 9.18: Commercially available miniature angle measuring device, incorporating an LCD screen and battery. Ability to zero the device at any angle, on off switch and auto power-on upon movement of the arms. Accurate to within 0.1^o

3. An adjustable heel, composed of two pieces of acrylic padded with ethylene vinyl acetate, to hold the heel in a secured position.

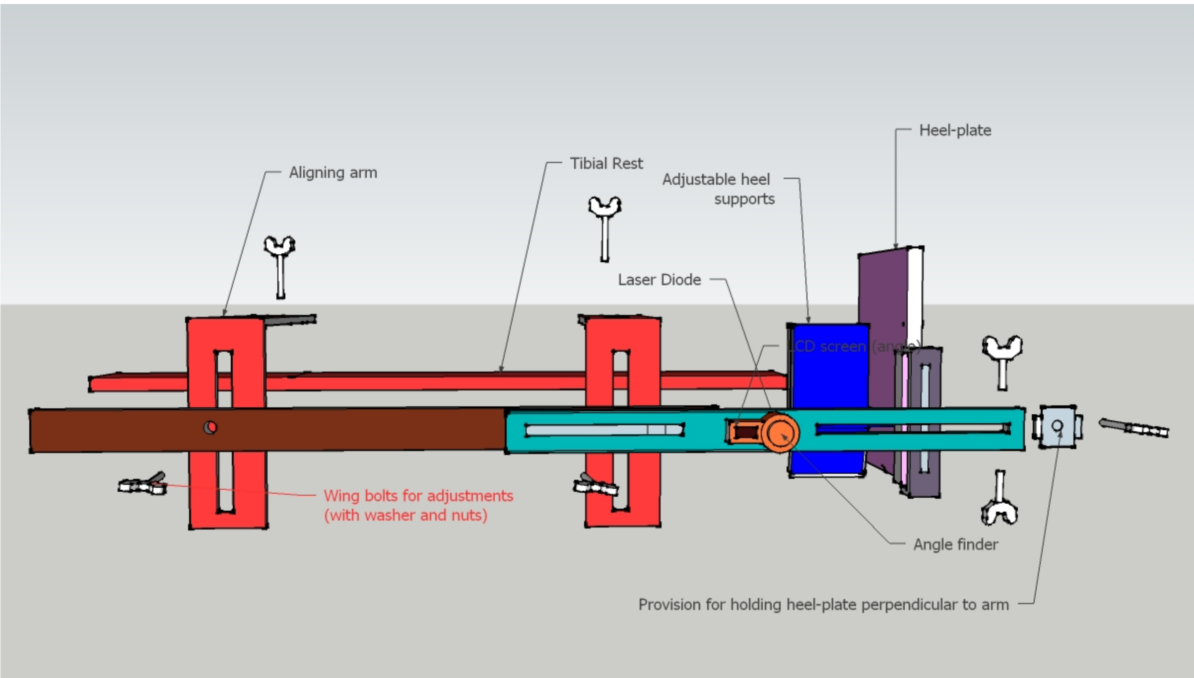
4. Use of the anterior aspect of the tibia as an anchor point to hold the device in position, instead of a base plate, called a ‘*Tibial rest*’.

5. Adjustable on the frontal plane, to follow the lateral contours of the leg.

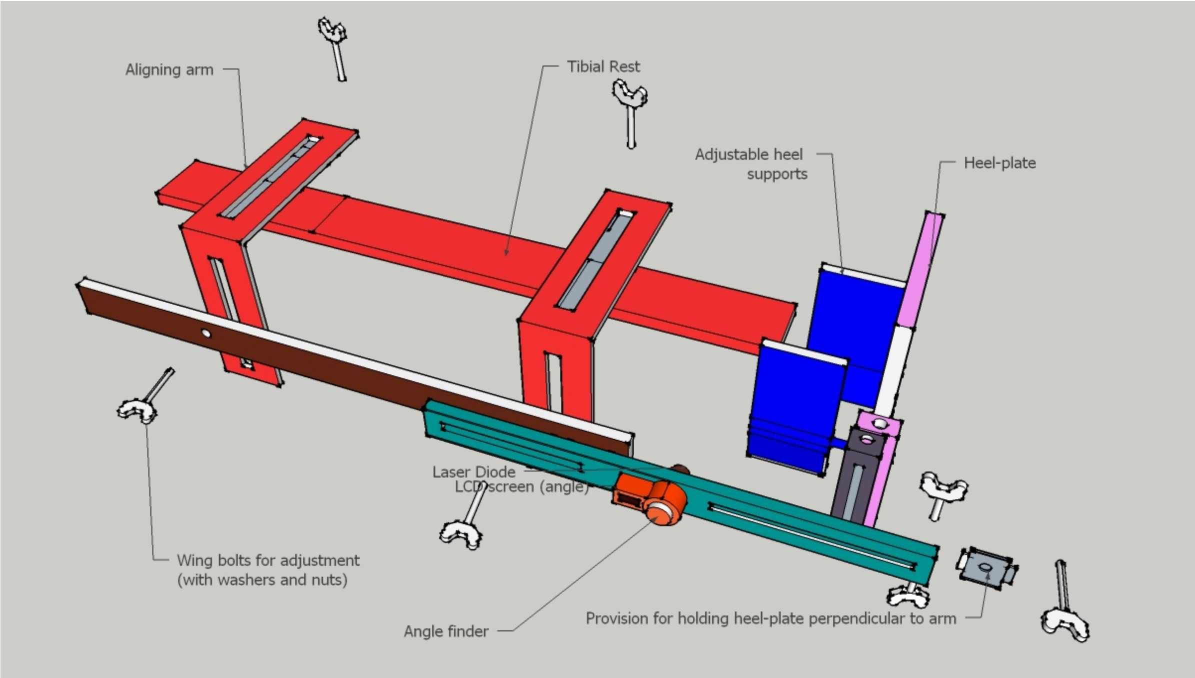
6. Adjustable on the sagittal plane, to align the device from the lateral head of the fibula to the lateral malleolus.

7. Adjustable axis, to align axis either to lateral malleolus or distal to the ankle, as per Rootian method, according to the wish of the examiner. Also adjustable distance from lateral malleolus to the footplate to accommodate various foot sizes.

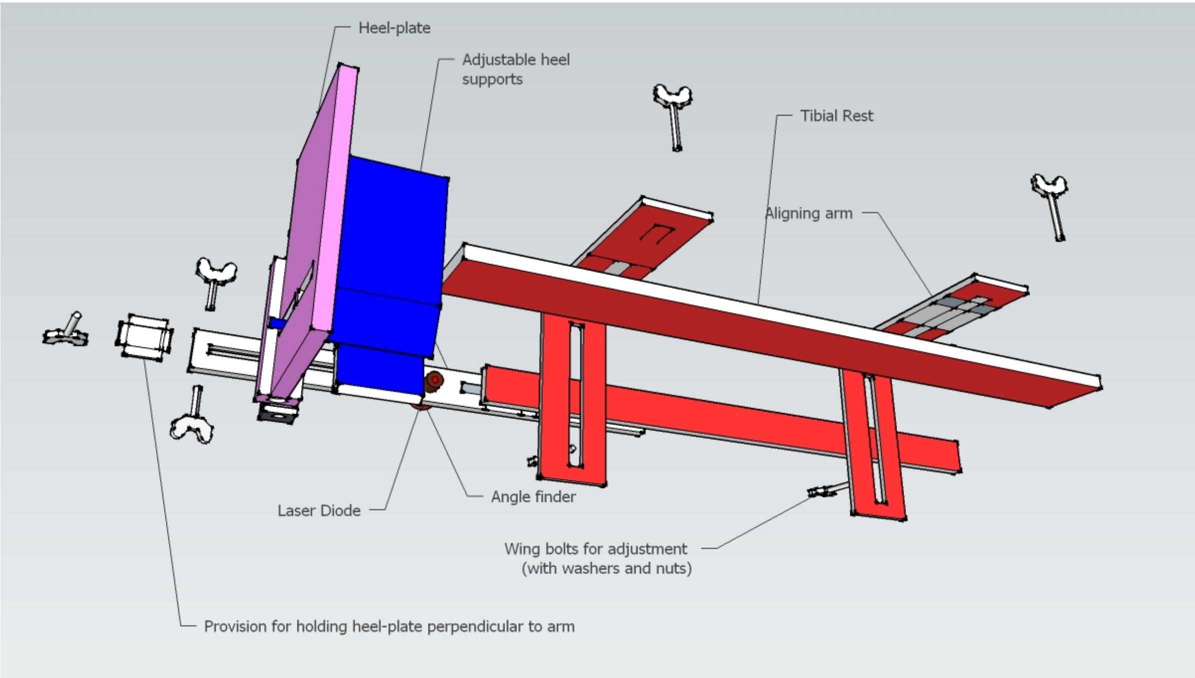
8. Adjustable heel-plate in the frontal plane; ability to lock the plate into the required position.



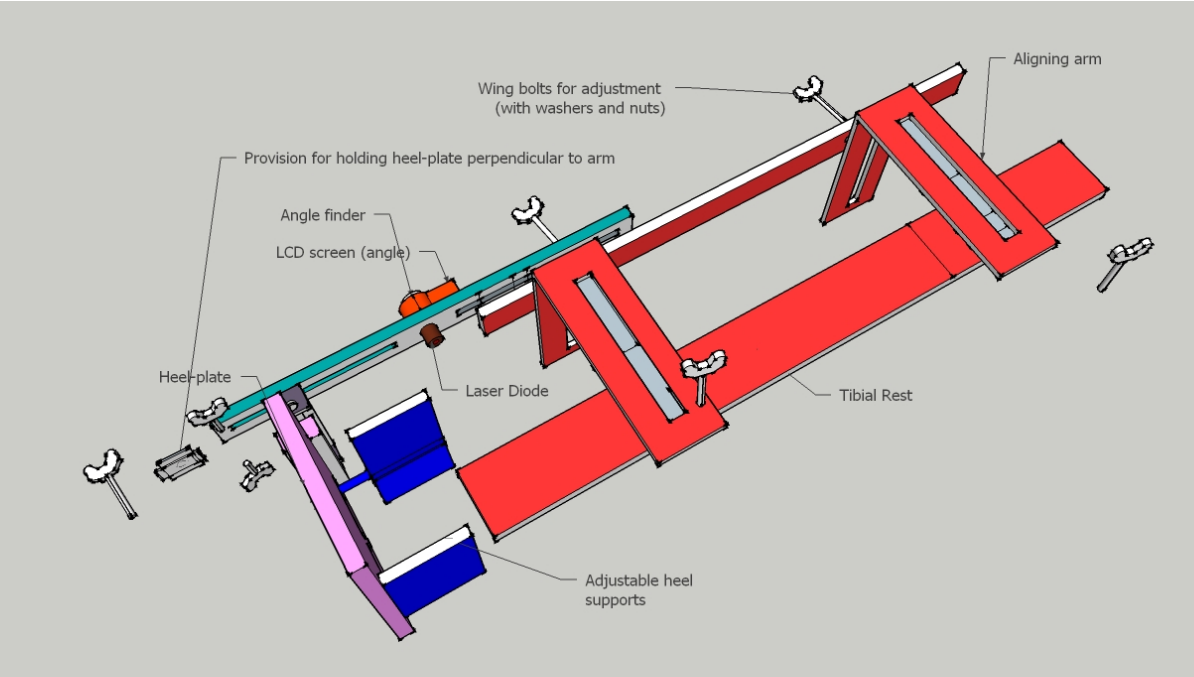
A


Aligning arm
Tibial Rest
Adjustable heel supports
Heel-plate
Laser Diode
LCD screen (angle)
Wing bolts for adjustment (with washers and nuts)
Angle finder
Provision for holding heel-plate perpendicular to arm

B.


Heel-plate
Adjustable heel supports
Tibial Rest
Aligning arm
Laser Diode
Angle finder
Wing bolts for adjustment (with washers and nuts)
Provision for holding heel-plate perpendicular to arm

C.



D.

Figure 9.19 A-D: Exploded view of the various components of the Ankle Goniometer from various angles.

Figure 9:20: The Ankle Goniometer. Left: padded tibial rest with Velcro straps. This provides a solid anchoring point for the device. The rest of the device is adjustable both in the frontal and sagittal plane by means of the butterfly screws on top (frontal) and lateral (sagittal). Middle: Digital readout mechanism and display. Adjustable length above and below malleolus by means of the slots in the aluminium ruler. Right: Adjustable, padded heel support with Velcro straps. The heelplate is adjustable forwards and backwards by means of the vertical slot on the right. Most importantly, it is adjustable in the frontal plane to lock the heel in an inverted/everted position by means of the butterfly screw.

Figure 9:21: Top view of the device, showing the heelplate in an inverted position

Figure 9.22a: The proximal part of the goniometer from the lateral side, showing tibial rest and adjusting arrangements

Figure 9.22b: The proximal part of the goniometer, from a dorsal view.

Figure 9.22c: The digital display and rotational measurement mechanism. Also showing adjusting arrangement for the heel

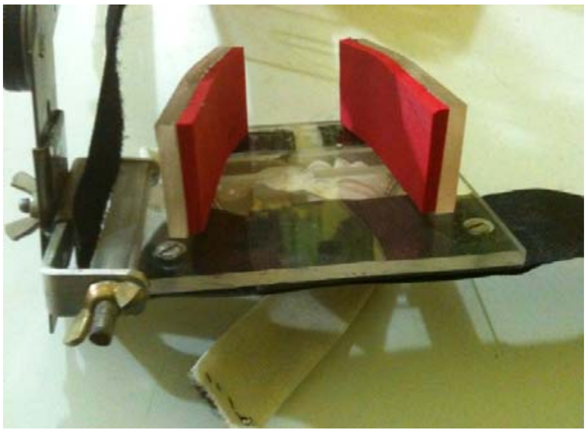


Figure 9.22d: The adjustable heel cup, which widens and narrows by means of two slots in the heel plate. Further Velcro straps hold the heel plate in plate

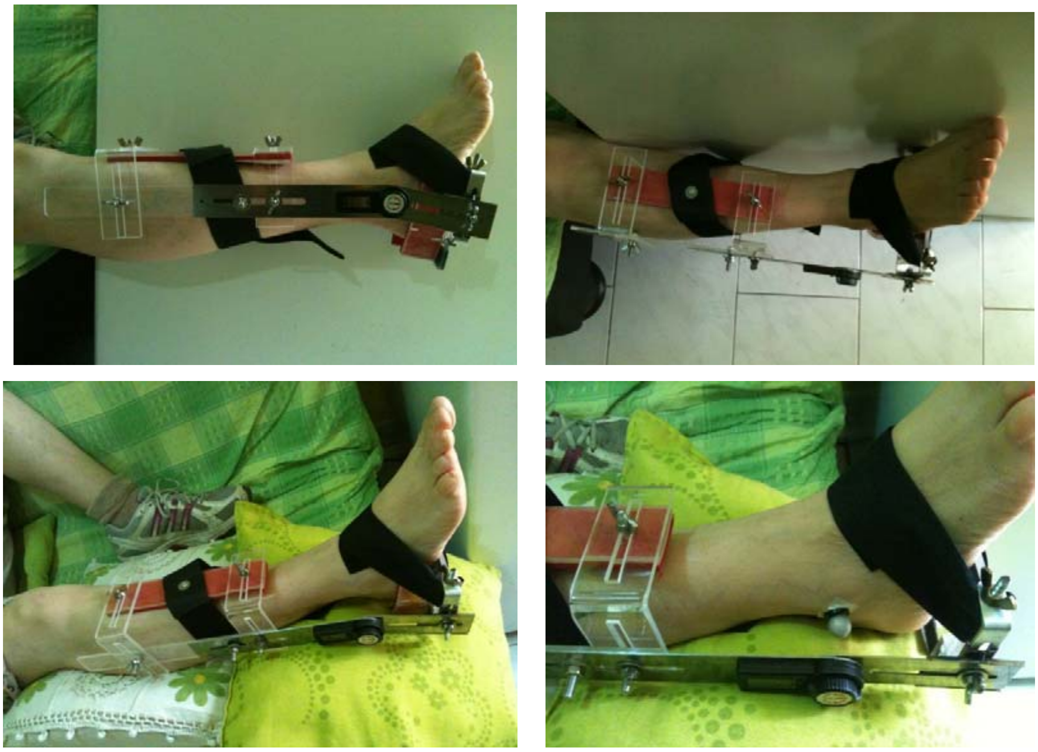


Figure 9:23 a-d: The goniometer in position

Conclusion:

The final design of the Ankle Goniometer was arrived at following extensive design alterations, actual manufacturing of the device at each stage and trying it on on willing participants.

It may be concluded that the design criteria have been reached, especially as regards the function, accuracy of the device, ease of construction and relatively little cost required. The next stage involved testing the validity and reliability of the device as is required before any new diagnostic tool could be applied to clinical practice.

Chapter 10

Reliability of a New Ankle Goniometer

Aspects of this chapter have been communicated as:

Gatt A, Chockalingam N. 2012. Validity and Reliability of a New Ankle Dorsiflexion Measurement Device. (Under review)

10.0 Introduction

Before any new diagnostic device can be put to clinical and/or research use, it must first be validated to ensure that the output is, in actual fact, the true, expected result, i.e. that the instrument is actually measuring what it purports to measure. Then test-retest reliability testing is performed to ensure that raters will produce consistent results utilising the said method, technique or equipment. Hence this chapter will investigate validity and reliability of the Ankle Goniometer.

According to Gajdosik and Bohannon (1987, pg 1867), ‘‘reliability in goniometry simply means the consistency or the repeatability of the [range-of-motion] measurements, that is, whether the application of the instrument and the procedures produce the same measurements consistently under the same conditions’’. This definition, however, does not consider validity, ie, whether the instrument is actually measuring the correct angle. This is one of the main reasons why any such procedure must be compared with the reference standard. In the case of ankle joint complex measurement, following the revelation of Tiberio et al (1981) and Woodburn (1991) that in a pronated foot there is 10^{o} more dorsiflexion, the instrument under review might actually be measuring both ankle joint complex and midtarsal joint complex dorsiflexion.

To complicate this further, it might also be actually measuring the summation of all of the dorsiflexion movements of joints distal to the ankle.

A diagnosis of ankle equinus or limited ankle dorsiflexion is arrived at after measuring the dorsiflexion angle. From this, important clinical decisions, including whether to intervene surgically, are reached. Notwithstanding this, however, as has been demonstrated previously, there are clear issues regarding the reliability of techniques used to measure ankle dorsiflexion. Although, traditionally, a goniometer is used to measure ankle dorsiflexion, there is overwhelming evidence that its inter-rater and intra-rater reliability is very poor (Elveru et al. 1988; Martin and Mcpoil 2005; Van Gheluwe et al. 2002). Rater experience does not overcome this limitation (Kim et al, 2011), implying that even “highly experienced experts” do not necessarily get the measurement right every time. Consequently, various types of goniometers have been designed to overcome the range of problems associated with this measurement, as shown in Chapter 4. A number of factors that may affect the ankle dorsiflexion angle measurement have been identified (Chapter 3). Hence it must be determined whether these factors have been addressed by these devices as these form the basis for the design criteria of an ankle goniometer.

One has to differentiate between "ankle dorsiflexion" and "foot dorsiflexion", as the latter involves the dorsiflexion at ankle, subtalar joint and midtarsal joint (Chapter 3). Midtarsal joint movement has been shown to be quite significant, often ranging more than ankle joint movement itself (Lundgren et al. 2008); measurement results arising from this situation would clearly lead to a mis-diagnosis in which limited ankle dorsiflexion would be masked by midtarsal joint movement.

The application of a known moment is another important factor. All goniometers designed to measure ankle dorsiflexion have controlled the amount of moment applied to the forefoot, which ranged from 10Nm to 25Nm. This has in fact made it easier for the goniometers to produce similar results when repeatability was investigated. However, during clinical measurement, it is doubtful how many practitioners carry a force gauge with them, so this solution is clearly impractical. Research carried out in Chapter 8 has demonstrated that it is possible to get results that are significantly homogenous without using a force gauge at both the neutral and supinated positions.

It has been postulated that, since there is no clinical significant difference between the neutral and supinated posture, with the difference amounting to just 2.5^{o}, this test can be performed at the supinated position, thus circumventing issues with reliability of establishing a neutral position which is notoriously difficult to achieve for many clinicians, especially those of little experience.

10.1 Reliability

Any new diagnostic device requires reliability testing to be performed. Reliability has been defined as "the consistency or reproducibility of a measure" (Martin and Mcpoil 2005). Test-retest, inter-rater and intra-rater reliability testing is required when evaluating new apparatuses designed to measure ankle dorsiflexion. The majority of trials assessing reliability of ankle dorsiflexion devices have used this type of testing, with test-retest designs being the preferred method of assessment, further analysed statistically through the use of Intraclass Correlation Coefficient (Chapter 3).

A quality methodological assessment on discovered devices designed to measure ankle dorsiflexion has reported quite poor scoring because of a number of factors, including: small convenience samples, lack of use of actual patient populations to test out the devices, lack of randomization reporting, lack of comparison to a "Gold Standard", i.e. comparison to a test that is known to produce valid results. It is, however, recognized that this gold standard may be x-rays and authors may encounter problems obtaining ethical approval purely for research purposes. Wilken et al (2011) have circumvented this problem by using an optoelectronic motion analysis system to simultaneously evaluate 12 participants together with their IAROM device (Wilken et al. 2011).

10.2 Method

Validity and reliability testing for the Ankle Goniometer spanned a number of different phases. Ethical approval was sought from and granted first by the Faculty of Health Sciences Ethics Board and consequently by the University of Malta Ethics Research Committee. All participants were adults and signed an informed consent after being provided with an information sheet. Relevant approval and documentation may be found in Appendix 1.

10.2.1 Validity Testing:

Validity testing presented significant technical hurdles. As mentioned previously, a 'Gold Standard' would have been x-raying the foot with the ankle goniometer in place, then comparing the angles from the X-ray viewing software and that output by the goniometer. The vertical midline of the fibula can be compared with a line dividing the talar trochlear (Backer and Kofoed 1989). However, because of obvious ethical issues, this could not be done, thus an alternative method had to be employed. It was consequently decided that convergent validity would be confirmed by comparison of ankle dorsiflexion angles measured simultaneously with the Ankle Goniometer and an optoelectronic motion analysis system as in (Wilken et al. 2011). However, unlike Wilken et al, the front of the tibia was not used as a reference point and it was decided to build a 3D model of hindfoot dorsiflexion utilising the lateral bisection of the lower leg, which is more conversant with the actual technique used by the Ankle Goniometer.

10.2.2 Method of Validation

Since the Ankle Goniometer had only a visual output and could not be synchronized electronically to another electronic device, an electrogoniometer (MIE Medical Research Ltd) was placed on the inner aspect of the Ankle Goniometer, crossing the joint that is placed in line with the lateral malleolus (Figure 9.0). The electrogoniometer was previously interfaced with its own data logger and its angles ouput to a laptop using proprietary software. This goniometer had been undergoing testing at the Staffordshire Biomechanics Lab and had been synchronized with the 8-camera Vicon system (OMG, Oxford, UK) in use at that laboratory. Validation of the two angles produced was carried out until it was confirmed that both goniometers were, in fact, outputting the same angles.

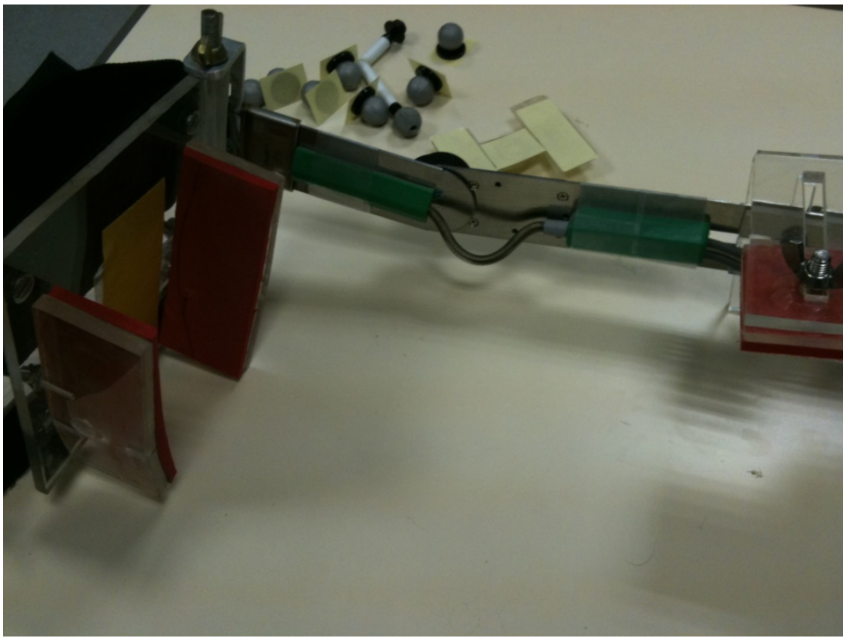


Figure 10.1: Alignment of the Ankle Goniometer with the Electrogoniometer

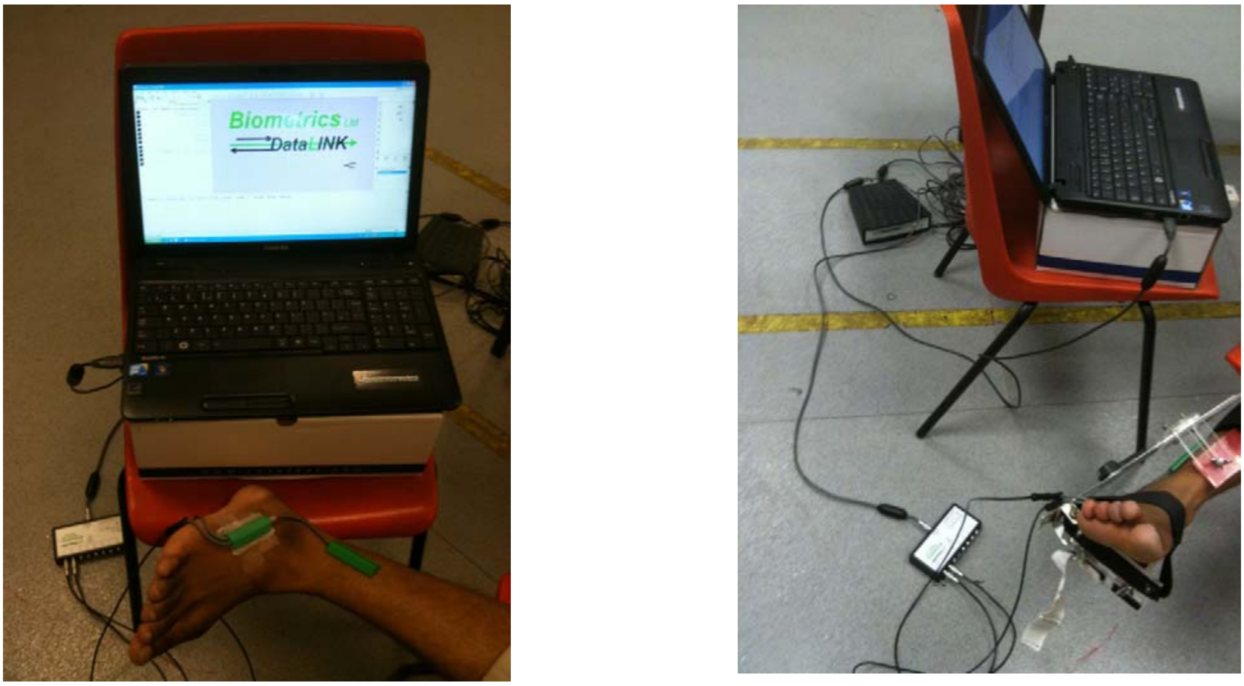


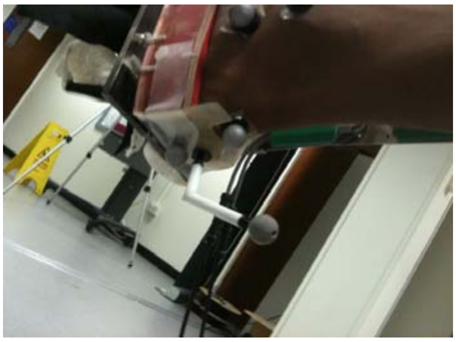
Figure 10.2: a) Electrogoniometer, datalogger and laptop setup during trials. b) actual setup with the Ankle Goniometer in place. This was a first trial in which the goniometer was adhered to the foot itself; this was consequently found to produce a number of errors and the output was very dependent on where the two ends of the goniometer were put. In fact, it was later decided to adhere the device to the ankle goniometer itself.

As outlined in Chapter 5, a hindfoot model, based on the Oxford Foot Model, was constructed using Visual 3D (C-Motion, Germantown, USA). (http://www.c-motion.com/v3dwiki/index.php?title=Oxford_Foot_Model). This uses the same axes and co-ordinate system as the original model, as initially outlined by Carson et al (2001).

Markers were placed over bony areas, where movement of underlying soft tissue could be minimized, to provide accurate measures of ankle ROM. It was possible to add markers with the ankle goniometer/electrogoniometer combination in place (Figure 10.3, a-c).

A

B



C

Figure 10.3: Ankle Goniometer/electrogoniometer with marker setup. a) Dorsal View b) medial view and C Posterior View

Subject was placed sitting on a table, with the apparatus in situ, and with his feet suspended. Since passive dorsiflexion by an operator could not be performed because the operator would block the view of some of the cameras (as may be appreciated, marker views were very limited with the goniometers in place), subject was instructed to look at the angle output on the monitor and to dorsiflex his foot from 0^o up to the limit of dorsiflexion at 5^o intervals. This was possible as the laptop screen was outputting the data in an easily visible manner. Subject trained in this procedure until he felt comfortable with the procedure.

The Vicon system was set to acquire data for 20 seconds. Data acquisition was synchronised with a Tekscan (Boston, USA) synchronization box. Data collection was performed 6 times. Data from both the kinematic hindfoot model and the electrogoniometer were exported into Microsoft Excel, where angles for both goniometer and Vicon were plotted over 1000 instances (Figure 10.4). A sample of the output in 5^o increments is presented in table 19 (Appendix 2).

Figure 10.4: Subject positioning

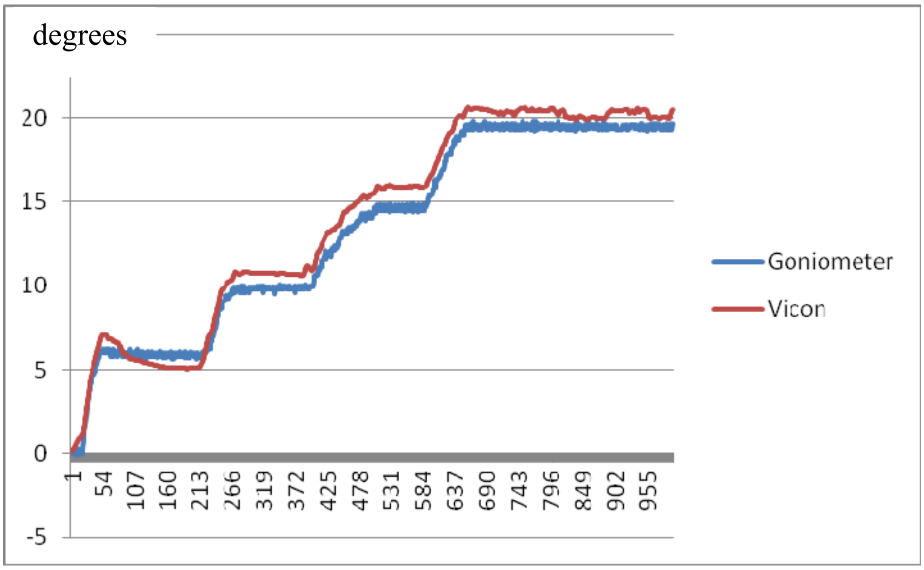


Figure 10.5: Validity: Angles output by goniometer and vicon

Pearson's correlation was employed to investigate correlations between the two results, utilising all 1000 data points for each. Correlation coefficient obtained was 0.996, with a p-value of .000.

As can be seen from the data, including the descriptive statistics in Table 20 (Appendix 2), the Ankle Goniometer correlated extremely well with the Vicon system. This is further evidenced by Figure 10.5 and Table 19 (Appendix 2), where the similarity between the angles produced by the two devices can be visualized.

Whilst the goniometer cost in the region of €100, a Vicon system costs x1000 as much, besides requiring extensive work by an expert person to perform any testing at all. Once validity of the Ankle Goniometer is established, its advantages over the Vicon system are obvious when investigating passive ankle dorsiflexion range of motion.

10.3 Reliability Testing:

Reliability testing normally takes the form of inter-tester and intra-tester studies in order to assess whether the same practitioner can obtain the same results over a period of time, and whether two or more practitioners can obtain comparable results. All the specifically-designed ankle goniometers employed this type of testing, however the Systematic Review performed has identified various shortcomings, thus making reliability testing results of these devices quite dubious.

These shortcomings include:

- The use of healthy populations (normally convenience samples of students)
- Many testing protocols did not employ an actual patient population, which is odd considering that these devices are meant to be used on patients.
- The use of a known moment, which makes the testing artificially appear to be correct. Once the applied force is the same for all subjects, it is this force which is controlling the resultant angle, which *has* to be consistent, even between different raters.

The series of trials that ensue attempted to address these shortcomings. It was decided to divide this trial into 3 different trials, each addressing a different research question.

10.3.1 Trial 1: Inter-rater and intra-rater test-retest reliability using a known moment; a double-blind design

Aim:

- To establish reliability (repeatability) of the Ankle Goniometer with controlled moment during passive ankle dorsiflexion

Objectives:

- o To measure the passive maximum ankle angle repeatedly between the same rater (inter-rater reliability) with controlled moment in a healthy population
- o To measure the passive maximum ankle angle repeatedly between two raters (inter-rater reliability) with controlled moment in a healthy population.
- o To establish consistency between the maximum ankle angles obtained.

10.3.1.1 Method

A convenience sample of 10 young healthy adults (mean age 18.9 years (range 18-20 years)), were assessed by two raters. None of the participants had any foot or lower limb problems or systemic conditions. Both raters were experienced clinicians, however with very little clinical experience in the use of the specific Ankle Goniometer. Rater 2 had just 15 minutes acclimatization with the instrument after its layout was explained by Rater 1.

All measurements were performed with the subjects supine. Rater 1 applied the goniometer to the subject, aligning the lateral arm with the tibial condyle and lateral malleolus, the pivot point of the instrument in line with the malleolus and firmly clasped the heel in the adjustable heel portion of the device. The foot was then placed in a slightly supinated position using the talo-navicular congruency method. The talar head was palpated with index finger and thumb of the rater's right hand until subtalar joint neutral position was identified by equally feeling the medial and lateral heads, then supinating slightly so that only the lateral aspect of the talar head was palpable. This position, also previously recommended by Woodburn (Woodburn 1991) was chosen as previous research (Chapter 6) had indicated a non-clinical difference between the neutral and supinated positions of only 2.5^{o} (and 3.5^{o} by Woodburn, 1991) thus bypassing issues regarding consistent finding of subtalar joint neutral. The rater then applied 20Nm of force to the forefoot through a calibrated force gauge to dorsiflex the foot maximally for 3 seconds, then released the applied force. A reporter recorded the maximum ankle angle when the Rater announced that 20Nm were applied. All raters and subjects were blinded.

This procedure was repeated for 5 times, for all subjects, by both raters (inter-rater reliability assessment). Rater 1 then repeated the whole performance after 1 hour (intra-tester reliability). Same day repeatability was chosen in order to exclude any factors that could influence the maximum dorsiflexion angle, such as soft tissue stretching characteristics. Since raters were blinded, it was decided that this same-day reliability testing would suffice.

10.3.1.2 Results and Statistical Analysis

The maximum ankle angles, as output by the Ankle Goniometer and as recorded by an independent recorder, are presented in Table 21 (Appendix 2). Rater1 (Test) and Rater 1(2) (Retest) weere compared for intra-rater (i.e. same rater) reliability, while Rater 1 and Rater 2 angles were utilised for statistical analysis of inter-tester (between raters) reliability.

Cronbach's Alpha is a useful tool for assessing internal consistency. According to Bland and Altman (1997), α values of 0.7 to 0.8 are regarded as satisfactory when comparing groups, however for clinical applications much higher values of α are needed. The minimum is 0.90, and α=0.95 is desirable.

Statistical testing has, in fact, resulted in a Cronbach's Alpha of 0.984 (Table 22, Appendix 2), when the maximum value of this test is 1, which shows high internal consistency.

Intraclass Correlation Coefficient (ICC) was chosen as the statistic of choice. An important application of this statistical test is the assessment of consistency or reproducibility of quantitative measurements made by different observers measuring the same quantity.

ICC (2,1) implies a Two-way random effects model where both people effects and measures effects are random (Consistency/Absolute agreement). Test-retest of 0.984 represents high reliability when the test is being carried out by the same rater (Table 23, Appendix 2).

As regards inter-rater reliability (that is, reliability between rater 1 and rater 2), ICC (2,1) produced the output in Tables 24 (Appendix 2) and 25 (Appendix 2). Means of $<2^o$ resulted, with the ICC value of 0.953 demonstrating very high reliability between the two raters (Table 24, Appendix 2). Statistical significance was also achieved.

10.3.2 Trial 2: Intra-tester reliability with uncontrolled moment and variable knee position; a double-blind design

Aim:

- To establish reliability (repeatability) of the Ankle Goniometer with uncontrolled moment

Objectives:

- To measure the passive maximum ankle angle repeatedly between the same rater (inter-rater reliability) with uncontrolled moment in a healthy population
- To establish consistency between the maximum ankle angles obtained.

10.3.2.1 Method

10 healthy adults (5 males, 5 females, mean age 40.3yrs (33-48years)); mean weight 77.8kg, mean height 167.9cm) were randomly recruited in order to undergo intra-rater reliability testing without the use of an applied controlled moment. Rater 1 assessed all subjects, who were lying supine. As previously done, a dorsiflexing force was applied to the forefoot until the maximum dorsiflexion angle was attained, at which point the angle was recorded by an independent observer, keeping both rater and subject blinded. Following 5 dorsiflexion measurements, the knee was flexed by approximately 20^{o}, to investigate the effect of the gastrocnaemius muscle, then the routine was repeated. For test-retest reliability purposes, the whole procedure was repeated after 1 hour.

10.3.2.2 Results and Statistical Analysis

As may be seen from the series of statistical tests in Appendix A, there is very high reliability for intra- and inter-tester, even though the moment is not controlled (p=0.000) (Table 28, Appendix 2). This confirms earlier findings arrived at in Chapter 8 utilising the Vicon System, however this time through the use of the Ankle Goniometer: that there is no need to control for moment when conducting ankle end of range of motion measurement. These findings also imply that the Ankle Goniometer can be used with no difference in reliability, which in turn is not effected by knee position (whether extended (ICC 0.94) or flexed (ICC=0.95), when ICC scores >8.0 are considered reliable (Tables 28 and 29, Appendix 2).

10.3.3 Trial 3: Intra-tester reliability with uncontrolled force on a patient population; a double blind design.

Aim:

- To establish reliability (repeatability) of the Ankle Goniometer with uncontrolled moment in a patient population

Objectives:

- To measure the passive maximum ankle angle repeatedly between the same rater (inter-rater reliability) with uncontrolled moment in a patient population
- To establish consistency between the maximum ankle angles obtained.

10.3.3.1 Method

The first 15 patients attending a foot clinic were invited to participate. The main criteria was a foot condition that could be possibly related to altered ankle function or that could possibly alter ankle function (Table 9.6 for subject demographics). All participants, as in all trials, signed informed consent. Following the previous protocol, a single rater assessed maximum ankle dorsiflexion on all participants. This time, however, the number of repetitions were reduced to just 2 instead of 5 so as not to cause any undue pain to the participants. The second ratings were done after one hour. As in all the previous reliability testing, the rater was blinded and an independent recorder documented the maximum ankle angle as output by the LCD screen of the Ankle Goniometer.

At the end of the whole trial, the independent observer handed in the final readings in an Excel spreadsheet. Data was then analyzed in SPSS 19.0.

10.3.3.2 Results and Statistical Analysis

Patient (participant) demographics and mean maximum ankle dorsiflexion angles for test and retest, are presented in Tables 10.1 and Table 30 (Appendix 2) respectively, with the latter illustrated in Figure 10.6. Prior to performing any statistical tests, a visual analysis of these tables and figure demonstrate the close relationship between the test and retest results. This is further confirmed by Intraclass Correlation Coefficient, which returned a highly significant correlation of 0.992, p value=0.000 (Table 32, Appendix 2).

Table 10.1: Participant Demographics

Patient	M/F	Age	Height	Weight	Medical Condition
1	F	57	5'3	62	Heel Pain
2	F	67	5'5	67	Forefoot Callus/ Hallux Abducto Valgus
3	F	52	5'2	73	Ankle oedema/nucleated forefoot corns
4	F	44	5'6	72	Plantar Digital Neuritis
5	F	23	5'6	65	metatarsalgia/hallux valgus/FHL
6	F	43	5’6	74	DM/ankle fracture/metatarsalgia
7	F	36	5'2	52	Plantar fasciitis
8	M	18	5'5	58	cerebral palsy/dropfoot
9	F	54	5'2	63	anterior knee pain
10	M	61	5'8	78	heel pain
11	M	43	5'10	92	posterior tibial tendinitis
12	M	72	5'7	88	metatarslgia
13	F	55	5'4	70	morton's neuroma
14	M	31	6'1	98	plantar fasciitis
15	F	47	5'7	59	forefoot callus

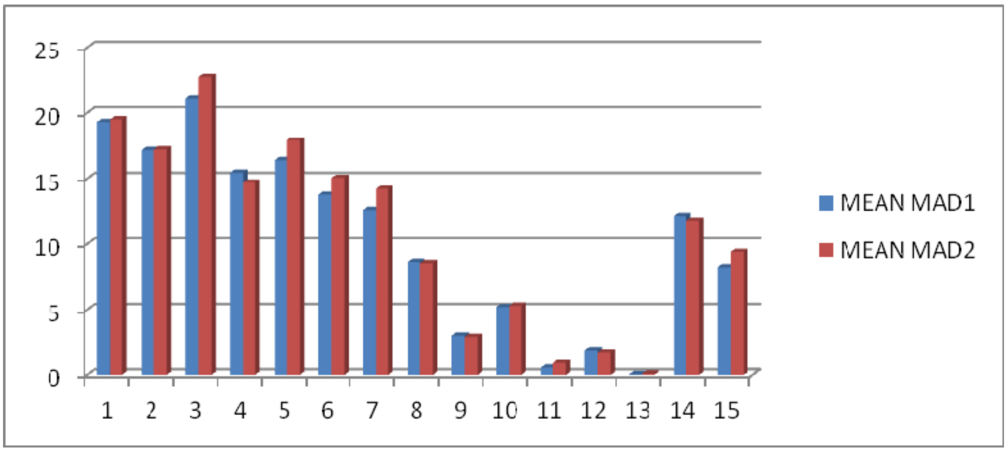


Figure 10.6: Test-Retest results for each subject.
Mean MAD=Mean Maximum Dorsiflexion angle (^{o}).

10.4 Conclusions

- The Ankle Goniometer has proven to be both a highly valid and reliable device, which is a requirement before it can be employed as a clinical and/or research tool.
- Validity testing against a Vicon 8-camera optoelectronic system has demonstrated very high Pearson Correlation.
- Reliability did not suffer when uncontrolled moment (reflecting a more normal clinical setting) was applied.
- This Goniometer has been shown to be reliable in two convenience populations: young adults (with controlled and uncontrolled moment) and middle-aged persons (with uncontrolled moment, with knees extended and flexed).
- Reliability has also been demonstrated in a patient population (with uncontrolled moment).

Chapter 11

Establishing reliability of the Ankle Goniometer between multiple raters with uncontrolled moment

11.0 Introduction

In previous chapters, it has already been established that there is high reliability of the Ankle Goniometer (ICC >0.9) in various examination scenarios. These included:

- Reliability between 2 raters, using controlled moment (inter-rater reliability)
- Reliability between the same rater (intra-rater reliability, i.e. repeated measures), in various situations, namely using:
  - Controlled moment in a healthy young adult population
  - Uncontrolled moment in a healthy adult population
  - Uncontrolled moment in a patient population

In order to ensure that the Ankle Goniometer can be employed as a valid and reliable clinical tool, the next step is to investigate reliability by a number of different raters. Thus in this chapter a trial will be conducted in which 4 clinicians with varying experience with the Ankle Goniometer will be assessed in their use of the device.

Summarizing two important findings of previous research (Chapters 5 and 7) that need to be considered when designing this trial and which will thus be utilised:

1. In adults, there is no clinical difference between utilising either the neutral or supinated position when assessing maximum ankle dorsiflexion.
2. It is possible to achieve homogenous results when measuring ankle dorsiflexion both in the neutral and supinated postures when moment is not controlled.

Once it has been established that it is possible to achieve homogenous results using uncontrolled moment (intra-rater) utilising a Vicon optoelectronic motion capture system (Chapter 8) and also achieve a high inter-rater reliability between two raters making use of the Ankle Goniometer (Chapter 10, under different scenarios), it would be much easier to employ the latter device for examination of ankle dorsiflexion for various reasons, including:

- Availability of the equipment: a Vicon or alternate system is not readily available to clinics because of the high costs involved
- Expertise required: with an optoelectronic motion capture system, high expertise is required for the setup, marker placement, data capture and analysis, thus increasing room for errors if less experienced practitioners make use of the system, leading to inaccuracies in the results.
- Time constraints: clearly, the time-frame required to use the Ankle Goniometer is a fraction of that required for a motion capture system

11.1 Background

As has been established, although foot posture affects the Maximum Ankle Dorsiflexion Angle, the amount of force applied to dorsiflex the foot does not, provided that end of range of motion is achieved. Notwithstanding this, in various trials that investigate maximum ankle dorsiflexion, the applied moment is given more attention than foot posture.

It is claimed that the Maximum Ankle Dorsiflexion Angle is also directly influenced by the applied torque (Assal et al. 2003). The torque, or moment, is the product of the force applied and the distance from the centre of rotation to the point of application of the force. When assessing reliability of ankle goniometric devices, authors have elected to maintain a constant moment between subjects in order to produce the same angles. This moment varies between studies, from 10 Nm, 12, 15, 16.1, 20 and 25Nm.

If, as quoted, the amount of force applied is such a determinant factor on the ankle angle produced, this assessment procedure would have poor inter-tester reliability since different practitioners are likely to induce different amounts of force during this procedure. It would thus be quite difficult to investigate treatment effectiveness in a pre- and post-intervention scenario, for example, or to compare results between different practitioners since, as has already been pointed out, a force gauge is not an instrument traditionally found in a practitioner's clinic. Using an optoelectronic motion analysis system, it has been demonstrated that the maximum ankle angle can be quite reliably assessed by the same practitioner (intra-tester reliability). Although the application of a known moment produced reliable inter-rater results, it has also been shown that the same rater can produce reliable results when not controlling for moment (Chapter 9). At this stage, all that remains is to determine whether the device would still produce reliable results with multiple raters and uncontrolled moment.

Although moment is important for the calculation of a passive torque versus angular displacement curve (Moseley et al. 2001), it has been postulated that, since maximum ankle dorsiflexion is an end of range of motion assessment determined by the stretching characteristics of the triceps surae, applying more force beyond the stretching limit would cause tendon damage. Consequently, further application of force beyond this limit should be avoided.

Thus the scope of this study was to investigate Ankle Goniometer reliability between different practitioners when the ankle joint was dorsiflexed to its end of range of dorsiflexion motion without controlling for applied moment. It was hypothesised that, since this measurement is an end of range of motion type of assessment, the maximum ankle dorsiflexion angle would be the same between practitioners even when the moment applied is not controlled.

Aim:

- To investigate whether it is possible to achieve reliable results between various raters of varying abilities utilising the Ankle Goniometer without controlling for moment.

Objective:

  - To determine if maximum ankle dorsiflexion is consistent between multiple raters of varying experience without controlling for moment (using end of motion)

11.2 Method

Following University of Malta Research Committee approval, four practitioners with varying experience in the use of the Ankle Goniometer assessed a convenience sample of 10 adults (5 males, 5 females mean age 36.4yrs (SD 9.5yrs); Table 11.1) using the previously validated ankle goniometer.

There were no inclusion or exclusion criteria, since this device is meant to be utilised as a diagnostic tool. However, all participants, who signed informed consent, were healthy consenting adults with no systemic disease and no apparent deformities of the feet.

Two male and two female raters (clinicians) were randomly asked to participate (Raters 1 and 2 were male, while Raters 3 and 4 were female practitioners). The aim of this was to eliminate any possible bias related to gender as it could be claimed that males may exert a larger moment than females. Two of the practitioners had never used this type of goniometer before and were instructed about its various characteristics and usage by the first practitioner. Each participant lay supine and told to relax, following which the goniometer was applied to the right foot, which was established in a slightly supine posture using the talo-navicular congruency method. At this position, the head of the talus on the lateral aspect could be palpated while the medial head could not. A force was applied at the ball of the foot until the foot was dorsiflexed maximally. An observer noted the angle on the digital scale of the goniometer. All raters and participants were blinded to the resultant angle. 5 repetitions were performed by each practitioner, with a 30 second pause in between. Subjects were not removed from the goniometer (Salsich et al. 2000; pg 357, since the aim was to assess the consistency of the angle produced. Each participant was then rated by a different rater until all raters had performed the required measurements. The order of raters was determined randomly so that the practitioner sequence differed with each participant.

Angular results were input in an Excel spreadsheet by the observer and then analyzed in SPSS version 19.0.

11.3 Results and statistical analysis

Table 11.1: Participant Demographics

	Participant	Demographics		
	M/F	Age (years)	Weight (Kg)	Height (cm)
1	F	39	60	165
2	F	26	69	157
3	F	30	80	167
4	F	51	51	163
5	M	36	82	169
6	M	53	106	180
7	F	37	59	160
8	M	26	69	175
9	M	29	88	170
10	F	37	50	168
MEAN		**36.4**	**71.4**	**167.4**

Table 33 (Appendix 2) shows the mean results of each rater for each participant, while Reliability results (ICC >0.9, p<0.05) are shown in Table 34 (Appendix 2).

11.4 Discussion

At present, it is clearly an unhappy situation for those practitioners who include maximum ankle dorsiflexion measurement as part of their clinical assessment in order to diagnose ankle equinus or limited ankle dorsiflexion, which are both important clinical conditions. The reported poor reliability of traditional goniometric measurement raises doubts about assessment of treatment effectiveness since errors during the measurement process could be considerable. Practitioners also have to contend with the problems of foot posture and moment applied.

A pronated foot posture will produce 8-10^{o} of dorsiflexion more than the supinated posture. Thus it is clear that foot posture should be taken into consideration when performing this measurement technique, since it was originally recommended to be performed at subtalar joint neutral position (Gastwirth 1996; Root et al. 1977). However, at neutral position the maximum angles reported are not homogenous (Chapter 6); this latter itself could be one of the sources of poor reliability of goniometric measurement. During this thesis, the issue of foot posture has been settled since it has been established that, although there is a statistically significant difference in the maximum ankle angle produced in the 3 postures, there is a negligible clinical difference of only 2.49^{o} between the supinated and neutral postures. Thus since the maximum angles are not homogenous at neutral posture and there is little difference between neutral and supinated, it is being recommended that the supinated posture should be assumed instead of the neutral posture.

The third factor that has been quoted as affecting the maximum ankle angle is the use of a constant force applied to the ball of the foot. The maximum angle is said to be dependent on the force applied. In fact, all reliability testing of specially designed ankle goniometers are performed with a constant moment applied (Assal et al. 2003; Meyer et al. 2006; Wilken et al. 2011). When translated into actual clinical use, it is evident that the whole procedure would become impractical. Thus an alternative method of measuring ankle dorsiflexion without controlling force had to be found in order to make the measurement a practical, yet reliable, procedure.

Reliability in various single-rater and two-rater situations for the Ankle Goniometer has already been established in the previous Chapter. All that remained was to establish whether different raters, without using force gauges, would repeatedly produce consistent results that can be comparable, thus establishing reliability of this tool that could be inferred to a larger population of raters.

This has been clearly achieved, as with an ICC (2,1) >0.9 the results are unambiguous. This high reliability is a result of the various features embedded into the design of the Ankle Goniometer, which reduce movement of the device during the measurement procedure itself, the holding of the heel in the assumed position and possibly also because the forefoot has been completely eliminated from the equation, since midtarsal joint dorsiflexion could be a significant component of induced errors.

11.5 Conclusion

- The Ankle Goniometer is a reliable device for measuring ankle dorsiflexion even by multiple raters of varying experience when the foot is dorsiflexed to its end of range of motion.

Chapter 12

Summative Discussion

12.0 Summative Discussion

This thesis set out to investigate, using various scientific methods, the important clinical issue of measuring ankle dorsiflexion. One of the principal aims was, indeed, to attempt to rectify an anomalous situation in which today's clinicians and researchers are faced with: that of having to utilise unreliable methods for quantifying ankle dorsiflexion notwithstanding the fact that nowadays technology is so highly advanced.

This thesis produced specific findings from which various important points were extracted, which conclusions should affect the way that clinicians/researchers examine ankle dorsiflexion and from which an Ankle Goniometer was devised.

It has been demonstrated that the unreliability of traditional goniometric measurements is well documented. New scientific papers in this respect keep being published as various authors tackle this problem from various angles. At the time of writing this thesis, the latest published paper, unlike Pierrynowsky et al. (1996), has shown that investigator experience does not increase reliability when this technique is used to measure ankle dorsiflexion (Kim et al. 2011). This is indeed an important revelation, as rater experience has always been a standard upon which this type of investigation was based. This paper has shown that a rater with little experience will produce similarly-unreliable results as an experienced rater. These conclusions add to the evidence base that this important field of clinical examination is still a grey area and that further study is required.

Two important questions invariably arise out of this bleak scenario regarding unreliability of goniometric measurements:

1. Where does this leave the plethora of research studies, involving ankle dorsiflexion measurement as an outcome measure, that have been, and are still being, performed throughout the scientific community? How dependable are the results, especially now that it is confirmed that rater experience does not increase reliability?

2. What about the important surgical and clinical decisions that are taken based on this measurement? Is this, perhaps, one of the reasons why, following Achilles Tendon lengthening, an apropulsive gait is one of the quoted side-effects? Could it be that this may result from the

unreliability of the measurements themselves, which could indicate that a person has a much more serious equinus condition, that what s/he in fact has, or vice versa?

Indeed, this unreliability of ankle dorsiflexion measurement has been a source of research over the years, with various research groups addressing various aspects of this problem and coming up with different designs of ankle goniometers (Chapters 3). As an example, at the time of writing this discussion, a new device to measure ankle joint range of motion has been published (Kobayashi et al. 2011). Some of these devices indeed would not be suitable for regular clinical use due to their cumbersome and complicated nature.

In order for the different lacunae to be addressed, various stages during the preparation of this thesis were designed. This enabled the analysis and synthesis of information necessary to make ankle dorsiflexion measurement as reliable as possible. Each section of this thesis was thus devised to address specific research questions which arose out of the literature and systematic reviews (Chapters 2 and 3).

From the onset, it was clear that the multi-segmental nature of the human foot was a prime causative factor that contributed to this unreliability. The results of the systematic review (Chapter 3) identified the pathway which this thesis had to follow, i.e.:

- Differentiate between ankle and foot dorsiflexion
- Analyse the large number of devices designed specifically to measure ankle (or foot?) dorsiflexion that have been presented in literature.
- Investigate how foot posture can affect the maximum ankle dorsiflexion angle.
- Investigate whether the amount of applied force actually affects the maximum ankle dorsiflexion angle.
- Explore how foot segment kinematics may also affect ankle dorsiflexion results
- Reliability testing of ankle goniometers scored poorly on quality controls, with devices giving the same results on small, healthy populations of subjects. Thus any new device had to be properly validated and reliability established, learning from the omissions of other research.

At the end of the systematic review, it was even suggested that a foot-plate be utilised, based on the fact that the majority of authors investigating foot dorsiflexion were using such plates. It later transpired, however, that this could contribute to produce erroneous results, as the forefoot should be eliminated from the equation due to midtarsal joint dorsiflexion.

The above points were then investigated independently, with results revealing interesting outcomes that contributed to make ankle dorsiflexion measurement a more reliable procedure, as has been proven in the various chapters of this thesis.

12.1 Summary of Results of various studies performed throughout this thesis

Foot Posture: It has been demonstrated that foot posture has a profound effect on the maximum ankle angle. A study carried out on kinematics of passive dorsiflexion in adults (Chapter 6) has confirmed two earlier studies that utilised much more rudimentary methods (Tiberio et al. 1989; Woodburn 1991). These studies reported an increase of 10^{o} when the foot is held in the pronated posture; likewise the trial (chapter 6) found a difference of 8.27^{o} between the pronated and supinated postures.

In conformity with the study by Woodburn (1991), this trial found no clinical difference between the neutral and supinated postures. Although there is a statistically significant difference, it has been concluded that 2.5^{o} would not affect any clinical decisions, rendering these as clinically unimportant. Thus adopting a supinated posture for measuring ankle dorsiflexion would be much simpler for those practitioners who do not have the required expertise in holding the foot at subtalar joint neutral position. Even the 'experts' would benefit from holding the foot at this position, as it has been shown that "expertise" does not increase reliability in the traditional goniometric methods.

In contrast, foot posture does not make any difference when assessing adolescents' feet, implying that any posture can be adopted for this measurement (Chapter 7). This may have been due to the highly flexible nature of adolescents' feet investigated. Certainly investigating a much larger population would provide more normative and more reliable data in this population.

Forefoot to hindfoot angle: Another important consideration is that there is always more forefoot than hindfoot movement, i.e. the forefoot travels through a greater angle than the hindfoot. This is confirmed by the forefoot to hindfoot angle, which increases with the application of a force at the metatarsophalangeal joint area. This means that there is sagittal plane movement at the midtarsal joint, disputing the traditional Rootian Theory that “locking the midtarsal joint” would eliminate forefoot movement.

Moment applied: During this thesis, it has been hypothesised that the amount of force applied should not be a critical factor determining the resultant maximum ankle dorsiflexion angle since this angle is dependent on the range of motion available, which in turn is dependable on the stretching characteristics of the calf muscle-tendon unit and the osseous structure of the ankle joint itself. It became clearly evident during reliability testing of the Ankle Goniometer that, keeping a constant moment makes inter-rater reliability testing much simpler especially when multiple raters are performing the assessment. However, controlling for moment makes this measurement technique clinically impractical as few clinicians have a force gauge handy in their domiciliary bag.

Passive calf muscle tendon unit stretching: Results show that, in the supinated position, there is no measureable increase in the maximum ankle dorsiflexion angle due to stretching of the calf MTU (Chapter 8). There was, however, one subject whose maximum ankle increased by 2.88^{o} with every stretch at neutral position. This evidence continues to build on the theory that maximum ankle angle measurement should, in fact, be conducted at a supinated posture, as opposed to the traditionally-advised neutral position.

Reliability of measurement: It has been proven, utilising both a motion capture system (Chapter 6) and the Ankle Goniometer (Chapters 10 and 11) that reliable results can be obtained using an end of range of motion technique with the foot held in a slightly supinated posture.

Implications for the Management of Professional and Patient Knowledge

The findings from the various research carried out during this project, and evidence from existing literature, have significant implications for both clinical practice and research. Important issues have been identified and investigated, some ‘traditionally accepted’ theories, like the midtarsal-joint locking mechanism, have been disputed and shown to be erroneous. Certainly, following scientific findings, it is the responsibility of the investigator to disseminate the relevant findings, for example in peer-reviewed journals and conferences, in order to ensure that correct clinical and research techniques are utilised during investigations of passive ankle dorsiflexion. It has been demonstrated, through literature, that current methods of measuring ankle dorsiflexion are highly unreliable, thus their results cannot be responsibly used to diagnose or treat a patient or as an outcome measure during scientific investigation. However, adopting the correct foot posture and the right technique and utilising a validated instrument such as the Ankle Goniometer, it is now possible to reliably measure passive dorsiflexion.

Thus the implications for clinical use are clear: there should be discontinuity of usage of the 'normal' clinical goniometer and an Ankle Goniometer should be adopted.

12.2 Limitations

The present work has some limitations that should be acknowledged.

All trials would benefit from a large number of participants, however this is not always possible due to various technical, human and financial difficulties. The trials performed during this project, except for those that investigated validity and reliability of the Ankle Goniometer, would ideally have required a power calculation to establish the number of participants necessary. This, however, was not possible because there is no baseline data available. It is hoped that results from this work will inform power calculations for future studies. It was not possible to increase the number of participants in both adult and adolescent studies. Notwithstanding this, it is common practice, when performing biomechanical trials, to have small sample sizes, as can be attested by a great number of published papers. Although it is certain that a greater sample size would have provided stronger conclusions, the results and conclusions throughout this thesis are supported by two previous studies which reported similar results, where the maximum foot dorsiflexion angle is concerned.

The adolescent study would have benefitted from some male participants; although various young gentlemen promised to attend, they did not turn up for the actual data collection.

Chapter 13

Conclusions

The main objective of this research was to study passive ankle joint complex dorsiflexion in order to produce a reliable ankle dorsiflexion measuring device, which to this investigator's knowledge, has never been done to date using sophisticated, motion analysis equipment. Various important factors that could impact this important clinical procedure, have been identified and investigated.

Following the systematic review and various trials carried out during this project, it can be concluded that:

- Ankle equinus, or limited ankle dorsiflexion, is an important clinical condition that needs to be investigated and possibly managed
- Traditional methods of measuring ankle dorsiflexion using a goniometer are highly unreliable, and should not be thought in schools or textbooks as no amount of training can make these more reliable.
- Ankle joint dorsiflexion measurement should be performed with the subject lying prone or supine.
- When placing the foot at subtalar joint neutral position, there is no 'locking' of the midtarsal joint, at least during passive dorsiflexion, and when the foot is dorsiflexed by applying a moment to the metatarsophalangeal joint, there is always sagittal plane movement in the midtarsal joint since the forefoot to hindfoot angle increases with the application of this moment. Conversely, the forefoot also travels through a larger angle than the hindfoot.
- Foot posture – i.e. placing the foot at subtalar joint neutral, supinated or pronated position – always has the most profound effect on the maximum foot dorsiflexion angle. The greatest angular difference of 8^{o} lies between the pronated and supinated

postures. Although there is a statistically significant difference of 2.49^o between the neutral and supinated posture, this is clinically insignificant and will certainly not affect clinical decisions taken when treating a patient.

- For various reasons, in adults, it is recommended to hold the foot in a slightly supinated posture and not as traditionally recommended at subtalar joint neutral position. These reasons include:
    - Ease of establishing required posture: it is much easier for the rater to hold the foot in a supinated posture than at a neutral position
    - There is no clinical difference between the two postures
    - There was no stretching of the calf muscle tendon unit in all subjects in the supinated posture, while there may be the possibility of stretching at neutral position (one subject did in fact stretch by 2.88^o).
- There is no stretching of the calf muscle tendon unit when passively dorsiflexing the foot at a supinated position.
- There is no need to control moment applied to the forefoot when dorsiflexing the foot, provided that the foot is dorsiflexed maximally to the end of its motion.
- An Ankle Goniometer should have the following design features:
    - It should enable itself to be held steadily without moving during the measurement process
    - It should be anchored securely; in the lower limb this appears to be the anterior part of the tibia
    - It should enable the hindfoot to be held securely
    - A footplate should not be used; rather a ‘heel plate’ should be employed.

    - Should be able to be adjusted wherever necessary in order to align the instrument as required by the rater
    - The axis of motion should parallel the ankle axis, i.e. in line with the malleolus
    - The goniometer should be able to hold the foot in the desired posture
    - The readout should be clearly visible
- When assessing maximum ankle dorsiflexion, the Ankle Goniometer provides similar output data as an optoelectronic motion capture system, however at a much cheaper cost, which should make it more readily available to clinics and research. This makes it a very valid instrument for measuring ankle dorsiflexion
- A properly designed and utilised Ankle goniometer is highly reliable between the same rater and two or more raters.

Chapter 14

Recommendations and Directions for Further Study

The following recommendations are based on the findings of this thesis. It is hoped that these recommendations are helpful both to practitioners and researchers alike, in order to improve clinical practices and research validity, respectively.

Recommendation for performing maximum ankle dorsiflexion angle measurement

- A normal clinical goniometer should never be used as there is overwhelming evidence that it is highly unreliable. Experience does not increase reliability (Kim et al. 2011).
- Examination should be performed supine or prone as sitting affects the maximum ankle angle (Thoms and Rome 1997).
- If subtalar joint neutral position or a supinated position is adopted for this measurement technique, the amount of force applied does not need to be controlled (Chapter 8).
- There is no resultant stretching of the calf muscles when performing short repetitive passive dorsiflexion movements at the supinated posture, such as required during multiple measurements of ankle dorsiflexion.
- There is little clinical difference of 2.49^{o} between the maximum angle measured with the foot at neutral and supinated posture. This angle is often unmeasureable using a normal goniometer. Thus it is recommended that a supinated posture be adopted (Chapter 6).
- In adolescents, foot posture may not be taken into consideration as there are no significant differences between the two postures due to the high flexibility of young feet (Chapter 7). However, caution is advised as we have not had, unfortunately, the opportunity to investigate the effect of foot posture on maximum ankle angle in adolescents with non-flexible feet.
- An ankle goniometer should only measure hindfoot movement and the forefoot should not be included in the examination procedure except as a lever to which a moment is applied. When the goniometer spans across hindfoot and forefoot (such as the traditional goniometer or those devices employing a plantar foot plate), a summation of hindfoot and forefoot angles is being measured.
- It has been demonstrated that an Ankle Goniometer with the design criteria as outlined in Chapter 9, is a reliable clinical tool that can be used by multiple raters even when moment is not controlled, thus making it easier for this device to be employed in pre- and post-intervention procedures and for comparative reasons between practitioners.

Recommendations for further study:

There arises a need for re-assessing research done, in which ankle dorsiflexion measurement is a main outcome measurement, to decide how relevant the results of such research remain relevant following the important revelations on unreliability that arose out of this thesis.

Trials should be replicated with more participants.

Now that a reliable Ankle Goniometer is available, ankle dorsiflexion should be investigated in specific patient populations, such as diabetics and those suffering from rheumatoid arthritis, since the effect of ankle equinus on forefoot pressure is well documented. However, once again, how valid are these results?

Although ankle dorsiflexion measurement in neurologically-impaired patients was outside the scope of this thesis, it is recognized that this area is an extremely important aspect of clinical practice to which the Ankle Goniometer may provide a significant contribution. Further study is in this area is certainly indicated.

The Ankle Goniometer could also be an important measurement instrument for the prescription of Ankle Foot Orthoses (AFOs). Further study in this area is warranted.

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Appendix 1

Ethical Approvals and Participant Information Sheets

Trial:

Sagittal Plane Kinematics of passive ankle joint complex dorsiflexion in healthy adults

STAFFORDSHIRE UNIVERSITY

Title of project: Determining the validity and reliability of a specifically-designed Ankle Goniometer for the measurement of ankle joint complex dorsiflexion.
Name of researcher(s): _________ Nachiappan Chockalingam, Alfred Gatt, Roozbeh Naemi, Helen Branthwaite, Thierry Chevalier___
Date: _______ 30 August 09_____________________________________

		YES	NO	N/A
1	Will you describe the main procedures to participants in advance, so that they are informed about what to expect?	X		
2	Will you tell participants that their participation is voluntary?	X		
3	Will you obtain written consent for participation?	X		
4	If the research is observational, will you ask participants for their consent to being observed?	X		
5	Will you tell participants that they may withdraw from the research at any time and for any reason?	X		
6	With questionnaires and interviews, will you give participants the option of omitting questions they do not want to answer?	X		
7	Will you tell participants that their data will be treated with full confidentiality and that, if published, it will not be identifiable as theirs?	X		
8	Will you give participants the opportunity to be debriefed i.e. to find out more about the study and its results?	X		

If you have ticked **No** to any of Q1-8, you should complete and submit the Full Ethics Approval Form

		YES	NO	N/A
9	Will your project deliberately mislead participants in any way?		X	
10	Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?		X	
11	Is the nature of the research such that contentious or sensitive issues might be involved?		X	

If you have ticked **Yes** to 9, 10 or 11 you should complete the Full Ethics Approval Form. In relation to question10 this should include details of what you will tell participants to do if they should experience any problems (e.g. who they can contact for help). You may also need to consider risk assessment issues.

			YES	NO	N/A
12	Does your project involve work with animals?			X	
13	Do participants fall into any of the following special groups? **Note that you may also need to obtain satisfactory CRB clearance (or equivalent for overseas students).**	Children (under 18 years of age)		X	
		People with communication or learning difficulties		X	
		Patients		X	
		People in custody		X	
		People who could be regarded as vulnerable			

		People engaged in illegal activities (e.g. drug-taking)		X X	
14	Does the project involve external funding or external collaboration where the funding body or external collaborative partner requires the University to provide evidence that the project had been subject to ethical scrutiny?			X	

If you have ticked **Yes** to 12, 13 or 14 you should complete and submit the Full Ethics Approval Form
There is an obligation to bring to the attention of the Faculty Ethics Committee any issues with ethical implications not clearly covered by the above checklist.

If you have ticked **Yes** to 13 and your participants are **patients** you should follow the Guidelines for Ethical Approval of NHS Projects

PLEASE **PROVIDE THE DETAILS REQUIRED** IN SUPPORT OF YOUR APPLICATION. THEN SIGN THE FORM.

Please tick

I consider that this project has no significant ethical implications requiring a full ethics submission to the Faculty Ethics Panel	X
Give a brief description of participants and procedure (methods, tests used etc) in up to 150 words. Goniometric measurement of ankle joint dorsiflexion is performed using a goniometer (an angle measuring device - a protractor with 2 moving arms). One arm of this goniometer is placed along the lateral side of the lower leg and the other, horizontal, arm is placed along the lateral border of the foot. The foot is then put into subtalar joint neutral position, thus enabling movement to occur only through the ankle joint, and an upward force is applied on the forefoot. This procedure creates a need for coordinating many actions at the same time, such as ensuring that the arms of the goniometer are placed exactly, that they do not move, that the midtarsal joint remains locked while the angle is read. To further complicate matters, this procedure is performed with the knees straight and flexed. It is clear that there are various things that can go wrong (Rome, 1996), so much so that research in this area has criticized this measurement technique, claiming that it is *unreliable* and *clinically unacceptable* (Van Gheluwe, Kirby, Roosen and Phillips, 2002). Various other authors have cast significant doubts as to whether the current method of measuring ankle joint dorsiflexion is reliable and valid. In fact, there appears to be consensus that this is not. With this in mind, an *Ankle Goniometer* was designed to overcome the various issues. The main aim of this project is to determine whether this specifically-designed Ankle Goniometer, which differs from any other such instrument in use nowadays, is a valid and reliable instrument that can be used for clinical and research use. This observational study will involve 15 – 20 subjects from both genders. After making some anthropometric measurements and joint range of movement measurements, the subjects will be required to walk on the lab surface with reflective markers placed in predetermined anatomical landmarks. Kinematic and Kinetic (movement and force) analysis will be conducted using a opto-electronic motion analysis system (Vicon), a set of strain gauge based force plates (AMTI Inc).	

Signed...
(*Lead Researcher*) Print Name... Nachiappan Chockalingam.... ... ... Date...30 August 2009

PLEASE FORWARD A COPY OF THIS FORM TO THE CHAIR OF YOUR FACULTY ETHICS PANEL

Form Received by Chair of Faculty Ethics Panel

Signed... ... ... Print Name DAVID CLARK-CARTER ... ... Date... 1.9.2009
(*Chair, Faculty Ethics Panel*)

STAFFORDSHIRE UNIVERSITY

Information Sheet

Study Title: **Sagittal Plane Kinematics of Passive Ankle Joint Dorsiflexion in Healthy Adults.**

Please read this information carefully. If there is anything that is not clear from the information provided please do not hesitate to ask. After you have read the information you can decide if you wish to take part in this study.

Why are we doing this study?

As a part of an ongoing research program we have developed a new type of joint angle measuring device. We are in the process of refining and validating this method. Once this method is validated, this can be employed both in clinical assessment and further research.

We propose to conduct some non-invasive movement analysis as a part of this validation process. The use of kinematic and kinetic analysis (movement and forces) will assist in gaining some baseline data

What is involved in the study?

A few basic questions such as age and date of birth will be asked and we will measure your height, weight and limb length to help our analysis. We will also measure some joint angles. We will then place small spherical reflective balls (markers) on predetermined landmarks on your body. These markers will be secured with double sided adhesive tape. You are required to wear tight clothing such as cycling shorts in case of men and cycling shorts and sports bra in case of women to avoid interference with these markers. Movement of these markers will be tracked by high speed cameras mounted on the lab walls or on the tripods.

Your foot will be passively flexed a number of times in order to determine whether changing the posture of the foot will affect the maximum angle, which is important information that will be used in order to investigate a clinical examination procedure. This procedure will be repeated a few times until we record a set of error free data.

What are the risks?

The testing procedures are non invasive and totally safe. There are no known risks involved.

What will happen to the results?

Your personal details such as name and age will be kept confidential and will not be shared with anyone at anytime. The data will be looked at as a group of people and patterns will be identified.
You will not have the results of the study and will not benefit from taking part. The data will be used only for research purposes.

Do I have to take part?

It is up to you to decide if you would like to take part or not. If you do, you will be given this information sheet and be asked to sign a consent form. You can still stop taking part at any time without giving a reason.

Where can I get further information from?

If you have any questions about this study you can contact the principal investigator on the address below:

Name: Professor Nachi Chockalingam
Address: Faculty of Health
Staffordshire University
Leek Road
Stoke on Trent ST4 2DF

Telephone: 01782 295853
Email: n.chockalingam@staffs.ac.uk

Consent form

Subject identification number:

Study Title: Sagittal Plane Kinematics of Passive Ankle Joint Dorsiflexion in Healthy Adults.

Name of Researcher: Nachiappan Chockalingam, Alfred Gatt, Roozbeh Naemi, Helen Branthwaite, Thierry Chevalier

Please initial box

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.	
3. I agree to take part in the above study	

....	....	....
Name of Subject	Signature	Date
....	....	....
Name of Person taking consent (if different from researcher)	Signature	Date
....	....	....
Researcher	Signature	Date

Trial:

Investigating sagittal segment motion in Adolescents during passive ankle joint complex dorsiflexion

UNIVERSITY OF MALTA

UNIVERSITY RESEARCH ETHICS COMMITTEE

Check list to be included with UREC proposal form

Please make sure to tick **ALL** the items. Incomplete forms will not be accepted.

		YES	NOT APP.
1a.	Recruitment letter / Information sheet for subjects, in English	✓	
1b.	Recruitment letter / Information sheet for subjects, in Maltese	✓	
2a	Consent form, in English, signed by supervisor, and including your contact details	✓	
2b	Consent form, in Maltese, signed by supervisor, and including your contact details	✓	
3a	In the case of children or other vulnerable groups, consent forms for parents/ guardians, in English	✓	
3b	In the case of children or other vulnerable groups, consent forms for parents/ guardians, in Maltese	✓	
4a	Tests, questionnaires, interview or focus group questions, etc, in English		✓
4b	Tests, questionnaires, interview or focus group questions, etc, in Maltese		✓
5a	Other institutional approval *for access to subjects*: Health Division, Directorate for Quality and Standards in Education, Department of Public Health, Curia...	✓	
5b	Other institutional approval *for access to data*: Registrar, Data Protection Officer Health Division/Hospital, Directorate for Quality and Standards in Education, Department of Public Health...	✓	
5c	Approval from person *directly responsible for subjects*: Medical Consultants, Nursing Officers, Head of School...		✓

Received by Faculty office on	24.01.11
Discussed by Faculty Research Ethics Committee on	28.02.11
Discussed by university Research Ethics Committee on	6.4.11

UNIVERSITY OF MALTA

Request for Approval of Human Subjects Research

Please type. Handwritten forms will not be accepted

You may follow this format on separate sheets or use additional pages if necessary.

FROM: *(name, address for correspondence)* *Alfred Gatt* *69, "Ir-Ragg", Triq il-Port Ruman* *Marsaxlokk* *MXK 1535*	PROJECT TITLE: **Sagittal Plane Kinematic analysis of passive ankle joint complex dorsiflexion in adolescents**
TELEPHONE: 23401157/99497886	
E-MAIL Alfred.gatt@um.edu.mt	
COURSE AND YEAR: PhD in Clinical Biomechanics, Staffordshire University: A Biomechanical Investigation of Passive Ankle Joint Complex Dorsiflexion 2nd year	
DURATION OF ENTIRE PROJECT: from _March2011___ to _December 2011______	FACULTY SUPERVISOR'S NAME: *Professor Nachiappan Chockalingam* *Faculty of Health* *Staffordshire University,* *Stoke on Trent* *England*

ANTICIPATED FUNDING SOURCE:

(include grant or contract number if known)

SELF

1. Please give a brief summary of the purpose of the research, in non-technical language.

Goniometric measurement of ankle joint dorsiflexion is performed using a goniometer (an angle measuring device - a protractor with 2 moving arms). One arm of this goniometer is placed along the lateral side of the lower leg and the other, horizontal, arm is placed along the lateral border of the foot. The foot is then put into subtalar joint neutral position, thus (it is claimed by Root et al, 1977), enabling movement to occur only through the ankle joint, and an upward force is applied on the forefoot. This procedure creates a need for coordinating many actions at the same time, such as ensuring that the arms of the goniometer are placed exactly, that they do not move, that the midtarsal joint remains locked while the angle is read. To further complicate matters, this procedure is performed with the knees straight and flexed. It is clear that there are various things that can go wrong (Rome, 1996), so much so that research in this area has criticized this measurement technique, claiming that it is *unreliable* and *clinically unacceptable* (Van Gheluwe, Kirby, Roosen and Phillips, 2002). Various other authors have cast significant doubts as to whether the current method of measuring ankle joint dorsiflexion is reliable and valid. In fact, there appears to be consensus that this is not.

As part of a larger PhD project, this investigator is designing a goniometer to assess ankle joint function in a valid and reliable manner. As an essential aspect of research relating to this, the foot movements that occur when this measurement is taken was done in a biomechanics laboratory at Staffordshire University, utilising a highly-accurate system known as a Vicon 3d motion capture system. This is a non-invasive, 8-camera system that uses infra-red to measure and track motion. This research has revealed a number of inconsistencies that cast doubt upon the reliability of the whole measurement technique and some fundamental issues regarding podiatric biomechanical theory; namely the mid-tarsal joint mechanism and its relationship to foot posture. It has been shown that, unlike traditionalistic theorists of Rootian Theory have pointed out (Root et al, 1977), placing the foot at subtalar joint neutral position does not lock the midtarsal joint to completely eliminate movement extraneous to the ankle and that the hindfoot to forefoot angle always increases when a dorsiflexing force is applied to the forefoot. These finding have been written in a paper which has been submitted for publication in a peer-reviewed journal.

It is now necessary to repeat this research with adolescents because their feet have more flexibility, thus there is the possibility that during the clinical measurement of ankle dorsiflexion, foot segment motion is much greater than that in adults, which would imply that most currently-available measurement methods are quite unsuitable.

2**.** Give details of procedures that relate to subjects' participation
(a) How are subjects recruited? What inducement is offered? *(Append copy of letter or advertisement or poster, if any.)*

Subjects will be recruited from the International Sports Club. The Head of this club has been contacted and permission obtained (relevant letter attached). 20 adolescent subjects will be invited to participate and an information letter in Maltese and English together with a Consent Form will be provided to their parents. The data collection process will be explained to the children as well. Parental informed consent will be essential for subject participation as they will all be minors.

No inducements will be offered.

(b) Salient characteristics of subjects—number who will participate, age range, sex, institutional affiliation, other special criteria: 20 healthy subjects with no systemic disease will be recruited, with the following Inclusion criteria: Age group: 12 to 16 year old No significant foot deformities No history of foot surgery
(c) Describe how permission has been obtained from cooperating institution(s)—school, hospital, organization, prison, or other relevant organization. *(Append letters.)* Is the approval of another Research Ethics Committee required? Permission from Professor Kenneth Camilleri, Head of Engineering, who is responsible for the running of the Biomechanics Laboratory at the Engineering Department Mr Albert Chun, Head of the International Sports Club, where subject recruitment will take place No approval of another Research Ethics Committee is required
(d) What do subjects do, or what is done to them, or what information is gathered? (Append copies of instructions or tests or questionnaires.) How many times will observations, tests, etc., be conducted? How long will their participation take? A number of reflective markers will be attached to the participants' lower extremities using double sided tape as per established protocol for the Oxford Foot Model (Carson et al., 2001). A standing calibration of the cameras will be performed by the operator, then the participant will be asked to sit on a couch with relaxed feet. The rater will dorsiflex the foot ten times in 3 postures; neutral, pronated and supinated. The order of foot postures will be determined randomly. During this time, movement will be captured non-invasively with a six-camera Vicon system. This system builds up a computerized model of the lower extremity and the movements performed, so that the required inter-segment analysis can take place. At no time would an actual picture or video of the participant be taken. Participation time should not exceed 1 hour.

(e) Which of the following data categories are collected?

Data that reveals – race or ethnic origin YES / NO

political opinions YES / NO

religious or philosophical beliefs YES / NO

trade union memberships YES / NO

health YES / NO

sex life YES / NO

genetic information YES / NO

3. How do you explain the research to subjects and obtain their informed consent to participate? (If in writing, append a copy of consent form.) If subjects are minors, mentally infirm, or otherwise not legally competent to consent to participation, how is their assent obtained and from whom is proxy consent obtained? How is it made clear to subjects that they can quit the study at any time?

The study, including the aims and methodology, will initially be explained verbally to both the prospective participants and their parents. An information sheet and a Consent Form for Minors in the language of choice (Maltese or English) will be presented and parents/adolescents left on their own to discuss the matter in private. Consent will be obtained from both the minor participants and their parents/legal guardians. Even if parents do consent for participation, if the adolescent does not agree s/he will not be included.

Both the information sheets and the Consent Form clearly state that the participant can quit the study at any time without giving any reasons. This would be emphasized verbally during recruitment.

The consent form will be collected after a few days when the parents and prospective participants would have had enough time to consider any issues and come to a decision in private.

4 .Do subjects risk *any* harm—physical, psychological, legal, social—by participating in the research? Are the risks necessary? What safeguards do you take to minimize the risks?

Subjects do not risk any harm at all. All they are required to do is sit on a couch while their feet are moved in an upward motion, a method which is done daily with every podiatric patient in the clinic.

The Vicon system is totally non-invasive and it is used extensively in Biomechanical Research worldwide. It is also used in 3D graphic animation for cinema, thus its use clearly cannot harm the subjects.

A risk assessment of the laboratory will be made prior to data collection to ensure that there are no potential hazards, such as loose wires on the floor, on which subjects can trip.

5. Are subjects deliberately deceived in *any* way? If so, what is the nature of the deception? Is it likely to be significant to subjects? Is there any other way to conduct the research that would not involve deception, and, if so, why have you not chosen that alternative? What explanation for the deception do you give to subjects following their participation?

Subjects will not be deceived in any way.

6. How will participation in this research benefit subjects? If subjects will be "debriefed" or receive information about the research project following its conclusion, how do you ensure the educational value of the process? *(Include copies of any debriefing or educational materials)*

Participants will not benefit directly from this research, which has been made clear in the information sheet.

However, they will benefit indirectly because nowadays, even though ankle dorsiflexion measurement is used to diagnose certain ankle conditions, there is still a lot of uncertainty and procedures are likely to produce wrong results, thus providing the wrong diagnosis which would, naturally, affect treatment.

The educational aspect of this whole research would then be aimed at the practitioner through scientific papers and conferences, from which ultimately it would be the patient who benefits

TERMS AND CONDITIONS FOR APPROVAL IN TERMS OF THE DATA PROTECTION ACT

Personal data shall only be collected and processed for the specific research purpose.
The data shall be adequate, relevant and not excessive in relation to the processing purpose.
All reasonable measures shall be taken to ensure the correctness of personal data.
Personal data shall not be disclosed to third parties and may only be required by the University or the supervisor for verification purposes. All necessary measures shall be implemented to ensure confidentiality and, where possible, data shall be anonymised.

Unless otherwise authorised by the University Research Ethics Committee, the researcher shall obtain the consent from the data subject (respondent) and provide him with the following information: The researcher's identity and habitual residence, the purpose of processing and the recipients to whom personal data may be disclosed. The data subject shall also be informed about his rights to access, rectify, and where applicable erase the data concerning him.

I, the undersigned hereby undertake to abide by the terms and conditions for approval as attached to this application.

I, the undersigned, also give my consent to the University of Malta's Research Ethics Committee to process my personal data for the purpose of evaluating my request and other matters related to this application. I also understand that, I can request in writing a copy of my personal information. I shall also request rectification, blocking or erasure of such personal data that has not been processed in accordance with the Act.

Signature:

APPLICANT'S SIGNATURE: *I hereby declare that I will not start my research on human subjects before UREC approval* DATE 21/01/2011	FACULTY SUPERVISOR'S SIGNATURE I have reviewed this completed application and I am satisfied with the adequacy of the proposed research design and the measures proposed for the protection of human subjects. Prof N. Chockalingam DATE 12/01/2011

MAKE SURE YOU ATTACH THE FOLLOWING TO YOUR APPLICATION: .

**** Recruitment letter, poster * Other institutional approval * Subject instructions***

**** Tests or questionnaires * Information sheets or debriefing materials***

**** Written consent form (or script) *Other***

Return the completed application to your faculty Research Ethics Committee

To be completed by Faculty Research Ethics Committee

We have examined the above proposal and advise

Acceptance **Refusal** **Conditional acceptance**

For the following reason/s:

Signature

Date 18/3/11

To be completed by University Research Ethics Committee

We have examined the above proposal and grant

Acceptance **Refusal** **Conditional acceptance**

For the following reason/s:

Signature

Date 18/5/11

Information Sheet

Study Title: **Sagittal Plane kinematic analysis of Passive Ankle Joint Complex Dorsiflexion in Healthy Adolescents**

Dear Parent/Guardian,

Please read this information carefully. If there is anything that is not clear from the information provided please do not hesitate to ask. After you have read the information you can decide if you wish to give permission to your son/daughter to take part in this study.

Why are we doing this study?

As part of the clinical examination of the foot, it is necessary to measure the movement of the foot at the ankle joint. We know that present methods are very unreliable and may produce misleading results. Consequently, we are designing a new kind of Ankle Goniometer (a device for measuring ankle joint movement). Before doing this, however, we need to investigate what happens to the various foot segments as this clinical investigation is carried out.
We would like to investigate how adolescents' feet function during clinical examination by measuring the amount of movement of the ankles and other foot segments.

What is involved in the study?

Your child's foot will be examined for the amount of upward movement using a Vicon 6-camera system. These cameras use infra-red light to accurately measure distances from the camera to reflective markers attached to the foot and leg using double-sided tape. The participant will be seated on a couch and the movement produced as the foot is moved upwards will be captured by the camera system. This experiment has already been carried out with adults and thus it is not the first time that this procedure will be carried out. The examination will be performed by a qualified, experienced podiatrist and should last for only than a few minutes. Naturally, you are invited to attend for the session in which your child's foot will be assessed.

What are the risks?

The testing procedures are non invasive and totally safe. There are no known risks involved.

What will happen to the results?

Each participant will be assigned a code number which will be the only method of identification. Personal details such as name and age will be kept confidential and will not be shared with anyone at any time. The data will be looked at as a group of people. At no time will participants' name or personal details be recorded or kept on file. If the results of these studies are published, your child's name will never be disclosed and the information given will be on a collective basis. After the study, all data of a personal nature will be destroyed.

You will not have the results of the study and will not benefit from taking part. The data will be used only for research purposes. However, it is hoped that a lot of patients will benefit directly from this research.

Do I have to take part?

It is up to you to decide if you would like to allow your son/daughter to take part or not. If you do, you will be given this information sheet and will be asked to sign a consent form. You can withdraw from this study at any time you wish. Should you decide not to participate, or to stop your participation at any time, any treatment that you will be undergoing at the Podiatry department will certainly not be affected.

Where can I get further information from?

If you have any questions about this study you can contact the principal investigator or the supervisor on the addresses below:

Researcher

Name: Alfred Gatt
Address: Faculty of Health Sciences
University of Malta
Telephone: 23401153/99497886
Email: alfred.gatt@um.edu.mt

Supervisor

Name: Prof Nachi Chockalingam
Address: Faculty of Health
Staffordshire University
Leek Road
Stoke on Trent ST4 2DF
Telephone: +441782 295853
Email: n.chockalingam@staffs.ac.uk

Prof N. Chockalingam

Alfred Gatt

CONSENT FORM

STAFFORDSHIRE UNIVERSITY

Title of Project: **Sagittal Plane kinematic analysis of Passive Ankle Joint Complex Dorsiflexion in Healthy Adolescents**

The aims and details of the project have been explained to me by the researcher. I have also explained to my child what this study entails.

I know that the information collected will remain confidential and that it will be used only for scientific purposes. I also know that a written report of the study will be drawn up and that myself/my child will not be identified in any way in this report. I know that data will be password protected and will be destroyed once the study is completed. There will be no video/audio recordings. I may attend the session together with my child.

I therefore give my consent to the person responsible for the research to make the necessary observations to my child.

I am aware that I am under no obligation to do so, and that I can withdraw my consent at any moment without giving any reason.

I case of any difficulty during the study, I can contact the researcher or supervisor.

________________________ ________________ ____________________

Name of Participant Name and Signature of Parent/Guardian

Tel: no: __________________ Email:________________

________________________ ________________ ____________________

Alfred Gatt Date Signature

Researcher: 99497886/Alfred.gatt@um.edu.mt

Prof N. Chockalingam Supervisor Date

n.chockalingam@staffs.ac.uk

Trial:

Investigating Reliability of Ankle Goniometer

UNIVERSITY RESEARCH ETHICS COMMITTEE

Check list to be included with UREC proposal form

Please make sure to tick **ALL** the items. Incomplete forms will not be accepted.

		YES	NOT APP.
1a.	Recruitment letter / Information sheet for subjects, in English	✓	
1b.	Recruitment letter / Information sheet for subjects, in Maltese	✓	
2a	Consent form, in English, signed by supervisor, and including your contact details	✓	
2b	Consent form, in Maltese, signed by supervisor, and including your contact details	✓	
3a	In the case of children or other vulnerable groups, consent forms for parents/ guardians, in English		✓
3b	In the case of children or other vulnerable groups, consent forms for parents/ guardians, in Maltese		✓
4a	Tests, questionnaires, interview or focus group questions, etc, in English		✓
4b	Tests, questionnaires, interview or focus group questions, etc, in Maltese		✓
5a	Other institutional approval *for access to subjects*: Health Division, Directorate for Quality and Standards in Education, Department of Public Health, Curia...	✓	
5b	Other institutional approval *for access to data*: Registrar, Data Protection Officer Health Division/Hospital, Directorate for Quality and Standards in Education, Department of Public Health...		✓
5c	Approval from person *directly responsible for subjects*: Medical Consultants, Nursing Officers, Head of School...		✓

Received by Faculty office on	01.10.09
Discussed by Faculty Research Ethics Committee on	06.10.09
Discussed by university Research Ethics Committee on	6/11/09

UNIVERSITY OF MALTA

Request for Approval of Human Subjects Research

Please type. Handwritten forms will not be accepted

You may follow this format on separate sheets or use additional pages if necessary.

<table>
<tr><td>FROM: (name, address for correspondence)

Alfred Gatt
69, Ir-Ragg, Triq il-Port Ruman
Marsaxlokk MXK 1535</td><td rowspan="4">PROJECT TITLE:

Determining the reliability of a specifically-designed Ankle Goniometer for the measurement of ankle joint complex dorsiflexion</td></tr>
<tr><td>TELEPHONE: +356 21652985
+356 99497886</td></tr>
<tr><td>E-MAIL alfred.gatt@um.edu.mt</td></tr>
<tr><td>COURSE AND YEAR:
Ph.D 1st year</td></tr>
<tr><td>DURATION OF ENTIRE PROJECT:

from <u>January 2010</u> to <u>March 2009</u></td><td>FACULTY SUPERVISOR'S NAME:

Professor Nachiappan Chockalingam
Faculty of Health
Staffordshire University,
Stoke on Trent
England</td></tr>
</table>

ANTICIPATED FUNDING SOURCE:
(include grant or contract number if known) Self

1. Please give a brief summary of the purpose of the research, in non-technical language.

Goniometric measurement of ankle joint dorsiflexion is performed using a goniometer (an angle measuring device - a protractor with 2 moving arms). One arm of this goniometer is placed along the lateral side of the lower leg and the other, horizontal, arm is placed along the lateral border of the foot. The foot is then put into subtalar joint neutral position, thus enabling movement to occur only through the ankle joint, and an upward force is applied on the forefoot. This procedure creates a need for coordinating many actions at the same time, such as ensuring that the arms of the goniometer are placed exactly, that they do not move, that the midtarsal joint remains locked while the angle is read. To further complicate matters, this procedure is performed with the knees straight, then flexed. It is clear that there are various things that can go wrong (Rome, 1996), so much so that research in this area has criticized this measurement technique, claiming that it is *unreliable* and *clinically unacceptable* (Van Gheluwe, Kirby, Roosen and Phillips, 2002). Various other authors have cast significant doubts as to whether the current method of measuring ankle joint dorsiflexion is reliable and valid. In fact, there appears to be consensus that this is not.

This investigator has analyzed the podiatric method of assessing foot dorsiflexion at the ankle joint and the theory behind it appears to be sound. However, the practical aspects of measurement are causing this reliability and validity problems. Main issues involve the actual placement of the goniometer, holding the subtalar joint at neutral position and performing the test with knees extended and then flexed at the same time (Rome, 1996).

With this in mind, an ***Ankle Goniometer*** was designed to overcome the various issues.
The main aim of this project is to determine whether this specifically-designed Ankle Goniometer, which differs from any other such instrument in use nowadays, is a valid and reliable instrument that can be used for clinical and research use.

2. Give details of procedures that relate to subjects' participation
(a) How are subjects recruited? What inducement is offered? *(Append copy of letter or advertisement or poster, if any.)*

Subjects will be recruited randomly from patients attending podiatry clinics in Malta, healthy volunteers and a convenience sample from podiatry staff so as to ensure a good mix of patients and healthy participants.

No inducement will be offered, except for an explanation as to the value of this research as related to musculoskeletal problems.

(b) Salient characteristics of subjects—number who will participate, age range, sex, institutional affiliation, other special criteria:

Patients attending Podiatry Clinics and healthy volunteers will be invited to participate. They will be picked at random so as to avoid *selection bias* and *spectrum bias.* Participants' agreement to take part in the study will be the only inclusion/exclusion criteria necessary, as the *pure* angle of ankle dorsiflexion (that is, foot dorsiflexion) is to be measured, irrespective whether there is disease, limited mobility or not. Thus a good mix of subjects will be ensured.

(c) Describe how permission has been obtained from cooperating institution(s)—school, hospital, organization, prison, or other relevant organization. *(Append letters.)* Is the approval of another Research Ethics Committee required?
As data collection will be taking place at the Podiatry Department at B'Kara Civic Centre, permission from the Data Protection Officer within the Primary Health Care Department will be sought.

This research is being done with Staffordshire University, however as data collection will be performed in Malta, no other Research Ethics Committee approval should be required.

(d) What do subjects do, or what is done to them, or what information is gathered? (Append copies of instructions or tests or questionnaires.) How many times will observations, tests, etc., be conducted? How long will their participation take?

A study to determine the Reliability of the Ankle Goniometer: a repeated measures design

A repeated-measures (test-retest) design on two separate days will be utilized for this study, using a sample of 35 participants, some of whom will be healthy participants and some of whom will be patients attending a podiatry clinic.

Each participant will be asked to relax in a supine position and the ankle joint dorsiflexion measurement will be taken on the lateral aspect of the leg and foot, using the Ankle Goniometer. At the same time, a video recording of the movement will be done in order to capture the movement using a 3D motion capture system. The cameras will be aimed only at the lower limbs and at no time can the subject be identified.

Two experienced podiatric clinicians will be using the Ankle Goniometer to measure participants' ankle dorsiflexion. Each subject will be assigned a code number, then will be examined by each clinician with the same procedure outlined above.

Each reading will be taken 3 times, and an average recorded against the participant code number. The procedure will be performed with the knees extended, then flexed.

After Examiner 1 has finished with the procedure, then Examiner 2 repeats the procedure.

This whole procedure will be performed again, by each examiner, both after one hour and then on another day. This procedure will be repeated again by two more podiatrists.

Examiners will be blinded to the other's results and the recorder files the results. Each Examiner will not have access to his/hers, and the other examiners', results

Subject participation for this study should not last for more than 30 minutes during each session.

(e) Which of the following data categories are collected?

Data that reveals –	race or ethnic origin	YES / NO
	political opinions	YES / NO
	religious or philosophical beliefs	YES / NO
	trade union memberships	YES / NO
	health	YES / NO
	sex life	YES / NO
	genetic information	YES / NO

3. How do you explain the research to subjects and obtain their informed consent to participate? (If in writing, append a copy of consent form.) If subjects are minors, mentally infirm, or otherwise not legally competent to consent to participation, how is their assent obtained and from whom is proxy consent obtained? How is it made clear to subjects that they can quit the study at any time?

All subjects will be adults over 18 years of age. The research will be explained verbally to each participant and an information sheet, in Maltese and in English, will be given.

Participants will be given a code number so that they cannot be identified. Any records will be kept in the investigator's computer, which is password protected. At the end of the study, all data pertaining to participants will be erased from this computer, including any images.

Informed consent will be obtained, with the participant signing a consent form in his/her preferred language. Participants will be informed, both verbally and in writing, that they can withdraw at any time and their rights to be treated at any podiatry clinic will not be affected in any way.

4 .Do subjects risk *any* harm—physical, psychological, legal, social—by participating in the research? Are the risks necessary? What safeguards do you take to minimize the risks?

No risk whatsoever to participants, as the procedure involves merely the measurement of ankle dorsiflexion. No participant will be at risk at any time. No interventions will take place.

5. Are subjects deliberately deceived in *any* way? If so, what is the nature of the deception? Is it likely to be significant to subjects? Is there any other way to conduct the research that would not involve deception, and, if so, why have you not chosen that alternative? What explanation for the deception do you give to subjects following their participation?

Participants will not be deceived in any way.

6. How will participation in this research benefit subjects? If subjects will be "debriefed" or receive information about the research project following its conclusion, how do you ensure the educational value of the process? *(Include copies of any debriefing or educational materials)*

There will be no direct benefit to participants. However, they will benefit indirectly from this research because nowadays, even though ankle dorsiflexion measurement is used to diagnose ankle equinus, which is a potentially harmful condition, there is still a lot of uncertainty and procedures are likely to result in wrong angles. This will have the undesirable effect that patients without limited ankle dorsiflexion may be diagnosed as having equinus, while those with equinus may be diagnosed as having normal ankle motion. This would, naturally, affect treatment; i.e. patients not requiring treatment may be getting it, while those requiring it, may not be receiving treatment they need. The educational aspect of this whole research would then be aimed at the practitioner through scientific papers and conferences, from which ultimately it would be the patient who benefits.

TERMS AND CONDITIONS FOR APPROVAL IN TERMS OF THE DATA PROTECTION ACT

- Personal data shall only be collected and processed for the specific research purpose.
- The data shall be adequate, relevant and not excessive in relation to the processing purpose.
- All reasonable measures shall be taken to ensure the correctness of personal data.
- Personal data shall not be disclosed to third parties and may only be required by the University or the supervisor for verification purposes. All necessary measures shall be implemented to ensure confidentiality and, where possible, data shall be anonymised.
- Unless otherwise authorised by the University Research Ethics Committee, the researcher shall obtain the consent from the data subject (respondent) and provide him with the following information: The researcher's identity and habitual residence, the purpose of processing and the recipients to whom personal data may be disclosed. The data subject shall also be informed about his rights to access, rectify, and where applicable erase the data concerning him.

I, the undersigned hereby undertake to abide by the terms and conditions for approval as attached to this application.

I, the undersigned, also give my consent to the University of Malta's Research Ethics Committee to process my personal data for the purpose of evaluating my request and other matters related to this application. I also understand that, I can request in writing a copy of my personal information. I shall also request rectification, blocking or erasure of such personal data that has not been processed in accordance with the Act.

Signature:

<table>
<tr>
<td>APPLICANT'S SIGNATURE:
I hereby declare that I will not start my research on human subjects before UREC approval

DATE 29/9/09</td>
<td>FACULTY SUPERVISOR'S SIGNATURE
I have reviewed this completed application and I am satisfied with the adequacy of the proposed research design and the measures proposed for the protection of human subjects.

Prof N. Chockalingam

DATE 19 April 2009</td>
</tr>
</table>

MAKE SURE YOU ATTACH THE FOLLOWING TO YOUR APPLICATION: .
**** Recruitment letter, poster   * Other institutional approval   * Subject instructions***
**** Tests or questionnaires   * Information sheets or debriefing materials***
**** Written consent form (or script)   *Other***

Return the completed application to your faculty Research Ethics Committee

To be completed by Faculty Research Ethics Committee

We have examined the above proposal and advise

Acceptance ✓   **Refusal**   **Conditional acceptance**

For the following reason/s:

Signature

Date 06.10.09

To be completed by University Research Ethics Committee

We have examined the above proposal and grant

Acceptance   **Refusal**   **Conditional acceptance**

For the following reason/s:

Signature

Date 6/11/09

STAFFORDSHIRE UNIVERSITY

Information Sheet

Study Title: **Determining the reliability of a specifically-designed ankle goniometer for the measurement of ankle joint complex dorsiflexion.**

Please read this information carefully. If there is anything that is not clear from the information provided please do not hesitate to ask. After you have read the information you can decide if you wish to take part in this study.

Why are we doing this study?

As a part of an ongoing research program we have developed a new type of joint angle measuring device. We are in the process of refining and validating this method. Once this method is validated, this can be employed both in clinical assessment and further research.

We propose to conduct some non-invasive movement analysis as a part of this validation process. The use of kinematic and kinetic analysis (movement and forces) will assist in gaining some baseline data

What is involved in the study?

A few basic questions such as age and date of birth will be asked and we will measure your height, weight and limb length to help our analysis. We will also measure some joint angles. We will then place small spherical reflective balls (markers) on predetermined landmarks on your body. These markers will be secured with double sided adhesive tape. You are required to wear tight clothing such as cycling shorts in case of men and cycling shorts and sports bra in case of women to avoid interference with these markers. Movement of these markers will be tracked by high speed cameras mounted on the lab walls or on the tripods.

Your foot will be assessed by podiatrists who will measure your ankle flexion using a specifically designed Ankle Goniometer in order to assess whether they will able to obtain the same results, thus confirming that this device is reliable.

What are the risks?

The testing procedures are non invasive and totally safe. There are no known risks involved.

What will happen to the results?

Your personal details such as name and age will be kept confidential and will not be shared with anyone at anytime. The data will be looked at as a group of people and patterns will be identified.

You will not have the results of the study and will not benefit from taking part. The data will be used only for research purposes.

Do I have to take part?
It is up to you to decide if you would like to take part or not. If you do, you will be given this information sheet and be asked to sign a consent form. You can still stop taking part at any time without giving a reason.

Where can I get further information from?

If you have any questions about this study you can contact the principal investigator on the address below:

Name: Professor Nachi Chockalingam
Address: Faculty of Health
Staffordshire University
Leek Road
Stoke on Trent ST4 2DF

Telephone: 01782 295853
Email: n.chockalingam@staffs.ac.uk

Consent form

Subject identification number:

Study Title:	**Determining the reliability of a specifically-designed ankle goniometer for the measurement of ankle joint complex dorsiflexion**
Name of Researcher:	Nachiappan Chockalingam, Alfred Gatt, Roozbeh Naemi, Helen Branthwaite, Thierry ChevalierPlease initial box

I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions.

I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason.

I agree to take part in the above study

Name of Subject	Signature	Date
....	....	....
Name of Person taking consent (if different from researcher)	Signature	Date
....	....	....
Researcher	Signature	Date

Appendix 2

Results and Statistical Analysis Tables

Chapter 6: A repeated measures study to explore the effect of foot posture on Sagittal Plane Kinematics Of passive dorsiflexion of the foot In Healthy Adults

6.3.1 Maximum Foot Dorsiflexion Angle

Table 1: Mean Maximum Foot Dorsiflexion Angle Scores in the Pronated, Neutral and Supinated Postures

Subject	**Mean Maximum Foot Dorsiflexion Angle Scores (Degrees)**		
	Pronated	Neutral	Supinated
1	33.58	32.18	28.9
2	37.88	24.9	24.74
3	19.04	14.96	13.84
4	19.22	15.48	13.1
5	19.6	14.34	17.44
6	25.66	20.6	12.36
7	16.36	12.9	12.8
8	12.66	5.56	6.88
9	16.44	14.64	8.7
10	30.94	20.56	19.84
11	13.46	9.6	7.78
12	14.1	9.5	9.18
13	0.92	-4.26	-10.82
14	7.64	4.62	2.84
15	31.5	13.66	11.02
16	20.6	17.84	8.68

Table 2: Forefoot to Hindfoot Angle range of movement in the pronated, neutral and supinated postures.

Subject	Mean Forefoot to Hindfoot Range of Movement (Degrees)		
	Pronated Range	Neutral Range	Supinated Range
1	6.1	11.4	12.2
2	15.4	11.8	14.8
3	15.5	13.4	15.2
4	10.4	13.4	11.3
5	10.2	10.1	11.8
6	17.8	16.5	14.3
7	9	10.5	13.1
8	9	9.6	10.8
9	6.1	11.5	12.5
10	6.1	6	12.5
11	6.4	11.2	12
12	6.5	7.8	8.8
13	5	11.9	9.2
14	10.6	9.6	11
15	11.1	13.8	16.2
16	6	8.6	10.4

Table 3: Descriptive Statistics: Mean differences: pronated angle – neutral angle = 5.78^o; pronated–supinated = 8.27; neutral–supinated=2.49^o

Descriptive Statistics of the 16 participants		
	Mean	Std. Deviation
Pronated	19.97	9.88
Neutral	14.19	8.51
Supinated	11.70	9.03

Table 4: One way repeated Anova Results for Maximum Foot Dorsiflexion Angle

Table shows that both statistical results for this angle return a significant p-value < 0.005

Tests of Within-Subjects Effects							
Measure:MEASURE_1							
Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Position	Sphericity Assumed	576.095	2	288.048	31.644	.000	.678
	Greenhouse-Geisser	576.095	1.740	331.008	31.644	.000	.678

Post Hoc Tests

Table 5: Pairwise comparisons between the Pronated, Neutral and Supinated postures

Pairwise Comparisons						
(I) Position	(J) Position	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
Pronated	Neutral	5.783*	1.100	.000	2.818	8.747
	Supinated	8.270*	1.215	.000	4.997	11.543
Neutral	Supinated	2.487*	.852	.032	.192	4.783
Based on estimated marginal means						
*. The mean difference is significant at the .05 level.						
a. Adjustment for multiple comparisons: Bonferroni.						

Table showing significance when foot postures are compared between them. One should also note the mean difference, which amounts to 8.3^{o} between pronated and supinated, 5.8^{o} between pronated and neutral and 2.49^{o} between neutral and supinated.

Table 6: Descriptive Statistics (Angle Range of Motion) of the Hindfoot and Forefoot in the Pronated, Neutral and Supinated postures

Foot Posture	Foot	Mean	Std. Deviation	Sample Size
Pronated	Forefoot	38.244	12.4417	16
	Hind foot	26.419	6.8388	16
Neutral	Forefoot	32.675	7.4769	16
	Hind foot	21.263	6.7179	16
Supinated	Forefoot	32.875	8.6617	16
	Hind foot	20.088	4.8387	16

6.3.2 Hindfoot and Forefoot Movement

Table 7: Multiple Comparisons of angle range of motion at the pronated, neutral and supinated postures.

(I) Foot Posture	(J) Foot Posture	Mean Difference (I-J)	Std. Error	P-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Pronated	Neutral	5.362*	2.0439	.027	.492	10.233
	Supinated	5.850*	2.0439	.014	.979	10.721
Neutral	Supinated	.488	2.0439	.969	-4.383	5.358

Table showing multiple comparisons of the angle range of motion at the various foot postures. There is a significant difference between the pronated and both neutral and supinated postures and a non-significant difference between the neutral and supinated postures.

6.3.3 Forefoot to Hindfoot Angle

Table 8: Hindfoot to forefoot angles in the pronated, neutral and supinated postures.

Pairwise Comparisons						
(I) Posture	(J) Posture	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
(Pronated)	Neutral	-1.619	.746	.139	-3.627	.390
	Supinated	-2.806*	.733	.005	-4.782	-.831
(Neutral)	Supinated	-1.188	.555	.147	-2.681	.306
Based on estimated marginal means						
a. Adjustment for multiple comparisons: Bonferroni.						
*. The mean difference is significant at the .05 level.						

Table showing significance between pronated to supinated postures, but non-significance in the other foot postures

Chapter 7: A repeated measures study to explore the effect of foot posture on Sagittal Plane KinematicsOf passive dorsiflexion of the foot In Adolescents

7.3.1 Maximum Foot Dorsiflexion Angle

Table 9: Descriptive Statistics for Maximum Foot Dorsiflexion Angles at the 3 postures for the 8 participants

Descriptive Statistics		
	Mean Maximum Foot Dorsiflexion Angles (^{o})	Std. Deviation
Pronated	36.3125	7.22781
Neutral	36.9500	4.00571
Supinated	32.9875	4.88246

Table 10: Repeated Measures Anova. "Sphericity Assumed" is the statistic to take into account, although it is clear that all tests are non-significant.

Tests of Within-Subjects Effects							
	Source	Type II Sum of Squares		df	Mean Square	Sig.	Partial Eta Squared
Posture	Sphericity Assumed	72.43	2	36.218	3.237	0.70	.316
	Greenhouse-Geisser	72.43	1.583	45.764	3.237	0.86	.315

Table 11: Pairwise comparisons of the Maximum Foot Dorsiflexion Angles between the 3 postures

Pairwise Comparisons						
Measure:MEASURE_1						
					95% Confidence Interval for Difference[a]	
(I) Posture	(J) Posture	Mean Difference (I-J)	Std. Error	Sig.[a]	Lower Bound	Upper Bound
Pronated	Neutral	-.638	1.970	1.000	-6.800	5.525
	Supinated	3.325	1.752	.299	-2.154	8.804
Neutral	Supinated	3.962*	1.200	.039	.209	7.716
Based on estimated marginal means						
a. Adjustment for multiple comparisons: Bonferroni. *. The mean difference is significant at the .05 level.						

7.3.2 Forefoot to Hindfoot Angle (FFHFA)

Table 12: Forefoot to Hindfoot Range of Motion Angles in the pronated, neutral and supinated postures

FFHFA			
	ROM (degrees)	**ROM** (degrees)	**ROM** (degrees)
	Pronated	**Neutral**	**Supinated**
1	10.7	8	7.8
2	9.7	13.2	14.3
3	7.9	12.85	3.55
4	5.7	9.6	8.5
5	8.2	4.2	9.1
6	7.9	11.2	7.7
7	9.66	11.3	13.6
8	6.2	11.3	6.8

Chapter 8: The effect of uncontrolled moment and short-term, repeated passive stretching on Maximum Ankle Joint dorsiflexion angle

Table 13: Maximum Ankle Angle results for the Neutral and Supinated Postures
This table shows the successive results of 5 successive angles per participant from which it was possible to determine whether stretching had occurred

	MaxAnkle Angles (degrees)			MaxAnkle Angles (degrees)	
Subject	**Neutral**	**Supinated**	**Subject**	**Neutral**	**Supinated**
No1	8.96	7.82	**No8**	25.33	22.7
	11.22	8.41		26.62	22.17
	10.24	7.95		24.2	25.89
	9.46	6.47		26.05	24.1
	8.8	4.88		22.43	29
No2	0.73	2.86	**N9**	10.9	12.75
	3.56	3.23		10.6	10.13
	1.96	1.26		13.55	17.11
	2.02	1.77		18.2	11.54
	0.2	1.57		21.5	14.1
No3	11.9	11.82	**No10**	16.72	6.1
	13.6	14.06		18.43	10.24
	13.12	13.23		18.73	9.71
	13.42	12.44		17.78	7.86
	12.29	12.18		17.6	9.54
No4	16.91	17.56	**No11**	19.31	19.15
	14.68	19.06		21.41	20.28
	14.52	16.41		18.85	21.33
	12.5	17.28		20.56	16.88
	13.91	17.03		22.79	21.5
No5	12.56	10.09	**No12**	15.15	13.71
	15.48	10.62		21.75	11.73
	13.64	10.28		25.67	11.41
	14.64	11.87		19.98	14.5
	11.67	11.28		16.89	13.34
No6	14.87	10.37	**No13**	-3.29	-11.94
	15.77	8.17		-4.76	-12.78
	14.29	8.67		-6.04	-10.74
	16.08	8.33		-4.59	-10.79
	14.16	7.91		-2.51	-7.73

No7	6	6.89	**No14**	16.8	14.91
	5.88	9.48		13.58	13.41
	5.81	4.37		13.61	12.19
	5.47	7.39		14.49	14.33
	4.53	6.21		16.42	16.04

Table 14: Mauchly's Test of Sphericity for Neutral Posture

Mauchly's Test of Sphericity[b]							
Measure:MEASURE_1							
					Epsilon		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
MaxAngle	.097	26.601	9	.002	.565	.690	.250

Table 15: Repeated Measures ANOVA, neutral position. Greenhouse-Geisser test was taken into consideration since Mauchly's Test (above) was significant

Tests of Within-Subjects Effects							
Measure:MEASURE_1							
Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
MaxAngle	Greenhouse-Geisser	9.704	2.261	4.291	.555	.601	.041
Error(MaxAngle)	Greenhouse-Geisser	227.105	29.396	7.726			

Table 16: Mauchly's Test of Sphericity for the Supinated posture

Mauchly's Test of Sphericity[b]							
Measure:MEASURE_1							
					Epsilon		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
SupMaxAnkle Angle	.290	14.128	9	.121	.654	.834	.250

Table 17: Repeated Measures ANOVA, supinated position. Sphericity Assumed was taken in consideration since Mauchly's test (above) was non-significant

Tests of Within-Subjects Effects							
Measure:MEASURE_1							
Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
SupMaxAnkleAngle	Sphericity Assumed	7.456	4	1.864	.664	.620	.049
Error(SupMaxAnkleAngle)	Sphericity Assumed	145.940	52	2.807			

Table 18: Regression analysis of all subjects at Neutral and Supinated postures. P-value shows whether average increase is significant. Only subject no9 had a significant increase in Maximum Ankle Angle at the Neutral position (an increase of 2.88^o, significant p-value=0.011)

	Max Angle Neutral Maximum Foot Dorsiflexion Angle (^{o})/(p-value)	Max Angle Supinated Maximum Foot Dorsiflexion Angle (^{o})/(p-value)
1	-0.208 (0.589)	-0.782 (0.062)
2	-0.260 (0.606)	-0.404 (0.149)
3	0.060 (0.837)	-0.090 (0.799)
4	-0.818 (0.096)	-0.284 (0.441)
5	-0.262 (0.661)	0.363 (0.121)
6	-0.111 (0.743)	0.257 (0.392)
7	-0.335 (0.045)	-0.345 (0.631)
8	-0.637 (0.279)	-0.208 (0.891)
9	2.88 (0.011)	-0.175 (0.309)
10	0.111 (0.717)	0.373 (0.529)
11	0.611 (0.279)	2.482 (0.345)
12	0.171 (0.917)	0.203 (0.694)
13	0.173 (0.748)	1.041 (0.061)
14	0.015 (0.980)	0.318 (0.571)

Chapter 10: Reliability of a New Ankle Goniometer

Table 19: Sample output of Goniometer/Vicon at approximately 5^{o} increments.

Goniometer Output Angle (degrees)	Vicon Output Angle (degrees)
0.00	0.10
5.20	5.49
10.10	10.75
15.00	16.19
19.70	20.48

Table 20: Descriptive statistics

Descriptive Statistics			
	Mean	Std. Deviation	N
Goniometer	13.2603	5.75923	1000
Vicon	13.9518	6.07161	1000

10.3.1 Trial 1: Inter-rater and intra-rater test-retest reliability using a known moment; a double-blind design

Table 21: Rater 1 (Test-Retest) and Rater 2 Maximum Ankle Dorsiflexion Angles

Rater1 Test (degrees)	Rater1(2) Re-Test (degrees)	Rater2 (degrees)
11.28	13.66	10.06
23.18	22.74	20.34
18.82	20.62	22.22
17.04	17.6	19.16
11.02	13.46	14.86
20.6	20.3	22.04
17.06	17.04	19.68
19.86	21.06	23.62
27.8	29.56	29.84
17.3	16.36	18.3

Table 22: Reliability Statistics and Means

Reliability Statistics
Cronbach's Alpha
.984

Item Statistics		
	Mean	Std. Deviation
Test	18.3960	5.03731
Retest	19.2400	4.77798

Table 23: ICC results for Test-Retest

Intraclass Correlation Coefficient							
	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.968[b]	.878	.992	62.087	9	9	.000
Average Measures	.984	.935	.996	62.087	9	9	.000
Two-way random effects model where both people effects and measures effects are random.							
a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.							
b. The estimator is the same, whether the interaction effect is present or not.							

Table 24: Reliability Statistics and Means

Reliability Statistics
Cronbach's Alpha
.953

Item Statistics		
	Mean	Std. Deviation
Test	18.3960	5.03731
Rater 2	20.0120	5.24992

Table 25: ICC of Rater1 vs Rater2; inter-rater reliability

Intraclass Correlation Coefficient							
	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.911[b]	.684	.977	21.432	9	9	.000
Average Measures	.953	.812	.988	21.432	9	9	.000
Two-way random effects model where both people effects and measures effects are random.							
a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.							
b. The estimator is the same, whether the interaction effect is present or not.							

10.3.2 Trial 2: Intra-tester reliability with uncontrolled moment and variable knee position; a double-blind design

Table 26: Cronbach's Alpha for Test-Retest with Knees extended and flexed

Reliability Statistics	
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items
.950	.954

Reliability Statistics	
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items
.947	.947

Table 27: Means of Test-Retest with the Knees Extended and Flexed.

Item Statistics			
	Mean	Std. Deviation	N
TESTKneeExt	17.3220	5.46285	10
RETESTKneeExt	19.3360	5.47988	10

Item Statistics			
	Mean	Std. Deviation	N
TESTKneeFlx	24.3980	4.64779	10
RETESTKneeFlx	23.7640	5.27982	10

Table 28: ICC (2,1) Test-Retest with the knees extended

Intraclass Correlation Coefficient							
	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.900[b]	.649	.974	18.913	9	9	.000
Average Measures	.947	.787	.987	18.913	9	9	.000

Two-way random effects model where both people effects and measures effects are random.
a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.
b. The estimator is the same, whether the interaction effect is present or not.

Table 29: ICC (2,1) Test-Retest with the knees flexed

Intraclass Correlation Coefficient							
	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.905[b]	.666	.976	20.062	9	9	.000
Average Measures	.950	.799	.988	20.062	9	9	.000

Two-way random effects model where both people effects and measures effects are random.
a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.
b. The estimator is the same, whether the interaction effect is present or not.

10.3.3 Trial 3: Intra-tester reliability with uncontrolled force on a patient population; a double blind design.

Table 30: Maximum Ankle Angles of Patient Population for the study

Patient	MEAN Maximum Ankle Dorsiflexion Angle (^{o}) Test1	MEAN Maximum Ankle Dorsiflexion Angle (^{o}) Retest
1	19.3	19.5
2	17.15	17.2
3	21.05	22.75
4	15.45	14.7
5	16.4	17.9
6	13.75	15.05
7	12.6	14.2
8	8.65	8.55
9	3	2.9
10	5.2	5.3
11	0.55	0.9
12	1.9	1.75
13	0.05	0.1
14	12.15	11.8
15	8.25	9.4

Table 31 a,b: Reliability statistics and means

Reliability Statistics	
Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items
.997	.997

Summary Item Statistics							
	Mean	Minimum	Maximum	Range	Maximum / Minimum	Variance	N of Items
Item Means	10.582	10.363	10.800	.437	1.042	.095	2
Item Variances	51.231	48.906	53.556	4.650	1.095	10.810	2

Table 32: ICC (2,1) for patients population

Intraclass Correlation Coefficient							
	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.992[b]	.973	.998	326.603	14	14	.000
Average Measures	.996	.987	.999	326.603	14	14	.000
Two-way random effects model where both people effects and measures effects are random.							
a. Type A intraclass correlation coefficients using an absolute agreement definition. b. The estimator is the same, whether the interaction effect is present or not.							

Chapter 11: Establishing reliability of the Ankle Goniometer between multiple raters with uncontrolled moment

Table 33: Means of results of 4 ratings for each participant

	Means (degrees)			
Participant	**Rater1**	**Rater2**	**Rater3**	**Rater4**
1	19.26	22.7	21.82	20.84
2	33.76	40.9	31.92	35.9
3	27.96	35.96	27.32	34.2
4	20.96	29.92	22.82	24.72
5	27.08	30.16	25.48	31.64
6	25.4	29.12	23.58	26.36
7	9.98	12.08	11.8	13.64
8	19.98	28.72	24.96	31.06
9	20.18	15.52	15.9	18.12
10	11.42	12.12	11.72	15.1

Table 34: Reliability Results for multiple raters

Reliability Statistics
Cronbach's Alpha
.977

Intraclass Correlation Coefficient

	Intraclass Correlation[a]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.915[b]	.798	.975	44.076	9	27	.000
Average Measures	.977	.940	.994	44.076	9	27	.000

Two-way random effects model where both people effects and measures effects are random.

a. Type C intraclass correlation coefficients using a consistency definition-the between-measure variance is excluded from the denominator variance.

b. The estimator is the same, whether the interaction effect is present or not.