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ABSTRACT

EXPLOITING THE CONCEPT OF HYSTERESIS IN ANKLE DYSFUNCTION AND ANKLE STRENGTHENING

By

Akshay Narendra Pujara

The ankle joint is an important part of the body which is responsible for normal gait cycle. Dorsiflexion, plantar flexion, inversion and eversion are four types of movements controlled by the ankle joint. All these movements are controlled by the ligaments and the muscles associated with the ankle. Disorders of these ligaments and muscles leads to ankle dysfunction.

The hysteresis concept was employed to determine if there is any ankle dysfunction. A recently developed device, the Ankle Torsion Monitor (AnTm) was employed to evaluate the viscoelasticity and stiffness of the ankle joint. The greater the hysteresis loop area (HLA) the more inelastic is the ankle joint. Similarly the greater the Range of Motion (ROM), the less stiff is the ankle joint. Nineteen subjects (12 control and 7 patients) were examined to evaluate their viscoelastic properties and passive ROM of the ankle joint. The control subjects were given four different types of exercises; it was found that these exercises are considered to be suitable to improve the viscoelasticity of their ankle joints, although there was variation in the results of four exercises.

A mathematical model was also developed to determine the elastic constants such as stiffness, damping and friction. This model could be employed for each individual subject based upon the experimental results obtained by using the AnTm. The values obtained can be used for designing ankle braces that will give strength to the ankle joint for preventing falls.

EXPLOITING THE CONCEPT OF HYSTERESIS IN ANKLE DYSFUNCTION AND ANKLE STRENGTHENING

by
Akshay Narendra Pujara

A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering

Department of Biomedical Engineering

May 2010

APPROVAL PAGE

EXPLOITING THE CONCEPT OF HYSTERESIS IN ANKLE DYSFUNCTION AND ANKLE STRENGTHENING

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"Shri Ram Jai Ram Jai Jai Ram"

This thesis is dedicated to the people who are determined and optimistic to be something whatever time it may take. I am thankful to all my family, teachers and friends who made me capable of reaching this point.

"There is always a reason for the reason you have today"

Akshay Pujara

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CHAPTER 1

INTRODUCTION

1.1 Overview

Ankle injuries are the most common type of injuries in any foot disorder. The ankle is an important part of the body which plays a main role in locomotion with any kind of surfaces. It is found that during walking it bears 120% of the body weight and during running 275% [1].

Ankle fracture, sprains are certain types of ankle disorders which are really common in our day to day life. The American Academy of Orthopedic Surgeons surveyed that each day there are 25000 people who experience ankle sprain and are treated either at home or by doctors. From 1 million ankle injuries reported by NIAMS every year, most of these injuries are ankle sprains. In sports there are 38-45% of sprained ankle injuries when compared to all other injuries [2].

In the cost analysis study, Soboroff et al found that the cost of treating these injuries ranged from $318 to $914 per sprain, with an annual aggregate cost in the United States of $2 billion [2]. Complete rehabilitation of a sprained ankle takes about 36-72 days of recovery [2].

The main aim of this research is to develop a method by which ankle dysfunction can be measured and quantified for normal subjects and patients with history of ankle disorder. The present study will evaluate ankle dysfunction, elaborate how to improve the ankle strength doing different exercises and develop a mathematical model to evaluate different viscoelastic constants for the ankle joint. Results obtained can later be used for rehabilitation of the patients by measuring the viscoelasticity of their ankle joints and its torsional effects.

1.2 Anatomy of Ankle

Ankle is one of the most important joints of the body as it bears more weight per unit area than any other joint in the body [3] as it connects the leg and the foot. The Ankle joint comprises two joints, mutually working together and placed one below the other. The upper joint is called the talocrural and lower is the subtalar joint. In the foot there are 28 bones and 55 joints which ease bipedal locomotion in all weight bearing and non-weight bearing functions. Ligaments are the primary restraints of bones. Having 2-6 ligaments in all the joints the talocrural consists of four ligaments: deltoid ligaments, the anterior talofibular ligament, the posterior talofibular ligament, and the calcaneofibular ligament, which are mainly responsible for ankle disorders.

Osteology

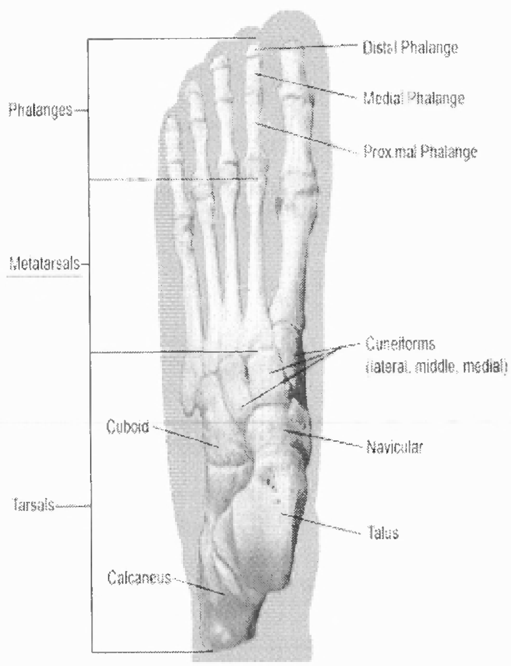

Figure 1.1 Foot anatomy [13]

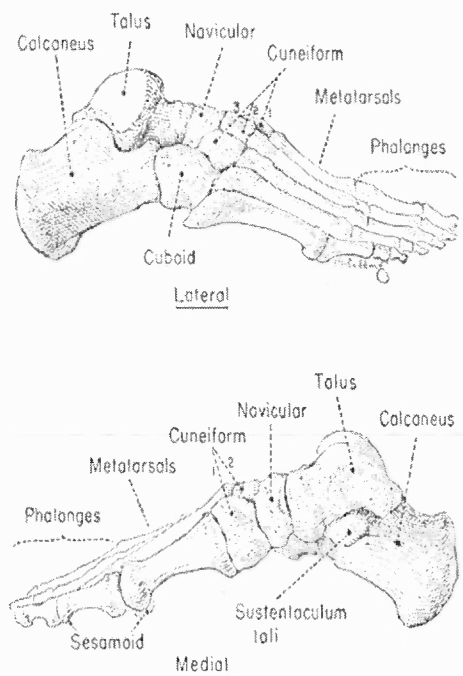

Figure 1.2 Medial and Lateral view [4]

Twenty eight bones can be classified as 7 tarsal, 5 metatarsals, 14 phalanges and 2 sesomoid bones of toe. Biomechanically the foot is divided into rear, mid and forefoot. The rearfoot comprises heel and ankle bones which influences movement of mid and forefoot. It converts the torque and transverse rotation of the lower extremities into sagittal, transverse, and frontal plane movements [3]. The midfoot is in between the heel and the toe. It is responsible for stability of the foot when it steps to uneven surfaces [3]. The forefoot comprises of tarsus, metatarsus and phalanges and these sub-divisions help to increase the weight bearing area of the foot.

The bones that make up the tarsus are medial cuneiform, intermediate cuneiform, lateral cuneiform, navicular, cuboid, talus, and calcaneus and are often called as the ankle bones and are shown in figure 1.1 and 1.2.

The talus attaches foot to the leg by articulating the distal surface of the tibiofibular ligaments. It is formed by three parts of the body corpus tali, column and caput. Calcaneous is the largest bone of the foot [4] and has prominence at back side of the foot. "It articulates with the talus superiorly, with the cuboid laterally, and with the navicular medially. The skin and fat over the distal-inferior area of the calcaneus are specialized for friction and shock absorption. Cuboid is intercalated between the calcaneous and base of 4th and 5th metatarsals. It is in contact with navicular (scaphoid) and supports cuneiform laterally. The navicular is positioned in between head of talus and three cuneiforms and it is firmly bound with ligaments. Proximally all the 3 cuneiforms are connected with the navicular and laterally with cuboid." [4]

Ankle Joints

Talocrural joint

The tibia is one of the longest bone, and weight bearing bone of the body. The tibia, fibula and talus all together form this joint. This joint acts as a mediator which transfers body weight from the tibia to the talus, and later is distributed everywhere within the foot. The talocrural joint plays a major role in providing stability to the talus. The ligaments of this joint can be divided into lateral or medial collaterals. [4]

Lateral collaterals are mainly responsible for all major kinds of ankle sprains. It stabilizes the ankle on the lateral side and it is also responsible for rotational stability (inversion) of ankle. It is divided into four ligaments:

The Anterior Talofibular Ligament (ATL)

The "ATL is 2-5 mm thick and 10-12 mm long in size extends from fibular malleolus to lateral facet of the talus and surface of talus neck [5]. It resists ankle inverion in planter flexion, resists anterior talar displacement and internal rotation of the talus." [5].

The Calcaneo Fibular Ligament (CFL)

It is stronger than the ATL [5] and fans out 10-40 degrees from tip of fibular malleolus to the lateral side of calcaneous [4]. This design works out in such a way that it does not restrict motion on any of the two ankle joints but it does give talar tilt inversion in dorsiflexed position of the ankle.

The Posterior Talofibular Ligament (PTL)

It is coalescent with joint capsule horizontally. It is considered to be one of the strongest ligaments and it is rarely injured [5].

Medial collateral are also called deltoid ligament, having superficial and deep fibers arranged in fan shaped structure.

There are 3 types of superficial fibers which are as follows:

Tibionavicular

These fibers extend from the medial malleolus to the tuberosity of the navicular. They resist lateral translation and external rotation of the talus [4].

Posterior talotibial

These fibers extend from the medial malleolus to the medial side of the talus and medial tuberosity of the talus. They resist ankle dorsiflexion and lateral translation and external rotation of the talus [4].

Calcaneotibial

These thin fibers extend from the medial malleolus to the sustentaculum tali. They are oriented in such way that they resist abduction of the talus, calcaneus, and navicular, when the foot and ankle are positioned in plantar flexion and eversion [4].

Anterior talotibial

They are also called as deep fibers and they extend from the tip of the medial malleolus to the anterior aspect of the medial surface of the talus. The orientation of this fiber is in such way that they resist abduction of the talus, when it is in plantar flexion and eversion.

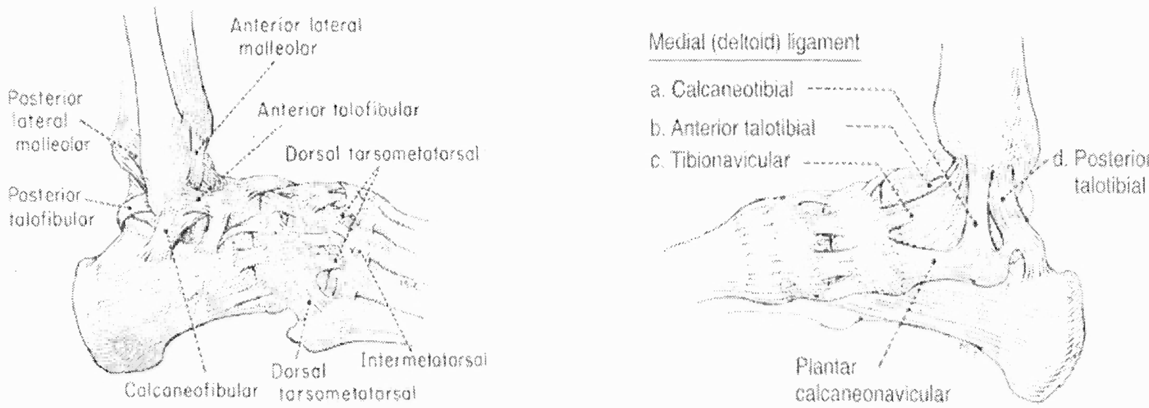

Figure 1.3 Lateral side of ankle showing ligaments [4]

There are many nerves, tendons and muscles that play an important role in the ankle joint. For example the Achilles Tendons connect the calf muscles and the calcaneous and are mainly responsible for jumping, walking and running as it will bear maximum weight. The basic study in this paper would be more limited to the ligaments.

Subtalar (Talocalcaneal joint)

It consists of anterior and posterior articulations having their own joint cavities. They are arranged in such a way that they move opposite to each other during ankle movements and are mainly responsible for ankle inversion and eversion. [4]

Talocalcaneal ligament

These ligaments are often referred as interosseous ligaments and are divided into cervical and talocalcaneal interosseous ligaments. [4]

Medial (Posterior) Talocalcaneal Interosseous

"The medial talocalcaneal interosseous ligament extends from the medial tubercle of the talus to the posterior aspect of the sustentaculum tali and the area of the calcaneus just posterior to the sustentaculum tali"[4]. By producing passive eversion of the talus, they stabilize against anterior translation of the talus.

Lateral (Anterior) Talocalcaneal Interosseous

It is responsible for joining talus and calcaneous during inversion movements and is more prone to injury during dorsiflexion and plantar flexion. It originates from the roof of sinus tarsi and extends from the lateral process of the talus to the lateral surface of the calcaneous.

1.3 Ankle disorders

Ankle disorders can be scrutinized based on ligament injury and bone fractures. There are other disorders like arthritis, deformation of foots and joints, inflammation, infections, instabilities and many more. But from all these injuries, ligaments and bone fractures are most common in sports and everyday activities.

During locomotion or twisting of the ankle joint, the ligaments guide the bones in their respective anatomical range of motion. They ensure even pressure on the articular surfaces and make the motion stable and in harmony.

Ankle sprain are the most common type of injuries in sports and everyday activities. The stepping of the foot on any uneven surface would lead to twisting of the ankle in the respective direction. This makes the bodies lose control over walking and the whole body weight comes to a respective side of the foot. This kind of condition leads to elongation of the ligaments which is responsible for sprain. In other words when a ligament is forced to stretch beyond its normal range, a sprain occurs. A severe sprain causes actual tearing of the elastic fibers. If the severity of the twisting is more, it might lead to tearing of the ligament and sometimes break the bone, which is often called a fracture.

As mentioned in the anatomy section the talus is the most weight bearing bone of the foot. Stormont and colleagues [4] showed that ankle sprain does not happen in dorsiflexed or neutral position, because during that time the wider part of the talus is inside the mortise, assuring the stability. They claimed that sprain occurs during "systematic loading and unloading". Thus it proves that sprain occurs more due to inversion, eversion and plantar flexed position.

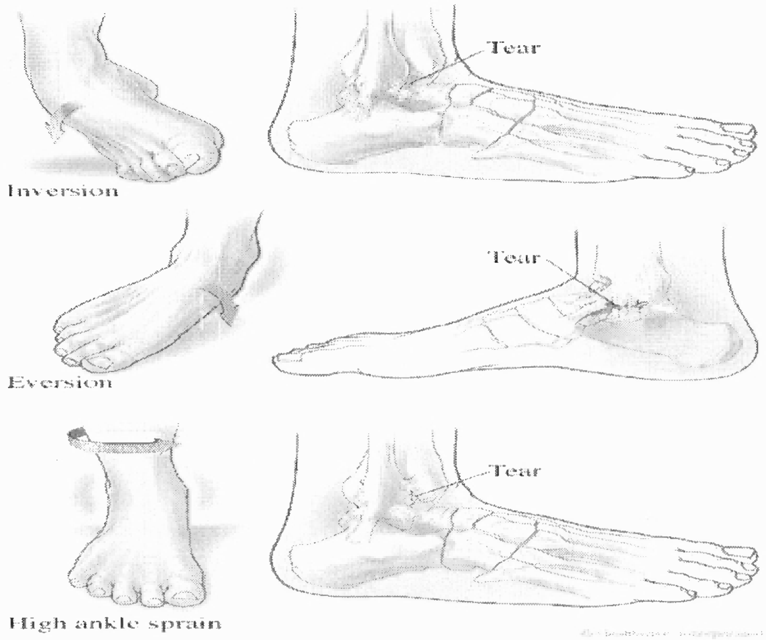

Figure 1.4 Types of sprain [14]

Inversion ankle sprain are the most common type of the ankle sprains occurring in general population. 85% of the sprains are due to inversion injury [4]. This type of sprain happens due to the inward rolling of the foot and stretching of lateral ligament as shown in figure 1.4.

ATFL is the least elastic ligament when compared to other lateral ligaments and is involved in 60-70% of all lateral ankle sprains and others are 20% [4]. It is necessary to have diagnosis and treatment as soon as possible, because progressive inversion strain results in further rupturing of other ligaments.

Eversion sprains contribute only 5% of total ankle sprains. During eversion the ankle is turned outwards and the tearing of deltoid ligaments will lead to eversion ankle sprain.

High ankle sprain are very rare and occur due to the rupture of large or syndesmotic ligament. This ligament is present above the ankle and joins the shin bone (tibia) and fibula.

Depending on the severity of ankle sprains, they are divided into grade I, grade II and grade III ankle sprains. Grade I is the stretching of the ligament. Grade II is partial tearing of the ligament accompanied with swelling, bruising and more pain than Grade I. Grade III is the complete tearing of the ligament, which is much more painful and ceases locomotion completely.

Ankle fractures

When one or more bones of the ankle break, this condition is known as ankle fractures. There are many causes of fractures. It may include twisting, rolling, tripping, car accidents and sudden load. Symptoms of fracture include immediate pain, swelling, tender touch and less ability to bear the weight. These symptoms are almost the same as sprain. That is why it is difficult to diagnose fractures without X-Rays and CT scan. Fractures occurring due to stress transfer from the muscle to the bone are called Stress fractures and usually happen in the second and third meta-tarsal. Building up of the stress is due to overuse of that body part for a long period of time.

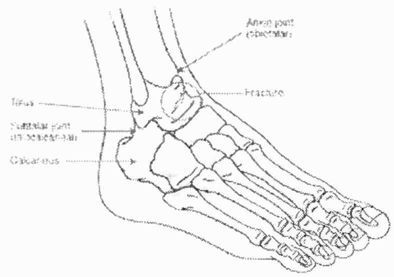

Figure 1.5 Talar fracture/Talus fracture [16]

The cause of talar fracture is excessive dorsiflexion and axial load with the foot in plantar flexion [4]. During excessive dorsiflexion, the talar head is compressed against the tibia resulting into crack in the talus head.

Pilon fracture is tibial fracture where the ankle joint is totally disruptured due to splitting and shattering of the distal end of the tibia. [4]

The Lateral malleolus fracture is a fibula fracture. Posterior malleolus fracture is the fracture of shin bone at the level of the ankle joint. Bimalleollar and trimalleolar fractures imply involvement of number of malleoli in the fractures.

Calcaneous fracture is one of the most common fractures and its occurrence rate is 60% [4] when compared to all other foot fractures. Some causes include mediolateral compression of the heel and jumping activities which precipitate architecture of the calcaneous.

1.4 Ankle diagnosis

Ankle diagnosis is based on the evaluation of changes in tissue and joint mobility. The primary concern of the physician is to check the dysfunction based on the effects of above two points. Ankle evaluation starts with history profile of the patient which will be much more helpful and will make the diagnosis fast and easy. It gives handy information related to the mechanism of the injury which will further ease the investigation for any kind of disorder. The doctors visually observe the gait, the swelling discoloration, the pronation and other irregularities in shapes. Observation of the gait helps the doctors to guess whether the subject passes the weight bearing test, calcaneous eversion and change in symptoms while walking.

The torsion of the tibia can be assessed in sitting position of the patient where his/her knee is flexed at 90 degrees [6]. The thumb of one hand is placed over the apex of one malleolus, and the index finger of the same hand is placed over the apex of the other malleolus [4]. A qualitative estimate of the direction and magnitude of the tibial torsion can be made by envisioning a line that passes through the malleoli and estimating its orientation to the frontal plane of the proximal tibia.

Palpation of ligaments and tendons are performed to differentiate the tenderness of the ligaments and other different structures. Palpation is also useful to diagnose fracture, sprains and other dislocations of the ankle bones. Stress fracture can be diagnosed by palpating the localized site of the pain. Palpation is useful in finding the subtalar neutral position. The place where the subtalar head bulges equally on the lateral and the medial side is called subtalar neutral position. It is discovered by grabbing the foot with the thumb and fingers and moving the foot inwardly and outwardly. The posterior aspect of the calcaneous is palpated for haglubds deformity [4]. Similarly, palpation is used to locate and to experience the tenderness and the crepitus of the ligaments and tendons.

The Range of Motion (ROM) test is divided into passive and active tests. During the diagnosis, mostly passive ROM is used which starts with weight bearing and non weight bearing tests. If the subject fails to do this general test they are not advised for other ROM tests.

At present goniometers are used by physiotherapist for finding the Range of Motions and have obtained standard values for dorsiflexion, plantarflexion, inversion and eversion. During dorsiflexion, the patient is laid in supine position and passive pressure is applied to the talar region of the foot. The knee is supported by a pillow in the flexed position. In was found that healthy subject usually have 20 degrees of the dorsiflexion and 30-50 degrees for the plantar flexion [4], based on above experiment.

The Hind foot Eversion and Inversion are tested by lining up the longitudinal axis of the leg and the vertical axis of the calcaneous. The passive motion of hind foot inversion was found to be 20 degrees and 10 degrees for eversion [4]. The Calcaneal Eversion and Inversion are measured by locking the talus and grabbing the calcaneous in the respective motion.

Radiography is a non-invasive diagnostic test that is used to observe the bony structures of the foot and the ankle. X-Rays are generally recommended by physician to diagnose bone fractures because at times, the symptoms of sprain and fracture are similar. To be more specific, they are very useful to find stress fractures by applying light load on the affected area and noticing the changes inside the body using X-Rays. CT scans are similar to X-Rays and are more precise in imaging modality. It gives the cross sectional images of internal structures and good reconstruction techniques to diagnose not only bony configurations but also some soft tissues. MRI (Magnetic Resonance Imaging) is useful for more accurate diagnosis of ligament injuries and other soft tissues.

1.5 Treatment

Intervention and prognosis depends on the type of injury. Non-surgical treatment approach includes medication, bracing, patient education, orthotics, symptom management, exercise and surgical options if needed. The best early treatment given to any patient after having an accurate diagnosis by any physician would be PRICEMEM (protection, rest, ice, compression, elevation, manual therapy, early motion, and medication) method. This treatment is customized for each patient depending on the type and the severity of the injury.

Rest: The healing of any ankle injury needs lot of patience because it may take several weeks for rehabilitation. At least all the daily activities should be curtailed till 24-48 hours at the time of recent injury and foot is made to be at complete rest till it resumes some kind of normal gait movement. This will also help in other pathological treatments to be more effective.

ICE: This treatment is effective for any sprain, strain, bruises and over stressed injury. It controls the swelling by local constriction of blood vessels. Moreover it decreases the pain to the injured area when applied till the treatment procedure is over. For this reason it is recommended to have ice therapy for at least 48 hours post sprain for 15-20 minutes at intervals. Again anything in excess leads to further disorder so it should not exceed the above time limit, failure to follow the instructions may lead, to other ligament or nerve injury.

Compression: Wrapping of the foot with bandage upward from the toe to the calf muscles. This will help to keep the foot intact and restrict any kind of motion during acute phase injury. The foot should be re-wrapped if it becomes cold or blue or numb.

To avoid the reducing of the blood circulation, the wrap should be taken care of and it should not be so tight that it blocks any artery or veins.

Elevation: The foot should be kept above the heart level during night or its treatment period in acute phase. The main reason for elevation of the foot is to prevent the formation of any edema in the blood vessels at the site of the ankle injury. This also limits the supply of neutrophils to the injured area. Neutrophils are a kind of leukocyte that is responsible for inflammatory process. It is recommended to use a splint in the dorisiflexed position at night for faster recovery.

Protection, medication and early motion

Following the RICE treatment, the main goal of the doctor is to improve the gait and the ROM. Braces or taping are recommended for any kind of injury to prevent lateral ankle sprain and other injuries [4]. Braces play an important role in the intervention and the prevention of injury, and their main role is to compress, protect and support the ankle. In functional phase injuries, it is kept in dorsiflexed position for a longer period of time so it keeps all the bones intact proximally and prevents any kind of motion. Tightening of the brace depends on the severity of the injury. Initially it can be less compressed and later as time passes it can be taken into more stressful situation for preventing ROM till the treatment is over. Taping can be an alternative source for bracing but for not all type of situations. It is mainly used to prevent inversion or eversion in the talocalceneal joint [4]. Along with bracing and taping it is important to keep this whole assembly in steady phase and preventing it from any movements. For injuries like broken bone or joint, it's important to have a cast and splint to prevent any kind of movement during the rest position. Orthotics can be also considered as a useful tool for support. It helps in distributing forces in planter aspect of the foot and forces to align joint segments during its instability [4]. After recovering from acute phase injury to functional phase; heel lifts, heel cups and wedges can be used in day to day life for preventing the same injury again as it helps in distributing forces evenly throughout the leg.

Ankle surgery is performed in worst cases where it is not possible to align the ankle in the appropriate position, using the non-invasive techniques described above. Such situation happens when there is a broken bone or chronic loosening of the ligaments. There are many other reasons to have ankle surgery depending on the present anatomy of the ankle after obtaining X-Rays, radiography, MRI etc.

Manual Therapeutic techniques

It should be started once the pain and swelling is receded from its functional phase and the range of motion is achieved. It will help in regaining the strength and flexibility of the ankle. Some exercises are recommended to regain the ankle strength. First it should be started with the Isometric exercise and once it is mastered, switch the same exercise to Isotonic and do it regularly as prescribed by a physiotherapist.

1.6 Objectives

The main objective of this study is to extend the concept of hysteresis for the diagnosis of the ankle dysfunction and to study the behavior of the ankle joint, when subjected to different kind of exercises. The study mentioned above discusses the passive ROM concept and other diagnostic modalities. The method described in this thesis will help to find the visocoelasticity of the ankle which will give accurate diagnosis during the rehabilitation and sprains. This evaluation will be helpful to the physician in choosing the best type of exercises which will improve the viscoelasticity and the strength of the ankle. Another objective is to develop a math model to determine viscoelastic constants such as friction, damping and stiffness coefficient of the ankle joint for an individual which will be helpful in designing the ankle brace to prevent falls.

CHAPTER 2

EXPLORING CONCEPT OF HYSTERESIS

2.1 Introduction

Hysteresis effect is present in a non deterministic system. A system with hysteresis has memory. A system in which output value is not a strict duplicate of input but also incorporates a lag is called as "Hysteresis". The Hysteresis curve (loop) is plotted as force vs. displacement or stress vs. strain as shown in Figure 2.1.

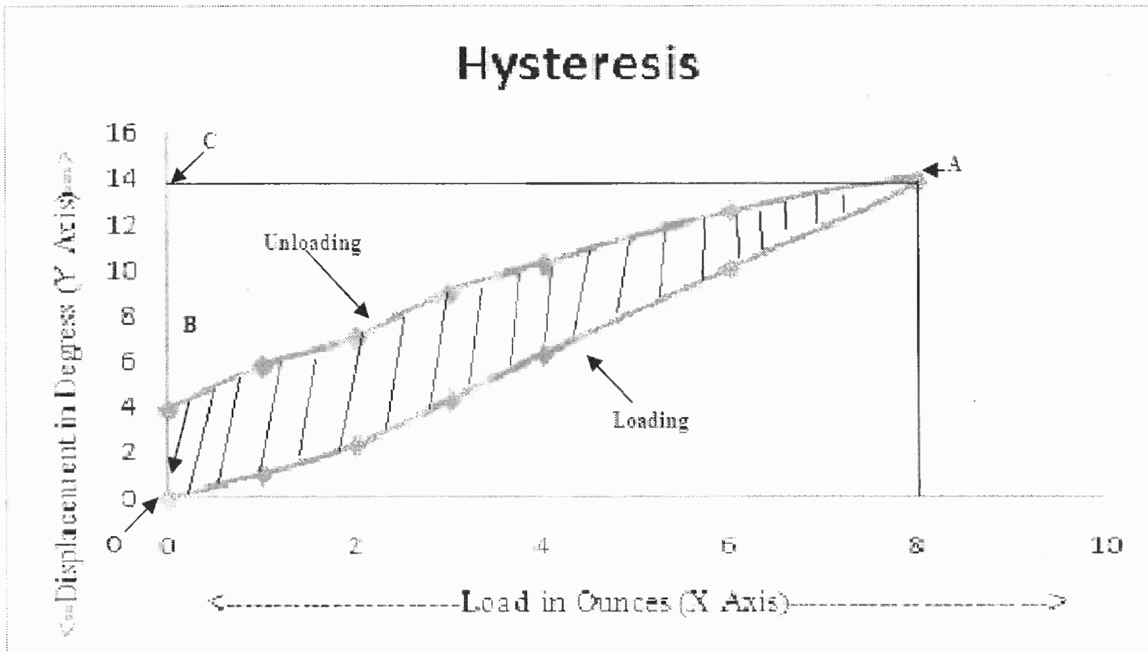

Figure 2.1 Hysteresis curve 1

The above figure shows loading and unloading of any material. This can be more explained by a rubber experiment as described below:

A rubber band is hung from a hook in its free position. Adding weights to the other end of the rubber will allow it to stretch accordingly. After reaching its maximum stretched position, start unloading the weight until all of them removed. Observing the whole experiment; it can be visualized that the rubber will not return to its original shape.

Based on this experiment an important concept of "energy dissipation" can be defined. Figure 2.1 shows the load vs. displacement curve for the rubber experiment. Work done on the material (rubber) is shown as the area included in the curve OACO. When unloading the weights, the work recovered is included in the area BACB. Thus work is lost, or in other words the dissipated energy is marked as area OABO (area OACO-BACB). This is called as Hysteresis loop area (HLA).

2.2 Definitions

The above concept of hysteresis is applied in this study for diagnosis of the ankle. This will give a quantifiable data, with the help of which we would be able to evaluate stiffness and viscoelasticity. The elasticity is the physical property of a material that returns the material to its original shape after removing the load from the system [11]. The stiffness is the property of the material to undergo a displacement subjected to a specific load. If the displacement is less under a given load, the material is stiffer and vice versa. For example steel is stiffer and more elastic than rubber. Figure 2.2 shows hysteresis loop of an ankle of certain male subject.

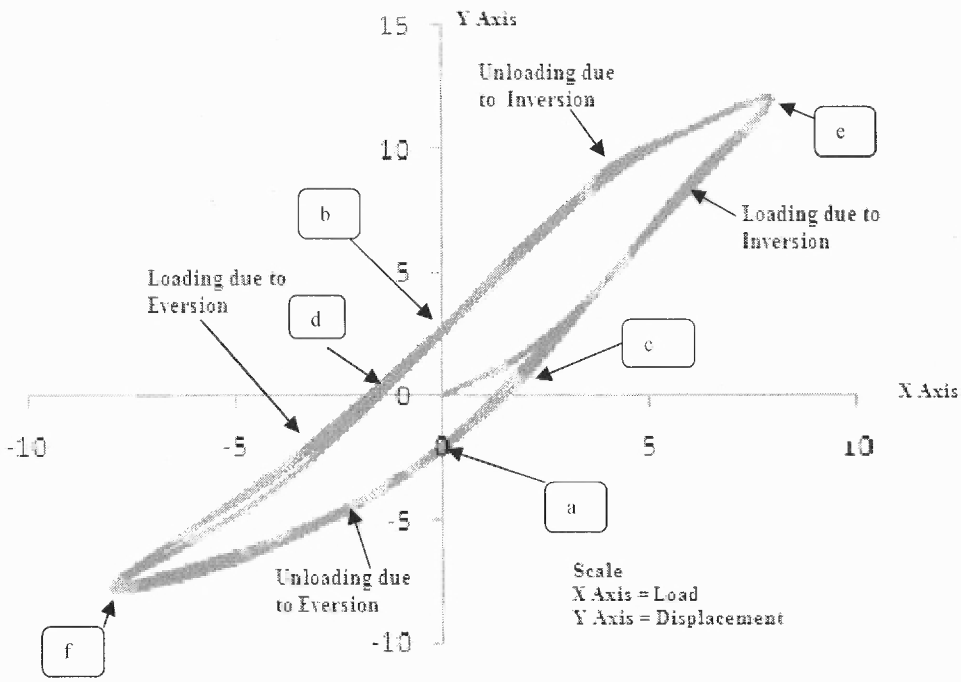

Figure 2.2 Hysteresis loop

In figure 2.2 c, d positions are marked as coercive forces. The coercive force is the amount of force needed in opposite direction to make our material come back to its original position. Again the points b and a are marked as retentivity. Retentivity means the retentive displacement after removing the load completely.

Range of motion (ROM) is defined as the maximum deflection of object under given applied force. As shown in figure 2.2 e and f are maximum ROM obtained under inversion and eversion respectively.

In this study the degree of viscoelasticity is measured as the area within the hysteresis loop (HLA). HLA and elasticity are inversely proportional to each other. The lower the HLA, the more elastic is the system while the greater the HLA, the less elastic is the system.

Viscoelasticity and passive ROM are focused in this study.

2.3 Ankle Torsion Monitor

Ankle Torsion Monitor (AnTm) was designed by Micheal John Warner and James Allen Mertz. This was based upon the concept Anatomic Torsion Monitor (ATM) [8] for low back evaluation. This device was used by Alissa Cohen [9] in her Master's thesis. In this study the concept of HLA was used to evaluate the effect of specific treatment for ankle sprain.

CHAPTER 3

ANKLE TORSION MONITOR

3.1 Background

MRI and ultrasound can be used to give physiological condition of ankle joint and ligaments associated with it. Information obtained from CT and X-Ray images can be mainly used to diagnose anatomical disorders of bones. From the radiographic techniques it can said that imaging studies do not measure degree of dysfunction which is proposed to quantify. These costly techniques may be useful but cannot be employed to diagnose simple injury for rehabilitation purposes.

The results of this present study can help the physician to assess the ankle joint and can be useful in predicting the effect of a particular treatment.

This study will focus on measuring ankle dysfunction which will exactly mimic the diagnostic studies done by a doctor with a subject having disorder related to ankle joint. The study will not only tabulate the passive ROM but also the viscoelasticity. Application of hysteresis concept described in previous chapters will help to find degree of dysfunction in the form of Hysteresis loop area. The ease of this study will prove to be beneficial to physicians and will cut short the current lengthy procedures for assessment of the ankle joint.

Brief Introduction to the Ankle Torsion Monitor

An Ankle Torsion Monitor (AnTM) includes a chair upon which a patient sits and an ankle unit. The ankle unit is composed of an adjustable strap and block with attached bar that is secured to a patient's foot. This assembly is utilized to measure rotational displacement of the ankle joint. A light beam is fixed on the bar to measure the rotational displacement. The output of the light beam is projected onto a scaled chart situated at a certain distance from the foot. Clockwise and counterclockwise rotational displacements of the patient's ankle about the medial long plantar axis as a function of applied forces are obtained by reading the projection of the light beam on the scaled chart as the forces are applied and withdrawn. Plotting the rotational displacement versus the applied force on a Cartesian coordinate system produces a continuous, bounded four-quadrant hysteresis loop. For details see section 3.3.

3.2 Other Methods Measuring Displacements

There are certain studies in which a goniometer is being used for studying eversion and inversion movements, but that cannot be used for all the studies due to its own limitations. However due to its frequent use; the procedure to use goniometer is explained below, although it is not used in the present study.

3.2.1 Goniometer

In medical terms, goniometer is an in-vitro device or a protractor that measures the joint angles in the human body. It basically consists of a stationary arm holding a protractor and a movable arm as shown in figure 3.1. The measuring units of goniometer are in degrees as it measures the angular moments made by the human body.

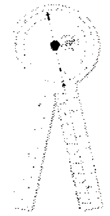

Figure 3.1 Goniometer

Procedure for using goniometer

The fulcrum is aligned with the joint to be measured.

The stationary arm is kept parallel as reference with the part of the body to be measured.

The movable arm moves along with the body part with respect to which angle is measured.

Till now, goniometer is successfully used in measuring joint angles in human body in active or passive ROM. Sometimes, it is combined with radiographic techniques to find accurate measure angles which aids in deep investigation of the injury.

3.2.2 Goniometric application in Hind foot Inversion and Eversion

Ball and Johnson [10] designed an apparatus measuring passive ROM of hindfoot inversion and eversion. They devised an assembled chair whose core component of measurement was electronic goniometer. Figure 3.2 shows a steel chair and other assembled apparatus.

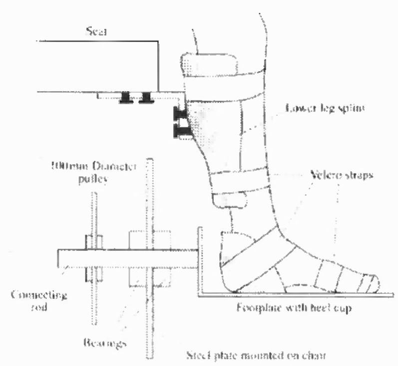

Figure 3.2 Apparatus for hind foot measurement

The steel chair is attached with sub plate carrying two bearings. The front end of the shaft is attached with right angle bracket which holds the foot splint and rear end of the shaft that is attached with a steel rod perpendicularly. The electrogoniometer was attached to the hind foot of the subject. Weights giving a 10nm force were attached to these steel rods which produce torque in eversion and inversion sides.

Certain assumptions are made to overcome limitations and involuntary movements of the body. The neutral position or zero position of the foot is fixed for all the subjects for each experiment. Method of loading and positioning of the subject influences the motion at the joint. These assumptions help to make a fair comparison between the subjects and minimize the error for statistical analysis.

The results obtained from this device proved that there were small decreases in the passive ROM in males when compared with females. Female data for the passive ROM showed significant change when compared with males, with increase in age. Also the ROM decreased with increase in age and most significant was eversion in males. There was no significant decrease in the ROM in between the right and the left leg and it showed a positive correlation.

3.3 Components of AnTm

Ankle Torsion Monitor consists of three important components: One is the chair on which the patient sits; second is the target where the light beam is projected; last, is the ankle unit which is fixed on the foot of the subject as shown in figure 3.3.

Chair

The chair should be firm and sturdy with the ground which will allow the subject's foot to stay at least one foot above the ground so that the ankle unit can be fixed and have enough space to rotate as shown in the figure 3.3.

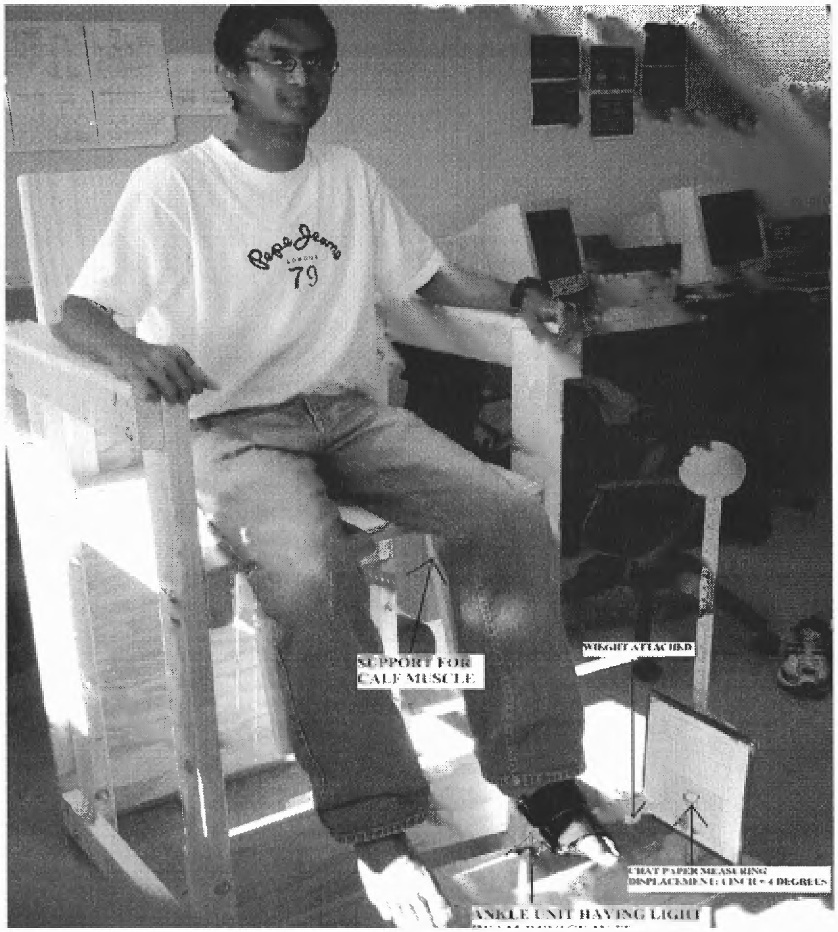

Figure 3.3 Ankle Torsion Monitor

The firm contact of the chair is ensured by the adjustable legs of the chair. As seen in the figure there is leg support to rest the calf muscles. It is very much necessary that during the test all the leg muscles should be at rest as the passive study of the ankle joint is being done. Because of this reason the leg support described above just touches the calf muscle and does not elevate it. The support is adjustable to 30^0, 45^0 and 60^0 as per the need. The chair assembly is made up of wood and not cushion. A very soft cushion can be provided at the place where the subject is sitting but not that soft that it affects the readings.

Ankle Unit

The ankle unit is much light and mainly consists of aluminum bar, wooden block, Velcro strap and light beam device. The whole assembly weights 368 grams (not including the foot).

The foot is attached to the wooden block, which is at a certain angle for both the left and the right ankle units. The tilt in the wooden block is due to plantar aspect of the foot. This will help the ankle unit to stay in horizontal position without any elevation or depression of the ankle unit, when fixed to the subject's foot. The Velcro straps provided are used to hold the foot firmly with the wooden block. Also the Velcro straps are not too tightened to avoid any tension on the foot.

The medial end and the lateral end carrier of the weights are hooked at two equally spaced end of the aluminum bar from the center. The weights (in ounces) are hung at these carriers. When the weight is hung on these carriers it displaces the ankle joint inwardly or outwardly depending on the side it is resting. The displacement of ankle happens as it is firmly bound with the Velcro straps and this result in the displacement of the light beam projected on the chart.

The light beam is attached in the L shape of the ankle unit as shown in the figure 3.4.

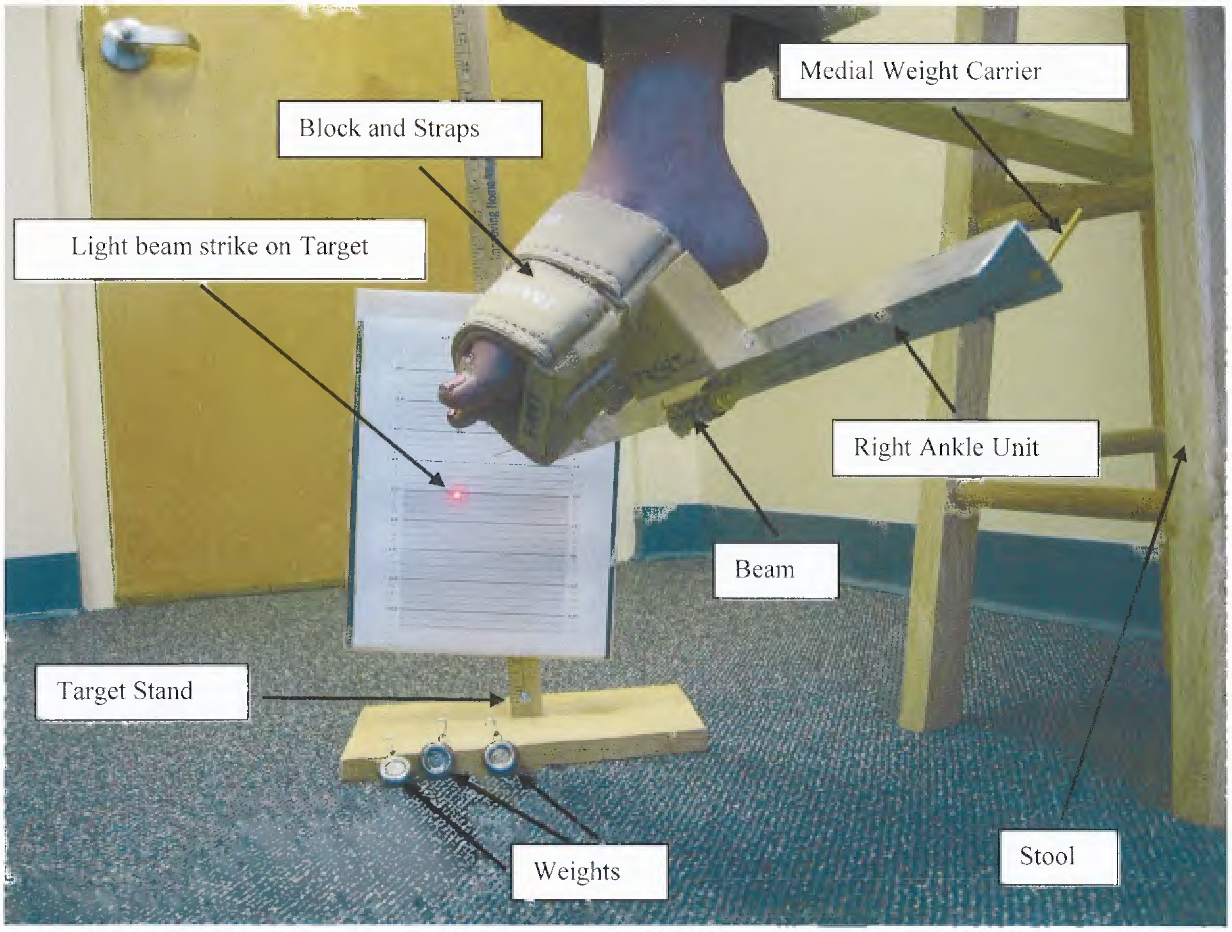

Figure 3.4 Detailed setup for AnTm

Light beam

It is soldered and is kept at a certain distance from the bar so that the beam strikes the target. It can be easily turned on by the screws attached to the light beam source.

Target

It consists of a chart which is attached to a vertical scale by a clip. The scale is rested on the wooden block by L shaped steel bars. The chart can be adjusted vertically depending on the height of the patient's leg. The chart is placed at 14.3 inches from the center of the ankle unit perpendicularly. This distance is determined through a trigonometric relationship, thus enabling one inch of the chart to represent four degree displacement. Ten lines per inch make an ideal chart. The chart is graduated vertically at $\pm 18^{\circ}$ from the centre of the chart.

Angular Measurement

The AnTm measures the angular rotation of the ankle joint when it is being deflected during application of loads.

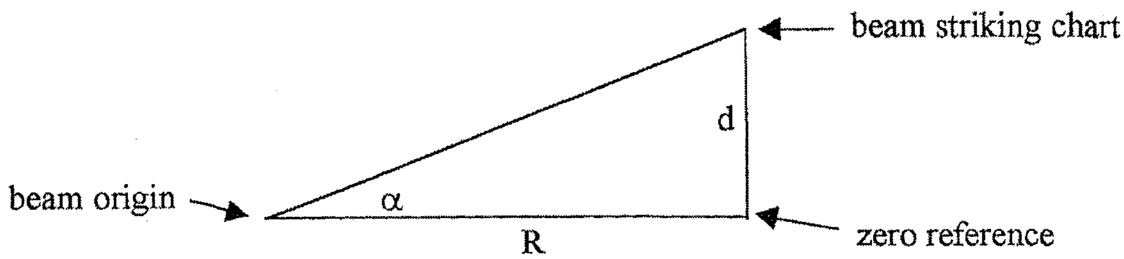

Figure 3.5 Right Angled Triangle

R=Distance from center of ankle joint to the target.

d=vertical distance from the light beam from the zero reference point,

α =Angular displacement

$d=R\alpha$

d=1 inch

R=14.3 inches

$1=14.3\alpha$

α =(1/14.3)radians=0.06993 radians=4 degrees.

That means

1inch= 4 degrees

The above equation proves that when there is a displacement of one inch on the chart it corresponds to 4 degrees of torsion.

3.4 Functions and Utility of AnTm

- AnTm is a medical device which is used to asses physiological characteristics of ankle joint.
- It measures degree of ankle dysfunction by analyzing hysteresis concept.
- It applies force on either medial/lateral side in order to move the ankle inwardly or outwardly respectively.
- Measures the viscoelasticity of the ankle joint in the form of HLA.
- Relaxes the leg muscles and make the ankle more eligible for passive studies.
- Fits to the plantar aspect of the foot.
- Deflection of the light beam on the chart gives rotational displacement of the ankle.
- Hold the foot firmly and in transverse direction from the target with the help of Velcro straps.
- Easy to take reading when compared to the goniometers.
- It investigates physiological condition of subject before and after treatment of the ankle joint.
- Rehabilitation of the human ankle joint at regular intervals.
- Non Invasive study of the ankle joint.
- Less harmful than CT, Radiography and X-Ray technologies.

CHAPTER 4

EXPERIMENTAL SECTION

The loading and unloading of the weights (1-10 oz) was done on one side and then on the other side ensuring that the foot is not in touch with the ground. This gives a light beam deflection on the chart. This deflection is plotted vs. the load in Cartesian coordinate system and a hysteresis curve is obtained, which gives a certain idea about behavior of the ankle joint movement when moved inwardly and outwardly.

Laboratories

For the current research, the Internal Review Board approved the Laboratory of New Jersey Institute of Technology and Dr. Thomas Findley clinic at Hackensack, Livingstone and Saddlebrook to use the AnTm. The exercise results were taken at NJIT from the healthy subjects and the AnTm was taken to Dr. Findley's clinic to collect data from the patients who have past history of ankle joint. Both the laboratories were fully enclosed at room temperature. The experiments were performed under the supervision of the principal investigators.

After interviewing them, the subjects were given a consent form approved by the Internal Review Board of NJIT. Consent forms were also signed by the principal investigator and data collected from the subjects was kept confidential with the advisor. Consent forms were signed by all the subjects.

4.1 Control Subjects and patients

Procedure involved in plotting the hysteresis curve is mentioned below:

1. Place subject on the chair in sitting position.

2. Locate leg over the leg support for the respective ankle to be assessed.
3. Attach the correct right or left ankle unit to subject's suspended foot without weights.
4. Turn on the light beam device using thumbscrew.
5. Attach the target to stand and place stand at 14.3 inches from the center of ankle rotation and in proper direction.
6. Subjects are been told to relax in the position where they are sitting and not to move when the experiment is performed. Also they are told not to look down to the target chart until the whole experiment is finished.
7. Move the target up/down on stand yardstick to intercept laser beam at 0 degree.
8. Add a 2 ounce weight to lateral weight carrier and read (visual observation) the angular displacement from target for inversion.
9. Repeat step 7 in 2 ounce increments until 8 ounces is reached.
10. Remove a 2 ounce weight from lateral weight carrier and take readings.
11. Repeat step 9 until all 2 ounce weights are removed from the lateral weight carrier.
12. Add a 2 ounce weight to medial weight carrier; read angular displacement from the target for eversion.
13. Repeat step 11 in 2 ounce increments until 8 ounces is reached.
14. Remove a 2 ounce weight from the medial weight carrier and take the readings.
15. Repeat step 13 until all 2 ounce weights are removed from the medial weight carrier.
16. Repeat steps 7 through 14 for as many cycles as desired.

17. Turn off the light beam device.

18. If done then stop. Otherwise move to the subject's other ankle by going to step 2.

19. Repeat the above steps for a desired number of cycles. For this study 3 cycles are taken into consideration.

20. Plot the results as hysteresis loops in Cartesian coordinate grids. 3 Hysteresis loop will be formed for each ankle joint. For patients, the same procedure is performed the only modification was done during initial loading of the weights. Instead of 2, 4, 6 and 8 ounces, 1, 2,3,4,6 and 8 ounces were used. This modification was done for the safety of the patient. If the patient felt any kind of discomfort during starting of the experiment, the procedure was discontinued since the existing condition of the past ankle injury was unknown.

21. The Hysteresis loop area (HLA) was calculated using MATLAB.

22. Passive ROM and other statistical analysis were done.

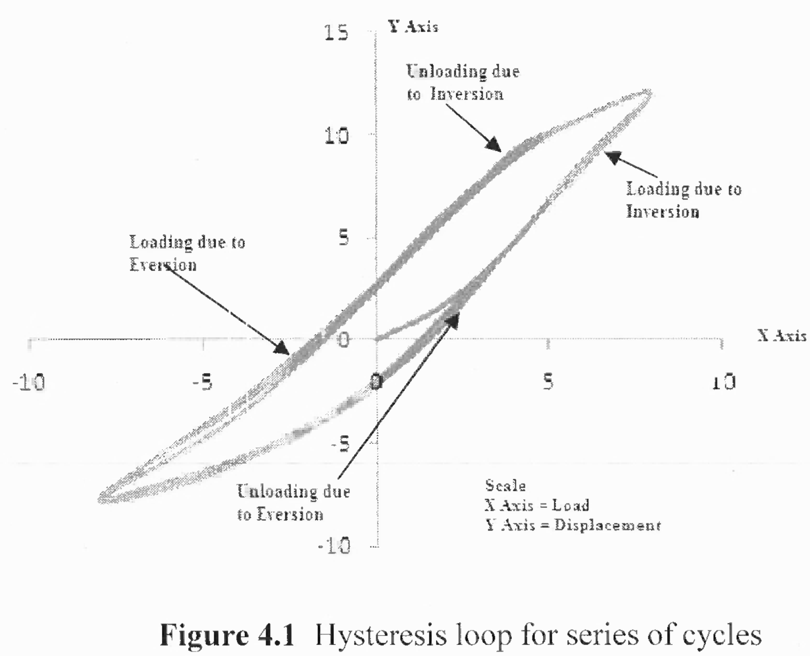

Figure 4.1 Hysteresis loop for series of cycles

Above figure 4.1 shows cyclic loading and unloading of the weights for a series of 3 cycles of a female left ankle joint.

4.2 Types of exercise

4.2.1 Introduction

The ankle joint carries the whole weight of the body and makes bipedal motion possible as mentioned in the introduction. This is one of the reasons for the ankle injuries to heal slower than any other injury. Strong ankles are important for prevention and recovery from ankle sprains. Strengthening exercise is important for faster recovery from ankle injury and also to prevent ankle injury by improving passive ROM and viscoelasticity of the ankle. These strengthening exercises should be performed once one can bear weight comfortably and when ROM is normal. There are several types of exercise but it is recommended to start from any kind of isometric exercise and then move towards isotonic exercises. Isometric exercise means pushing of the ankle towards a fixed object while isotonic exercise is the same as the isometric exercises with the only difference that some kind of resistance (for example weights) is used to arrive at the fixed object. In this study we have used commercially available resistance band and resistance bars to obstruct the ROM in a specific direction.

4.2.2 Dorsi flexion

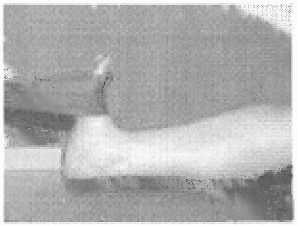

Figure 4.2 Isometric Dorsiflexion [15]

1. In this exercise, the resistance band is tied around a fixed object and the ends are wrapped around the forefoot as shown in figure 4.2
2. Start with the foot pointing down and pull the ankle up as far as it can.
3. Keep this position for 5 seconds and release it for 3 seconds
4. Do the above procedure for 5 minutes

4.2.3 Plantar flexion

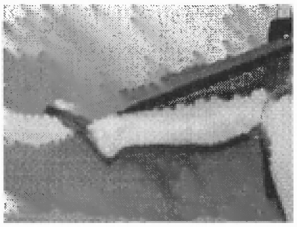

Figure 4.3 Isometric plantar flexion [15]

1. As shown in figure 4.3. Wrap a resistance band around your forefoot.
2. Hold the ends of the band with hand and gently push the ankle down as far as it can and then back to the starting position.
3. Keep this position for 5 seconds and release it for 3 seconds
4. Do the above procedure for 5 minutes.

4.2.4 Inversion

Figure 4.4 Isometric Inversion [15]

1. As shown in Figure 4.4, Isometric Inversion is done by tying the bands around an object to the outer side of the ankle. This exercise can be further divided into elevation of the Inversion side during exercise.
2. Start with the foot relaxed and then move the ankle down and inward.
3. Keep this stretched position for 5 seconds and release it for 3 seconds
4. Do the above procedure for 5 minutes.

4.2.5 Eversion

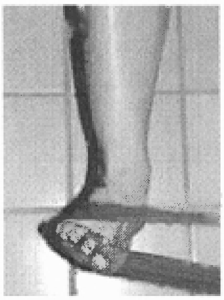

Figure 4.5 Isometric Eversion [15]

1. Tie the ends of the bands around an object to the inside of the ankle and hold the foot relaxed as shown in figure 4.5. Elevation of the foot during the exercise can divide the exercise into mild and full Isometric Eversion.
2. Elevate the foot outwardly and then back to the resting position.

3. Keep this stretched position for 5 seconds and release it for 3 seconds

4. Do the above procedure for 5 minutes.

Initially, before doing above exercises the subject's ankle is evaluated on the AnTm. Once the exercise session is over the subject is allowed to rest for 5 minutes and again the ankle is re-evaluated on the AnTm and the HLA obtained is tabulated.

CHAPTER 5

MATHEMATICAL MODEL FOR DETERMINATION OF VISCOELASTIC CONSTANTS FOR THE ANKLE JOINT

In order to determine visco elastic constants such as stiffness, damping and friction, the differential equation for the torsion of the ankle joint is given below.

$$I\theta'' + B\theta' - K(90 - \theta) + Tf(\pm) = -mglsin\theta$$

where

I is the Moment of Inertia of the ankle unit.

θ'' is the angular acceleration.

θ' is the angular velocity

θ is the torsion.

B is the damping constant of the ankle joint.

K is the stiffness constant of the ankle joint.

T is the coulombs coefficient of friction.

The experimental data for inversion of an individual was used to determine the curve for load (ounces) vs. deflection (torsion). See figure 5.1.

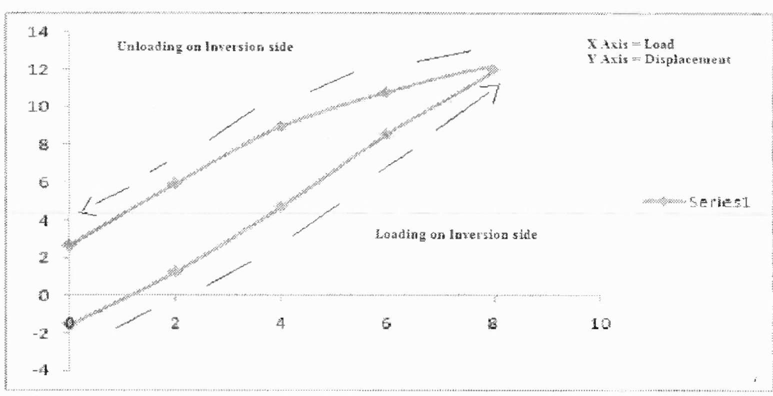

Figure 5.1 Inversion data for an individual

The theoretical curve for load vs. deflection was obtained in MATLAB. In the figure 5.2, the horizontal axis is time and vertical axis is displacement. It was assumed that readings are taken every one second for each 2 ounces added/removed. One sec is divided into 1/100th of the second and plotted vs. displacement. The weights were also plotted with respect to same time as displacement and modeled at every second. Displacement was measured at every one second with respect to the 2 ounces of load entered in the MATLAB command window. . Henceforth we get our theoretical curve in the form of time vs. displacement as shown in figure 5.2. The units of vertical axis is radians and for SIMULINK model instead of zero degrees it starts from 1.57 radians (90 degrees) and decreases/increases as we load and unload the weights.

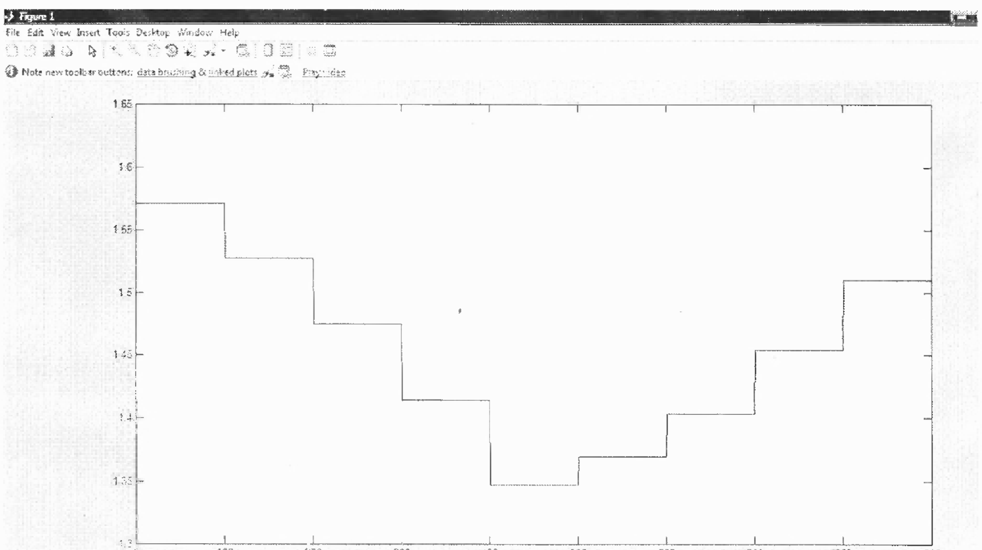

Figure 5.2 Theoretical curve plotted using reading obtained from Inversion data of individual

The designed SIMULINK model is given below. Figure 5.3

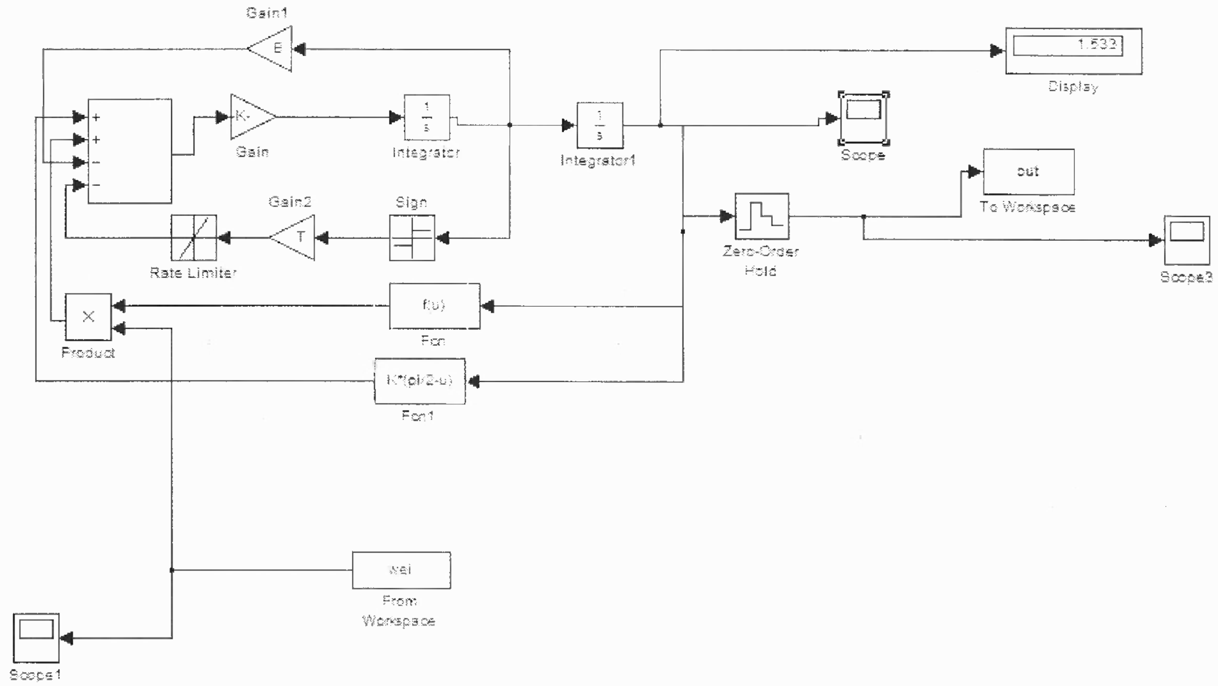

Figure 5.3 Simulink model

Initially K, B and T were assumed to get the best possible curve in the Simulink model based on the readings. Later optimization code [12], as shown in Appendix 3, was used to call the Simulink model to do iterations. The Method of least square was then employed to minimize the error between the theoretical and the experimental curves by varying the B, K and T using optimization code.

The most suitable constants were then determined so that the error becomes minimum and approaching zero.

The figure 5.4 and figure 5.5 shows some iterations of the optimization code. The red line is theoretical curve and blue line overlapping are the iterations done by the optimization code. The thin magenta (bottom) line is the difference between the red and blue lines.

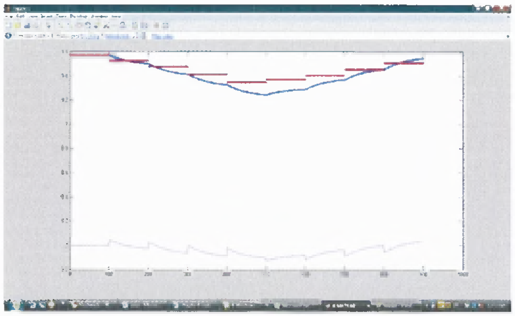

Figure 5.4 Optimize 1

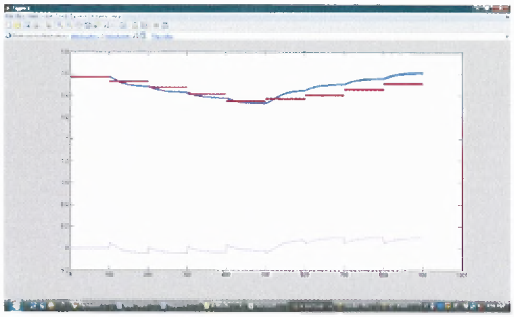

Figure 5.5 Optimize 2

Figure 5.6 shows the final optimization in MATLAB and figure 5.7 shows the scope of the final graph obtained after running the optimization code.

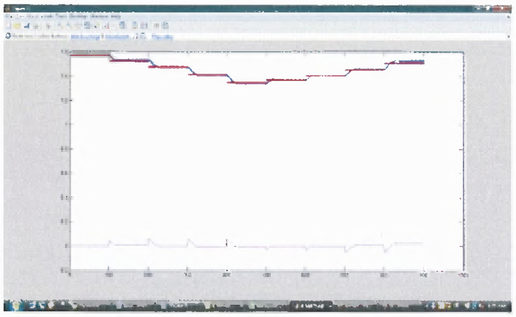

Figure 5.6 Final optimize

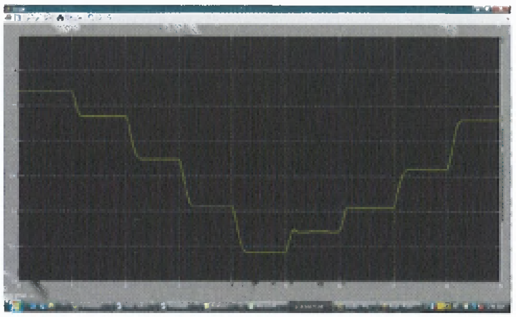

Figure 5.7 Scope

The values of K, B and T were obtained as below for the theoretical graph given in figure 5.1

K= 2.0102 N m/rad

B=0.1842 N m-s/rad

T=0.0956 N m

The values of K, B and T obtained from the model will be helpful to devise an ankle brace in future.

CHAPTER 6

RESULTS

19 Human subjects Fwere tested, out of which 7 patients have past history of physiological disorder. The average age of patients was 56 years, the average weight 193 pounds and the average height being 5'8". The control subjects were in the range of 24-30 years, having 155 pounds of average weight and 5'6" average height.

The resulting angular displacements from testing all human subjects are tabulated and presented in Appendix A. These values are plotted in Cartesian coordinate system having horizontal axis as load and vertical axis as displacement (Tables A.1 to A.7 patients and A.8 to A.19 controlled subjects). .

Certain assumptions are made while performing the experiments to quantify the energy dissipated.

- Subjects tissue volumes are considered to be homogeneous
- Tissues and muscles are at complete rest while performing the experiment.

6.1 Reproducibility Test

Reproducibility is defined as ability of the AnTm to produce similar results when tested again for the same subject; with the same methods and procedures described in section 4.1. Two healthy subjects volunteered for this experiment and the results obtained are presented in table 6.1 as shown below.

Table 6.1 Reproducibility test results

Subject	Age	Sex	Height	Leg	BMI	Weight (Pounds)	P.ROM		HLA	
							B	A	B	A
8	24	M	5"11"	R	20.2	117	7.6	8.33	41.63	41.99
9	24	F	5'3"	R	20.7	146	10	9.65	38.78	40.15

B stands for before, A stands for after and R stands for right.

P stands for passive.

The AnTm procedures were carried out at an interval of 30 minutes. We found 99.6% reproducibility for male subject and 96.46% reproducibility for female subject.

6.2 Plots and data from subject 1 to 7

Table 6.2 Data obtained from 7 patients

Subject	Age	Sex	Height (Inches)	Weight (Pounds)	BMI	HLA		P.ROM	
						L	R	L	R
1	59	M	6'2"	257	33	26.79	36.81	4.2	7.02
2	66	M	5'10"	160	23	29.87	34.62	5.1	6.2
3	57	M	6'0"	200	27.1	19.08	21.70	4.62	5.84
4	63	F	5'2"	145	26.5	43.32	21.95	7.69	8.73
5	54	F	5'6"	167	27.0	48.46	44.67	10.01	13.45
6	48	M	5'8"	181	27.5	49.67	32.21	6.82	4.29
7	43	M	5'7"	241	37.7	31.06	51.4	5.38	9.17
Mean	55.71		5'7"	193	28.82	35.46	34.76	6.26	7.81

L stands for left and R stands for right leg. P stands for passive.

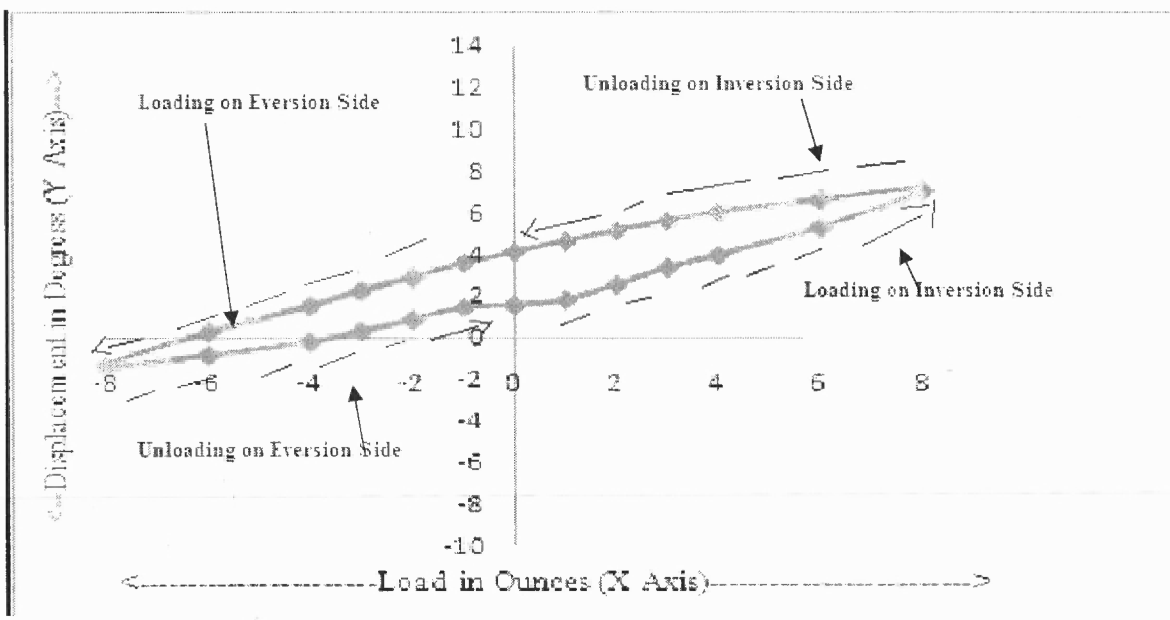

Figure 6.1 Detailed Hysteresis plot for Subject 1 left leg for formation of Average Hysteresis loop

As shown in figure 6.1, the horizontal axis represents the load (ounces) and the vertical axis represents the displacement. The positive values of the weights on horizontal axis and the positive values of the displacement on the vertical axis are the readings for Inversion. The negative values of the weights on horizontal axis and the negative values of the displacement on the vertical axis are the readings for Eversion. The above curve is obtained by averaging 3 cycles of Hysteresis loop is as shown in figure 6.2. All the figures from 6.3 to 6.27 follow the same horizontal and vertical axis and also its loading and unloading on respective side.

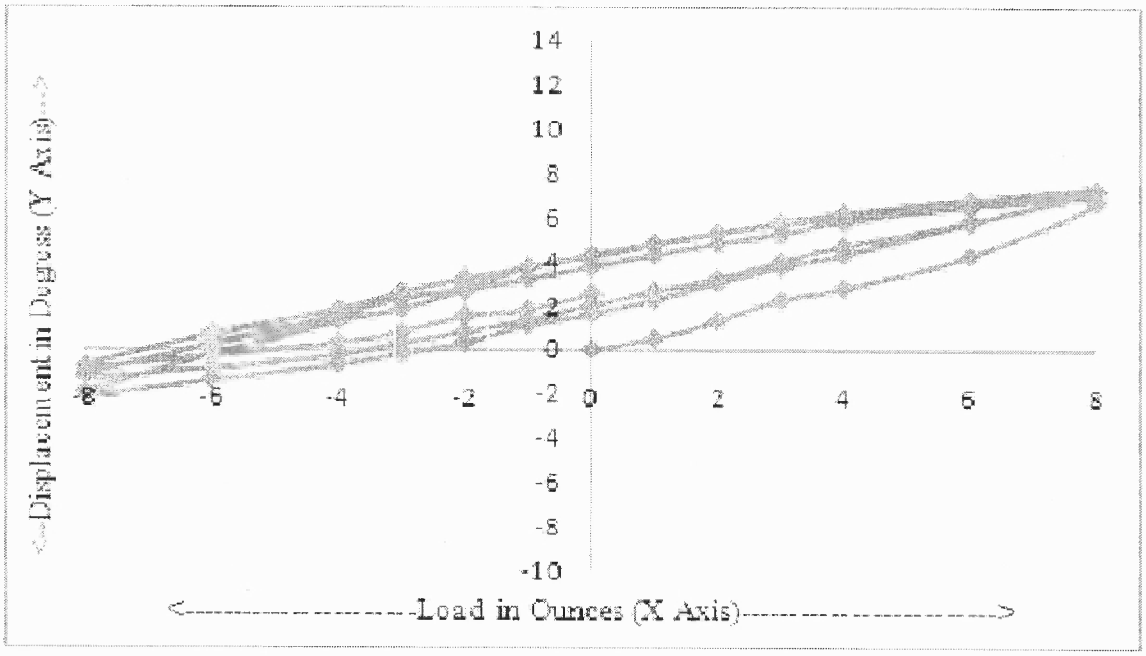

Figure 6.2 3 cycles of Hysteresis loop obtained for Subject 1 left leg.

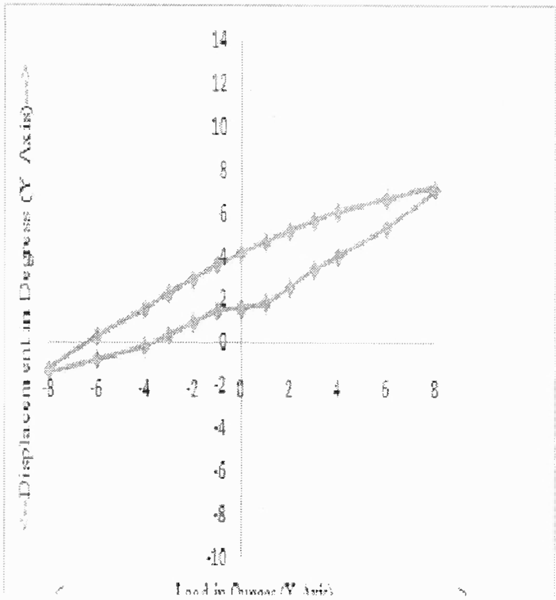

Figure 6.3 Subject1 Left Leg

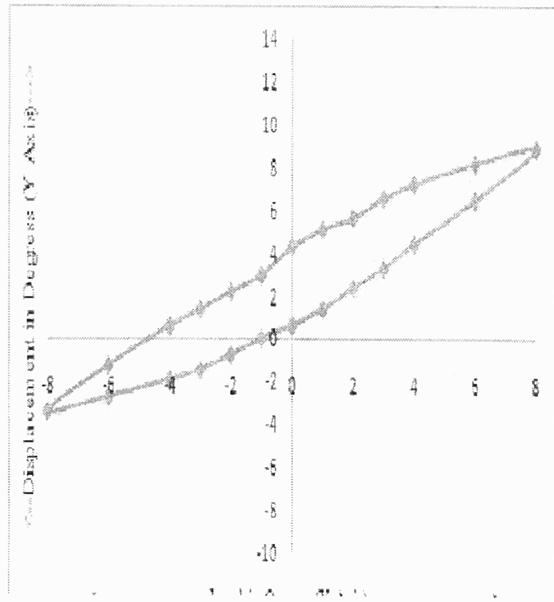

Figure 6.4 Subject1 Right Leg

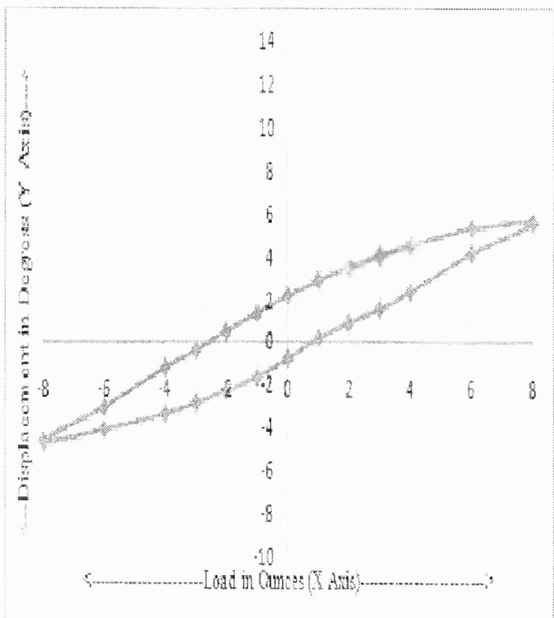

Figure 6.5 Subject2 Left Leg

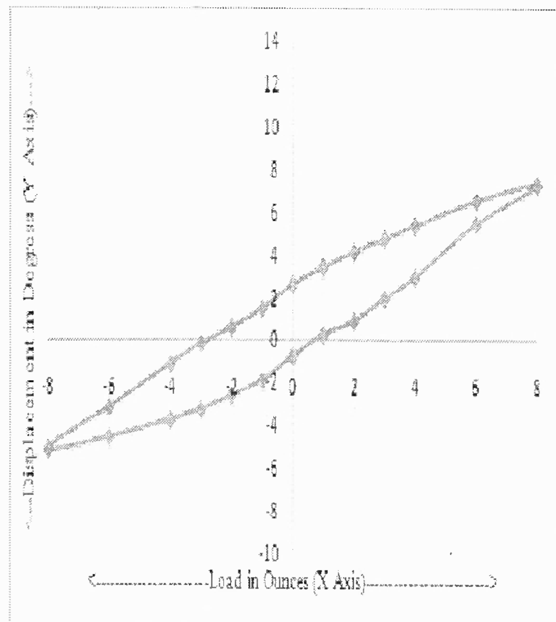

Figure 6.6 Subject2 Right Leg

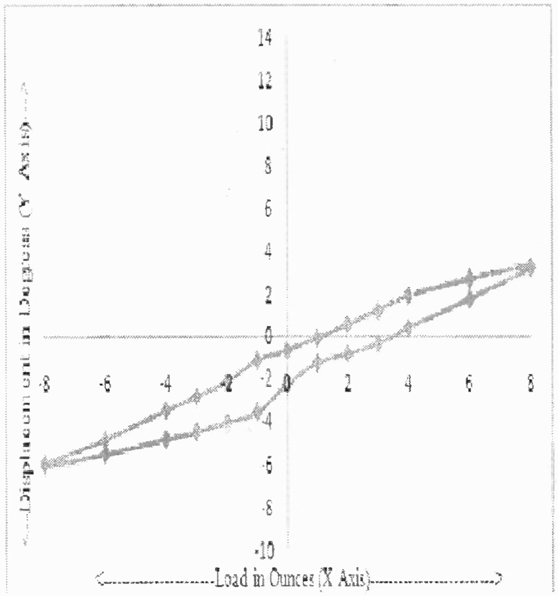

Figure 6.7 Subject3 Left Leg

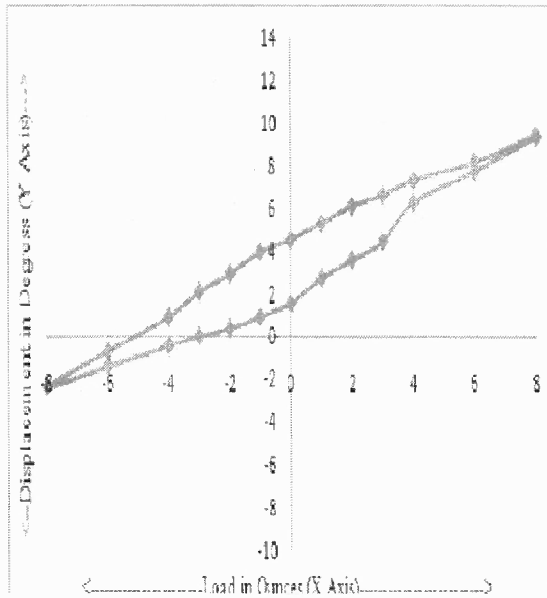

Figure 6.8 Subject3 Right Leg

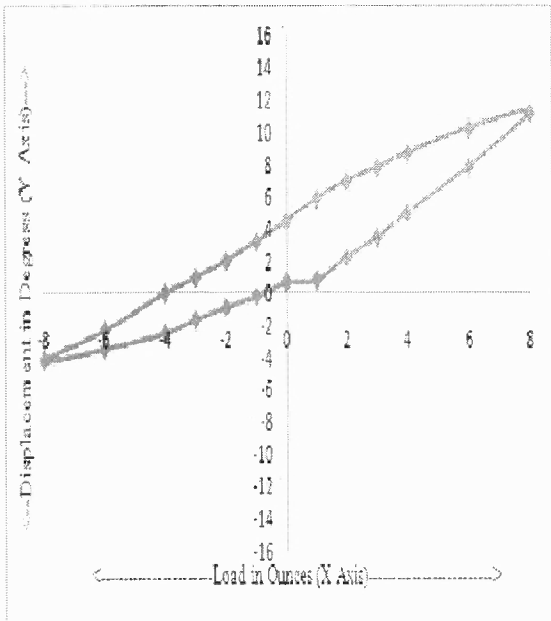

Figure 6.9 Subject4 Left Leg

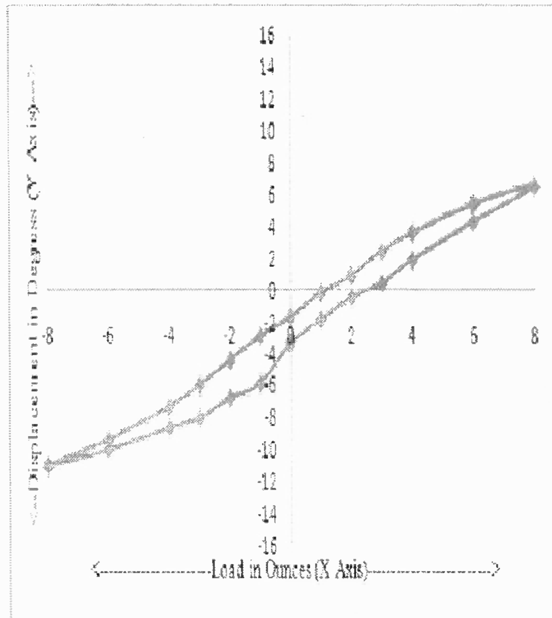

Figure 6.10 Subject4 Right Leg

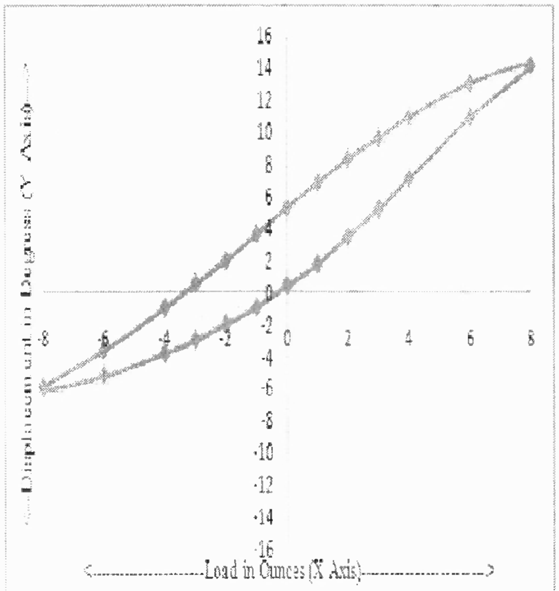

Figure 6.11 Subject5 Left Leg

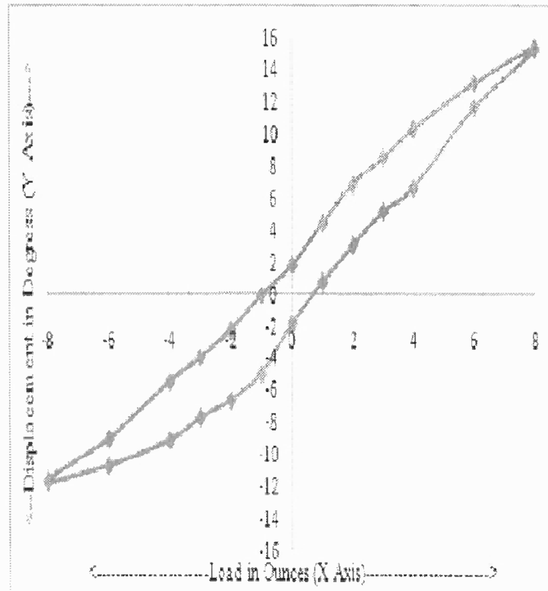

Figure 6.12 Subject5 Right Leg

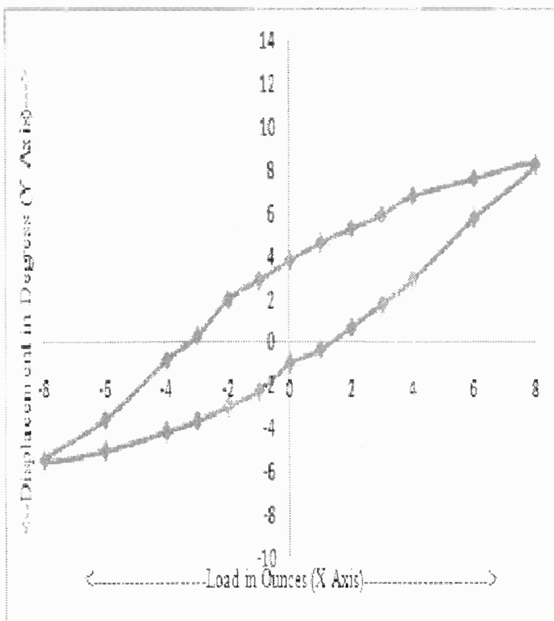

Figure 6.13 Subject6 Left Leg

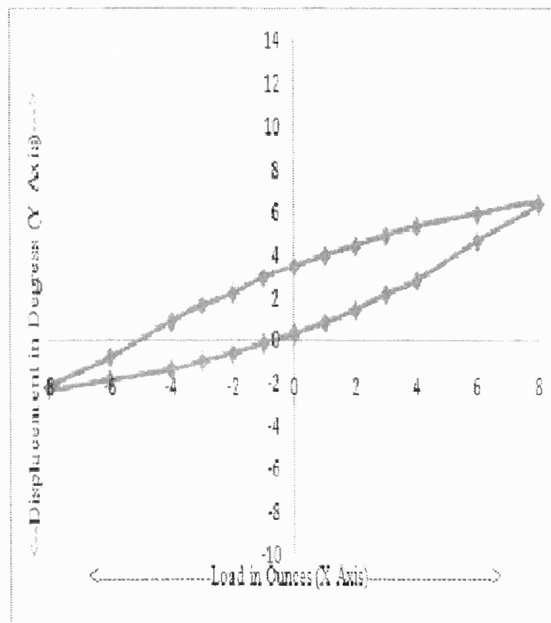

Figure 6.14 Subject6 Right Leg

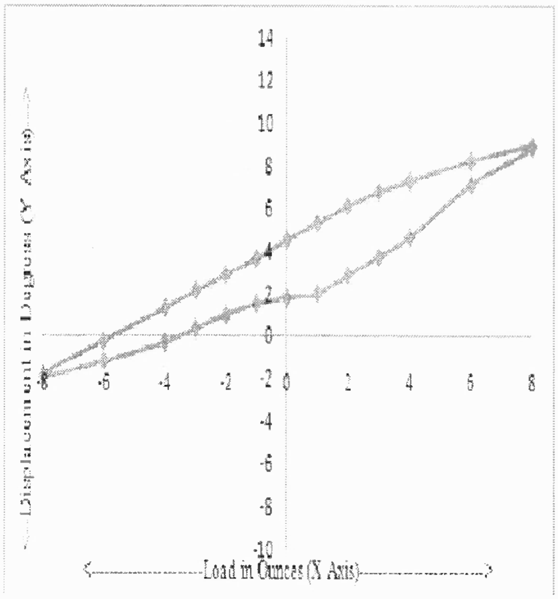

Figure 6.15 Subject7 Left Leg

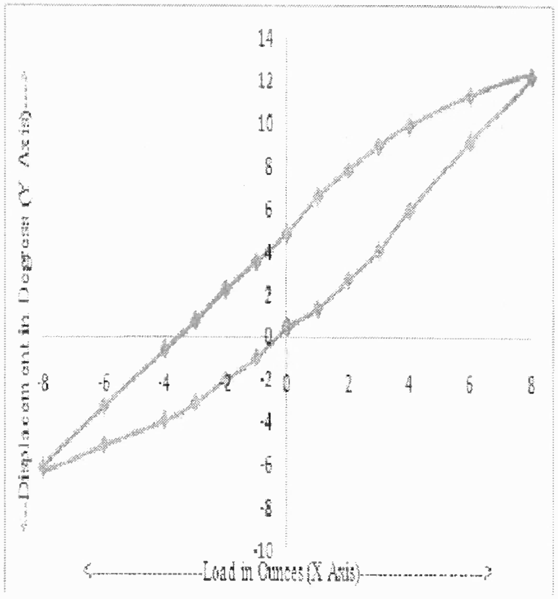

Figure 6.16 Subject7 Right Leg

As shown in all these figures above, the passive ROM and HLA vary for all the subjects with different BMI's. The right leg proves to be less stiff due to its more passive ROM when compared to left leg for all the subjects. HLA and ROM are independent variables. Their correlation coefficient was found to be 0.65.

6.3 Plots and data from subject 9 to 19

Table 6.3 Percentage change in HLA before and after exercise for subject 9 to 19

Subject	Exercise`	Leg	BMI	Percentage % Change in HLA
9	Isometric Inversion	L	20.2	-23.86%
10		R	16.6	-12.06%
11		R	17.2	17.96%
12	Isometric Eversion	L	23.1	-12.6%
13		L	20.5	3.35%
14	Isometric Dorsiflexion	R	23.6	8.13%
15		R	20.4	-26.36%
16	Isometric Plantarflexion	R	33.1	-14.76%
17		L	25	-14.4%
18		L	24	1.55%
19		L	21.3	0.9%

The plots shown below have two hysteresis loops in one graph. The blue line shows hysteresis loop before exercise and the red line shows hysteresis loop after exercise.

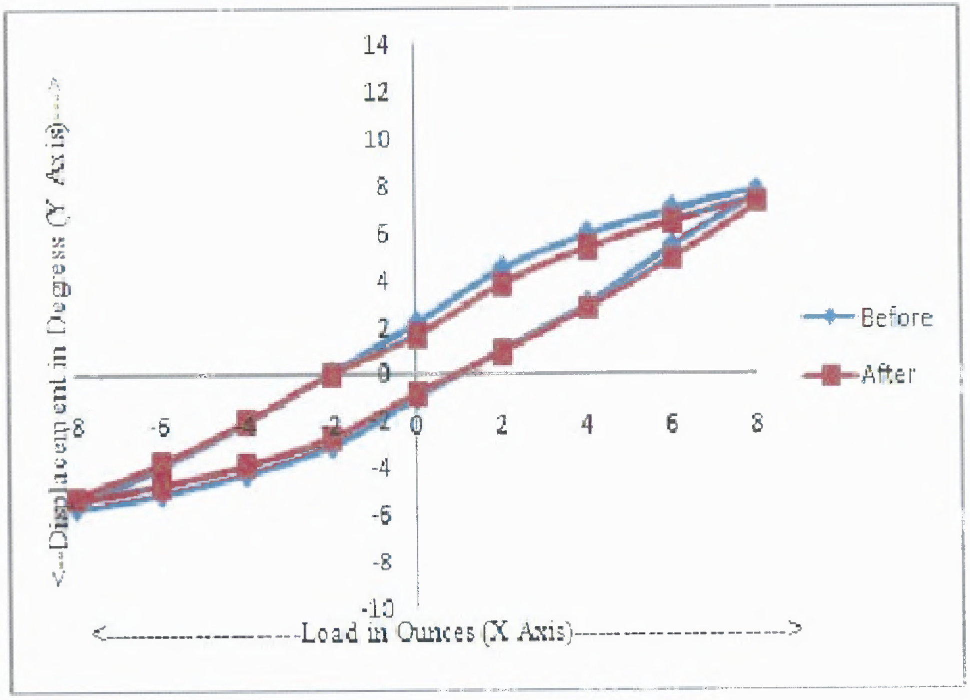

Figure 6.17 Hysteresis plot for subject 9

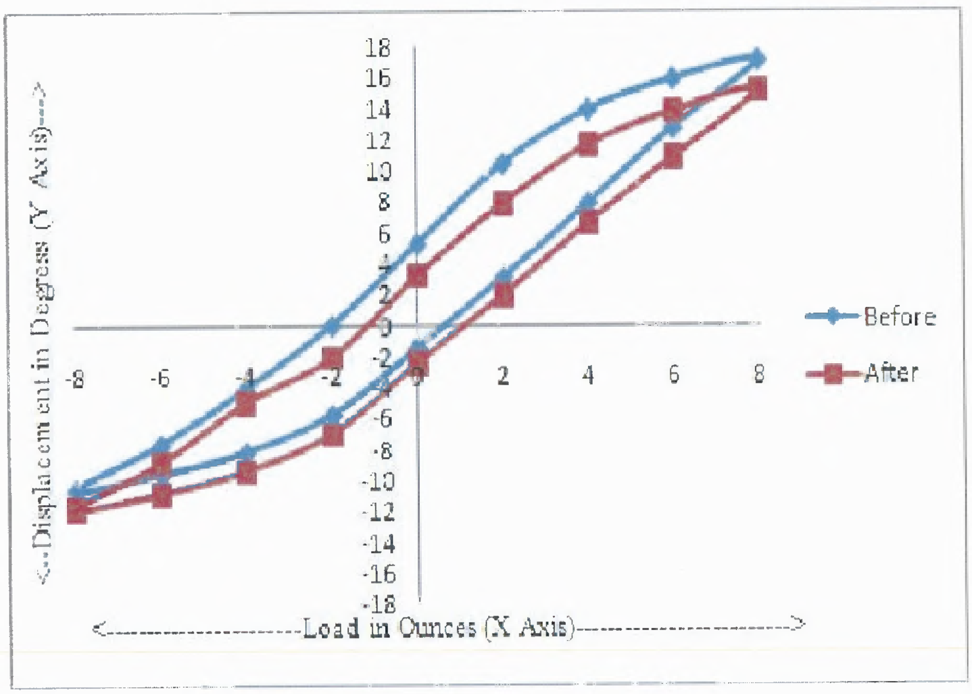

Figure 6.18 Hysteresis plot for subject 10

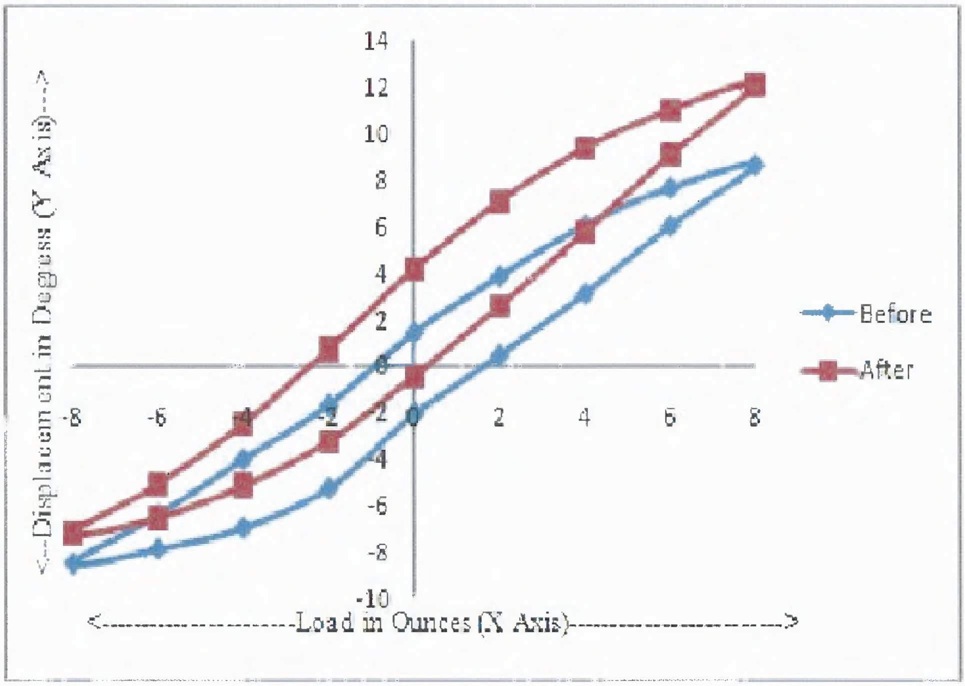

Figure 6.19 Hysteresis plot for subject 11

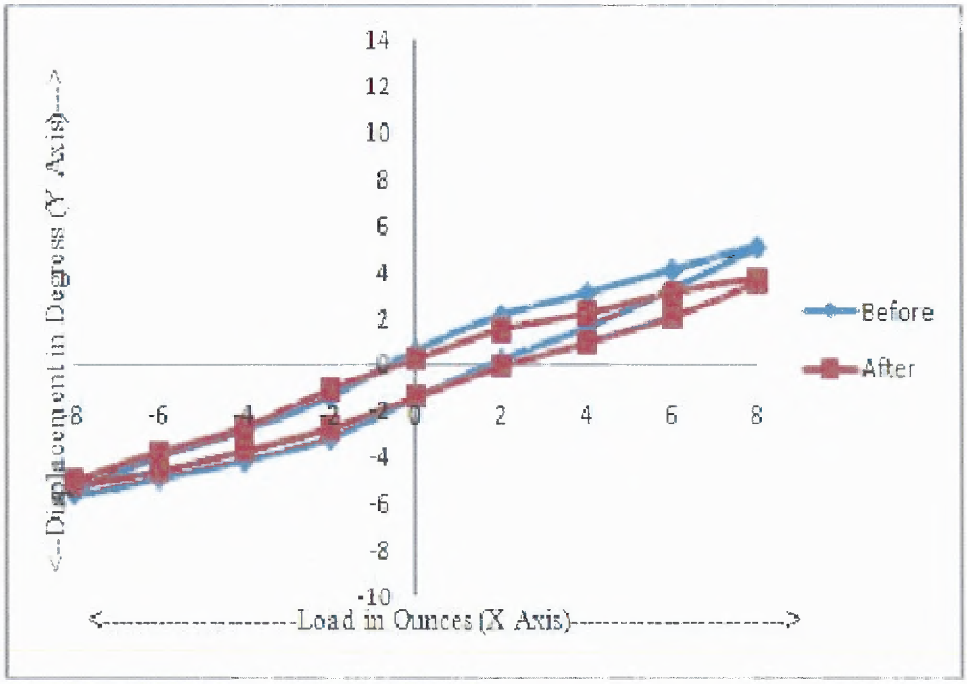

Figure 6.20 Hysteresis plot for subject 12

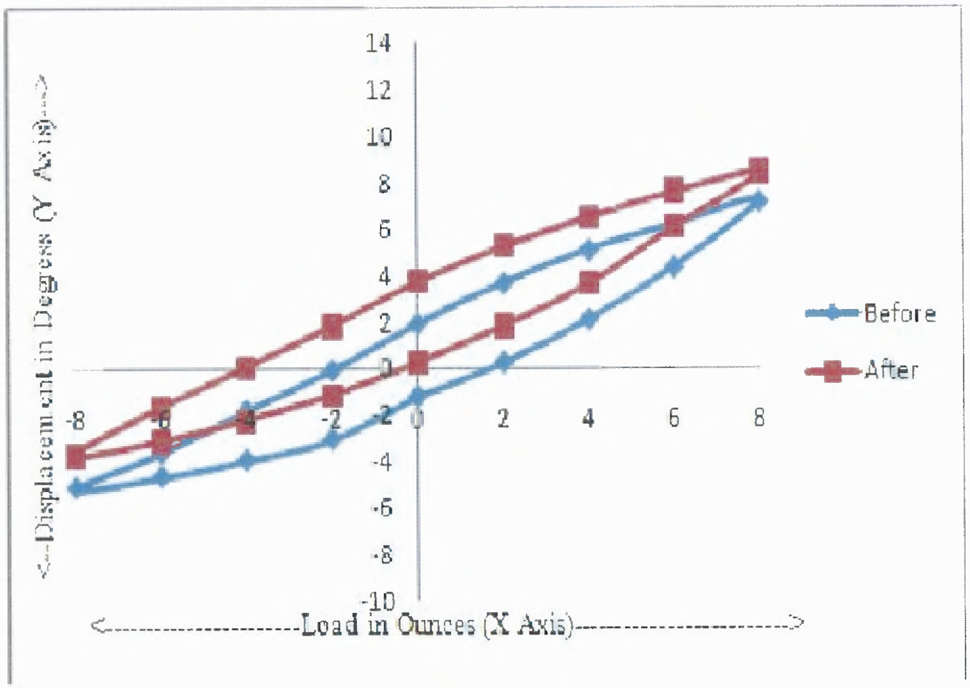

Figure 6.21 Hysteresis plot for subject 13

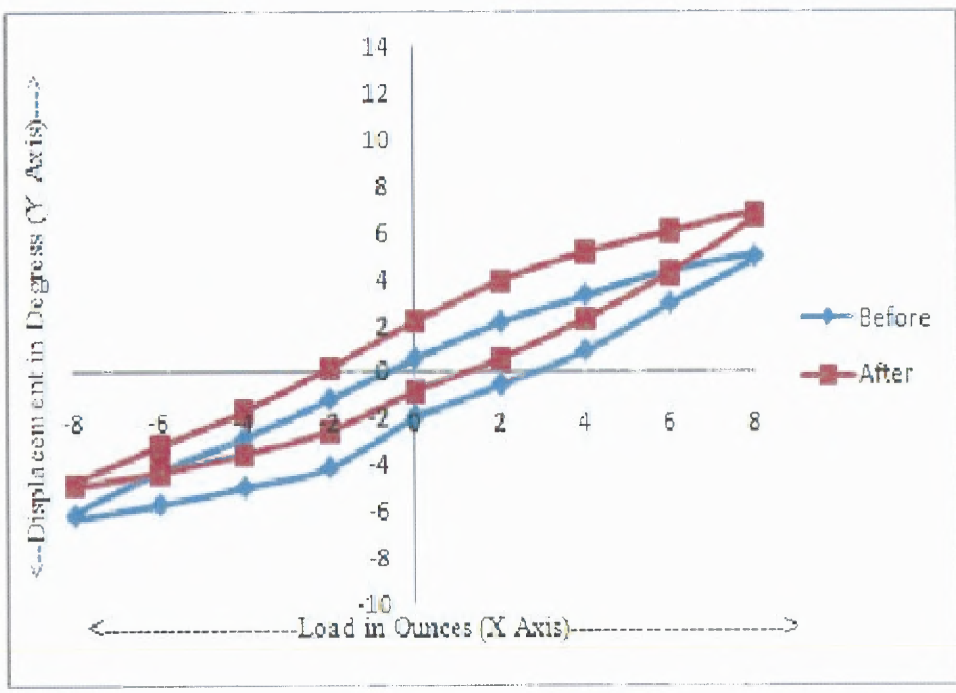

Figure 6.22 Hysteresis plot for subject 14

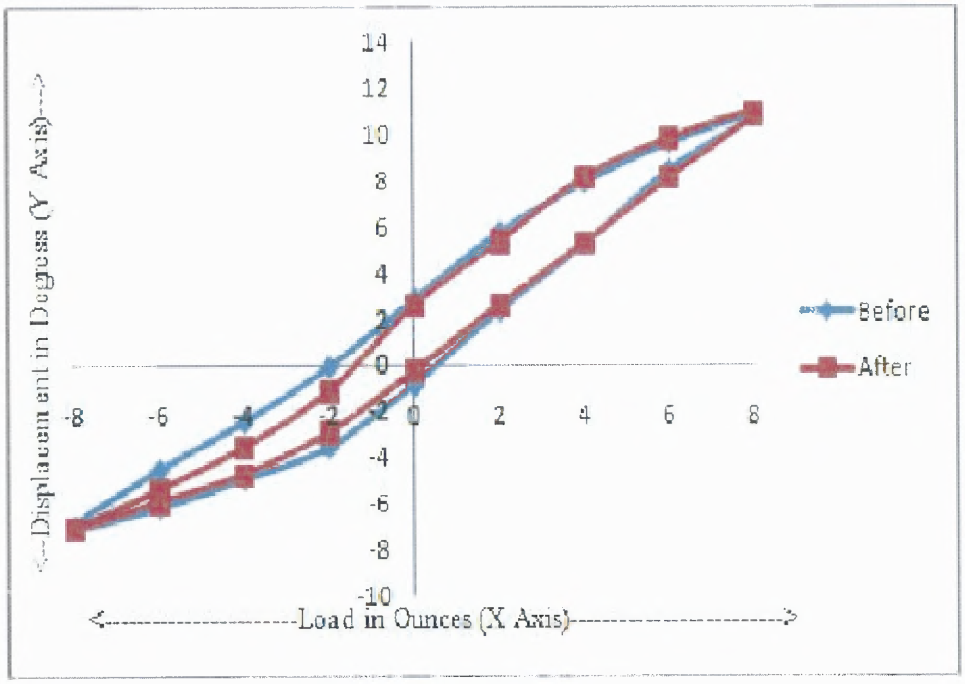

Figure 6.23 Hysteresis plot for subject 15

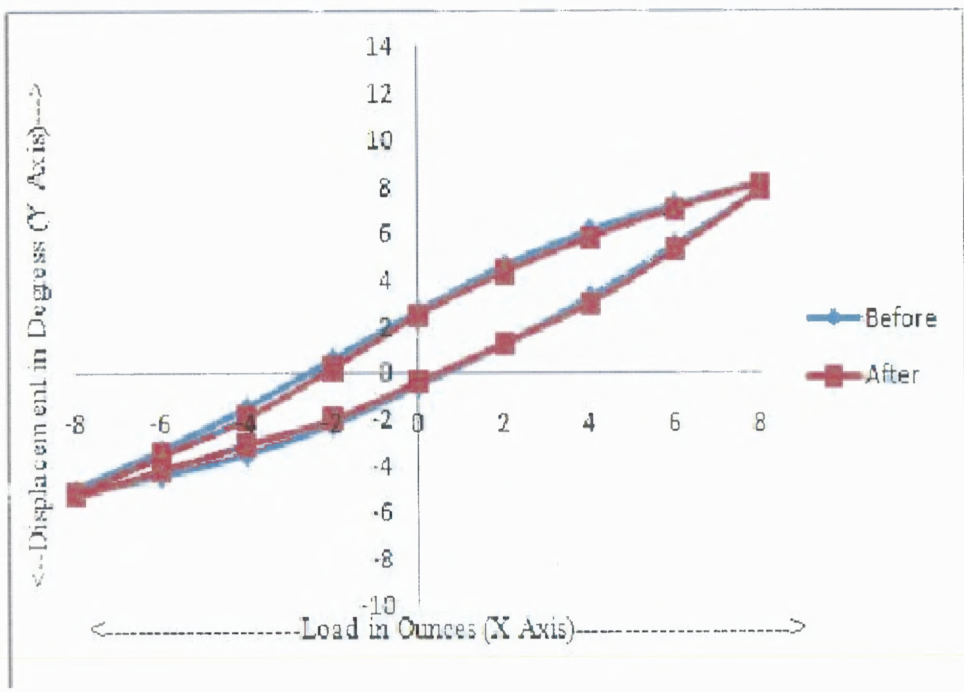

Figure 6.24 Hysteresis plot for subject 16

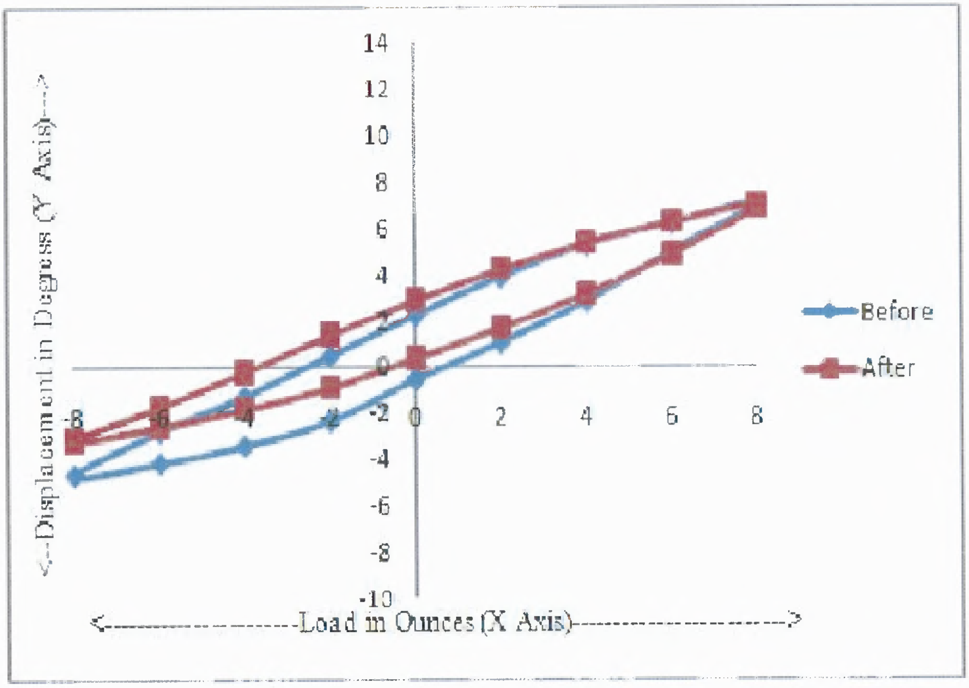

Figure 6.25 Hysteresis plot for subject 17

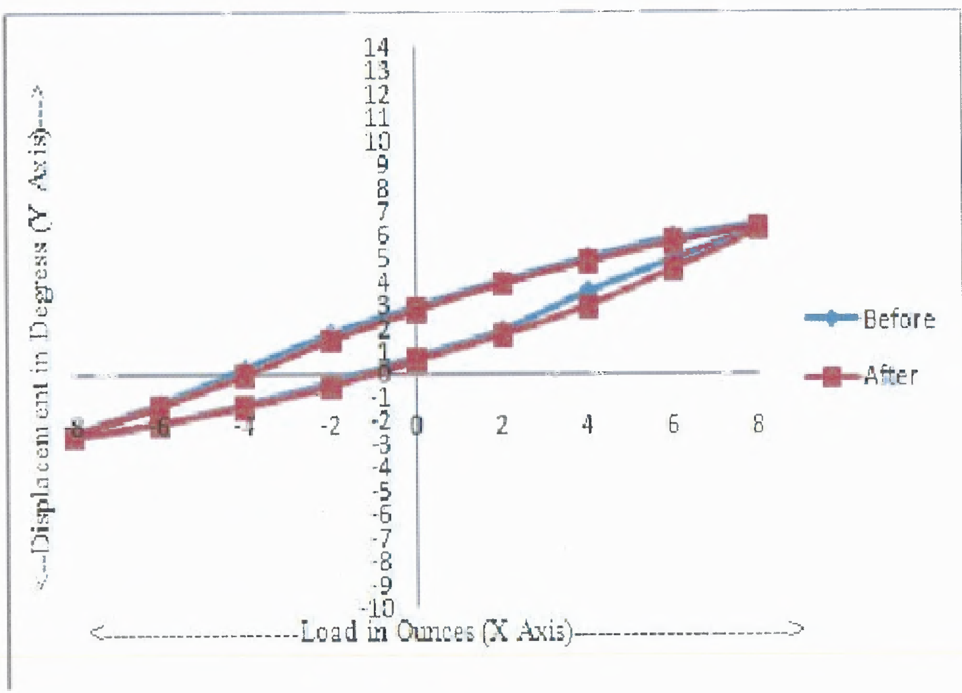

Figure 6.26 Hysteresis plot for subject 18

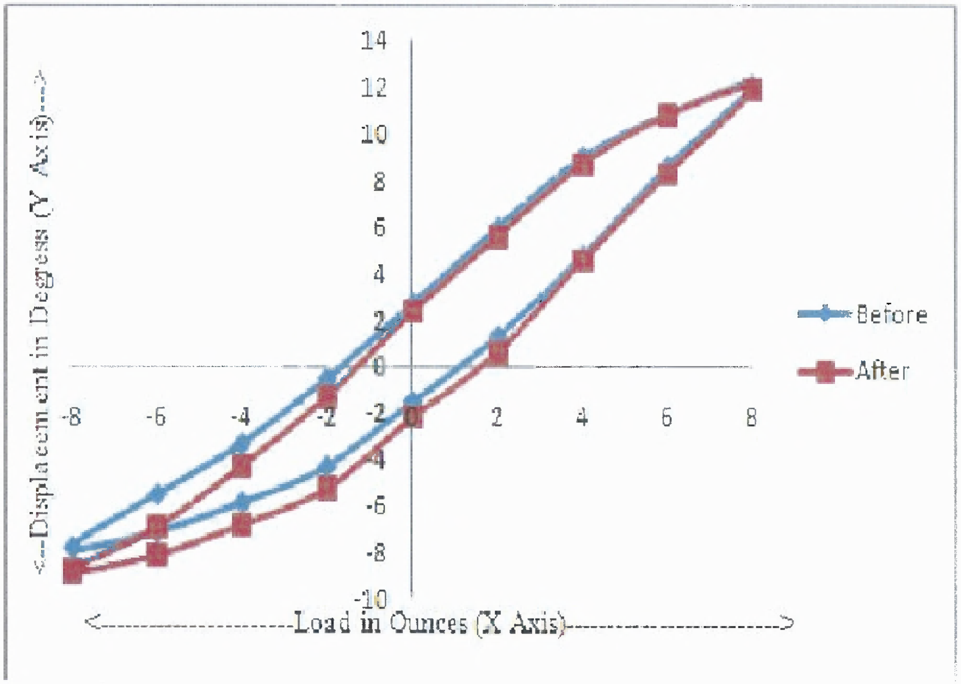

Figure 6.27 Hysteresis plot for subject 19

6.4 Results obtained from SIMULINK model for all the subjects.

Table 6.4 K, B and Tf for all the subjects

Subject	Leg	Passive ROM	Retentivity	K	B	Tf	Error
1	Left	84.47	87.45	3.88	0.462	0.147	0.03
	Right	81.79	86.37	2.59	0.2160	0.1481	0.08
2	Left	83.67	87.05	3.24	0.2835	0.1415	0.08
	Right	81.96	86.62	2.78	0.18	0.1445	0.08
3	Left	84.5	88.42	4.34	0.2189	0.1246	0.03
	Right	82.11	86.98	2.92	0.1005	0.1441	0.05
4	Left	79.47	86.2	2.253	0.2020	0.13	0.1
	Right	80.20	88.42	2.801	0.1631	0.061	0.14
5	Left	76.31	72.81	1.693	0.0965	0.1411	0.28
	Right	85.16	86.31	1.5629	0.1857	0.05	0.62
6	Left	83.8	85.28	2.19	0.2313	0.1632	0.1
	Right	83.92	86.86	3.380	0.4030	0.1595	0.04
7	Left	82.89	87.29	3.709	0.2702	0.1357	0.04
	Right	78.3	85.11	1.983	0.1503	0.1302	0.18
8	Before	76.52	86.65	1.87	0.07	0.1194	0.22

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CHAPTER 7

CONCLUSION

The reproducibility tests were performed by calculating the HLA for two control subjects with the interval of 30 minutes between the two tests. 99.6% reproducibility was observed for a control male subject and 96.4 % for a control female subject. This test was done to show that the same subject had the same results obtained after 30 minutes.

The varied results obtained from Appendix (B.9 to B.19) in the terms of percentage change in the HLA and the passive ROM, proves that all exercises give increase/decrease in the HLA as well as in ROM. So it is suitable to give all these exercises to patients for the ankle strengthening. It is also observed that a period of 5 minutes interval after the exercise gives expected results for all the controlled subjects.

This non-invasive study provides very useful information for the diagnosis of ankle joint disorders. The hysteresis loop obtained due to the cyclic loading of weights during the inversion and the eversion process gives a quantifiable data. This data will help in predicting existing physiological condition of the ankle joint.

Observing the hysteresis plots in Appendix B, one can see that the passive ROM towards for the Inversion is more than the Eversion for all the subjects. This proves that the Inversion side is more flexible than the Eversion side.

From the results section for the patients, one can observe that in the first cycle of the tests performed, the inversion side has more retentivity than the eversion side. Again for all the subjects the hysteresis can have separated plots of the inversion and the eversion side and then can compare the viscoelasticity of each side of ankle joint.

Discontinuity in hysteresis loops is frequently observed in the patients as compared to the control subjects. This can be interpreted for prognostic purposes by the physicians.

For the normal subjects, it was found that the results of the second and the third cycle are almost identical whereas for patients, one has to perform more cycles of tests to obtain identical results.

A correlation of 0.65 is found between the viscoelasticity and the passive ROM from the data for all the 19 subjects including the patients.

Finally, it is concluded that the Ankle torsion monitor has a great potential to become a diagnostic tool for physicians in the near future.

CHAPTER 8

FUTURE RESEARCH

The present study includes passive study for detection of the viscoelasticity of the ankle and its dysfunction. This is done by obtaining the hysteresis loop from the AnTm device. But while doing this procedure it was assumed that the ankle is passive as all the forces are neutralized. If the subject becomes curious to see the light beam, then the reading might change. It is therefore suggested that the experiments may be performed under general anesthesia. This might give useful information in the field of neurology.

It is recommended that subjects with the same BMI and age group may be tested to determine the hysteresis loop. This will establish a standard baseline for comparison purposes for the patients of the same BMI and age group. Also, the experiments should be done separately for both the sexes, as the stiffness and viscoelasticity of the female ankle joint are different from that of the male.

Current study involves testing procedures of un-automated AnTm. The readings obtained are manually taken by visual observation resulting in personal error. Automation of the AnTm with necessary changes will help in removing personal error from the reading. The physicians will not have to hire an assistant for getting the results from the un-automated AnTm. Calculations of the results will become quicker using appropriate software. Elimination of adding weights can be done by having a designed motor application or by some other mechanism. Flock of birds with the appropriate MATLAB coding can be employed to find deflection at all stages.

Innovative design for AnTm can include measurement of the dorsiflexion and the plantar flexion apart from the inversion and the eversion. This will give a complete diagnosis of the Ankle Joint.

Using the ATM (Anatomic Torsion Monitor) for low back, the AnTm for ankle joint and Knee Torsion Monitor (under consideration in this lab) will give a correlation between the hip, the knee and the ankle joints which might be useful information for physicians for diagnosing the disorder of the leg.

The plantar plane of the foot varies from an individual to another. At the present time, the wooden block in the AnTm is designed in such a way that it will not fit all foot with respect to the two wings being exactly perpendicular to the target. It is recommended that the wooden block, which is being used now, should be flexible and must have some kind of mechanism that will fit the plantar plane of the foot for every individual.

Furthermore, it is recommended that some kind of strap should be wrapped over the calf muscles in the leg that will keep whole leg in the same position and control the tremor of the foot. But the strap should not be tightly wrapped; it is done only to avoid any kind of activation of the tissues into tension or compression.

Finally, the position of the ankle unit relative to the foot should be the same for all the subjects otherwise it will give different readings.

APPENDIX A

LOAD V/S DISPLACEMENT TABLE FOR THREE CYCLES.

APPENDIX A.1

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 1

Name : Subject 1
Weight: 257 Pounds
Date: 09/08/09
Sex: M

Age: 59
Height: 6"2"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

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	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I /E												
L1	0	0.5	1.3	2.25	2.8	4.25	6.75	6.5	5.8	5.25	4.8	4.3
L1	3.75	3.2	2.65	1.8	1.25	-0.25	-2	-1.4	-0.7	-0.2	0.3	1.1
L2	1.6	2.25	3	3.75	4.3	5.75	7.2	6.5	6	5.7	5.25	4.75
L2	4.2	3.7	2.8	2.3	1.5	0.25	-1.25	-0.85	-0.25	0.3	0.8	1.35
L3	2	2.65	3.25	4	4.7	5.8	7.25	6.8	6.2	5.8	5.3	4.8
L3	4.3	3.75	3.2	2.6	1.8	0.7	-0.8	-0.25	0.3	0.8	1.5	1.8
L4	2.55	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I /E												
R1	0	0.75	1.9	2.8	4.25	6.75	9.8	8.9	7.9	7	5.8	5.2
R1	4.4	2.2	2	1.3	0.4	-1.7	-4.25	-3.55	-2.65	-2	-1.3	-0.5
R2	0.1	1.3	2.25	3.25	4.25	6.25	8.4	7.8	6.85	6.25	5.5	5
R2	4.2	3.5	2.25	1.25	0.35	-1.3	-3.2	-2.65	-1.6	-1.2	-0.5	0.25
R3	1.15	2	2.9	3.75	4.65	6.3	8.25	7.7	6.75	6.25	5.5	5
R3	4.1	3.2	2.3	1.5	1	-0.8	-2.8	-2	-1.5	-1.2	-0.5	-0.25
R4	1.2	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.2

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 2

Name : Subject 2
Weight: 160 Pounds
Date: 09/22/09
Sex: M

Age: 66
Height: 5"10"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
L1	0	0.75	1.25	1.75	2.5	4.15	6	5.45	4.7	4.25	3.75	3.15
L1	2.4	1.65	0.85	-0.2	-1.2	-3.2	-5.15	-4.5	-3.8	-3.3	-2.75	-2
L2	-1.3	-0.5	0.45	1.25	2.05	4.1	5	5.3	4.5	4	3.4	2.8
L2	2.2	1.25	0.25	-0.6	-1.3	-3.2	-4.65	-4.15	-3.4	-2.85	-2.25	-1.75
L3	-1.25	0.15	0.85	1.5	2.3	4	5.5	5	4.2	3.75	3.2	2.5
L3	1.75	1	0.25	-0.5	-1.25	-2.85	-4.3	-3.75	-3	-2.5	-2	-1.3
L4	-0.75	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
R1	0	1.1	1.6	2.3	3.25	5.5	7.75	7	6.1	5.5	4.75	4.2
R1	3.3	2.3	1.25	0.3	-0.75	-3.2	-5.55	-4.8	-4.1	-3.4	-2.85	-2.2
R2	-1.3	-0.3	0.25	1.7	2.75	5	7.25	6.5	5.4	4.7	4.25	3.5
R2	2.7	1.5	0.65	-0.2	-1.25	-3.1	-4.8	-4.3	-3.5	-3	-2.25	-1.5
R3	-0.85	-0.1	0.75	1.75	2.75	5.75	6.75	6	4.5	3.9	3.3	2.5
R3	1.75	0.55	-0.2	-0.7	-1.5	-3.3	-5.1	-4.65	-3.7	-3.4	-2.8	-2
R4	-1	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.3

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 3

Name : Subject 3
Weight: 200 Pounds
Date: 09/22/09
Sex: M

Age: 57
Height: 6'

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
L1	0	1.45	0.8	1.3	2.2	3.9	5.5	4.7	3.75	2.5	1.5	0.75
L1	-0.2	-1	-2	-3	-4	-5.25	-6.5	-5.8	-5.2	-4.75	-4.25	-3.75
L2	-3.2	-2.25	-1.75	-1.25	-0.35	0.75	2.5	2	1.15	0.75	0.25	-0.4
L2	-0.85	-1.3	-2.25	-2.7	-3.2	-4.5	-5.95	-5.5	-4.75	-4.45	-4.1	-3.5
L3	-2.75	-2	-1.65	-1.2	-0.75	0.5	1.7	1.25	0.7	0.25	-0.2	-0.65
L3	-1	-1.2	-2.2	-2.85	-3.25	-4.75	-5.6	-5.2	-4.5	-4.25	-3.8	-3.5
L4	-3.1	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
R1	0	0.55	1.2	1.75	2.65	4.8	7.25	6.7	5.8	5.25	4.7	4
R1	3.3	2.75	1.95	1.3	0.5	-1.2	-2.85	-2.2	-1.35	-0.85	-0.4	0.25
R2	1.75	3.25	4.2	5.15	7.5	8.2	9.5	8.9	7.75	7	6.75	6.25
R2	5.6	5.25	4.25	3.4	2.75	0.75	-1.25	0.5	1.2	1.5	1.75	2.2
R3	3	4.25	5.25	6.3	8.5	10.05	11.25	8.8	8.25	7.5	6.75	5.5
R3	4.65	3.75	2.5	1.5	-0.6	-1.65	-3	-2.5	-1.2	-0.65	-0.25	0.25
R4	1.25	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.4

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 4

Name : Subject 4
Weight: 145 Pounds
Date: 09/23/09
Sex: F

Age: 63
Height: 5"2 1/2"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
R1	0	0.8	2.1	3.2	5.25	7.15	9.3	8.2	6.3	5.2	3.75	2.3
R1	0.75	-0.75	-3.1	-5	-6.5	-9.2	-11.25	-10.35	-8.5	-7.75	-6.7	-5.3
R2	-3.65	-2.25	-1.2	-0.8	0.05	2.35	4.85	4.05	2.3	1.2	-0.5	-1.5
R2	-3.75	-5	-6.25	-7.75	-8.75	-10.2	-11.55	-10.4	-9.2	-8.45	-7.55	-6.6
R3	-5.5	-4.25	-2.5	-1.2	0.2	3.2	5.25	3.8	2	0.75	-0.7	-1.5
R3	-2.25	-3.1	-4	-5.25	-6.75	-8.7	-10.25	-9.2	-8.3	-7.9	-6.2	-5.75
R4	-4.15	XX	XX	XX	XX	XXX	XXX	XXX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
L1	0	0.65	1.65	2.75	4	7.81	11.2	10.15	8.2	7.5	6.8	5.4
L1	4.05	3.1	1.75	0.4	-0.75	-3.65	-6.1	-5.4	-4.5	-3.75	-3.2	-2.5
L2	-1.5	-0.35	2	3.35	4.25	6.25	10.35	9.25	7.8	6.5	5.35	4.5
L2	3.3	2	0.85	-0.2	-1	-3.2	-4.7	-3.75	-2.8	-2.25	-1.3	-0.75
L3	0.75	2.1	3	4.25	6.75	9.5	12.1	11.3	10.1	9.5	8.75	7.75
L3	6.1	4.5	3.4	2.7	1.75	-0.1	-1.75	-1.25	-0.2	1	1.75	2.65
L4	3.5	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.5

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 5

Name : Subject 5
Weight: 167 Pounds
Date: 09/23/09
Sex: F
Age: 54
Height: 5"6"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
R1	0	1.2	3.15	4.8	5.5	9.75	14.5	12.7	9.8	8.25	6.5	4.6
R1	2.4	0.5	-1.25	-2.75	-4.5	-7.75	-10.45	-9.5	-8.15	-6.75	-5.7	-3.75
R2	-0.75	2	3.55	6	7.75	12.6	15.5	13.25	10.1	8.15	6.2	3.8
R2	1.21	-0.75	-3.35	-5.2	-6.5	-10.7	-12.5	-11.5	-9.75	-8.25	-7.25	-5.75
R3	-3	-1	2.25	4.5	6.5	12.25	15.75	13.25	10.75	8.9	7.75	4.75
R3	1.65	-0.1	-2.25	-4.1	-5.5	-8.7	-12	-11.1	-9.5	-8.25	-7	-5.45
R4	-3.75	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
L1	0	1.2	2.75	4.8	6.75	10.75	14.2	13.1	11.2	10.15	8.75	7.2
L1	5.5	4	2.25	0.75	-0.95	-3.75	-6.35	-5.7	-4.25	-3.35	-2.2	-1.25
L2	-0.1	1.75	3.8	5.4	7.15	10.9	14.2	13.2	10.8	9.15	8.25	6.75
L2	5.35	3.65	1.85	0.5	-1.1	-3.75	-6.1	-5.25	-4	-3.2	-2.2	-1.15
L3	-0.2	2.1	3.7	5.25	7.15	10.75	13.75	12.5	10.5	9.25	7.75	6.25
L3	4.75	3	1.65	0.25	-1	-3.5	-5.5	-4.75	-3.3	-2.5	-1.65	-0.6
L4	1.75	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.6

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 6

Name : Subject 6
Weight: 181 Pounds
Date: 09/29/09
Sex: M

Age: 48
Height: 5' 8"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
L1	0	0.55	1.2	2.25	3.2	6.75	8.7	8.15	7.2	6.25	5.7	5.05
L1	3.85	3.2	2.8	0.8	-0.75	-3.7	-5.8	-5.25	-4.3	-3.85	-3.3	-2.7
L2	-1.85	-0.8	0.2	1.3	2.65	5.2	8.2	7.75	7.15	6	5.2	4.5
L2	3.7	2.7	1.4	-0.25	-1.2	-3.8	-5.8	-5.55	-4.75	-4.25	-3.35	-2.6
L3	-1.8	-0.8	0.55	1.7	2.8	5.15	7.7	6.8	5.85	5.35	4.8	4.2
L3	3.7	2.7	1.7	0.25	-0.55	-3.25	-4.75	-4.25	-3.4	-2.85	-2.25	-1.5
L4	-0.2	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
R1	0	0.5	1.2	1.8	2.25	4.05	5.7	5.2	4.65	4.25	3.8	3.3
R1	2.9	2.35	1.7	1.15	0.25	-1.2	-2.75	-2.3	-1.75	-1.35	-1.05	-0.5
R2	-0.1	0.7	1.3	2.2	3	4.55	6.7	6.25	5.6	5.25	4.75	4.3
R2	3.75	3.25	2.25	1.8	1.15	-0.55	-2.1	-1.7	-1.25	-0.85	-0.45	-0.15
R3	0.6	1.3	1.75	2.5	3.1	5.3	6.75	6.25	5.7	5.2	4.7	4.3
R3	3.7	3.25	2.6	1.95	1.25	-0.6	-1.8	-1.5	-1	-0.7	-0.25	0.25
R4	0.75	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.7

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 7

Name : Subject 7
Weight: 241 Pounds
Date: 10/08/09
Sex: M

Age: 43
Height: 5"7"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)
R1, R2 and R3=Right foot first, second and third series respectively.
L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	0	0.7	1.5	2.25	3.3	6.7	8.1	7.25	8.3	5.8	5	4.25
L1	3.35	2.25	1.5	0.7	-0.15	-1.8	-3.35	-2.8	-1.8	-1.2	-0.5	0.25
L2	1.2	2	2.7	3.75	4.66	6.75	8.75	8.2	7.25	6.7	6.2	5.25
L2	4.4	3.7	2.8	2.3	1.5	0	-1.65	-1.1	-0.2	0.7	1.2	1.75
L3	2.65	3.2	4.2	5	5.85	7.8	9.75	9.2	8.25	7.75	7	6.3
L3	5.65	4.8	4.2	3.25	2.5	1	-0.7	0.2	1	1.5	2.2	2.45
L4	3.2	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	0	0.75	1.85	2.5	4.75	8.5	11.75	10.75	9.25	8.25	7.15	5.8
R1	3.75	2.65	1.5	-0.1	-1.25	-3.85	-8.1	-7.25	-5.7	-4.75	-3.6	-2.65
R2	-1	0.35	2.25	4.2	5.8	9	12.2	11.25	9.8	8.75	7.65	6.5
R2	4.9	3.4	.2	0.7	-0.8	-3.5	-5.75	-4.2	-3.5	-2.8	-1.5	-0.5
R3	1.2	2.75	3.8	5.25	7.1	9.8	12.5	11.75	10.5	9.7	8.5	7.25
R3	5.7	4.35	2.8	1.5	0.1	-2.55	-4.75	-3.85	-2.65	-1.85	-1	0.1
R4	1.6	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.8

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 8

Name : Subject 8
Weight: 116.6 Pounds
Date: 03/5/10
Sex: F

Age: 23
Height: 5"3"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	2.3	5.25	9.2	12.2	10.8	8.75	5.75
R1	2.25	-0.8	-3.75	-6.1	-8.3	-7.6	-6.75	-5.2
R2	-2.7	0.75	4.3	7.9	11.3	10.2	8.2	5.2
R2	1.4	-1.75	-4.7	-5.85	-7.75	-6.9	-5.6	-3.75
R3	-1.2	2.25	6	9.75	13.25	12.1	9.75	6.25
R3	2.7	-0.75	-3.3	-5.3	-7.25	-6.35	-5.3	-3.7
R4	-1	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	2	5.2	8.85	12.3	11	9	5.9
R1	2.4	-0.3	-2.8	-5.2	-7.25	-6.3	-5.2	-3.3
R2	-0.75	2.6	6.25	9.25	12.8	11.75	9.75	6.75
R2	3.6	0.25	-2.75	-4.5	-6.5	-5.7	-4.7	-2.75
R3	-0.2	3.25	6.75	9.75	12.9	12.2	9.85	7.1
R3	4.75	0.8	-1.8	-4.15	-6.2	-5.3	-4.25	-2.4
R4	0.1	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.9

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 9

Name : Subject 9
Weight: 143 Pounds
Date: 10/23/09
Sex: M

Age: 23
Height: 5'10"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

.

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	1.6	3.75	6.7	10.25	9.35	8.2	6.25
R1	3.8	1.25	-1.25	-3.25	-5.8	-5.2	-4.2	-2.4
R2	-0.4	2.1	4.75	7.2	9.8	9.2	8	6.25
R2	3.75	1.25	-1.2	-3.25	-5.25	-4.35	-3.3	-1.8
R3	0.1	2.2	4.75	7.55	9.8	9.2	8.2	6.25
R3	4	1.5	-0.75	-2.8	-4.75	-4	-2.8	-1.35
R4	0.7	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	2	4.25	7.25	9.8	9	7.75	5.75
R1	3.7	1.2	-2.1	-4.75	-7.25	-6.3	-5.3	-3.5
R2	-1	1.25	4.2	7.75	9.75	9	7.75	5.75
R2	3.4	0.3	-2.2	-4.5	-6.7	-5.85	-4.75	-3.2
R3	-0.75	1.75	4.25	7.25	9.75	8.75	7.3	5.25
R3	3.2	0.5	-2.35	-4.65	-6.75	-5.9	-4.75	-3.2
R4	-1.1	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.10

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 9

Name : Subject 9
Weight: 143 Pounds
Exercise: Isometric Inversion
Sex: M
Date: 10/23/09

Age: 24
Height: 5'10"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

L1, L2 and L3= Left foot first, second and third series respectively.

	0 (wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.2	3.25	5.75	7.8	7.2	6.15	4.75
L1	2.3	0.3	-1.75	-3.75	-5.8	-5.3	-4.35	-3.25
L2	-1.7	0.75	2.8	5.2	7.6	6.8	5.8	4.25
L2	1.9	0	-2.3	-4.2	-5.75	-5.2	-4.3	-3.2
L3	-1.4	1	2.75	5.25	7.7	6.8	5.75	4.25
L3	2.25	-0.25	-2.3	-4	-5.5	-4.85	-4.2	-2.85
L4	-1.1	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.35	2.8	4.75	7.25	6.4	5.3	3.75
L2	1.75	-0.1	-2.25	-4.1	-5.55	-5	-4.2	-2.9
L2	-1.25	0.55	2.65	4.75	7.25	6.3	5.25	3.75
L3	1.9	-0.2	-2.1	-3.75	-5.25	-4.75	-3.8	-2.75
L3	-1.1	0.8	2.75	5	7.25	6.5	5.35	3.8
L4	1.15	0.2	-1.75	-3.6	-5.1	-4.4	-3.7	-2.5
L4	-1	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.11

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 10

Name : Subject 10
Weight: 96.8 Pounds
Excercise: Isometric Inversion
Sex: F
Date: 12/14/09

Age: 23
Height: 5'4"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	3.5	7.25	12.6	17.2	15.8	13.75	10.25
R1	5.2	0.25	-3.8	-7.8	-10.81	-9.9	-8.5	-6.35
R2	-2.35	2.25	7.5	12.25	16.75	15.25	13.5	10.2
R2	5	0.5	-4.3	-7.5	-10.75	-9.5	-7.8	-5.25
R3	-1.75	3.	8.8	13.3	17.2	16.5	14.4	10.75
R3	5.5	-0.7	-4.2	-7.75	-10.25	-9.35	-8.2	-5.75
R4	-1.7	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	3.3	7.5	11.8	15.75	14.45	12.3	8.35
R1	3.7	-1.2	-4.2	-8.1	-11.35	-10.5	-9.2	-6.8
R2	-3.2	1.75	6.5	10.25	14.35	13	10.75	7.2
R2	2.7	-2.75	-4.5	-9.3	-12.2	-11.2	-9.7	-7.35
R3	-3.3	0.75	5.75	10.35	15.25	13.85	11.7	7.9
R3	3.2	-2.3	-6.25	-9.2	-11.75	-10.8	-9.25	-6.8
R4	-3.1	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.12

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 11

Name : Subject 11
Weight: 100 Pounds
Excercise: Isometric Inversion
Sex: F
Date: 3/10/10

Age: 24
Height: 5'4"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	1.35	3.75	6.5	9.5	8.5	7.2	4.75
R1	2.3	-0.75	-3.3	-5.75	-8.3	-7.7	-7.2	-5.3
R2	-3.25	-0.25	2.75	5.35	8.7	7.7	5.75	3.5
R2	1.2	-2.15	-4.5	-6.75	-8.5	-7.9	-6.9	-5.2
R3	-2.7	0.25	2.8	5.9	7.75	6.75	5.2	3.25
R3	0.75	-2.2	-4.3	-6.75	-8.7	-8	-6.8	-5.3
R4	-2.25	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	2.3	5.65	8.65	11.8	10.7	9.1	6.7
R1	3.7	0.2	-3.3	-6.25	-8.25	-7.65	-6.3	-4.2
R2	-1.2	2.1	5.35	9.2	12.2	11	9.3	7.2
R2	4.25	0.9	-2.2	-4.7	-6.75	-6.2	-4.8	-3.25
R3	-0.3	3.3	6.25	9.3	12.3	11.3	9.7	7.3
R3	4.5	1	-2	-4.35	-6.6	-5.75	-4.35	-2.3
R4	-0.3	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.13

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 12

Name : Subject 12
Weight: 143 Pounds
Excercise: Isometric Eversion
Sex: M
Date: 10/21/09

Age: 25
Height: 5'6"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	1.25	2.7	4.2	5.75	4.5	3.3	2.3
R1	0.7	-2.25	-3.5	-4.35	-6.2	-5.25	-4.7	-3.25
R2	-2.25	-0.35	1.25	2.75	4.75	4	3.2	2.25
R2	0.75	-0.75	-2.3	-3.4	-4.75	-4.25	-3.3	-2.25
R3	-1.2	-0.25	0.75	2.75	4.65	3.7	2.7	1.8
R3	0.35	-1.2	-2.7	-4.1	-5.7	-5.2	-4.4	-4
R4	-2.25	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.2	2.25	3.75	5.75	5.2	4.3	3.25
R1	1.35	-0.25	-2.2	-3.25	-4.75	-4.2	-3.25	-2.25
R2	-1.65	-0.75	0.25	1.1	2.25	1.75	0.75	0.5
R2	-0.2	-1.2	-2.7	-3.75	-5.2	-4.75	-4	-3.2
R3	-2.25	-0.75	0.25	1.2	2.75	2.25	1.5	0.7
R3	-0.5	-1.75	-3.2	-4.25	-5.2	-4.75	-3.8	-2.75
R4	-1.7	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.14

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 13

Name : Subject 13
Weight: 138.6 Pounds
Excercise: Isometric Eversion
Sex: M
Date: 12/14/09

Age: 24
Height: 5'9"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.3	2.4	4.65	7.75	6.2	5.2	3.75
L1	2.25	0.4	-1.25	-3.75	-5.25	-4.7	-4.1	-3.2
L2	-1.7	-0.4	2	4.25	7.25	6.2	5.2	3.5
L2	1.7	-0.5	-2.5	-3.9	-5.3	-4.75	-4	-3.2
L3	-1.8	-0.2	1.8	4.1	6.5	6	4.8	3.7
L3	1.7	-0.2	-1.75	-3.2	-4.8	-4.5	-3.75	-2.8
L4	-1.4	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.2	3.3	5.25	7.7	7	6	4.75
L1	3.2	1.2	-0.8	-2.3	-4.7	-4	-3.2	-2.2
L2	-0.7	2	3.75	6.2	8.2	7.5	6.2	5.2
L2	3.7	1.8	0.2	-1.5	-3.75	-3.2	-2.25	-1.1
L3	0.3	2.2	3.8	6.75	9.3	8.3	7.25	5.75
L3	4.25	2.4	0.7	-1.25	-2.75	-2.2	-1.3	-0.2
L4	1.3	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.15

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 14

Name : Subject 14
Weight: 151 Pounds
Excercise: Isometric Dorsi-Flexion
Sex: M
Date: 10/21/09

Age: 24
Height: 5'7"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	0.8	2.15	3.4	5.25	4.7	3.75	2.75
R1	1.35	-0.25	-2	-3.1	-5.7	-5.3	-4.55	-3.85
R2	-2.7	-1.25	0.25	2.6	4.7	4.2	3.2	2
R2	0.4	-1.35	-3.2	-4.75	-6.5	-6	-5.3	-4.3
R3	-2.25	-1.3	0.2	2.7	4.7	4	2.8	1.5
R3	-0.1	-2	-3.3	-5	-6.3	-5.75	-5	-4.2
R4	-2.8	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	1.25	2.7	4.2	6.75	6.2	5.2	4.2
R1	2.5	1.2	-1.2	-2.8	-4.75	-4.25	-3.5	-2.7
R2	-1.35	0.25	2.2	4.7	6.7	6.2	5.25	3.75
R2	1.75	-0.75	-2.25	-4.2	-5.75	-5.2	-4.5	-3.4
R3	-1.75	0.35	1.75	3.65	6.25	5.25	4.5	3.25
R3	1.5	-0.75	-2.75	-3.75	-5.25	-4.7	-4	-2.8
R4	-1.3	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.16

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 15

Name : Subject 15
Weight: 134.2 Pounds
Excercise: Isometric Dorsi Flexion
Sex: M
Date: 3/31/10

Age: 27
Height: 5'8"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	2.75	5.75	9.75	11.7	10.3	8.5	5.75
R1	2.9	-0.25	-2.8	-5.2	-8.3	-7.3	-5.8	-4.25
R2	-1.25	2.2	4.8	8.25	10.75	9.8	8.25	6.2
R2	3.2	0.25	-2.3	-4.3	-6.7	-5.85	-4.7	-3.5
R3	-1.7	2.2	5.2	7.25	9.85	8.75	7	5.25
R3	2.5	-0.2	-2.2	-4	-5.8	-5.2	-4.2	-2.8
R4	-0.4	XX	XX	XX	XX	XX	XX	XX

L=Lateral Side (Weights Positive)
M=Medial Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	0	2.75	5.7	8.7	11.5	10.25	8.25	5.3
R1	2.5	-1.75	-4.25	-6.25	-7.75	-6.3	-5.25	-3.3
R2	-0.2	2.75	5.75	8.2	10.75	9.8	8.25	5.3
R2	2.5	-1.75	-4.25	-6.25	-7.75	-6.3	-5.25	-3.3
R3	-0.2	2.2	4.25	7.2	10.2	9.2	7.75	5.3
R3	2.7	-2.25	-3.75	-2.2	-0.75	-2.25	-1.45	-0.6
R4	0.8	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.17

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 16

Name : Subject 16
Weight: 205 Pounds
Excercise: Isometric Planter Flexion
Sex: M
Date: 3/29/10

Age: 24
Height: 5'6"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	1.3	3.25	5.75	8.3	7.7	6.35	4.9
R1	3	0.9	-1.35	-3.5	-5.2	-4.65	-3.75	-2.3
R2	-0.75	1.2	3.25	5.3	7.8	6.85	5.7	4.2
R2	2.25	0.2	-1.7	-3.3	-5.2	-4.4	-3.65	-2.3
R3	-0.75	1.2	3.2	5.35	7.8	7	6.2	4.7
R3	2.7	0.7	-1.35	-3.1	-4.7	-4	-3	-2
R4	-0.5	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	1.2	2.7	4.75	7.6	6.7	5.3	4
R1	1.9	-0.2	-2.3	-4.2	-5.7	-4.1	-2.75	-1.75
R2	-0.75	1.2	2.85	5.2	7.9	7	5.8	4.3
R2	2.65	0.1	-2.3	-3.3	-5.2	-4.2	-3.15	-2.25
R3	-0.7	1.3	3.3	5.75	8.2	7.25	6.2	4.6
R3	2.8	0.7	-1.2	-3.1	-4.7	-4.2	-3.28	-2
R4	-0.1	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.18

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 17

Name : Subject 17
Weight: 169.4 Pounds
Excercise: Planter flexion
Sex: M
Date: 10/23/09

Age: 23
Height: 5'9"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

R1, R2 and R3=Right foot first, second and third series respectively.

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	1.3	2.8	5.2	7.3	6.1	5.35	4.2
R1	2.65	0.8	-1.25	-2.75	-5.25	-4.75	-4.15	-2.9
R2	-0.75	1	2.85	4.75	6.8	6.2	5.2	3.8
R2	2.15	0.35	-1.3	-2.8	-4.5	-4	-3.25	-2.25
R3	-0.85	0.8	2.75	4.85	6.8	6.2	5.2	3.6
R3	1.8	0.25	-1.3	-2.8	-4.25	-3.7	-2.8	-1.9
R4	-0.55	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	0	1.3	2.75	4.55	6.75	6.15	5.25	4.1
R1	2.7	1.2	-0.35	-1.85	-3.5	-2.95	-2.25	-1.25
R2	0.1	1.8	3.25	4.85	7	6.35	5.4	4.3
R2	2.85	1.25	-0.15	-1.7	-3.1	-2.5	-1.7	-0.8
R3	0.65	2	3.5	5.2	7	6.3	5.4	4.25
R3	3.1	1.7	-0.15	-1.55	-2.8	-2.25	-1.45	-0.6
R4	0.8	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.19

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 18

Name : Subject 18
Weight: 162.8 Pounds
Excercise: Isometric Planter Flexion
Sex: M
Date: 3/24/10

Age: 24
Height: 5'9"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.25	3.25	4.7	6.25	5.7	4.7	3.7
L1	2.45	1.35	-0.1	-1.85	-3.25	-2.7	-1.85	-0.8
L2	0.5	2	3.3	4.5	6.25	5.7	4.8	3.9
L2	2.8	1.5	0	-1.3	-2.65	-2.2	-1.3	-0.3
L3	1.2	2.3	4	5.5	6.65	6.15	5.35	4.4
L3`	3.35	2.25	0.7	-0.7	-2	-1.45	-0.8	-0.1
L4	1.2	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1	2.3	4.1	6.2	5.65	4.8	3.75
L1	2.5	1.2	-0.3	-1.75	-3.2	-2.7	-1.8	-1.2
L2	0.5	1.75	3.1	4.5	6.2	5.5	4.7	3.8
L2	2.75	1.3	0.25	-1.2	-2.4	-1.85	-1.25	-0.3
L3	0.8	2.15	3.2	4.75	6.2	5.7	4.8	4
L3	2.8	1.75	-0.25	-1.25	-2.35	-1.85	-1.2	-0.2
L4	1	XX	XX	XX	XX	XX	XX	XX

APPENDIX A.20

LOAD V/S DISPLACEMENT TABLE FOR SUBJECT 19

Name : Subject 19
Weight: 116.6 Pounds
Excercise: Isometric Planter Flexion
Sex: F
Date: 3/24/10

Age: 24
Height: 5'2"

Load (wT) in ounces and displacement in degrees (1inch=4 degree torsion)

L1, L2 and L3= Left foot first, second and third series respectively.

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.75	4.7	8.6	12.05	10.8	8.9	6.2
L1	2.75	-0.25	-3	-5.3	-7.8	-7.1	-5.8	-4.3
L2	-2.2	0.8	4.75	8.35	12.05	10.8	9.2	5.8
L2	2.7	-0.5	-3.25	-5.35	-7.7	-6.85	-5.75	-4.2
L3	-2	1.25	4.75	8.75	12.05	10.8	8.8	5.8
L3	2.5	-0.8	-3.7	-5.8	-7.8	-7.25	-6	-4.35
L4	-2	XX	XX	XX	XX	XX	XX	XX

I=Inversion Side (Weights Positive)
E=Eversion Side (Weights Negative)

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0	1.8	5.2	8.7	12.2	11	9.2	6.25
L1	2.75	-0.75	-4.25	-7.7	-9.25	-8.5	-7.3	-5.75
L2	-3.3	-0.25	4.2	7.85	11.75	10.65	8.35	5.2
L2	2	-1.8	-4.35	-6.75	-8.75	-8.1	-6.8	-5.25
L3	-2.85	0.2	4.25	8.3	11.75	10.65	8.5	5.25
L3	2.2	-1.4	-4.25	-6.25	-8.25	-7.65	-6.3	-4.75
L4	-2.65	XX	XX	XX	XX	XX	XX	XX

APPENDIX B

AVERAGE LOAD AND DISPLACEMENT TABLE

APPENDIX B.1

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 1

Name: Subject 1

Left Leg:

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
L1	1.53	1.8	2.51	3.33	3.93	5.26	7.06	6.6	6	5.58	5.11	4.61
L2	4.08	3.55	2.88	2.23	1.51	0.23	-1.35	-0.83	-0.21	0.3	0.86	1.41
L3	1.53	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	**1**	**2**	**3**	**4**	**6**	**8**	**6**	**4**	**3**	**2**	**1**
I/E												
R1	0.61	1.35	2.35	3.26	4.38	6.43	8.81	8.13	7.16	6.5	5.6	5.06
R2	4.23	2.96	2.18	1.35	0.58	-1.26	-3.41	-2.73	-1.91	-1.46	-0.76	0
R3	0.61	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.2

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 2

Name: Subject 2

Left Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	-0.82	0.13	0.85	1.5	2.28	4.08	5.5	5.25	4.46	4	3.45	2.81
L2	2.11	1.3	0.45	-0.43	-1.25	-3.08	-4.7	-4.13	-3.4	-2.88	-2.33	-1.68
L3	-0.82	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	-0.78	0.23	0.86	1.91	2.91	5.41	7.25	6.5	5.33	4.7	4.1	3.4
R2	2.58	1.45	0.56	-0.2	-1.16	-3.2	-5.15	-4.58	-3.76	-3.26	-2.63	-1.9
R3	-0.78	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.3

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 3

Name: Subject 3

Left Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	-2.26	-1.26	-0.86	-0.38	0.36	1.71	3.23	2.65	1.86	1.16	0.51	-0.1
L2	-0.68	-1.16	-2.15	-2.85	-3.48	-4.83	-6.01	-5.5	-4.81	-4.48	-4.05	-3.58
L3	-2.26	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	1.5	2.68	3.55	4.4	6.21	7.68	9.33	8.13	7.26	6.58	6.06	5.25
R2	4.51	3.91	2.9	2.06	0.88	-0.7	-2.36	-1.4	-0.45	0	0.36	0.9
R3	1.5	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.4

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 4

Name: Subject 4
Left Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	0.68	0.8	2.21	3.45	5	7.85	11.21	10.23	8.7	7.83	6.96	5.88
L2	4.48	3.2	2	0.96	0	-2.31	-4.18	-3.46	-2.5	-1.66	-0.91	-0.2
L3	0.68	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	-3.32	-1.9	-0.53	0.4	1.83	4.23	6.46	5.35	3.53	2.38	0.85	-0.23
R2	-1.75	-2.95	-4.45	-6	-7.33	-9.36	-11.01	-9.98	-8.66	-8.03	-6.81	-5.88
R3	-3.32	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.5

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 5

Name: Subject 5
Left Leg

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	0.36	1.68	3.41	5.15	7.01	10.8	14.05	12.93	10.83	9.51	8.25	6.73
L2	5.2	3.55	1.91	0.5	-1.01	-3.66	-5.98	-5.23	-3.85	-3.01	-2.01	-1
L3	0.36	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	-1.87	0.73	2.98	5.1	6.58	11.53	15.25	13.06	10.21	8.43	6.81	4.38
R2	1.75	-0.11	-	-	-5.5	-9.05	-11.65	-10.7	-9.13	-7.75	-	-4.98
R3	-1.87	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.6

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 6

Name: Subject 6

Left Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	0.36	1.68	3.41	5.15	7.01	10.8	14.05	12.93	10.83	9.51	8.25	6.73
L2	5.2	3.55	1.91	0.5	-1.01	-3.66	-5.98	-5.23	-3.85	-3.01	-2.01	-1
L3	0.36	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	-1.87	0.73	2.98	5.1	6.58	11.53	15.25	13.06	10.21	8.43	6.81	4.38
R2	1.75	-	-2.28	-	-5.5	-9.05	-11.65	-10.7	-9.13	-	-	-4.98
R3	-1.87	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.7

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 7

Name: Subject 7

Left Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
L1	1.76	1.96	2.8	3.66	4.6	7.08	8.86	8.21	7.26	6.75	6.06	5.26
L2	4.46	3.58	2.83	2.08	1.28	-0.26	-1.9	-1.23	-0.33	0.33	0.96	1.48
L3	1.76	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	1	2	3	4	6	8	6	4	3	2	1
I/E												
R1	0.45	1.28	2.63	3.98	5.88	9.1	12.15	11.25	9.85	8.9	7.76	6.51
R2	4.78	3.46	2.16	0.7-	-6.2	-3.3	-6.2	-5.1	-3.95	-3.13	-2.03	-1.01
R3	0.45	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.8

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 8

Name: Subject 8

Left Leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-1.22	1.76	5.18	8.95	12.25	11.03	8.9	5.73
L2	2.11	-1.1	-3.91	-5.75	-7.76	-6.95	-5.88	-4.21
L3	-1.22	XX	XX	XX	XX	XX	XX	XX

Right Leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	-0.21	2.61	6.06	9.28	12.66	11.65	9.53	6.58
R2	3.58	0.25	-2.45	-4.61	-6.65	-5.76	-4.71	-2.81
R3	-0.21	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.9

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 9

Name: Subject 9

Left Leg

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0.1	1.96	4.41	7.15	9.95	9.25	8.13	6.25
L2	3.85	1.33	-1.06	-3.1	-5.26	-4.51	-3.43	-1.85
L3	0.1	XX	XX	XX	XX	XX	XX	XX

Left Leg after Exercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-0.71	1.66	4.23	7.41	9.76	8.91	7.6	5.58
L2	3.43	0.66	-2.21	-4.63	-6.9	-6.01	-4.93	-3.3
L3	-0.71	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.10

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 9

Name: Subject 9

Left Leg

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-1.05	0.98	2.93	5.4	7.7	6.93	5.9	4.41
L2	2.15	0.01	-2.11	-3.98	-5.68	-5.11	-4.28	-3.1
L3	-1.05	XX	XX	XX	XX	XX	XX	XX

Left Leg after Excercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-0.83	0.9	2.73	4.83	7.25	6.4	5.3	3.76
L2	1.6	-0.03	-2.03	-3.81	-5.3	-4.71	-3.9	-2.71
L3	-0.83	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.11

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 10

Name: Subject 10.

Right Leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	-1.45	3.08	7.85	12.71	17.05	15.85	13.88	10.4
R2	5.23	0.01	-4.1	-7.68	-10.60	-9.58	-8.16	-5.78
R3	-1.45	XX	XX	XX	XX	XX	XX	XX

Right Leg after exercise:

	0(wT)	1	2	3	4	6	8	6
I/E								
R1	-2.4	1.93	6.58	10.8	15.11	13.76	11.58	7.81
R2	3.2	-2.08	-4.98	-8.86	-11.76	-10.83	-9.38	-6.98
R3	-2.4	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.12

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 11

Name: Subject 11

Left Leg

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-2.05	0.45	3.1	6	8.65	7.65	6.05	3.83
L2	1.41	-1.7	-4.03	-6.41	-8.5	-7.86	-6.96	-5.26
L3	2.05	XX	XX	XX	XX	XX	XX	XX

Left Leg after exercise

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-0.45	2.56	5.75	9.05	12.1	11	9.36	7.06
L2	4.15	0.7	-2.5	-5.1	-7.2	-6.53	-5.15	-3.25
L3	-0.45	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.13

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 12

Name: Subject 12

Left Leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-1.42	0.21	1.56	3.23	5.05	4.06	3.06	2.11
L2	0.6	-1.4	-2.83	-3.95	-5.55	-4.9	-4.13	-3.16
L3	-1.42	XX	XX	XX	XX	XX	XX	XX

Left Leg after exercise

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-1.4	-0.1	0.91	2.01	3.58	3.06	2.18	1.48
L2	0.21	-1.06	-2.7	-3.75	-5.05	-4.56	-3.68	-2.73
L3	-1.4	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.14

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 13

Name: Subject 13

Left Leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-1.22	0.23	2.06	4.33	7.16	6.13	5.06	3.65
L2	1.88	-0.1	-1.83	-3.61	-5.11	-4.65	-3.95	-3.06
L3	-1.22	XX	XX	XX	XX	XX	XX	XX

Left leg after exercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0.22	1.8	3.61	6.06	8.4	7.6	6.48	5.23
L2	3.71	1.8	0.03	-1.68	-3.73	-3.13	-2.25	-1.16
L3	0.22	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.15

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 14

Name: Subject 14

Right Leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	-1.93	-0.58	0.86	2.9	4.88	4.3	3.25	2.08
R2	0.55	-1.2	-2.83	-4.28	-6.16	-5.68	-4.95	-4.11
R3	-1.93	XX	XX	XX	XX	XX	XX	XX

Right leg after excercise

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	-0.86	0.52	2.22	4.2	6.7	5.98	5.1	3.86
R2	2.12	0.12	-1.73	-3.23	-4.87	-4.33	-3.58	-2.56
R3	-0.86	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.16

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 15

Name: Subject 15

Left Leg

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
L1	-0.83	2.38	5.25	8.41	10.76	9.61	7.91	5.73
L2	2.86	-0.06	-2.43	-4.5	-6.93	-6.11	-4.9	-3.51
L3	-0.83	XX	XX	XX	XX	XX	XX	XX

Left Leg after excercise

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
L1	-0.28	2.56	5.23	8.05	10.81	9.75	8.08	5.3
L2	2.56	-1.16	-3.58	-5.41	-7.1	-5.93	-4.75	-2.93
L3	-0.28	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.17

AVERAGE LOAD AND DISPLACEMENT FOR SUBJECT 16

Name: Subject 16

Right Leg

	0(wT)	**2**	**4**	**6**	**8**	**6**	**4**	**2**
I/E								
R1	-0.5	1.23	3.23	5.46	7.96	7.18	6.08	4.6
R2	2.65	0.6	-1.46	-3.3	-5.03	-4.35	-3.46	-2.2
R3	-0.5	XX	XX	XX	XX	XX	XX	XX

Right leg after excercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
R1	-0.38	1.23	2.95	5.23	7.9	6.98	5.76	4.3
R2	2.45	0.2	-1.93	-3.53	-5.2	-4.16	-3.06	-2
R3	-0.38	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.18

AVERAGE LOAD AND DISPLACEMENT FOR SUBJECT 17

Name: Subject 17

Left leg

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-0.53	1.03	2.8	4.93	6.96	6.16	5.25	3.86
L2	2.2	0.46	-1.28	-2.78	-4.66	-4.15	-3.4	-2.35
L3	-0.53	XX	XX	XX	XX	XX	XX	XX

Left Leg after excercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0.38	1.7	3.16	4.86	6.91	6.26	5.35	4.21
L2	2.88	1.38	-0.21	-1.7	-3.13	-2.56	-1.8	-0.88
L3	0.38	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.19

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 18

Name: Subject 18.

Left:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0.72	1.85	3.51	4.9	6.38	5.85	4.95	4
L2	2.86	1.7	0.2	-1.28	-2.63	-2.11	-1.31	-0.4
L3	0.72	XX	XX	XX	XX	XX	XX	XX

Left leg after excercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	0.57	1.63	2.86	4.45	6.2	5.61	4.76	3.85
L2	2.68	1.41	-0.1	-1.4	-2.65	-2.19	-1.41	-0.56
L3	0.57	XX	XX	XX	XX	XX	XX	XX

APPENDIX B.20

AVERAGE LOAD AND DISPLACEMENT VALUES FOR SUBJECT 19

Name: Subject 19.

Left leg:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-1.55	1.26	4.73	8.56	12.05	10.8	8.96	5.93
L2	2.65	-0.51	-3.31	-5.48	-7.76	-7.06	-5.85	-4.28
L3	-1.55	XX	XX	XX	XX	XX	XX	XX

Left leg after exercise:

	0(wT)	2	4	6	8	6	4	2
I/E								
L1	-2.2	0.58	4.55	8.28	11.9	10.76	8.68	5.56
L2	2.31	-1.31	-4.28	-6.9	-8.75	-8.08	-6.8	-5.25
L3	-2.2	XX	XX	XX	XX	XX	XX	XX

APPENDIX C:

OPTIMISATION CODE IN MATLAB TO FIND CONSTANTS

```
function ankleopt(K1, B1, T1, Fdataf, tt, wei)
%  ANKLEOPT is a function that accepts three estimated parameters
%  K, stiffness, B, damping, Tf, joint friction,along with
%  the experimental trajectory and its matching time vector.
%  The function uses LSQNONLIN from the MATLAB Optimization
%  Toolbox that calls a SIMULINK model of the plant that contains the
%  time varying torque changes applied to tghe ankle.
%
%  LSQNONLIN initially calls the Simulink model using the initial
estimates
%  of K, B and Tf.  It computes the SEE associated with the
%  difference between the experimental trajectory and the model output.
%  It uses the Levenberg-Marquart method to adjust B, K and Tf to lower
the
%  SSE reruns the Simulink model.  It continues to adjust B, K and Tf
until
%  the SSE reaches some acceptable level.  At this level, B, K,and Tf
are
%  optimized to allow the model to produce correct output.
%  Written by R. Foulds, BME dept NJIT  3/26/2010
warning off all

%% Initial values of paramters MUST BE ESTIMATED
pd0=[K1 B1 T1];
global Fdataf  tt wei
%%
% Since you have discrete data, you will need to
% build a fake trajectory of your data over time

% load Fdata; % load experimental trajectory
% load tt.mat;% load tme vectot to match trajectory


%  Optimization options  Set for L-M, medium scale
options = optimset('LargeScale','off','Display','iter',...
      'TolX',.0000010,'TolFun',0.0000010,'MaxFunEvals',400);

%  Call to Least-squares, nonlinear optimization function
%  lsqnonlin calls the subfunction tracking() that is included below
%  the returned variable, pd, will be a vector containing the current
%  optimized values of K, B and Tf
% [pd sse]=lsqnonlin(@tracking,pd0, [0 0 0], [ ], options)
[pd sse]=lsqnonlin(@tracking,pd0, [ ], [ ], options)
disp(pd);%DISPLAY OPTIMIZED PARAMETERS After optimization is complete
sse
%**************************************************************
function F=tracking(pd)
```

```
%Subfunction whose output is used in the optimization
K=pd(1);% relative stiffness
B=pd(2);% viscous damping
T=pd(3);% Friction


global Fdataf tt wei;

%Options for Simulink Model
simopt = simset('solver','ode45',...
                  'SrcWorkspace','Current');
%Call Simulink Model to generate new trajectory data, setexecution time
in vector

[t, x]=sim('mathmodel1',[0 9],simopt);


% x=x(:,1); % output values of Simulink model
% plot(x(1:1),1); %plot model trajectory

% hold on
plot(out,'b.');
hold on
% plot (x(:,1), 'm');
% l=length(out);
% out=(out)';
plot(Fdataf,'r.'); %plot experimental trajectory

F=out(1:900)-Fdataf'; %Compute difference between exp and model
trajectories
%% F is the variable that is returned to lsqnonlin
plot(F,'m');
S=sum(F.^2)
hold off
pause(.2);% pause long enough so you can see the plot before
% the next optimization is run
```

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