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DEPARTMENT OF KINESIOLOGY

MUSCULOSKELETAL DIFFERENCES IN FOOT STRUCTURE IMPROVE SPRINT PERFORMANCE

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ABSTRACT

During a race sprinters need to generate large forward impulses to reach top speeds during a race. Trained sprinters work to maximize their biomechanical parameters to achieve the fastest times possible. Past research has shown that trained sprinters are biomechanically different from non-sprint trained athletes, but many questions remained which variables, and to what extent, were different between the two groups. Eight trained sprinters and eight height-matched controls underwent magnetic resonance (MR) imaging of their lower legs and feet. Subjects' right ankles were scanned at four different joint angles according to a previously-developed protocol. Achilles tendon moment arm length, first toe length, first metatarsal length, first ray length, and first ray to moment arm ratio were all shown to be significantly different between the two groups at the $p=0.05$ level. Sprinters were shown to have smaller Achilles tendon moment arms, which would allow them to generate the same amount of foot motion through a smaller change in muscle length, allowing the foot plantarflexor muscles to maintain a better position on the muscle force-velocity curve. Sprinters were also found to have longer toes than non-sprinters despite having feet that were the same size, suggesting a structural change to allow sprinters to generate greater forward impulse during the acceleration phase of the race. Further research will be directed towards understanding how similar differences in musculoskeletal structure might be indicative of locomotor ability later in life.

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Chapter 1

Introduction

1.1 Statement of the Problem

The idea of human beings having incredible running capability can be traced back for millions of years (Grine, et. al. 2009). As running becomes more about sport and less about survival, questions arise regarding the continual improvement of this ability. Over the last 100 years the time world record time for the 100m dash has dropped by about a second (USA Track and Field 2011). This time interval over a long distance is practically insignificant, but on a short track this represents an enormous improvement. Elite sprinters are constantly trying to shave even a hundredth of a second off their times, and so any advantage is crucial. There are many trainable variables that can affect sprint performance (Dintman and Ward, 2003); however, according to former Olympian Maurice Greene, "among the world elite there are a handful of athletes who are physically capable of winning it." (Greene, M.) The question then persists: what elevates an individual into that category? Can it be done through training or are genetics the key factor? Both training and genetic causes have been suggested (Decluse, et. al. 1995; Abe et. al. 1999), but more needs to be done to investigate these causes and examine the differences that advantage elite sprinters over untrained counterparts.

When beginning to consider variables that could affect sprint performance, looking at the different joints is a reasonable way to start. Research has also shown that the ankle is one of, if not the, major contributors to sprint success for its ability to generate a large amount of energy (Stefanyshyn et. al.1997). One of these variables, Achilles tendon moment arm length, could potentially be a significant contributor to sprinting ability (Lee and Piazza 2009). The Achilles tendon moment arm is the distance between the line of action of the tendon force and the center of rotation. The hindfoot anatomy and tendon path define this distance, but the way this variable could contribute to sprint ability is still somewhat of a mystery. Examining differences in musculoskeletal structure could very well explain some of the subtle mechanisms that provide sprinters with their elite speed.

1.2 Previous Works

Many ankle variables such as gear ratio, work output, and power output have all been examined to better understand how to maximize ankle biomechanical efficiency (Carrier et. al. 1994; Erdemir et. al. 2004; Nagano and Komura 2003). These have all been related to the structure of the Achilles tendon. Much has been done to examine different relationships between Achilles tendon moment arms and other variables, such as fiber length and muscle thickness (Maganaris et. al. 1998a; Maganaris et. al. 2005) as well as the relationship of these variables to the Achilles tendon moment arm (Maganaris e. al. 2006). It has also been reported that runners with shorter heels have a better running economy, albeit using an exterior imaging model (Scholz et. al 2008).

There are two general methods used to measure the Achilles tendon moment arm: ultrasound or magnetic resonance imaging (MRI) (Maganaris et. al. 1998a). The ultrasound technique has measured the Achilles tendon moment arm by a tendon excursion method (Lee et. al. 2008) by taking the derivative of the change in length of the tendon versus the joint excursion. The ultrasound tendon excursion technique has been compared to MRI (Maganaris et. al. 1998b) and differences were found between the two. MRI is used to compute moment arms (Rugg et. al. 1990; Maganaris et. al 2000; Maganaris et. al. 2005) as the imaging techniques have provided a clearer standard of accuracy. The MRI protocol to measure moment arms was then applied to sprinters (Lee and Piazza 2009) along with anthropometric measurements. The authors found that sprinters had shorter moment arms, along with shorter lower legs and longer toes (Lee and Piazza 2009). Shorter moment arms have been associated with higher power output and joint moments (Nagano and Komura 2003). A shorter moment arm could mean a faster joint excursion velocity of the foot with a slower muscle contraction; however, a smaller moment arm would have to be able to develop more force through stronger muscles. Sprinters have been shown to have a larger proportion of type II muscle fibers than other athletes (Thorstensson et. al. 1977), and research has proposed that there is a correlation between the mechanical advantage that a muscle has and its percentage of type II muscle fibers (Mahutte and Gandevia 1980).

If sprinters do have different Achilles tendon moment arms, it remains unclear how those differences in anatomy have come about. Research has shown that bones may have different shapes in athletes: different studies on elite baseball throwers have shown differences in humeral torsion values in the throwing arm compared to both the non-throwing arm and the general population (Warden et al. 2009; Myers et. al 2009). These differences could be a result of years of throwing stress on the arm, but it could also be true that these athletes have continued to excel in their sport because they were born with this slight advantage. Similar questions arise when discussing origins of sprint ability, and research needs to be done to first identify the causes of sprint ability to greater understand what makes people fast.

1. 3 Objectives

The goal of this study is to examine some of the same variables measured by Lee and Piazza (Lee and Piazza 2009) using magnetic resonance imaging (MRI) to collect the structural data. Research has shown that MRI is a very effective way to examine Achilles tendon moment arms, as it allows direct image measurement of the desired variables. This study will Achilles tendon moment arm length, toe length, and calcaneal pitch in height-matched sprinters and non-sprinters to examine the structural differences between the two groups.

1.4 Specific Aims:

Specifically, we will:

1. Test whether or not there is a difference in the location of the center of ankle rotation and Achilles tendon moment arm length between sprinters and non-sprinters with MRI;

2. Examine calcaneal pitch for differences between sprinter and non-sprinters; and

3. Measure toe lengths with MRI and test for differences between sprinters and non-sprinters.

1.5 Hypotheses

Hypothesis #1: Sprinters will have significantly shorter Achilles tendon moment arms than height-matched non-sprinters.

Rationale: These findings have been previously reported (Lee and Piazza, 2009), and there may be advantages gained with each difference.

Hypothesis #2: Sprinters will have different locations for their centers of tibiotalar rotation than their height-matched controls.

Rationale: Different centers of rotation will mean changes in Achilles tendon moment arm length.

Hypothesis #3: Sprinters will have significantly longer toes than height-matched non-sprinters

Rationale: Longer toes will allow sprinters to stay in contact with the ground longer and generate a greater forward impulse during push-off (Lee and Piazza 2009).

Chapter 2

Review of Literature

2.1 Overview

Studying the musculoskeletal structure of trained athletes may answer questions related not only to the determinants of elite performance, but also help to answer questions about the relationship between structure and mobility in non-athletes. The study of ankle and foot biomechanics in sprinters is often geared toward finding ways that these athletes differ from non-athlete populations and seeing what advantages such individual differences may convey. Further understanding of this topic may lead to increased understanding of ways to improve sprint performance and may also provide insight as to the relationship between form and function in non-athlete populations. Much research has investigated foot and ankle biomechanics but there is a need to further investigate some of the specific variables related to differences in sprint performance between trained athletes and non-sprinters. By examining factors that give sprinters advantages over non-sprinters, it may be possible to identify variables that determine locomotor ability in humans.

This literature review will focus on three aspects of examining sprinters and non-sprinters: the determinants of sprint performance, how one of those potential determinants, Achilles tendon moment arm, is measured, and how differences in bone structure may affect the performance of athletes from various sports. The determinants of sprint performance will be discussed to examine how sprinters differ from non-sprinters and how sprinters of different abilities may differ from one another. Different Achilles tendon moment arm measurement techniques will be discussed to examine their respective methodologies and how they compare to one another. Effects of bone structure on athletic performance will be evaluated to see how bone may change shape over time and how these adaptations may factor in to create a performance advantage.

2.2 Determinants of Sprint Performance

Sprint performance may be affected by both physiological and anatomical differences. Muscle fiber type has been shown to differ between athletes and sedentary individuals: sprint-trained athletes have a higher percentage of fast-twitch fibers in their vastus lateralis muscle while endurance athletes have a higher percentage of slow-twitch fibers in the same muscle (Thorstensson et. al. 1977). For this reason, fiber-type-specific training is often considered when preparing for athletic performance, and the vastus lateralis muscle is part of the quadriceps, one of the main muscles commonly used for measuring large-muscle exercise effects. It has also been found that Type-II, or fast-twitch, muscle fibers have been associated with increased mechanical leverage at a joint (Gandevia and Mahutte, 1980). Sprint-trained athletes who had a larger proportion of these fibers in their ankle plantarflexor muscles may have developed this advantage as an adaptation to the existing leverage, and the ability to generate plantarflexor moment is crucial in developing the large forward accelerations required of an elite sprinter.

Muscle fiber length and pennation angle have been shown to differ between trained 100 m sprinters and non-sprinter control subjects, and these differences appear to be associated with variation in performance, as longer muscle fascicles and smaller pennation angles are associated with a faster sprint time. (Abe et. al. 2000; Abe et. al. 2001). A longer fascicle length would benefit sprinters because it might reduce the shortening velocities of the sarcomeres. Muscles with longer fascicles may have longer optimal fiber length and a greater number of sarcomeres. With muscle shortening among a greater number of sarcomeres, individual sarcomere shortening velocities would be expected to be smaller. According to the force-velocity property of muscle, such muscles with longer fascicles could generate a greater force at the same muscle shortening velocity than would a muscle with shorter fascicles. Muscles with longer fascicles would thus be able to generate larger forces and greater ankle power that might contribute to greater forward impulse during sprinting. Furthermore, the pennation angle of the muscle fascicles fibers with respect to the line of action of a muscle could also have an effect, as a smaller pennation angle would mean that the fibers would pull more along the line of action of the tendon. Thus, with the muscle fibers and tendon line of action being more parallel to one another, the force vectors generated would contribute more directly to the joint movement, allowing sprinters to transmit their generated muscle force into their forward acceleration

Muscle dimensions have also been shown to be correlated with sprint time. Muscle volume has been found to have a strong correlation with the torque it can create about a joint. Athletes have also been found to have greater muscle volumes and muscle torques, providing them with significant mechanical advantages about a joint. (Fukunaga et. al. 2001). Newtonian mechanics quantifies that torque and force are directly proportional, and the physiological cross-sectional area (PCSA), which is muscle volume divided by fiber length, was further correlated with increased muscle force. Muscles that generate larger forces are capable of producing larger rotational accelerations at the joints they span. Force development has been correlated with enhanced athletic performance, as it has been shown to have a positive correlation with both sprint performance and jumping ability (Wisloff 2004). These larger forces could be used to generate greater torque about the desired joint; additional functional benefits could then be created by optimizing this strength with an advantageous moment arm length. Furthermore, the product of developed force and generated velocity, or muscle power, has been found to be positively correlated with better performance during sprinting (Chelly and Denis 2001). Greater power means greater work per unit time, so the generated force would be produced more rapidly.

Sprint performance may also be affected by structural differences in the joints. Longer moment arms about joints have been proposed to decrease joint moments, work output, and power output during actions in which the muscle shortens rapidly (Nagano and Komura 2003). A smaller joint moment would mean that the muscles would do less work. Muscles that do less work individually do less work on the entire body as a whole, leading to a decreased acceleration of the body's center of mass and thus a decreased forward impulse during a plantarflexion contraction. The longer moment arm would mean that the muscle fibers have to shorten at a greater velocity during a similar movement, leading to less force being generated within the muscle due to the force-velocity property.

2.3 Measuring Moment Arms

A moment arm is the distance from a center of rotation to the line of action for a given force. The product of the moment arm of a force and force itself is the “moment of force”, or simply “moment”. Since the moment of a given force increases if its moment arm is increased, moment arm serves as a geometric indicator of the capability of a force to generate moment. Moment arms of muscles and tendons about joints have been measured using several different techniques both *in vivo* and *in vitro.* There are three established ways that moment arms can be measured: from measurements of tendon-excursion, geometrically, and by direct load measurement (An et. al. 1984). The geometric method involved measurement of the perpendicular distance from the center of joint rotation to the line of action of a muscle or tendon. The tendon excursion technique involves the measurement of the displacement of the tendon during a known change in joint angle. The moment arm is then calculated as the first derivative of tendon excursion with respect to joint rotational displacement (An et. al. 1983). The direct load involves simultaneous measurement of the force applied to the tendon and the force required to resists the motion of the limb. The moment arm is calculated by substituting these values into an equation specifying rotational equilibrium of the limb.

The tendon excursion method has been implemented in vivo using ultrasound images of tendon displacement. Work has been done on human cadaver limbs to develop and validate techniques for automated processing of ultrasound images for this purpose (Lee et. al. 2008). These findings created an algorithm to that was applied to a tendon-excursion technique to measure Achilles tendon moment arms in sprinters in actively contracting muscle (Lee and Piazza 2009). Ultrasound was used to track the muscle-tendon junction of the gastrocnemius and Achilles tendon, and the moment arm was calculated as the first derivative of tendon excursion with respect to plantarflexion angle. The idea has been used to calculate moment arms in the ankle in a passive state, although there is a chance there could have been an artifact created due to tendon laxity (Ito et. al. 2000; Maganaris et. al 2004). This technique has been improved, as an algorithm was developed to integrate the tendon-excursion in vivo (Lee et. al. 2008). It has also been used to quantify moment arm, pennation angle, and fiber length in sprint-trained athletes (Lee and Piazza 2009). Ultrasound imaging has also been used to quantify pennation angle and fiber length (Maganaris et. al. 1998a), Achilles tendon moment arm (Maganaris et. al. 1998b; Lee and Piazza 2009), and fascicle-length-to-moment-arm ratio (Maganaris et. al. 2006). These studies illustrated ultrasound's ability to be time-efficient and accessible while still generating the desired images. One major benefit with this technique is that it is not necessary to find the location of the joint center of rotation, as the moment arm can be calculated as a function of the force and joint rotation. One assumption that must be made with ultrasound techniques is that no energy enters or leaves the tendon during this process. This is not practical, especially in vivo, creating a potential tendon-related artifact in the data.

The geometric method has been applied to quantify Achilles tendon moment arms from magnetic resonance images. This method requires finding the center of rotation between the bones comprising the joint from images of two static poses (Reuleaux 1875). In the case of the ankle joint, this method for finding the center of rotation has been applied to the fixed tibia and the rotating talus using MR images to find the center of tibiotalar rotation. The moment arm is then taken to be the perpendicular distance from the line of action of the Achilles tendon (Maganaris et. al 1998c; Maganaris et. al. 2000; Maganaris et. al. 2004; Maganaris et. al. 2006). These methods mark identical bony landmarks and use perpendicular bisectors to pinpoint the center of rotation. Lines are drawn between two fixed points on each talus, and then a first line is drawn perpendicular to that with a second line drawn perpendicular from the end of the first line. Perpendicular bisectors are then drawn on lines between each end of the second line and its corresponding point on the second image; the intersection of these lines is the center of rotation. The Reuleaux method does provide a center of rotation, but the large number of different points, lines, and measurements create a greater number of degrees of freedom for error, potentially reducing the accuracy and precision of the measurement. It may also be possible that the talus undergoes slight translational movement with respect to the tibia during rotation, which would make the Reuleaux method less accurate.

The center of rotation has also been defined as the center of a circle that is best-fit to the sagittal-plane cross section of the talar dome, and the Achilles tendon moment arm is measured as the perpendicular distance from that point (Csapo et. al. 2010). Another definition of the Achilles tendon moment arm is the perpendicular distance between the sulcus calcanei and the Achilles tendon (Raichlen et. al. 2011). The methods of using a fixed bone as the center of rotation does provide a consistent set of points to go off of; since each joint can rotate in a slightly different manner, however, it is uncertain that these methods accurately pinpoint the center of rotation. The geometric method has the distinct advantage of allowing the direct visualization of the ankle joint using MR scanning. A drawback to using MR, however, is the financial and labor costs associated with acquiring an image. Although these methods do provide precise measurements, it is yet to be established which method is the best representation of the Achilles tendon moment arm.

2.4 Running Performance and Bone Structure

One hypothesis that may explain performance differences between trained athletes and non-trained athletes is that some advantage is conveyed by changes in bone structure that are adaptations to training. Such differences have been found in athletes who play a wide array of sports. Research has shown that female tennis players developed increased bone mass in their dominant forearm, specifically the distal humerus and the radius, as opposed to their non-dominant arm; those who start tennis training before menarche will also develop more normalized bone mass than those who started at an older age(Kontulainen et. al. 2002). This finding is an excellent example of Wolff's law, which states that bone grows in response to increased loading (Bodner et. al. 1993). This study also suggests that a larger effect can be seen by starting the training at a younger age, when the skeleton is immature. Similar findings have also been shown in the femoral neck bone density of female athletes playing high-impact sports, i.e. volleyball, hurdling, and soccer (Nikander et. al. 2004). Athletes had an increased bone area, cross-sectional area, and section modulus, although no unilateral comparisons were able to be made.

Other studies have shown changes in bone shape over periods of time, potentially in response to training. Studies on human fossils have shown that there are differences in humeral torsion angles between different races of adults, specifically African-American and Caucasian people (Krahl 1976). Humeral torsion is the angle between joint axes on the proximal and distal humerus, and it was suggested that these differences are due to different-sized forearm muscles pulling on the bone over a long period of time. Differences in humeral torsion have been further investigated as a response to training, specifically in overhand throwing. Research has shown that male, college-aged baseball players have significant differences in humeral torsion between their throwing and non-throwing arms (Myers et. al. 2009) and have greater differences between arms than do matched controls (Warden et. al. 2009). The throwing arm was found to have greater torsion than the non-throwing arm, which could be due to the chronic pulling of stronger muscles in that arm. This could also be an indicator of shoulder tightness, or how strongly the tissue around wraps around the shoulder to support the oft-used joint. Research has also shown that in-toeing (having the feet turned slightly inward instead of pointing straight ahead) may confer an advantage to sprinters (Fuchs and Staheli 1996). A study of high school sprinters showed that they are significantly more likely to in-toe than non-sprinting controls. In-toeing may prove advantageous by placing the first and second metatarsal heads directly in line with the plantarflexor muscles by angling them slightly inwards. Since these two toes are the ones that make the most contact with the ground during a sprint, this would imply a more effective force transfer from the muscles.

On the other hand, having shorter heels have been shown to mean a better running economy, or a low rate of energy consumption at a given speed (Scholz 2008; Raichlen et. al. 2011) in distance runners. If the moment arm is small but the required moment is the same, the resulting muscle force must be greater. A greater muscle force could stretch the tendon more and cause the tendon to store more energy. This could also imply that there may certain heel-to- foot length ratios that optimize energy expenditure during distance running. Simulations have shown that shorter toes and longer heels would create less forward impulse but allow for more efficient energy expenditure for distance running; it was also mentioned that increasing toe length 20% could double forward impulse, so longer toes and shorter heels may be more beneficial to sprinting (Rolian 2009).

Research has further shown that bone shapes and lengths differ in trained versus untrained athletes. Osgood-Schlatter's disease, or an anterior tibial tuberosity apophysis, is caused by the distal patellar tendon pulling on the anterior tibial tubercle and subsequent irritation or even separation of the growth plate (Gholve et. al. 2007). Clinical data have shown that adolescent athletes are ten times more likely to develop the disease than non-athletes (Kujala et. al. 1985). This could be caused by the athletes' stronger quadriceps muscles pulling too hard on the anterior tibial tubercle, causing it to separate from the tibia. It has also been shown that trained sprinters have significantly longer toes, as defined as the external distance between the head of the first metatarsal and the end of the first toe (Lee and Piazza 2009). Longer toes would allow sprinters to remain in contact with the ground for a longer period of time during the acceleration phase. Although it seems counterintuitive to want to stay on the ground longer, it would allow sprinters to generate a much greater forward impulse and thus a greater forward acceleration. Since these findings are based on palpated external foot measurements, more research is necessary to look at the specific toe segments in MR to examine what specific differences in bone structure between trained, elite sprinters and non-sprinters exist.

Chapter 3

Methodology

3.1 Subjects

Eight collegiate sprinters and eight height matched controls, ages 18-25, participated in the study (Table 4-1). The sprinters had 100m dash times of 10.5-11.1, with one sprinter having a 200m dash time of 24.3 and another of 21.43. They all had been consistently doing sprint-specific training for at least the past five years. The controls were all height-matched and did not have any history of sprint training. None of the subjects had a lower-body injury in the past 12 months nor had a history of using corrective prosthetics. Participants gave informed consent (Appendix B) and all procedures were approved by the Institutional Review Board at the Pennsylvania State University.

3.2 MRI Scanning

An MR (3.0T Siemens Magnetom Trio, SLEIC, The Pennsylvania State University) scanner was used to scan the foot, ankle, and shank. Before scanning, two MRI-visible 4cm gel markers were placed on the right foot, one over the palpated space between the distal heads of the second and third metatarsals and one over the Achilles tendon approximately 12cm from the base of the heel to help define consistent sagittal-plane images. The subject was placed supine on the scanning table with their feet pointed towards the scanner. The subject's foot was placed in a specially-designed footplate apparatus (Fig 1-3) and surrounded by a local coil. The foot and ankle were scanned at 15° dorsiflexion, neutral, 15° plantarflexion and 30° plantarflexion with respect to the ankle joint; these angles matched up with pre-drilled holes in the footplate apparatus and were confirmed with a goniometer prior to scanning. The subject's heel was placed flush against the bottom surface of the apparatus. A triangular foam wedge was placed under the knee to keep the knee at 15° of flexion throughout the protocol to allow for subject comfort at each angle. The height of the wedge could be adjusted in one-inch increments based upon the height of the subject and the angle was confirmed with a goniometer prior to each scan.

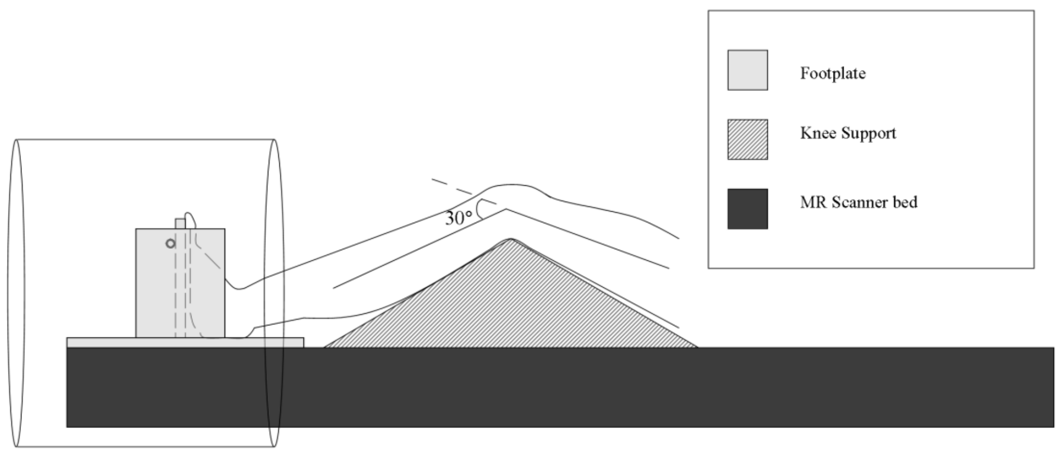


Figure 3-1: MR Scanner Bed

MR scanner bed experimental setup. The subject's knee was positioned at 30° from complete extension and additional supports could be placed under the knee support to obtain the correct angle. The subject was instructed to rest his heel flat against the base plate and footplate and keep it in that position during the duration of scanning at each position. The footplate could be adjusted to angles at 15° dorsiflexion, 0°, 15° plantarflexion, and 30° plantarflexion based upon the position of the support. Between each position the scanner bed was removed from the MR bore, the plate was re-adjusted for the next angle, and the subject was repositioned on the plate before the bed was slid back in.

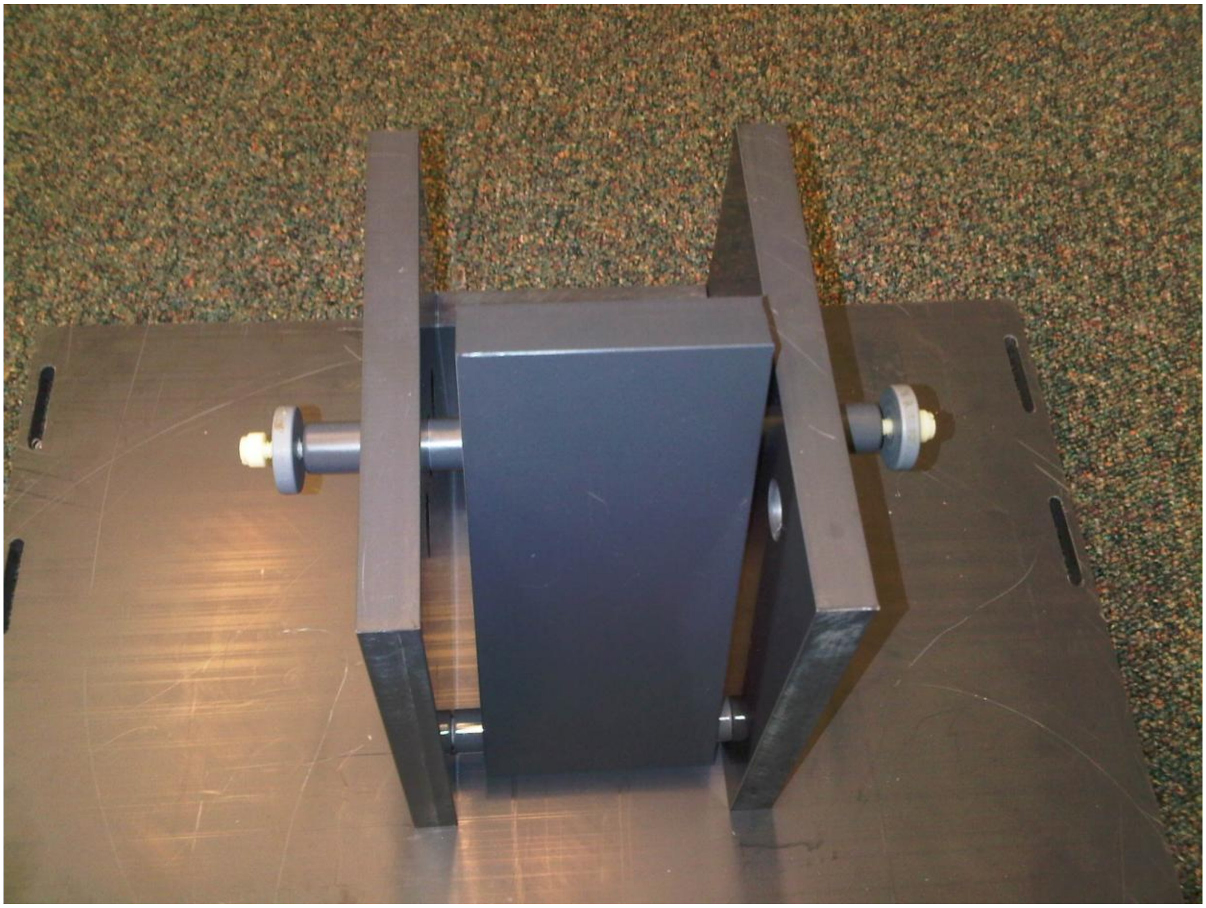


Figure 3-2 MR Footplate

A front view of the footplate used during the scanning protocol. The plate was able to freely rotate about the axis through its base, allowing the plate to support the foot at different angles. The rod at the top of the plate worked as a support to keep the plate in place during the experiment and was designed to hold the weight applied during the contracted trials. The screw and washer at the ends of the top rod were removed to adjust the rod and were replaced prior to each scan. The slots drilled in the baseplate were used to anchor the plate to the MR scanner bed.

The subject was instructed to lie as still as possible during the time in the MR in order to reduce error in scanning from subject movement The subject was given time to practice the contraction under the supervision of the researchers before being placed in the scanner. Localizer scans were done to find both of the luminescent markers and lined up to collect a consistent sagittal plane images. Two three-second sagittal plane scans were made at each ankle angle, beginning at 15° plantarflexion and moving along serially through 30° dorsiflexion. The first scan at each angle was taken when the subject in a relaxed state so the Achilles tendon would have the associated slack. For the second scan the subject was asked to isometrically maximally contract all of the muscles of their foot and shank while keeping their heel against the bottom plate and their foot against the footplate. The subject stayed in this contracted position during the duration of one of the scans, after which they were instructed to relax.

The subject’s ankle was then returned to a neutral angle and the subject was instructed to lie as still as possible. Two 3-D imaging scans, each lasting approximately six minutes, were then done on the foot/ankle complex. The scanning coil was then moved to the shank and a similar 3-D scan was done between the malleoli and the tibial plateau.

3.3 Moment Arm Measurement

Moment arm measurement was done using a geometric method. The particular protocol used was the Reuleaux method (Maganaris, 1998), which is a graphical method for determining the center of rotation. Sagittal-plane images were printed out on transparencies and the adjacent rest and maximal contraction angles were matched up. In the Reuleaux method, the center of rotation is found by comparing the change in rotation of one object between two different positions in reference to another fixed object in the frames.

A sagittal scan of the foot at two different joint angles was used to compare this rotation. The tibia from the second of the two images was fitted over top of the first image, showing the different positions of the talus. The base segments were drawn between the two inferior points on the talus. A 10cm line was drawn perpendicularly from the posterior end of this line, and the new end of the first 10cm line was point A. A second 10cm line was drawn perpendicularly from point A to the new point B. This was done for the talus at both positions to create two sets of points. Perpendicular bisectors were then drawn between points A and A' and B and B', and the intersection of these lines was the center of rotation. A straight line was drawn down the length of the Achilles tendon, and the moment arm was measured as the perpendicular distance between this line and the center of rotation.

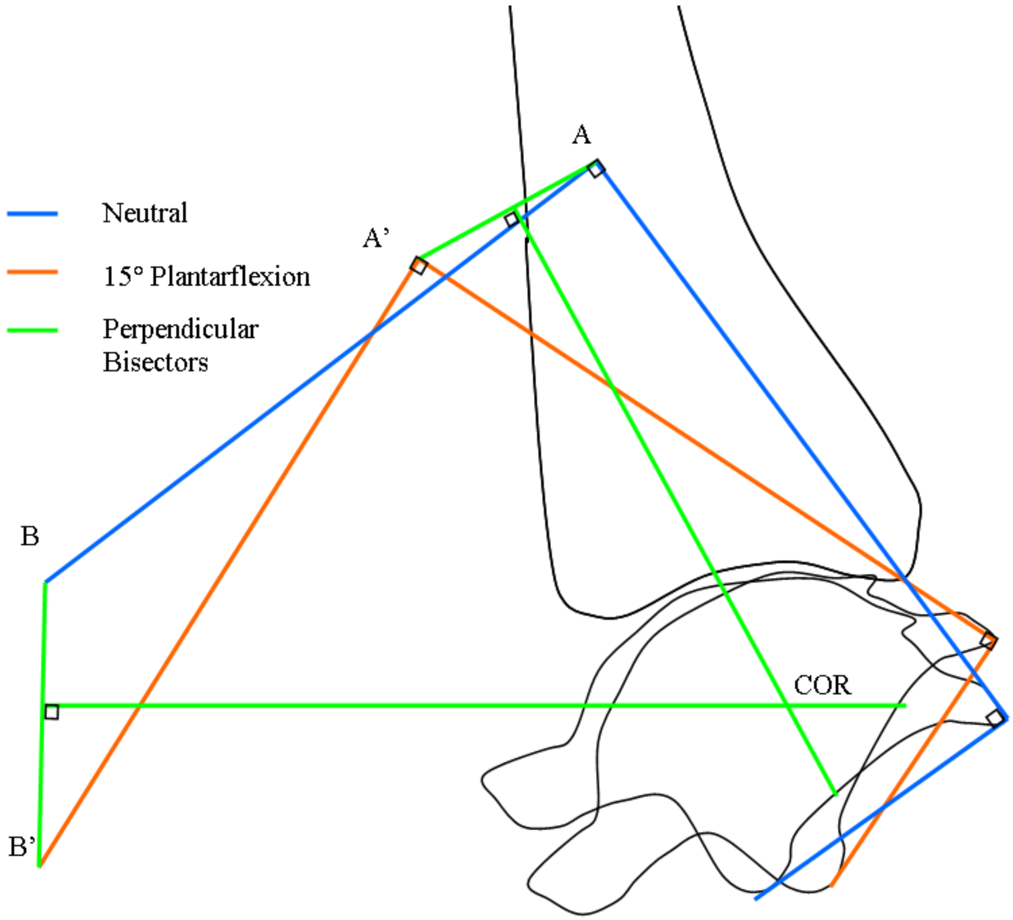


Figure 3-3 Reuleaux Diagram

The Reuleaux Method for finding the center of rotation between two objects. A sagittal scan of the foot at two different joint angles was used to compare this rotation. The tibia from the second of the two images was fitted over top of the first image, showing the different positions of the talus. The base segments were drawn between the two inferior points on the talus. A 10cm line was drawn perpendicularly from the posterior end of this line, and the new end of the first 10cm line was point A. A second 10cm line was drawn perpendicularly from point A to the new point B. This was done for the talus at both positions to create two sets of points. Perpendicular bisectors were then drawn between points A and A' and B and B', and the intersection of these lines was the center of rotation.

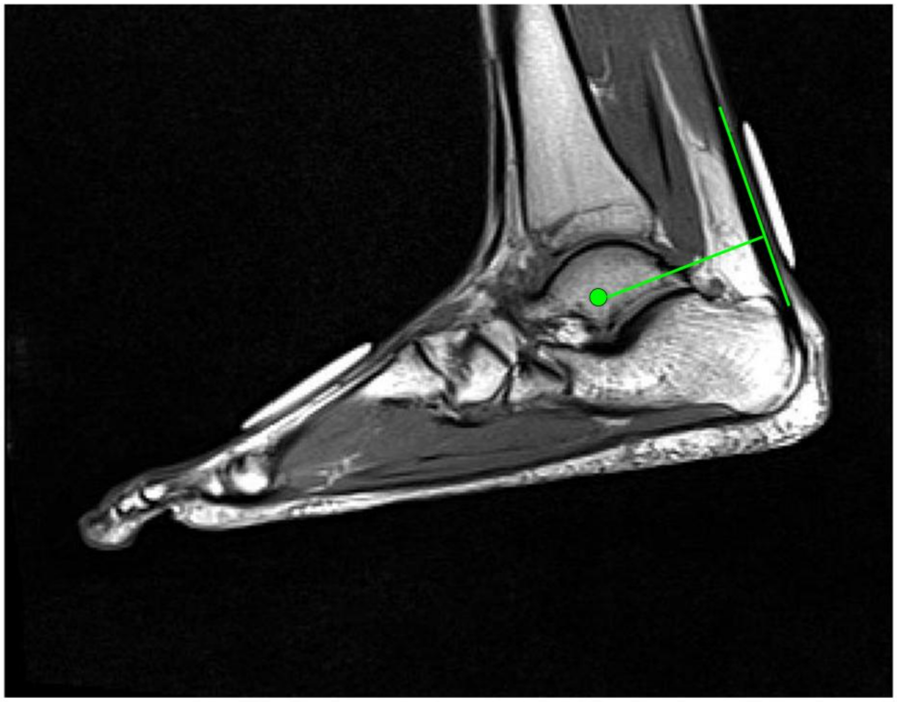


Figure 3-4 Achilles Tendon Moment Arm Measurement

An Achilles tendon moment arm measurement. The green circle represents the center of rotation for the ankle joint as determined by the Reuleaux method. The moment arm is the perpendicular distance between the center of rotation and the line of action of the Achilles tendon.

3.4 Center of Rotation Coordinates

The center of rotation calculated from the Reuleaux method was plotted on a coordinate system with respect to the tibia. The Y-axis was drawn from the midline of the tibia, and the X-axis was drawn perpendicular to this at the most distal aspect of the articular surface of the tibia. Positive X was defined as moving posteriorly towards the Achilles tendon and positive Y was defined as moving superiorly from the distal tibia**.**

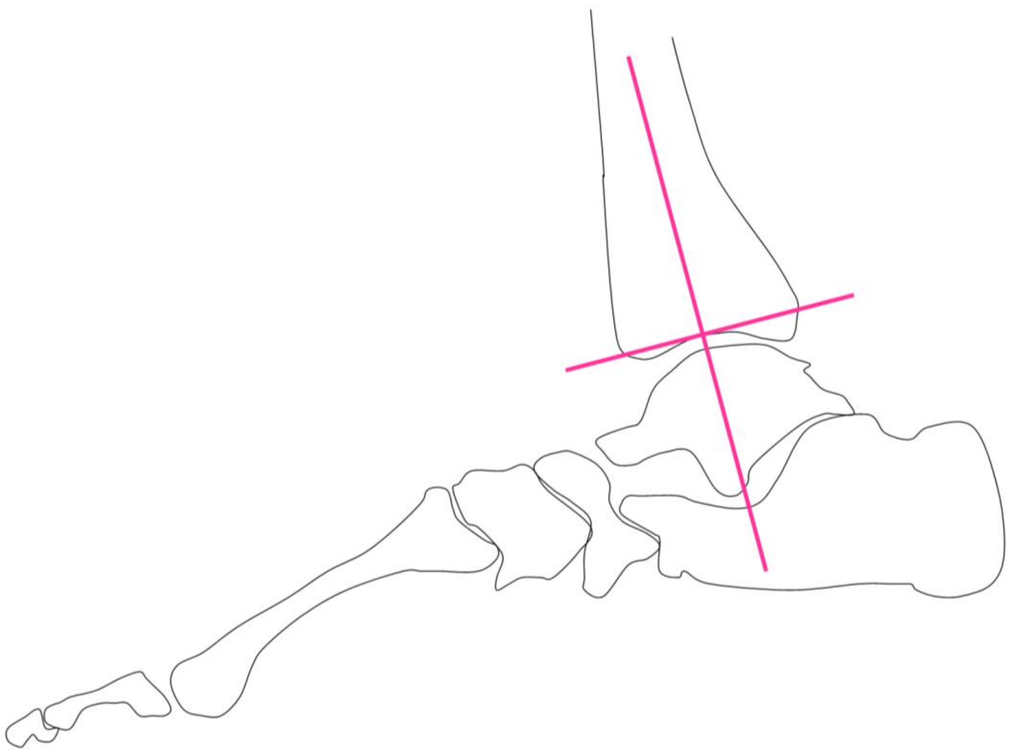


Fig 3-5: Coordinate Plane for Center of Rotation Coordinates

The foot coordinate plane. +X was directed posteriorly and +Y was directly superiorly.

3.5 Bone Measurement

Measurements of foot bone lengths were made using quasi-sagittal plane images recreated from 3D image data. The bones measured were the first and second metatarsals, the proximal and distal phalanges of the first ray, and the proximal, middle, and distal phalanges of the second ray. The length of a bone was defined as measured down the long axis of the bone between points in the center of the proximal and distal articular surfaces. The computer program Osirix was used to locate the center of the articular surface by examining frontal, sagittal, and coronal plane images. The correct bone was located in the sagittal plane images, and the center of the articular surface was located using frontal and coronal plane images on the same screen. Individual lengths were recorded for each bone, and truncated lengths were calculated for the toes by adding the individual lengths of the phalanges.

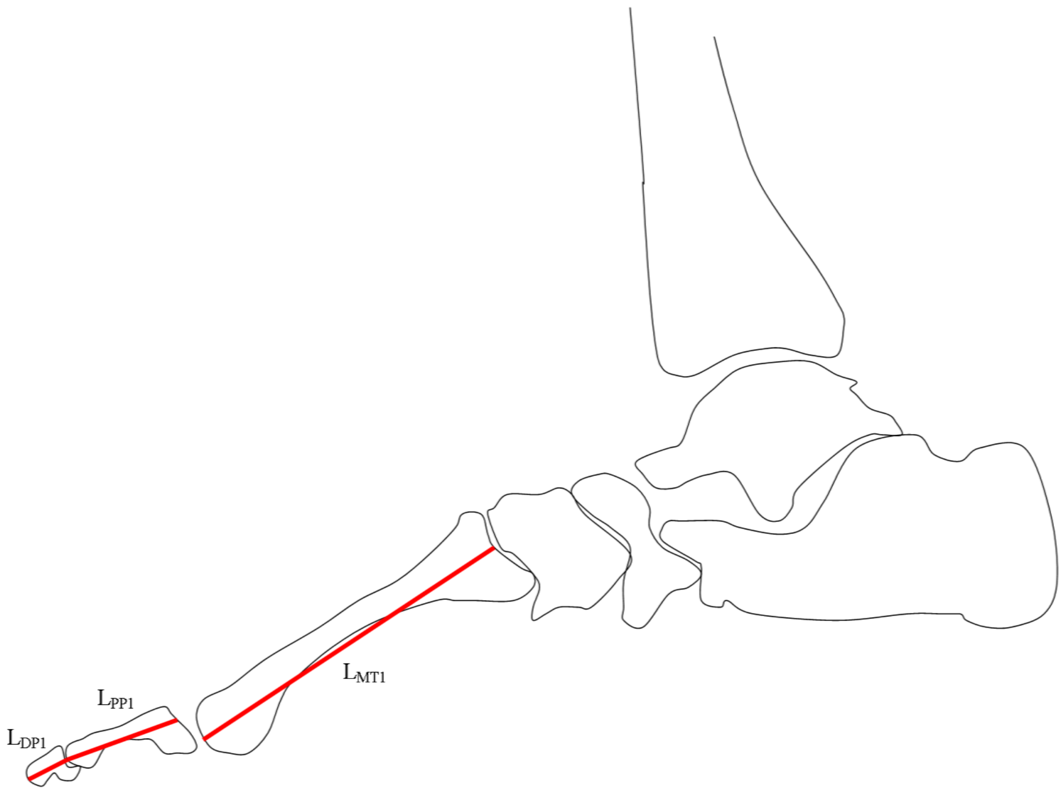


Figure 3-6 Toe Length Measurement

The foot bone lengths measured during the study. The lengths of the first distal phalanx (DP1), first proximal phalanx (PP1), and first metatarsal were measured using Osirix. Length was defined as the distance between the middle of the proximal and distal articular surfaces of each bone.

3.6 Calcaneal pitch

Calcaneal pitch was calculated from recreated sagittal plane MR images. Calcaneal pitch is defined as the angle of the calcaneus with respect to the floor of the foot (Fig 3-7). The first segment was drawn from the most inferior surface of the calcaneus to the most anteriorly-protruding point on the plantar surface of the calcaneus. The second segment was drawn from the most inferior surface of the calcaneus to the most inferior surface of the head of the third metatarsal; the angle formed by these two segments was recorded as calcaneal pitch.

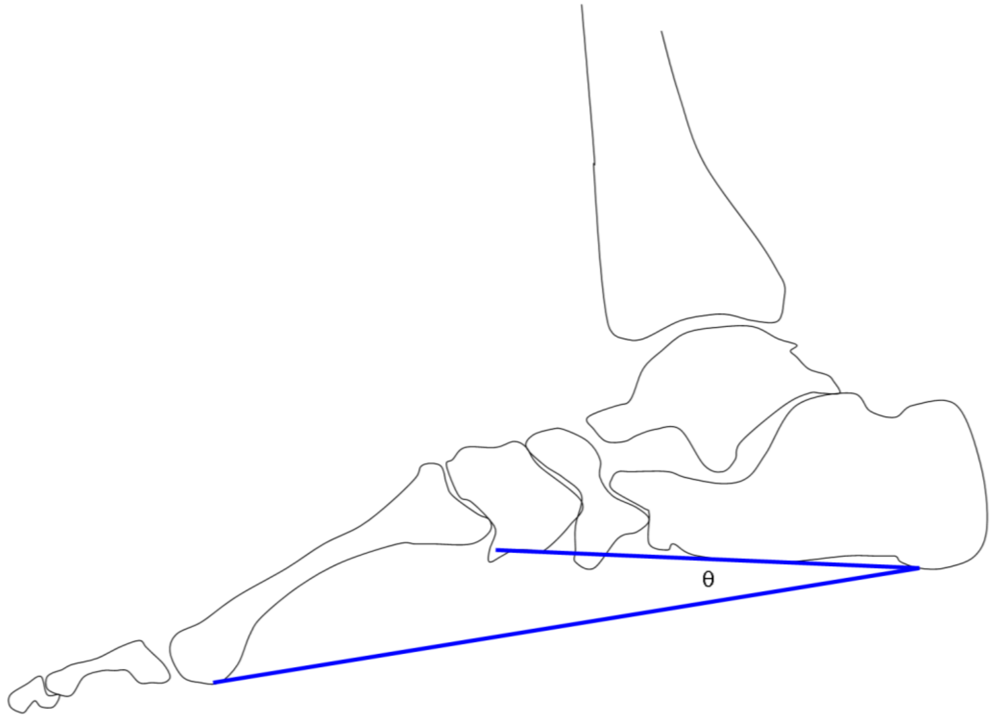


Figure 3-7 Calcaneal Pitch

The measure of calcaneal pitch, defined as the angle of the calcaneus with respect to the base of the foot. The base of the foot is the line between the posterior, inferior protruding aspect of the calcaneus and the head of the third metatarsal. The calcaneal line is drawn from the same posterior point of the calcaneus through the protruding point on the anterior, inferior aspect of the calcaneus, and the angle is taken between these two lines.

3.7 External Foot Measurements

External foot measurements were taken before the scans with a tape measure. The subject was instructed to stand with feet shoulder-width apart in a fully erect position. Measurements of foot length, leg length, first metatarsal length, lateral malleolus length, and first toe length. Foot length was defined as the distance between the most distal point on the most anterior toe to the most posterior aspect of the heel. Leg length was defined as the distance between the center of the head of the fibula and the center of the lateral malleolus. First metatarsal length was defined as the distance between the head of the first metatarsal and the most posterior aspect of the heel. Lateral malleolus length was defined as the perpendicular distance between the middle of the lateral malleolus and the most posterior aspect of the heel. First toe length was defined as the difference between foot length and first metatarsal length values.

3.8 Statistical tests

Mean values were taken for stature, body mass, age, foot length, length of the first proximal phalanx, length of the first distal phalanx, length of the first metatarsal, length of the first ray, length of the plantarflexor moment arm, and the ratio between the length of the first ray and the plantarflexor moment arm for both the sprinter and the non-sprinter group. One tailed t-tests were used to test for differences between these two groups (α=0.05) based on previous results (Lee and Piazza 2009). Different abbreviations were used throughout the paper to indicate the different measured values (Table 3-1).

Table 3-1: Description of Abbreviations

Abbreviation	*Description*
Lpp1+Ldp1	Sum of the length of the proximal and distal phalanges of the first toe
Lmt1	Length of the first metatarsal
Lr1	Length of the first ray, calculated as the sum of proximal and distal phalanges and the metatarsal of the first toe.
pfMA_P	Plantarflexor moment arm-passive state
pfMA_C	Plantarflexor moment arm- contracted state
Lr1:pfMA_P	Ratio of the length of the first ray to the passive-state plantarflexor moment arm
Lp1:pfMA_C	Ratio of the length of the first ray to the contracted-state plantarflexor moment arm
tibX_P tibY_P tibX_C tibY_C	Position of the Achilles tendon with reference to a coordinate system about the long axis of the tibia; X indicates anterior-posterior, Y indicates superior-inferior; P indicates passive tendon state, C indicates contracted tendon state

A description of the abbreviations of the used to describe different measures made in the study.

Chapter 4

Results

The measured results supported the initial hypotheses. The average heights of the sprinters (177.4±7.2cm) and non-sprinters (177.1±7cm) were not significantly different (p=0.944), nor did they differ in body mass (sprinters 76.3±7.9kg, non-sprinters 82±8.9kg). The non-sprinter group (24±2.6 years) did have a higher mean age than the sprinter group (21.3±2.5 years), which was significant at a $p=0.1$ level (p=0.0507). Sprinters' years of sprint-specific training (6.5±2.8 years) were measured to quantify the training aspect of the study's qualifications. Sprinters either gave their best 100m or 200m dash times; the averages of both the 100m (10.82±0.2s) and 200m times (22.745±1.86s) were taken. Years training and personal best sprint times did not pertain to the non-sprinters and were thus not recorded (Table 4-1).

Table 4-1: Mean demographics differences between groups

	Units	*ES_avg*	*ES_stdev*	*NS_avg*	*NS_stdev*	*2-tailed p-value*
Stature	cm	177.4	7.2	177.1	7	0.944
Body mass	kg	76.3	7.9	82	8.9	0.2523
Age	Years	21.3	2.5	24	2.6	0.0507
Training	Years	6.5	2.8			
best 100	s	10.82	0.2			
best 200	s	22.745	1.86			

Table 4-2: Mean measured value differences between groups

	Units	*ES_avg*	*ES_stdev*	*NS_avg*	*NS_stdev*	*1-tailed p-value*	*2-tailed p-value*
footLength	cm	27.5	1.2	27.5	0.9	`	0.9462
Lpp1+Ldp1	mm	59.7	2	56.2	3.2	0.0109	0.0218
Lmt1	mm	70.1	2	67.2	4.2	0.0498	0.0996
Lr1	mm	129.7	3.7	123.4	7	0.0197	0.0394
pfMA_P	mm	51.5	3.9	58.5	6.6	0.0112	0.0224
pfMA_C	mm	52.9	4.8	58.7	5.4	0.0205	0.0411
Lr1:pfMA_P	1	2.53	0.24	2.13	0.02	0.0013	0.0027
Lp1:pfMA_C	1	2.47	0.25	2.11	0.13	0.0014	0.0029
tibX_P	mm	-0.3	2.42	-5.3	2.4	`	0.00095
tibY_P	mm	-21.9	2.3	-19.3	4.2	`	0.1554
tibX_C	mm	1.2	2.1	-6	3.1	`	0.00008
tibY_C	mm	-21	3.9	-21.8	5.1	`	0.7295
CalcPitch	deg	26.38	7.54	27.94	6.98	0.33340	0.66682

No significant difference (p=0.9462) was found between the foot lengths of the sprinters (27.5±1.2cm) and non-sprinters (27.5±0.9cm). There were, however, differences in the lengths of the first toe (sprinters 59.7±2mm, non-sprinters 56.2±3.2mm, p-value 0.0109), the first metatarsal (sprinters 70.1±2mm, non-sprinters 67.2±4.2mm, p-value 0.0498), and the first ray (sprinters 129.7±3.7mm, non-sprinters 123.4±7mm, p-value 0.0197). With this change in forefoot length was a change in Achilles tendon moment arm length, as sprinters had significantly shorter moment arms in both the passive (51.5±3.9mm) and contracted (52.9±4.8mm) states than non-sprinters in the passive (58.5±6.6mm, p-value 0.0112,) or contracted states (58.7±5.4mm, p-value 0.205). Along with the differences between individual forefoot and Achilles tendon moment arm lengths was a difference in the ratio between these two values in the passive (sprinters 2.53±0.24, non-sprinters 2.13±0.02, p-value 0.0013) and contracted (sprinters 2.47±0.25, non-sprinters 2.11±0.13, p-value 0.0014) states. No difference was found between the calcaneal pitch angle values (sprinters 26.38±7.54, non-sprinters 27.94±6.98, p-value 0.3334).

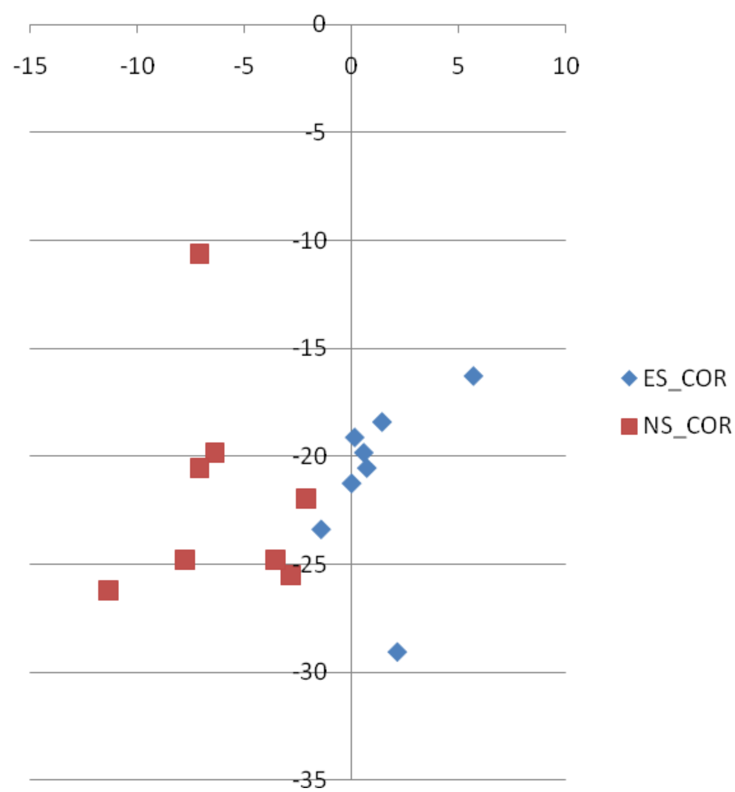


Fig 4-1 Center of Rotation Coordinates: Passive State

The center of rotation of the ankle during the passive state. The Y-axis is defined as a line that goes down he midline of the tibia and the X-axis is defined as perpendicular to that at the point at the center of the articular surface on the distal tibia. The centers of rotation for the sprinters (ES) are shown as the diamonds and the non-sprinters (NS) as shown as the squares. Sprinters' centers of tibiotalar rotation were found to be located father anterior than those of non-sprinters in the passive state.

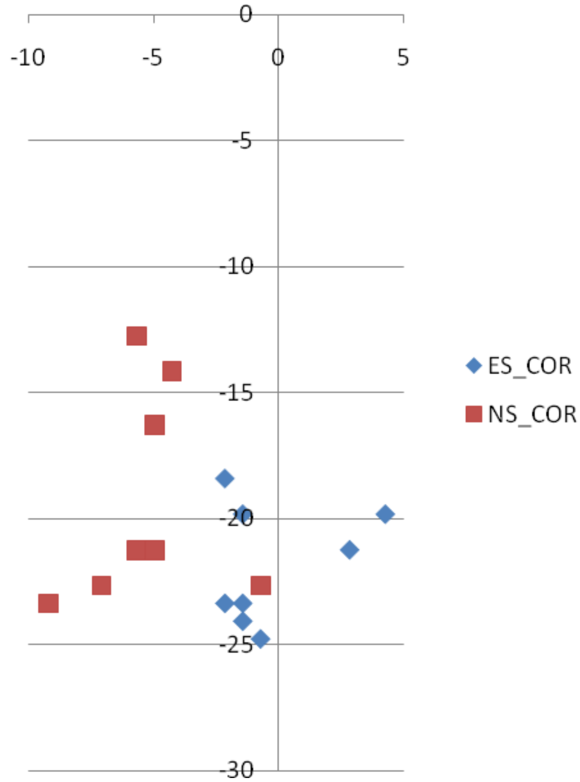


Fig 4-2: Center of Rotation Coordinates: Contracted State

The center of rotation of the ankle during the contracted state. The Y-axis is defined as a line that goes down he midline of the tibia and the X-axis is defined as perpendicular to that at the point at the center of the articular surface on the distal tibia. The centers of rotation for the sprinters (ES) are shown as the diamonds and the non-sprinters (NS) as shown as the squares. Sprinters' centers of tibiotalar rotation were found to be located father anterior than those of non-sprinters in the contracted state.

The measurement of the location of the Achilles tendon with reference to a coordinate system defined by the tibia also showed differences (Fig 4-1 and 4-2). Significant differences were found in the X-coordinate plane between in the passive (sprinters -0.3±2.42mm, non-sprinters -5.3±2.4mm. 2-tailed p-value 0.00095) and contracted (sprinters 1.2±2.1mm, non-sprinters -6±3.1mm, 2-tailed p-value 0.00008) states. No differences were found in the Y-coordinate system plane between the passive (sprinters -21.9±2.3mm, non-sprinters -19.3±4.2, 2-tailed p-value 0.1554) and contracted (sprinters -21±3.9mm, non-sprinters -21.8±5.1mm, 2-tailed p-value 0.7295) states.

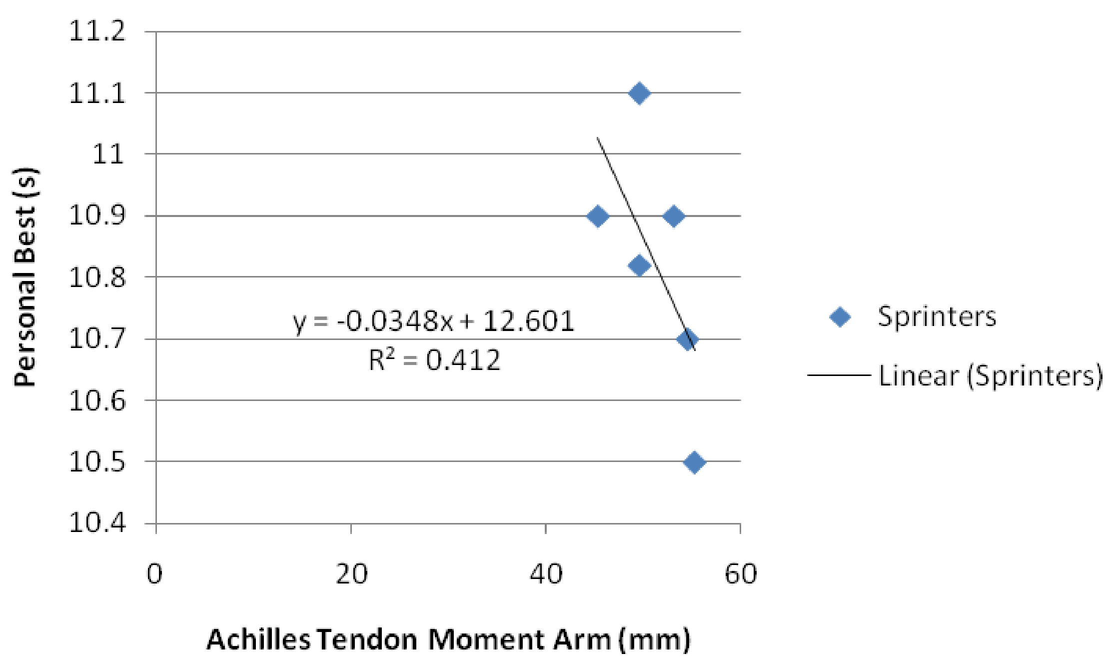


Fig 4-3: Achilles Tendon Moment Arm vs. 100m Personal Best

The correlation between the sprinters' Achilles tendon moment arm and their personal best time in the 100m dash. Two subjects were not included in this graph, as their personal bests were reported in the 200m. Correlation shown as a linear line of best fit. There is only a weak correlation between sprinter's moment arm length and their 100m personal best.

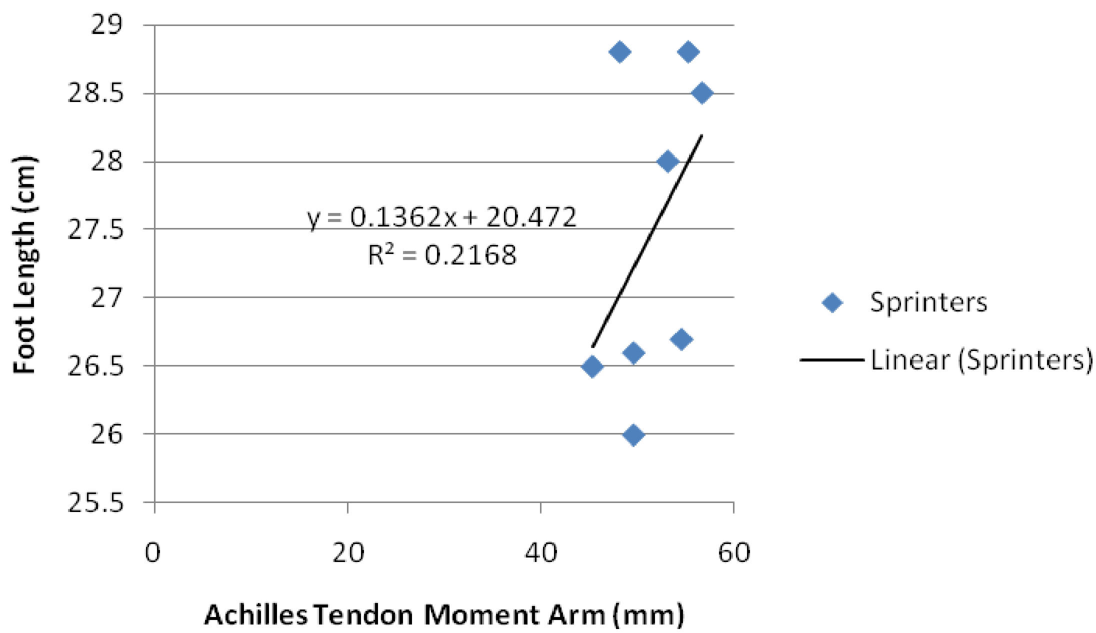


Fig 4-4: Sprinters' Achilles Tendon Moment Arm vs. Foot Length

The sprinters' Achilles tendon moment arm vs. foot length. Correlation shown as a linear line of best fit. There is a weak correlation between moment arm length and foot length for sprinters.

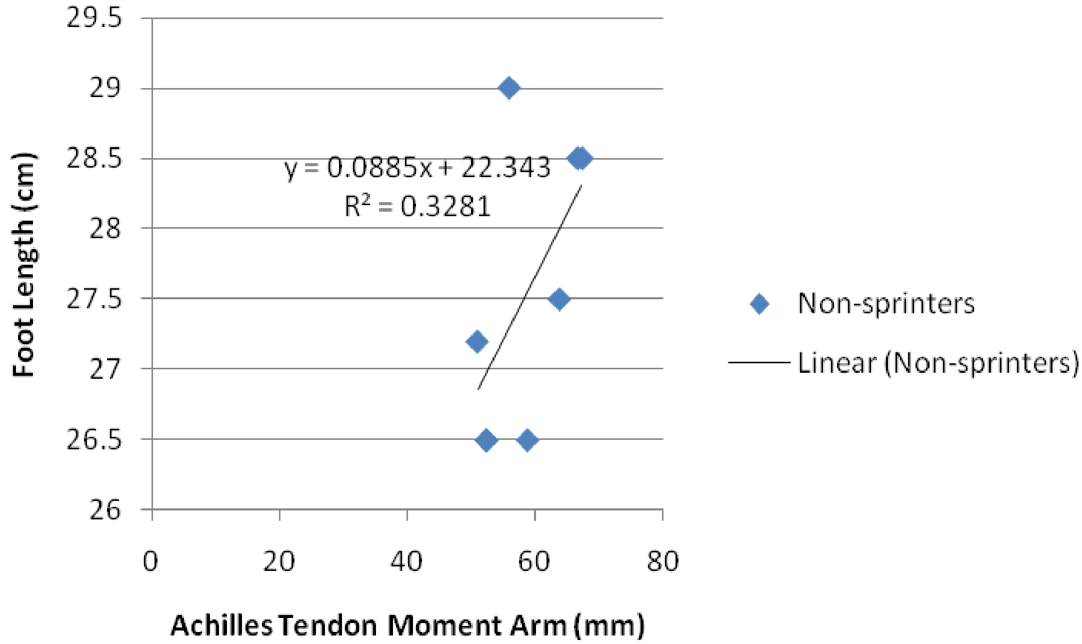


Fig 4-5: Non-Sprinters' Achilles Tendon Moment Arm vs. Foot Length

The non-sprinters Achilles tendon moment arms vs. foot length. Correlation shown as a linear line of best fit. There is a weak correlation between foot length and moment arm length for non-sprinters.

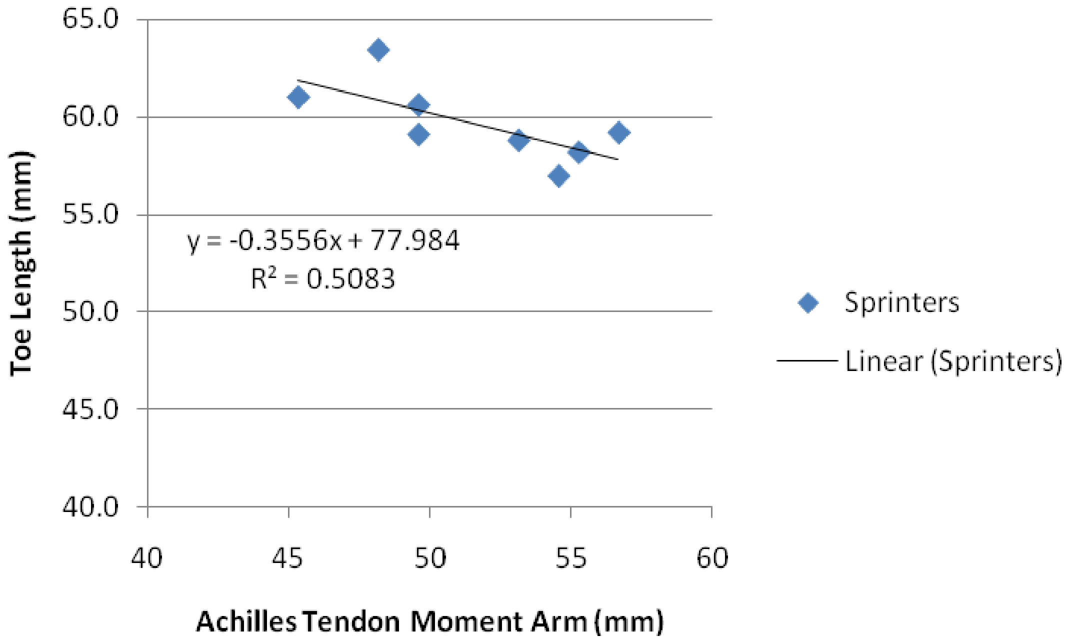


Fig 4-6: Sprinters' Achilles Tendon Moment Arm vs. Toe Length

The sprinters' Achilles tendon moment arm vs. toe length, which is quantified as the sum of the lengths of the first proximal and distal phalanges. Correlation shown as a linear line of best fit. There is a mild correlation between toe length and moment arm length for sprinters.

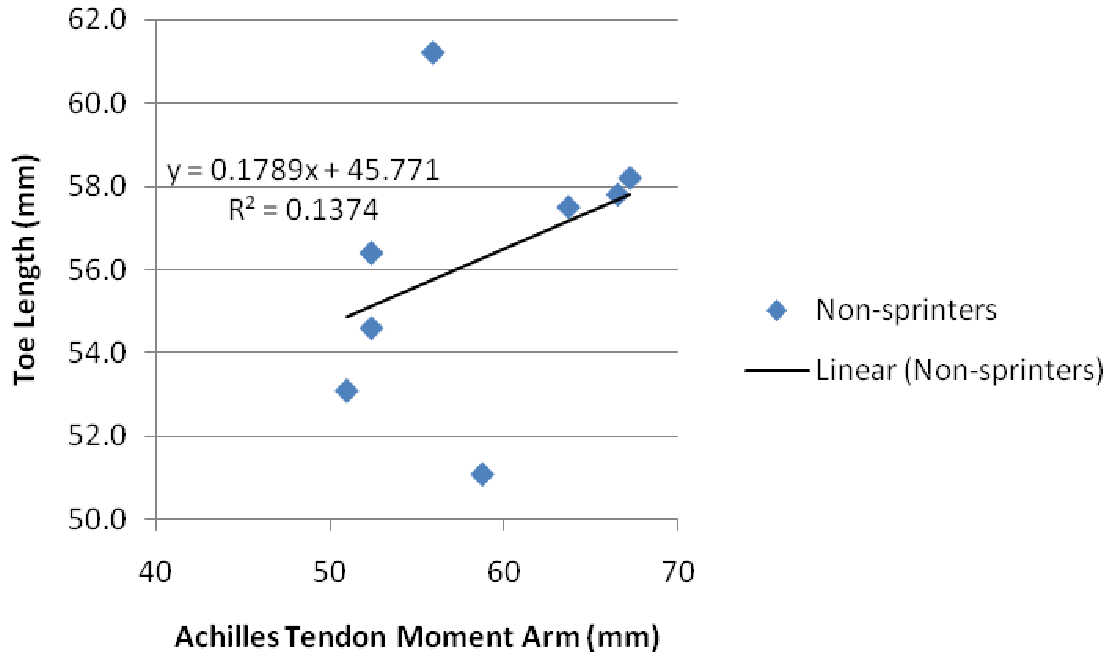


Fig 4-7: Non-sprinters' Achilles Tendon Moment Arm vs. Toe Length

The non-sprinters' Achilles tendon moment arm vs. toe length, which is quantified as the sum of the lengths of the first proximal and distal phalanges. Correlation shown as a linear line of best fit. There is no correlation between toe length and moment arm length for non-sprinters.

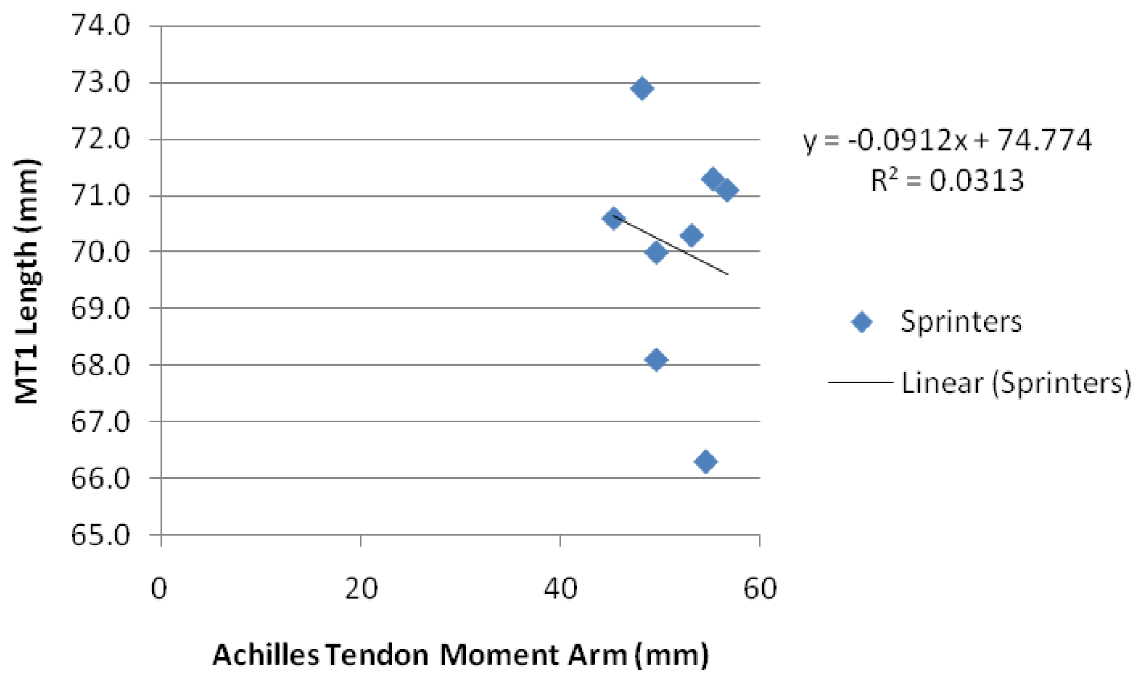


Fig 4-8: Sprinters' Achilles Tendon Moment Arm vs. MT1 Length

The sprinters' Achilles tendon moment arm vs. metatarsal 1 length. Correlation shown as a linear line of best fit. There is no correlation between first metatarsal length and moment arm length for sprinters.

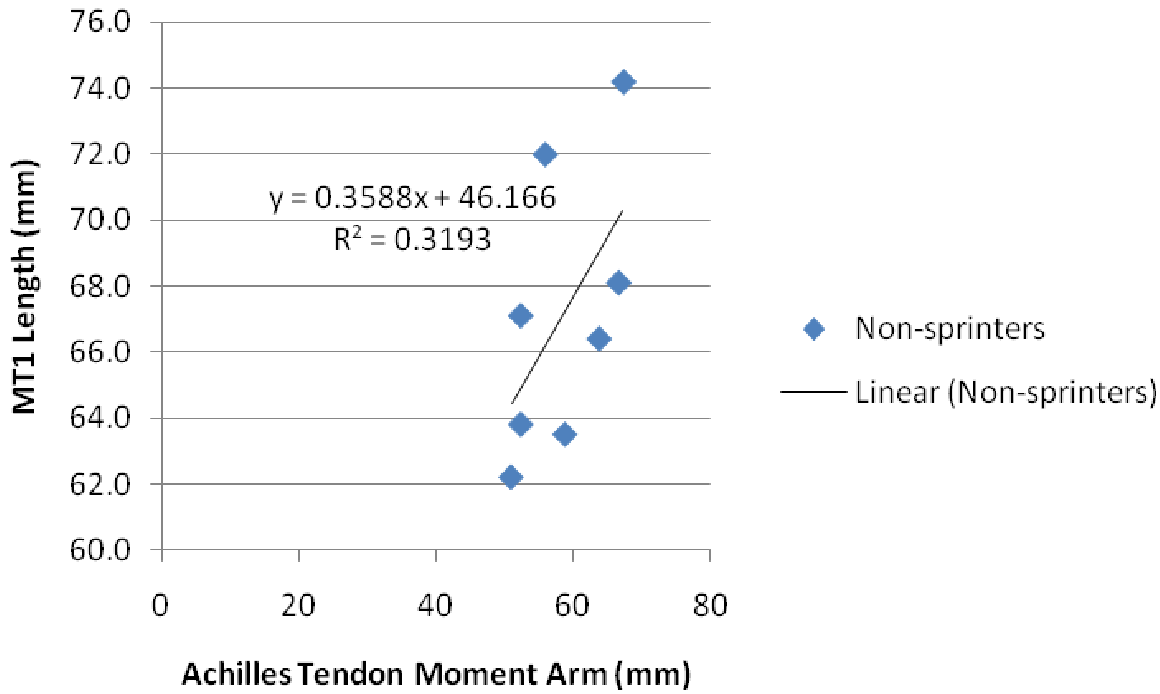


Fig 4-9: Non-sprinters' Achilles Tendon Moment Arm vs. MT1 Length

The non-sprinters' Achilles tendon moment arm vs. metatarsal 1 length. Correlation shown as a linear line of best fit. There is a weak correlation between first metatarsal length and moment arm length for non-sprinters.

There was only a weak correlation found between sprinters' Achilles tendon moment arms and their self-reported personal best 100m dash times (r^2= 0.412). Only six of the sprint subjects were used for this correlation, as two of the subjects were included on the basis of their 200m personal best times. There was only a weak correlation between Achilles tendon moment arm and foot length for sprinters (r^2= 0.2168) or non-sprinters (r^2= 0.3281). There is a mild correlation between Achilles tendon moment arm and toe length for sprinters (r^2= 0.5083), with shorter moment arms correlating with longer toes.There was no correlation between Achilles tendon moment arm and toe length for non- sprinters (r^2= 0.1374). There was no correlation between Achilles tendon moment arm and first metararsal length between sprinters (r^2= 0.0313) or non-sprinters (r^2= 0.31393).

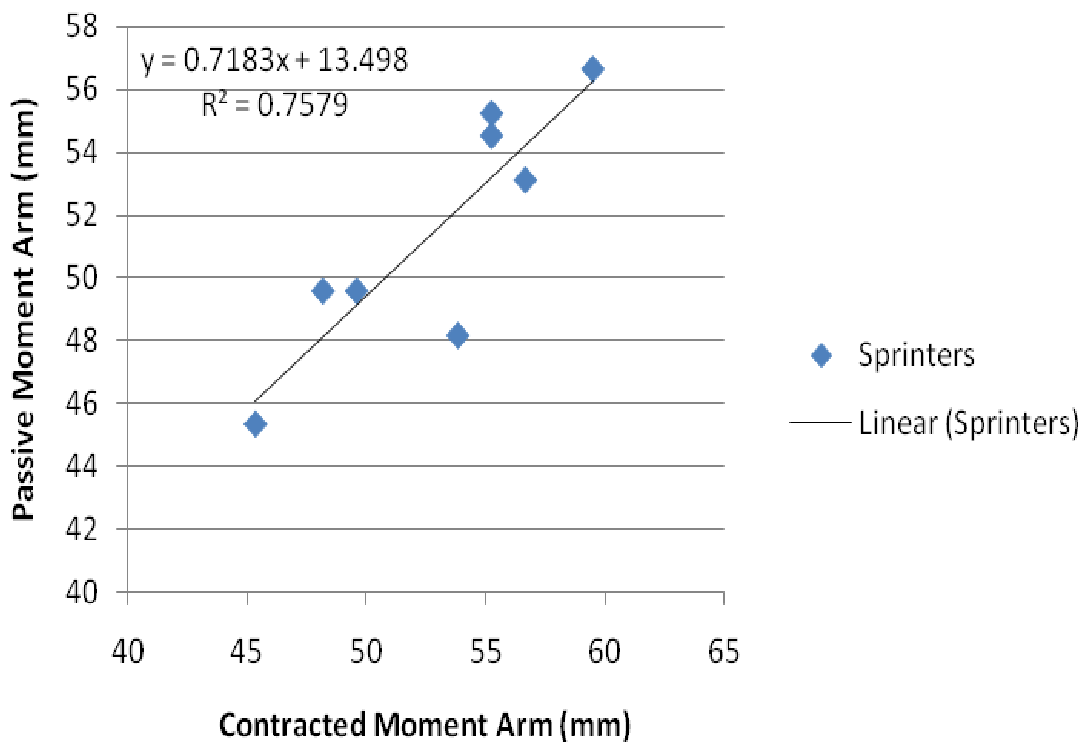


Fig 4-10: Sprinters' Passive vs. Contracted Moment Arm

The comparison between Achilles tendon moment arm values for sprinters in the passive and contracted states. Correlation shown as a linear line of best fit. There is a strong correlation between passive and contracted moment arm for sprinters (p=0.1335).

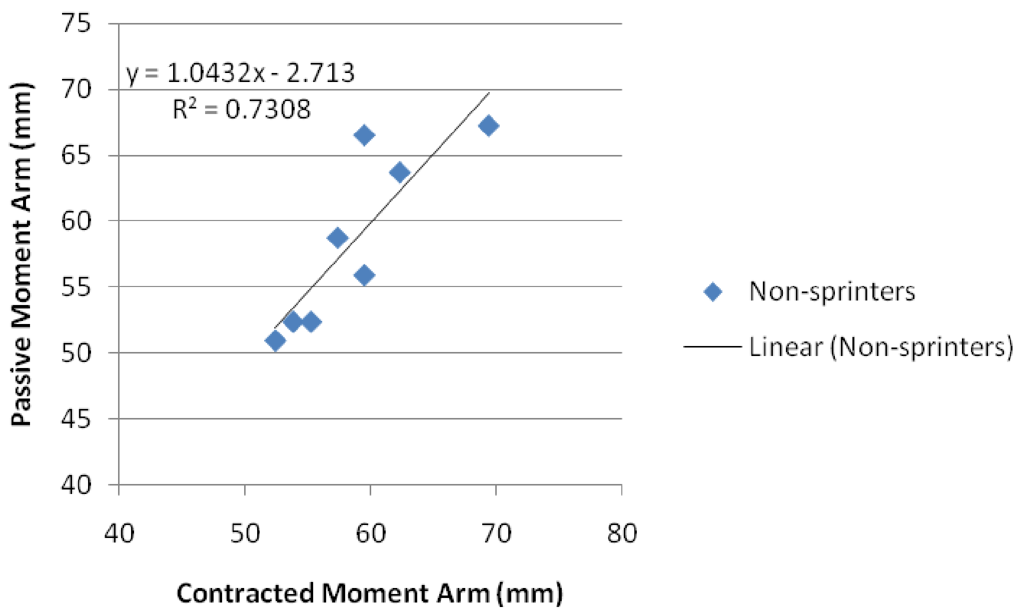


Fig 4-11: Non-sprinters' Passive vs. Contracted Moment Arm

The comparison between Achilles tendon moment arm values for non- sprinters in the passive and contracted states. Correlation shown as a linear line of best fit. There is a strong correlation between passive and contracted moment arms for non-sprinters. (p=0.8669).

Measures were made to compare the Achilles tendon moment arm measurements made from scans in the passive and contracted states. There was a strong correlation between passive and contracted measurements for sprinters (r^2= 0.7579) and no significant difference was reported (2-tailed paired t-test p=0.1335). There was also a strong correlation between passive and contracted states for non-sprinters (r^2= 0.7308) and no significant difference was reported (2-tailed paired t-test p= 0.8869).

Chapter 5

Discussion

5.1. Summary of Results

It was found that elite, sprint-trained athletes have shorter Achilles tendon moment arms than untrained athletes, as shown in Table 4-2. Sprinters also have shorter toes, as defined by the sum of the distal and proximal phalanges of the first ray, as well as a shorter first metatarsal and first ray. Following with this, sprinters also have a greater first ray to moment arm ratio. Sprinters have a more posteriorly-placed center of rotation in reference to the X- coordinate system about the tibia in both the passive and contracted state, as seen in Figures 4-1 and 4-2. There were no significant differences between the calcaneal pitch or superior/inferior displacement with reference to a tibia coordinate system. No correlation was found between self-reported personal best 100m dash times and Achilles tendon moment arms for the six sprinters who reported their 100m time for inclusion in the study (Fig 4-3). There was also no correlation between Achilles tendon moment arm and foot length or first metatarsal length for either group, along with Achilles tendon moment arm and toe length for non-sprinters (Figs 4-4, 4-5, 4-7, 4-8, 4-9. There was a mild negative correlation between Achilles tendon moment arm and toe length for sprinters (Fig 4-6). There was a strong correlation between passive and contracted moment arm measurements within each group, with neither showing any significant differences at the p=0.05 level.

The first hypothesis of this study was that sprinters would have shorter Achilles tendon moment arms than height-matched non-sprinter controls. This hypothesis was supported, as sprinters had significantly shorter moment arms in both the passive and contracted states (Table 4-2). The second hypothesis was that sprinters and non-sprinters would have different centers of tibiotalar rotation. This hypothesis was supported, as sprinters appear to have anteriorly-located centers of rotation in both the passive (Fig 4-1) and contracted (Fig 4-2) states. The third hypothesis was that sprinters would have significantly longer toes than the non-sprinters. This hypothesis was supported, as sprinters had significantly longer first toes, metatarsals, and rays (Table 4-2).

5.2. Results Compared to Past Findings

Previous moment arm research has shown that elite, sprint-trained athletes have shorter Achilles tendon moment arms and longer toes than untrained non-sprinters (Lee and Piazza 2009), when those moment arms are found using an ultrasound measurement technique and external anatomical measurements. Using MR imaging in the present study, it was also found that sprinters have shorter Achilles tendon moment arms. Moment arms were found in this study using sagittal-plane MR scans in combination with the Reuleaux method to find the centers of tibiotalar rotation. The moment arm was taken to be the shortest distance between this point and the line of action of the Achilles tendon (Maganaris et. al. 1998). Although ultrasound does allow for a quicker, cheaper, and easier imaging process, the quality and directness of the MR image is a pro to using the more technologically advanced method.

Previous research by Lee has also shown that sprinters have longer toes than non-sprinters. These findings were made from external foot anatomy measurements, where toe length was defined as the difference between two measured values: the length of the lateral malleolus to the first metatarsal head and the lateral malleolus to the end of the first toe. This study used more direct measurements of bone lengths using MR images. Toe length was defined as the sum of the proximal and distal phalanges of the first ray. Using these same techniques, sprinters were also found to have longer first metatarsals. The difference in toe length and moment arm was found despite no difference in foot length between the sprinters and the height-matched controls. This gives the overall idea that sprinters feet are more anteriorly located with reference to the tibia, as seen in the fact that the center of rotation is thus more posteriorly located in sprinters (Fig 4-1 and 4-2). There was also no correlation between foot length or first metatarsal length and Achilles tendon moment arm for either group (Fig 4-4, 4-5, 4-8, 4-9). There was a slight correlation between toe length and Achilles tendon moment arms for sprinters (Fig 4-6), but none for non-sprinters (Fig 4-7), implying that toe length, when combined with moment arm length, may produce the key combination for improved performance.

Research in distance runners has shown that elite distance runners may also have changes in ankle structure, as longer moment arms have been found to be strongly correlated with VO_2 and running economy (Scholz et. al. 2009; Raichlen et. al. 2011). A smaller moment arm would mean a better running economy, as runners would be able to use these small moment arms to stretch the tendon and store energy in it, which would allow more energy to be fed back into the running process. In distance runners a longer moment arm has been hypothesized to be beneficial because of the decreased force necessary to generate the same forward moment, albeit at the expense of improved economy.

Sprinting is not an event commonly associated with efficient running, as sprinters aim to expend the maximal amount of energy possible in the usual sub 12-second race. These shorter heels, however, may prove to be advantageous by putting the runner on a more optimal location on the muscle force-velocity curve. Although the muscle will need to generate more force to create the same forward torque, sprinters' large plantarflexor muscles are able to large powers during the sprint start (Johnson and Buckley 2001). The decreased muscle shortening distance will allow the muscle to shorten at a slower rate generating a larger force.

There has also been research showing that distance runners may benefit from having shorter toes by decreasing the metabolic cost necessary for forward propulsion; it was also suggested, however, that increasing toe length could lead to large increases in forward impulse and work (Rolian et. al. 2009). This study found that sprinters do have longer toes, defined as both the sum of the lengths of the first two phalanges and the length of the first metatarsal. Impulse is the product of force and contact time, and longer toes would allow the foot to stay in contact with the ground for a longer period of time, generating the larger forwards impulses associated with better propulsion of the body's center of mass.

Changes in bone shape and structure have been shown to occur as a result of long-term participation in athletics (Kontulainen et. al. 2002; Myers et. al. 2009). This study found a difference in toe and moment arm lengths between sprinters and non-sprinters, although research was not done to examine the reason behind these differences. It is possible that athletes that begin sprint training at a young age may consistently apply forces to their feet and lower legs that would cause these differences. It is also possible, however, that these differences arise from genetic origins and naturally allow athletes to run faster. Furthermore, it could be some combination of the two, in that younger athletes with naturally longer toes and shorter Achilles tendon moment arms are more likely to elect to begin sprint training at a younger age, and developments during training further increases their advantages.

Past research has also shown there to be different Achilles tendon moment arm differences associated with measurements being taken while the tendon is in the passive or contracted state (Maganaris et. al. 1998a; Maganaris et. al. 1998b Maganaris et. al. 2000; Maganaris et. al. 2003). There was a strong correlation between the passive and contracted states for both the sprinter and non-sprinter groups, with no statistically significant distance between them (Fig 4-10, Fig 4-11). It is possible that previous MR scanning techniques used a strapping technique that affected the path of the tendon during contraction, creating an artificial difference. This protocol did not involve strapping of the foot or ankle, so there was no such artifact created. There could have been a small amount of error due to the foot coming off the footplate slightly during contraction, but great care was taken to center each scan around the foot to avoid this problem.

5.3. Implications of Results

There are many significant implications of these results. It was found that sprinters have significantly longer toes and shorter Achilles tendon moment arms, so it could be possible to screen for these in young athletes to predict whether or not they could be elite sprinters. This could have a major effect at the high school sports level, as it would help predict which athletes are going to be the best sprinters. This has greater potential at the youth sports level, however, as young athletes with naturally longer toes and shorter moment arms could be directed into sprint training at a younger age; it may be possible that these advantaged may further increase by starting at a younger age, before the bone has fully formed.

This study also supported the idea that there are certain structural differences that correlate with a conferred advantage in some task. This is not a novel idea in principle, as it would make sense that a person with a longer femur would be more likely to be able to reach an object on a high shelf than a person with a shorter femur. In athletics a person with a longer femur may be taller, potentially giving them one advantage in a sport that has a large height component, such as basketball. The differences found in this study, however, were much more subtle, looking at the lengths of smaller bones and joint distances. Furthermore, the differences found in toe length between sprinters and non-sprinters occurred despite similarities in foot length, making these measurements more difficult to observe with the naked eye. This finding could form the basis for more research examining similar subtle differences in anatomical structure that could convey major functional advantages.

The idea of certain structural differences correlating with functional advantages could be extrapolated to other groups outside of sprinters. The elderly population in America is growing rapidly, and as more people enter old age there will be an increase in the gait-challenged subpopulation. It may be possible to use these established correlations to target middle-aged adults and predict whether or not they will have gait problems in their near future. If it were found that they have, for example, shorter toes and longer moment arms, they could be put on an exercise program that would work to increase the strength of their plantarflexors so they can have a larger forward impulse despite smaller moment arms. It may be possible that, since shorter toes and longer moment arms are more economical it would be more beneficial to have those parameters (Rolian et. al. 2009). More research on elderly population is necessary before these extrapolations may accurately be made.

A shorter Achilles tendon moment arm would be beneficial to sprinters because of how it would allow the muscle to work more efficiently. A moment arm is the perpendicular distance between the center of rotation and the line of action of an object. The product of the moment arm and the applied force is the moment, which is directly proportional to the angular acceleration driven by the moment. A shorter moment arm will mean a larger force will be necessary to create the same angular acceleration. This will also mean, however, that the displacement along the line of action of the force can be smaller to generate the same angular displacement. Angular acceleration is simply the quotient of the angular displacement per the square of unit time, thus to create the same angular acceleration a smaller linear displacement per unit time, or shortening velocity, along the line of action of force is necessary. The inverse relationship between muscle force and velocity has been around for a number of years (Fenn et. al. 1935; Bigland et. al. 1954, Perrine et. al. 1978). A smaller shortening velocity would mean the muscle would be able to generate a greater amount of force during the contraction, overcoming the mechanical disadvantage posed by having a smaller moment arm and creating a large forward acceleration of the body's center of mass.

Longer toes would also be beneficial to sprinters by allowing sprinters to generate a greater forward impulse with each step. Impulse is the product of force and time, and longer toes would allow sprinters to stay in contact with the ground for a longer period of time with each step. It may be counterintuitive that sprinters would want their feet on the ground longer, but the far greater impulses generated during this time greatly improves their forward acceleration.

5.4 Limitations

This study was affected by certain limitations. Achilles tendon moment arms were measured using the Reuleaux method on transparency scans. Although this method has been used in the past to measure these moment arms, it is possible that other methods, such as a tendon-excursion method using ultrasound imaging (Lee and Piazza 2009) or a method that defines the ankle center of rotation differently (Raichlen et. al. 2011) may be more accurate. It is also of note that the significance in this study may be muted due to a lack of subject power. It proved to be difficult to recruit sprint-trained subjects who fit the parameters to be considered elite sprinters and to get time to scan in the MR on campus. It was also tricky to determine the classification of an "elite sprinter" as personal bests and years sprinting do provide qualifiers but do not exactly measure ability at the time of the scan as a VO_2 measurement could be made for elite distance runners to determine top ability. There was also a discrepancy in subject ages between sprinters and non-sprinters, as care was taken to match the control subjects to the height of the sprinters rather than their age. The study also does not offer an explanation behind the difference in toe lengths between sprinters and non-sprinters, as it primarily aimed at quantifying the bone lengths. Finally, the study did not look at truly “elite,” Olympic-class sprinters, as it would have proved difficult to bring them in to test. Qualifying times were set to reflect national competition-level times.

5.5 Future Research

Some possibilities for future projects include the following:

- Repeating the studying using Olympic-level sprinters
- Increasing the number of sprint and non-sprinter subjects scanned
- Examining other populations of athletes, such as elite jumpers
- Looking at how the musculoskeletal variables observed in sprinters could be measured and correlated with walking ability in elderly populations
- Examining children with diseases such as cerebral palsy to see if certain locomotor variables can be optimized to improve gait ability

5.6. Conclusion

In track and field circles, or even the average sports debate, the question has continuously been debated on what makes certain athletes faster than others. Much research has been done to examine the many different muscle properties that could affect athletic performance, but there has been little done seeing if certain structural differences about the foot and ankle may convey a functional advantage. Previous research had shown that elite, trained sprinters have significantly shorter Achilles tendon moment arms and toes than non-sprint-trained individuals in a study done with ultrasound imaging; Achilles tendon moment arms have also been found using a geometric or force-loading technique. It has also been shown that athletes may develop changes in bone structure as a result of playing certain sports, so the link between athletics and structural changes in bone structure has already been established.

This study used MR imaging to examine structural differences between sprinters and non-sprinters about the ankle joint. It was found that sprinters have significantly shorter Achilles tendon moment arms, shorter toes, and more posteriorly-located centers of ankle rotation. Shorter moment arms would mean a mechanical disadvantage, but it would place the sprinters' plantarflexor muscles on a more favorable location on the muscle force-velocity curve, easily overcoming this disadvantage and creating a greater forward acceleration. Longer toes would allow sprinters to stay in contact with the ground for a longer period of time, allowing them to create a greater forward impulse. A more posteriorly-located center of rotation illustrated these differences despite similar foot lengths, implying that it may be possible to see these differences without detailed scanning techniques.

There are a number of limitations with this study, including a small sample size and the lack of truly elite sprinters. The results do corroborate with previous research using a more advanced scanning tool, supporting that the data may still be significant. These results could be used to screen athletes at young ages to determine which ones are predisposed to be better sprinters and guide them into more sprint-specific training. It may also be possible to take these results and extrapolate them into other subpopulation. Further research could examine these variables in the growing elderly populations and potentially act a screening technique to determine functional gait ability into older age.

Appendix A
Total Subject Data

Subject	Height (cm)	Mass (kg)	Foot Length (cm)	Leg Length (cm)	MT-1 Length (cm)	L. Malleolus Length (cm)	Toe1 length	scan date	birth date	Age	PR	PR Event	PR Year	Years training
ES01	178	77.8	26.6	37.5	20	4	6.6	6/17/2010	2/2/1984	26.370979	11.1	100	2006	11
ES02	184	84.5	28.8	39	21.5	6	7.3	6/22/2010	9/2/1991	18.803559	10.5	100	2010	4
ES03	184	70.53	28.8	39	20.3	5	8.5	7/9/2010	6/8/1991	19.085558	24.06	200	2009	2
ES04	169.5	69	26	37	18.8	5	7.2	10/6/2010	4/14/1989	21.478439	10.82	100	2010	5
ES05	173	65.5	26.5	37	19.5	3.5	7	10/19/2010	5/5/1991	19.457906	10.9	100	2007	8
ES06	172.5	85	28	39	20.5	5.5	7.5	11/18/2010	9/2/1990	20.210815	10.9	100	2010	8
ES07	170	81.5	26.7	36.9	19.5	4.5	7.2	12/1/2010	12/13/1987	22.96783	10.7	100	2005	8
ES08	188	81.8	28.5	43	20.5	5.5	8	3/23/2010	4/6/1988	21.960301	21.43	200		6
NS01	180	92.6	28.5	39	20.8	6.7	7.7	9/23/2010	8/27/1988	22.072553				
NS02	168	75.6	27.2	34	21.5	4.3	5.7	11/12/2010	1/26/1989	21.793292				
NS03	180	88.2	27.5	37	20.5	5.7	7	11/24/2010	2/1/1989	21.809719				
NS04	184	93	28.5	38.5	21	5.5	7.5	11/24/2010	7/19/1984	26.349076				
NS05	172	77.4	26.5	36.8	19.6	4.7	6.9	1/20/2011	8/29/1988	22.392882				
NS06	175	72.3	26.5	38	19.5	5.5	7	2/28/2011	5/12/1982	28.799452				
NS07	170	75	26.5	37.5	19.5	5.5	7	3/3/2011	10/14/1987	23.383984				
NS08	188		29	39.5	20.5	5.5	8.5	3/23/2011						

Appendix B

IRB Consent Forms

PENNSTATE

Informed Consent Form for Biomedical Research
The Pennsylvania State University

ORP OFFICE USE ONLY:
DO NOT REMOVE OR MODIFY
IRB#33612 Doc. #1001
The Pennsylvania State

Title of Project: "Ankle structure and human mobility

Principal Investigator: Stephen J. Piazza, Ph.D.
Address: Biomechanics Laboratory
29 Recreation Building
The Pennsylvania State University
University Park, PA 16802
Phone: 814-865-3413
Email: piazza@psu.edu

Other Investigator(s): Josh Baxter MS, Thomas Novack, David Pennell MS, Huseyin Celik MS

1. **Purpose of the study:** The purpose of this research is to understand how the structure of the ankle and foot affect the ability to walk and run.

   If you agree to participate in the study, magnetic resonance imaging (MRI) scans will be taken. The MRI scans will assist us in understanding the structure and function of different parts of the body. There are two types of scans that may be done. Anatomy scans are used to determine the structure of the body. Scans of function are used to determine areas of activity when you perform different tasks.

   NONE of the scans done during this study are designed to detect or evaluate any medical condition you may have. They are intended solely for research purposes.

2. **Procedures to be followed:** To date, 150 million patients have undergone MRI examinations around the world. We will be following standard MRI procedures and safety guidelines. MRI has been shown to be extremely safe as long as proper safety precautions are taken. MRI uses strong magnetic fields and radio waves to make pictures of the body. There is no exposure to x-rays or radioactivity during an MRI scan. Levels of energy used are within FDA safety limits. This study will use a 3.0 Tesla MRI scanner.

   You will be asked to leave metal objects and personal belongings in lockers provided in the prep room of the MRI center. You will also be asked to remove any articles of clothing with metal inserts or clasps before entering the MRI room. Please ask the experimenter if you are unsure about any items.

   You will be asked to lie on a bed that slides into the long tube of the scanner. You will be given earphones and/or earplugs for hearing protection since the MRI scanner makes loud noises during normal operation. You will be asked to remain very still at these times. You will be able to talk to the MRI technologist by an intercom, and he/she will be able to see you and hear you at all times. You will also be given a squeeze-ball signaling device. If at any time you would like to discontinue the study, you can tell the investigators over the intercom or press the squeeze-ball signaling device and you will be removed immediately from the scanner. You can discontinue the study at any time without penalty.

This study consists of a series MRI scans of your leg and foot. Two small adhesive gel-caps will be placed on your foot and lower leg. These gel-caps will help with orientating the scanning equipment. You will then be asked to lay on a bed with your knees slightly bent and supported by a foam block. Your right foot will be strapped to an apparatus and you will have handles to grasp which will prevent your foot and body from moving, respectively. During the scans, your right foot will be placed in three positions; slightly pointed toward the body, slightly pointed away from the body, and neutrally positioned. In the first two positions several scans will be taken: a short series of scans will be used to orientate the scanning equipment, one scan with the foot relaxed and another scan with the foot undergoing a maximal toe-pointing of 4 seconds, much like pressing down on a gas pedal. These scans will only last a few seconds to help ensure a maximal effort is possible. When your foot is in the third position several more scans will be taken; the short series of orientating scans and the two scans previously described for the other positions, one scan of the entire foot and one scan of the lower leg during which you will asked to relax and remain motionless. These last two scans will last between 1-3 minutes each. If your foot moves during a scan we will reattempt the scan.

3. **Discomforts and risks of the MRI:** Risk of injury is very low during an MRI scan. However, MRI is not safe for everyone. It may not be safe for you to have an MRI scan if you have any metal containing iron in or on your body. This is because metal containing iron can pose a safety risk when in the presence of strong magnetic fields. Radiowaves may also heat the body and metallic objects within or on the body, possibly resulting in burns. Before you are allowed in the scanner room, you will be asked a set of questions to determine if it is safe for you to have an MRI scan at this time. For example, it may not be safe to have an MRI scan if you have a cardiac pacemaker, aneurysm clips, an intrauterine device (IUD), etc. For your safety, it is very important that you answer all questions truthfully.

   It is possible that you may feel uncomfortable or confined once inside the scanner. This feeling usually passes within a few minutes as the experimenters talk with you and the study begins. You might experience dizziness, mild nausea, or tiny flashing lights in your field of vision. These sensations are mostly due to movement while inside the magnet and can be minimized by holding still. All of these sensations should stop shortly after you leave the magnet.

4. **Other discomforts and risks:** You may experience some skin irritation due to the foot straps or adhesive gel-caps used during the scans. These are both necessary to make sure accurate scans are made. You may also experience some muscle soreness resulting from the maximal muscle efforts you will perform during the study. As with any maximal muscle effort there is a possibility of injury to the muscle.

5. **Benefits:** There are no benefits to you for participating in this study.

   The benefits to society include an increased understanding of how the structure of the ankle joint affects mobility.

6. **Duration/time of the procedures and study:** A number of MRI scans will be performed with the entire procedure lasting up to 45 minutes. You will be asked to lie still for up to 10 minutes at a time.

   The time you will spend participating in this research will take not longer than 1 hour. This time includes all necessary paperwork, measurements, and MRI scans.

7. **Alternative procedures that could be utilized:** Ultrasound scans and external measurements have been used to measure important aspects of ankle joint structure; however, these results may not be as accurate as MRI scans.

8. **Statement of confidentiality:** Your participation in this research is confidential. All possible steps have been taken to assure your privacy. For the MRI, you will be assigned a code number that will be used throughout the scan. Only this code (and never your name) will be used when analyzing or reporting the data. Any identifying information will be kept in a locked location and password protected electronic files located on computers in Chandlee lab as well as the Biomechanics Lab in Rec Hall. All study data on the Kinesiology network will be deleted following the conclusion of the study. Confidential data will be destroyed 3 years after the conclusion of the study.

   The Pennsylvania State University's Office for Research Protections, the Institutional Review Board, and the Office for Human Research Protections in the Department of Health and Human Services may review records related to this research study.

   In the event of any publication or presentation resulting from the research, no personally identifiable information will be shared. The results of the research, including but not limited to your images, may be published and presented at lectures and professional meetings, but you will not be identified in any such publication or presentation.

   After the scans are made, your data will be paired with a code number and will be stored in secure cabinets and computers which only the investigators of this study have access to. During the analysis and presentation of your data, no identifying information will be present.

   The MRI scans will take place in a secure facility where only authorized individuals are allowed to enter. The facility has secure lockers and a private area to change clothes if needed and secure possessions during the scans.

9. **Right to ask questions:** You can ask questions about this research. Please contact Dr. Stephen Piazza at (814) 865-3413 with questions. You can also call this number if you have complaints or concerns about the research. If you have any questions, concerns, problems about your rights as a research participant or would like to offer input, please contact The Pennsylvania State University's Office for Research Protections (ORP) at (814) 865-1775. The ORP cannot answer questions about research procedures. All questions about research procedures can only be answered by the research team.

10. **Permission for future use of records:** May the researcher make and retain your video and photo records for future use, education, or presentation? No identifiable markings on any of the images will be present. (Please circle two choices)

1. I agree that segments of the recordings made of my participation in this research may be used for conference presentations.

2. I do not want segments of the recordings made of my participation in this research to be used for conference presentations. Recordings will be destroyed by 2017

3. I agree that segments of the recordings made of my participation in this research may be used for education and training of future researchers/practitioners.

4. I do not want segments of the recordings made of my participation in this research to be used for education and training of future researchers/practitioners. Recordings will be destroyed by 2017

11. **Payment for participation:** You will receive $15 for participation in this portion of the study. If you withdraw from the study before completion you will be compensated for the time you participated to the ½ hour (i.e., ½ hour = $7.50).

12. **Voluntary participation:** Your decision to be in this research is voluntary. You can stop at any time. In order to participate you must answer all Participant Safety and Screening questions accurately; however, you do not have to answer any other questions that you do not want to answer. Refusal to take part in or withdrawing from this study will involve no penalty or loss of benefits you would otherwise receive.

13. **Injury Clause:** In the unlikely event you become injured as a result of your participation in this study, medical care is available. It is the policy of this institution to provide neither financial compensation nor free medical treatment for research-related injury. By signing this document, you are not waiving any rights that you have against The Pennsylvania State University for injury resulting from negligence of the University or its investigators.

14. **Incidental findings:** The investigators for this project are not trained to perform medical diagnosis, and the scans to be performed in the study are not optimized to find abnormalities. On occasion, a member of the research team may notice a finding on a scan that seems abnormal. When a finding is noticed, the investigator or designate may consult a physician specialist, such as a radiologist or neurologist, as to whether the finding merits further investigation. If the specialist recommends further follow-up, the investigator or another designate will contact you within **48 hours** of the recommendation and suggest that you contact your private medical provider for follow-up. To facilitate follow-up care, you may be given a copy of your images upon written request. Being told about a finding may cause anxiety as well as suggest the need for additional tests and financial costs. Medical insurance may be affected whether or not the finding is ultimately proved to be of clinical significance. Costs for clinical follow-up are not budgeted in the cost of research. The decision as to whether to proceed with further examination or treatment lies with you.

15. **Abnormal test results:**

In the event that abnormal test results are obtained, you will be made aware of the results in ***3*** days and recommended to contact your private medical provider for follow-up.

Please provide contact information so that you can be reached in the event of an incidental finding and/or abnormal test results.

Address____

Phone____

By consenting to participate, you agree to:

- Answer the SLEIC 3T MRI Participant Safety & Screening questions accurately,
- Tell the investigators about all metallic devices in/on your body, and
- Not bring any metal devices (e.g., pens, coins, keys, credit cards) into the scanning room without staff approval.

You must be 18 years of age or older to take part in this research study. If you agree to take part in this research study and the information outlined above, please sign your name and indicate the date below.

You will be given a copy of this signed and dated consent form for your records.

___________________________________ ___________________________ ________________

Participant Signature Printed Name Date

___________________________________ ___________________________ ________________

Person Obtaining Consent Printed Name Date

PENNSTATE

SOCIAL AND LIFE SCIENCES IMAGING CENTER
3T MRI PARTICIPANT SAFETY & SCREENING

This information is strictly confidential. Please PRINT LEGIBLY. ATTENTION: ***It is important that you complete this form carefully and completely***

Today's Date _____/_____/_____ 3T MRI ID# __________________ Body Part to be Scanned ________________________
month day year

Date of Birth _____/_____/_____ Age ________ Height ________ Weight ________
month day year

1. Have you had prior surgery or an operation (e.g., arthroscopy, endoscopy, etc.) of any kind? ☐ No ☐ Yes
If yes, please indicate the date and type of surgery:
Date _____/_____/_____ Type of surgery ______________________________
Date _____/_____/_____ Type of surgery ______________________________

2. Have you had a prior diagnostic imaging study or examination (MRI, CT, Ultrasound, X-ray, etc.)? ☐ No ☐ Yes

If yes, please list:	Body part	Date	Facility
MRI	____________	____/____/____	____________
CT/CAT Scan	____________	____/____/____	____________
X-Ray	____________	____/____/____	____________
Ultrasound	____________	____/____/____	____________
Nuclear Medicine	____________	____/____/____	____________
Other	____________	____/____/____	____________

3. Have you experienced any problem related to a previous MRI examination or MR procedure? ☐ No ☐ Yes
If yes, please describe: ______________________________

4. Have you had an injury to the eye involving a metallic object or fragment (e.g., metallic slivers, shavings, foreign body, etc.)? ☐ No ☐ Yes
If yes, please describe: ______________________________

5. Have you ever been injured by a metallic object or foreign body (e.g., BB, bullet, shrapnel, etc.)? ☐ No ☐ Yes
If yes, please describe: ______________________________

6. Are you currently taking or have you recently taken any medication or drug? ☐ No ☐ Yes
If yes, please list: ______________________________

7. Are you allergic to any medication? ☐ No ☐ Yes
If yes, please list: ______________________________

8. Do you have a history of asthma, allergic reaction, respiratory disease, or reaction to a contrast medium or dye used for an MRI, CT, or X-ray examination? ☐ No ☐ Yes

9. Do you have anemia or any disease(s) that affects your blood, a history of renal (kidney) disease, renal (kidney) failure, renal (kidney) transplant, high blood pressure (hypertension), liver (hepatic) disease or seizures? ☐ No ☐ Yes
If yes, please describe: ______________________________

For Female Participants:

10. Date of last menstrual period: _____/_____/_____ Post menopausal? ☐ No ☐ Yes

11. Are you pregnant or experiencing a late menstrual period? ☐ No ☐ Yes

12. Are you taking oral contraceptives or receiving hormonal treatment? ☐ No ☐ Yes

13. Are you currently breastfeeding? ☐ No ☐ Yes

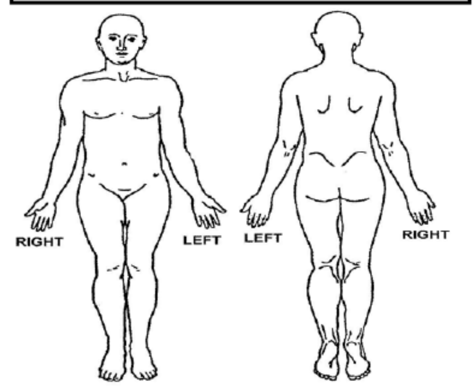
14. Are you taking any type of fertility medication or having fertility treatments? ☐ No ☐ Yes
If yes, please describe: ______________________________

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, MR angiography, functional MRI, MR spectroscopy). Do not enter the MR system room or MR environment if you have any question or concern regarding an implant, device, or object. Consult the MRI Technologist or Radiologist BEFORE entering the MR system room. The MR system magnet is ALWAYS on.

Please indicate if you have any of the following:

☐ Yes ☐ No Claustrophobia (fear of enclosed spaces)
☐ Yes ☐ No Tattoo or permanent makeup
☐ Yes ☐ No Body piercing jewelry
☐ Yes ☐ No IUD, diaphragm, or pessary
☐ Yes ☐ No Dentures or partial plates
☐ Yes ☐ No Hearing aid
☐ Yes ☐ No Joint replacement (hip, knee, etc.)
☐ Yes ☐ No Bone/joint pin, screw, nail, wire, plate, etc.
☐ Yes ☐ No Aneurysm clip(s)
☐ Yes ☐ No Cardiac pacemaker
☐ Yes ☐ No Implanted cardioverter defibrillator (ICD)
☐ Yes ☐ No Electronic implant or device
☐ Yes ☐ No Magnetically-activated implant or device
☐ Yes ☐ No Neurostimulation system
☐ Yes ☐ No Spinal cord stimulator
☐ Yes ☐ No Internal electrodes or wires
☐ Yes ☐ No Bone growth/bone fusion stimulator
☐ Yes ☐ No Cochlear, otologic, or other ear implant
☐ Yes ☐ No Insulin or other infusion pump
☐ Yes ☐ No Implanted drug infusion device
☐ Yes ☐ No Any type of prosthesis (eye, penile, etc.)
☐ Yes ☐ No Heart valve prosthesis
☐ Yes ☐ No Eyelid spring or wire
☐ Yes ☐ No Artificial or prosthetic limb
☐ Yes ☐ No Metallic stent, filter, or coil
☐ Yes ☐ No Shunt (spinal or intraventricular)
☐ Yes ☐ No Vascular access port and/or catheter
☐ Yes ☐ No Radiation seeds or implants
☐ Yes ☐ No Swan-Ganz or thermodilution catheter
☐ Yes ☐ No Medication patch (Nicotine, Nitroglycerine)
☐ Yes ☐ No Any metallic fragment or foreign body
☐ Yes ☐ No Wire mesh implant
☐ Yes ☐ No Tissue expander (e.g., breast)
☐ Yes ☐ No Surgical staples, clips, or metallic sutures
☐ Yes ☐ No Breathing problem or motion disorder
☐ Yes ☐ No Other implant______________________

Please mark on the figure(s) below the location of any implant or metal inside of or on your body.



IMPORTANT INSTRUCTIONS

Before entering the MR environment or MR system room, you must remove all metallic objects including hearing aids, dentures, partial plates, keys, beeper, cell phone, eyeglasses, hair pins, barrettes, jewelry, body piercing jewelry, watch, safety pins, paperclips, money clip, credit cards, bank cards, magnetic strip cards, coins, pens, pocket knife, nail clipper, tools, clothing with metal fasteners, & clothing with metallic threads.

Please consult the MRI Technologist if you have any question or concern BEFORE you enter the MR system room.

NOTE: You may be advised or required to wear earplugs or other hearing protection during the MR procedure to prevent possible problems or hazards related to acoustic noise.

I attest that the above information is correct to the best of my knowledge. I read and understand the contents of this form and had the opportunity to ask questions regarding the information on this form and regarding the MR procedure that I am about to undergo.

Participant Signature: ____________________________Printed Name: _______________________ Date ____/____/_____

This form has been reviewed by the Scanner Operator and the information is deemed current at the time of the scan. It is considered safe for this individual to have an MRI scan at this time.

Scanner Operator Signature: ______________________Printed Name:________________________ Date ____/____/_____

Appendix C

MRI Footplate Images

Fig C-1: Footplate front view with foot

Fig C-2: Footplate side view

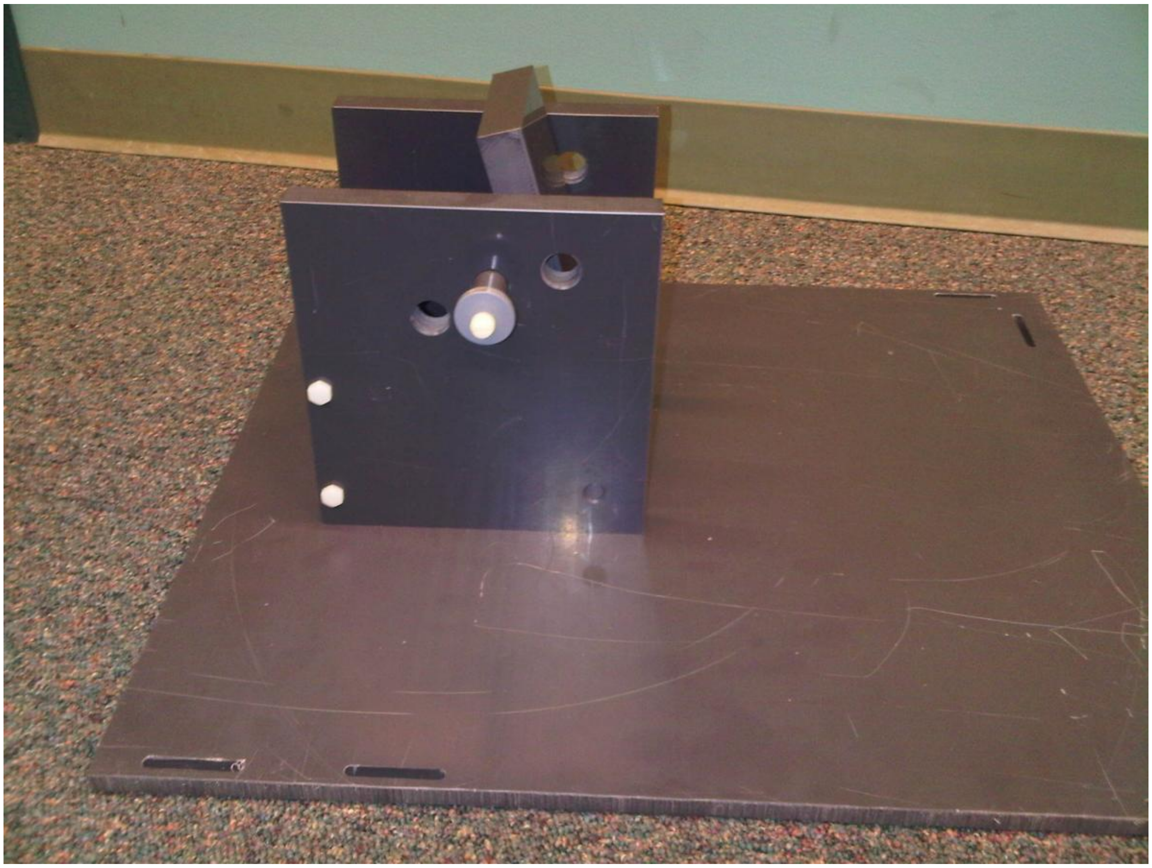
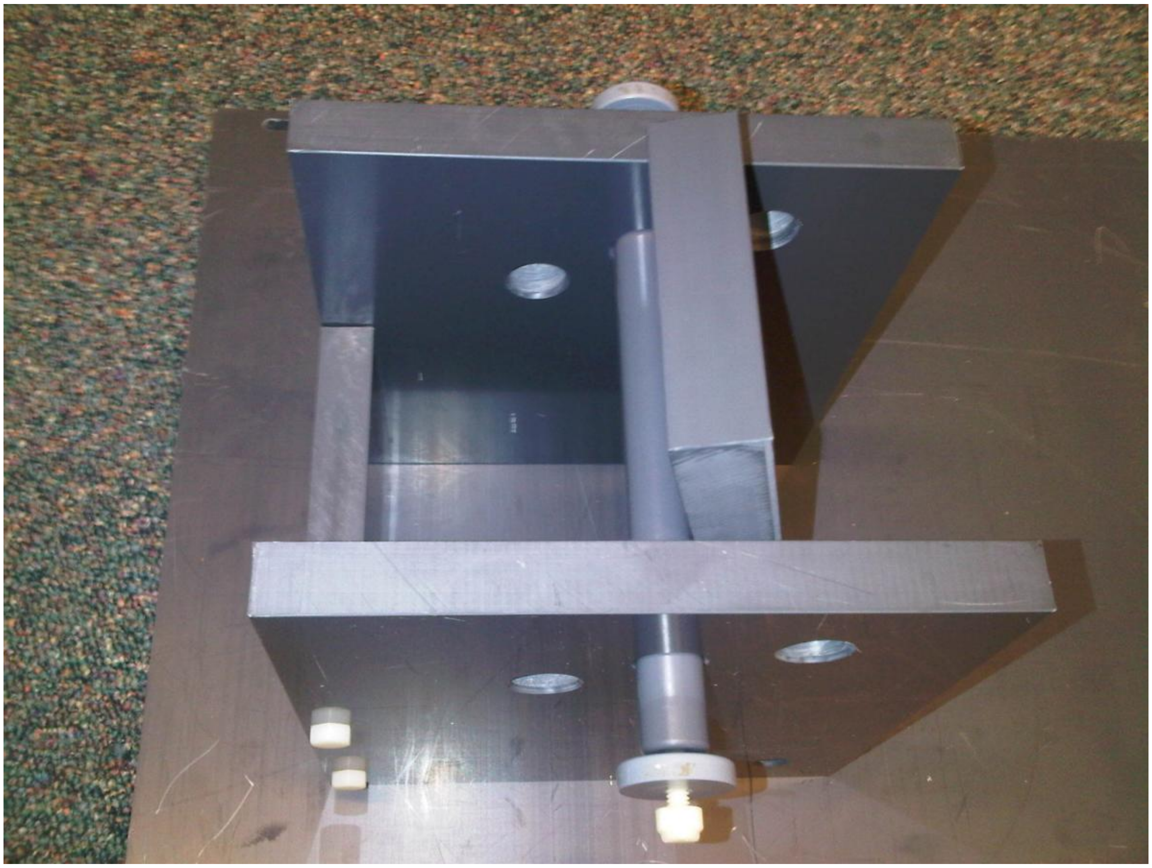


Fig C-3: Footplate top view



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