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THE STATIC MEASUREMENT AS A PREDICTOR TO THE
DYNAMIC AXIS OF ROTATION OF THE HUMAN FOOT

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THE STATIC MEASUREMENT AS A PREDICTOR TO THE DYNAMIC AXIS OF ROTATION OF THE HUMAN FOOT

By

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ABSTRACT

THE STATIC MEASUREMENT AS A PREDICTOR TO THE DYNAMIC AXIS OF ROTATION OF THE HUMAN FOOT
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The purpose of this study is to determine a static measurement from previous research that mimics the dynamic axis of rotation of a human foot as that subject is walking. The static measurement used is a derivation of two measuring techniques combined to create an axis of rotation. The dominant feet of 10 male subjects were measured statically on Pressurestat paper to determine the hypothetical static axis of rotation. They then completed a minimum of 3 and a maximum of 5 walking trials across a force plate mounted in the track of a local athletic club. The forces collected were then placed into an Excel spreadsheet and graphically represented for comparison to the measured static axis of rotation. The graphs were compared using the angles created by the axes, both static and dynamic, and a line perpendicular to the bisection of the foot.

Acknowledgements

There are a few people that played an integral role in the completion of this study. Dr. John Powell, thank you for being my advisor and head of my committee, but, most of all thank you for giving me the chance to be a graduate student at Michigan State University. Dr. Kavin Tsang, thank you for all of your support and intuitiveness. You have helped me greatly. Dr. Roger Haut, thank you for keeping me on my toes and making sure that I was on top of the issues that I was working with as well as the humor involved. Ray Fredericksen, thank you for introducing me to the world of feet and their intricate workings. Joanne Ewen, your technical skills are excellent and nothing would run smooth without you. Last and most certainly not least I would like to thank my family and God, without whom I would not be here.

To all that have taken a chance on me, don't worry, I won't let you down. I promise.

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Chapter 1: Introduction

Lower extremity injuries and pathologies have plagued athletes' performances for as long as sports have been played. Some injuries are due to direct contact produced in collisions, while others are due to overuse. Most overuse injuries to the foot are due to a structural abnormality resulting from a wide range of issues such as rigid or flat arches, coxa valgus (knock-knees), or an extreme q-angle at the hips of a runner. There have been multiple studies performed that examine the different aspects of each link in the lower extremities [1-4]. Researchers have indicated that between one-third to one-half of all runners will experience at least one overuse injury to the lower extremities that will prohibit them from being active for at least a week [4]. This project will examine the foot as a critical link to overuse injuries.

The foot is a complex structure made up of 26 bones that work in unison with numerous ligaments and tendons to produce a stable base for the human body during stance and ambulation. Researchers have studied the inner workings of the foot extensively and with new technology arises new ways to look at how the foot functions. Originally, clinicians visually observed how a person stood and walked to determine his or her pathology. Upon the advent of x-ray technology clinicians were able to look at the bones of the foot to determine how they were aligned when a person was standing erect. This created much insight as to what the structures did to keep the foot in correct or incorrect alignment. Today, computers and sensors technically examine what the structures of the foot are doing when a person is standing, walking or even running. These instruments can analyze where the contact of the foot is when it first lands on the ground and how much force is being created as the foot lands and takes off for another step.

The most recent technology being used inspects the center of pressure of the foot (COP). The COP is the point at which there is no moment from all of the applied forces acting on the foot [5]. In other words, COP is the balance point where the foot is stable and can balance on a point with no movement or rotation. When a person is walking, the COP is ever changing to continue the forward motion that is desired. Researchers can track this COP with the help of force plates and sensors that create a computer image of the COP path. The COP path imprints an axis about which the foot rotates medially and/or laterally; this axis is aptly named the axis of rotation. With the axis of rotation identified, clinicians and researchers then can identify how the foot is rotating, in a medial, everted state (pronation) or a lateral, inverted state (supination) through each center of pressure. This has enabled clinicians to see how a person ambulates and enhance their ability to correct any abnormalities that may be causing problems.

The next step in the advancement of modern technology and science is to correctly predict the center of pressure's axis of rotation from a static standing position to study the COP. A simple manner for a clinician to study a person's gait as they are moving is through expensive equipment that requires a skilled, educated person to run the instrumentation. What is proposed therein is a formula that allows a clinician to examine a subject statically, and be able to predict the axis of rotation that the subject will create as he or she walks.

The overall goal in this study is to be able to fit persons for possible necessary orthotic inserts based on the correlation between static axis of rotation and walking style.

Chapter 2: Literature Review

> "Walking is the body's natural means of moving from one location to another. It is also the most convenient means of traveling short distances. Functional versatility allows the lower limbs to readily accommodate stairs, doorways, changing surfaces, and obstacles in the path of progression. Efficiency in these endeavors depends on free joint mobility and muscle activity that is selective in timing and intensity...Because of the numerous advantages of walking, patients strive to retain capability even in the presence of severe impairment. As the various types of pathology alter mobility and muscular effectiveness, the patients substitute wherever possible, yield when they must, and accept compensatory reactions of adjacent segments as they occur. The resulting walking pattern is a mixture of normal and abnormal motions that differ in significance. Energy costs are increased and functional versatility is compromised."
>
> \- Jacquelin Perry, introduction[6]

Foot and gait abnormalities plague a large portion of people in society and they don't even realize that walking is the root of their pains. There are many different types of abnormalities that can occur. The Pathokinesiology department of Rancho Los Amigos Physical Therapy has classified forty-eight different abnormalities in a person's gait [6]. This is just visually observing a person walking. If it is broken down even further, one can see that there are numerous reasons for each different abnormality in a person's gait. For example, a simple blister on the great toe of a person's foot can create a shortened toe off of the gait cycle. This shortened toe off period could also be created because that same person has a longer second toe than great toe, which is termed a Morton's toe [7]. This, and many other complications, required researchers to break down each phase of how a person walks to see where corrections can be made either through treatments or orthotic devices. With the advances in technology, researchers are able to look at things as toe placement, heel strike in relation to foot orientation, and center of pressures at a given point in the gait cycle. This research examines prior procedures that were used to measure the proper placement of the foot in order to create a more efficient gait cycle. If a more efficient gait cycle is produced, then there will be less stress placed on structures of the foot and less overuse injuries will occur.

Foot Structure, Pathologies and Measurements

Root et al. [7] have set standards for classification and measurement of foot structures for over three decades. First, one must look at the concepts of pronation and supination. Pronation is eversion of the calcaneus, adduction and plantarflexion of the talus, abduction of the forefoot, lowering of the medial longitudinal arch, and internal rotation of the tibia [8]. Supination would then be the opposite, inversion of the calcaneus, adduction and dorsiflexion of the talus, adduction of the forefoot, rising of the medial longitudinal arch, and external rotation of the tibia (Figure 2.1). The concepts of excessive pronation as well as supination have been tied to pathologies by research and experimentation with foot orthoses. Orthoses are devices that are created to fit into a person's shoe that compensate for any idiosyncrasies in the mechanics of the foot that may cause problems for that person. In order to determine what orthoses to use, there is a need to have a set of norms to determine the characteristics of excessive pronation or supination.

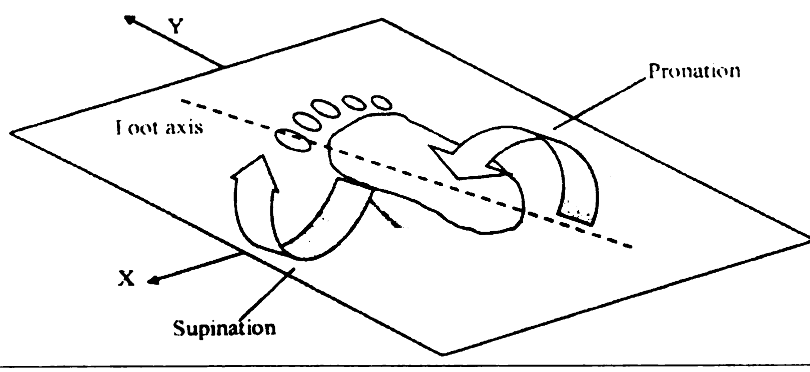


Figure 2.1. Pronation and supination of the foot around the foot axis

Root's measurement validity has been criticized somewhat because he looked at tri-planar motion, or the way a foot moves in three dimensions, using only frontal plane clinical measurements of the calcaneus [9]. This is to say that the foot moves in more than one plane when a person walks, but Root only studied how a foot moves in one motion rather than all three planes of motion.

Medial longitudinal arch height is another structure in the foot that has been used to determine foot type as well as ways to counteract chronic pathologies. A person that has a foot with a flatter arch than normal is said to have a pes planus condition. This condition is much less rigid than a normal arch [8], leading to such problems as plantar fasciitis, development of hallux abducto valgus and Morton's neuroma [8, 10]. Plantar fasciitis is a condition in which the tissue on the bottom of the foot, also known as the fascia, has become inflammed due to excessive tightness or another issue related to chronic overuse. Hallux abducto valgus is a condition in which the great toe, or first toe, is angled in a manner that places the distal part of the toe toward the second toe and the proximal end of the toe more prominent medially. This condition causes painful callous tissue that can solidify and become what is known as a bunion. Morton's neuroma is a condition in which a nerve is trapped between two metatarsal heads and has become inflammed, causing the person to be in pain upon placing weight on his or her affected foot.

On the other hand, a person with pes cavus condition, or excessively higher arch height than normal, is said to have a more rigid foot. This can lead to low back pain [1] as well as knee pain [11]. The reasoning behind the fact that the pain is seen in the low back and knees is because the higher arches do not absorb the force of the foot landing on the ground as well as does a normal or flat arch. The force is then transferred throughout the rest of the lower extremity and is seen to arise in the knees and low back regions. The disadvantages with exact measurement of the medial longitudinal arch height are the validity and consistency of measurements. The validity of the measurement was questioned when Benink [12] saw a significant discrepancy between x-ray photographs and visual observation of the navicular height, the height of the navicular bone directly adjacent to the medial longitudinal arch, from the visual tissue height of the medial longitudinal arch. Benink found that many of his subjects were visually flat footed, but the x-rays showed the navicular height to be within normal limits. Also, Cowen et al. [13] found the level of agreement of six clinicians on classification of foot types among normal, flat and high arches, was unacceptable among interclinician variability in classifying 246 army trainees. Medial longitudinal arch height has been looked at as a source of information for researchers to help determine functions of the foot. Subotnick [14] has recorded that 60% of society have "normal" arches that lie in a range that is within the midpoint of heights, while 20% have high arches and approximately 20% of society have flat feet, or pes planus status. Researchers have looked at the different foot types and seen that high, rigid arches are a major factor in the formation of stress fractures in the femur and tibia bones [15]. This is presumed to be due to the fact that a rigid high arch has less flexibility and transfers more energy to the bone above the foot/ankle complex. Conversely, a low arch tends to cause the foot to absorb more of the stress caused by continual pounding on a hard surface during exercise and has a higher tendency to cause stress fractures in the metatarsal bones [15]. A low arch has an increase in flexibility of the foot and hence, more of the pressure is distributed throughout the foot instead of the bones of the lower leg. Arch height is a problematic issue when looking at and correcting disorders of the foot. Nachbauer and Nigg [16] found that arch height was an independent variable in the testing of the foot for variables that affect ground reaction forces of the foot. What this means is that arch height has an effect on the foot, but it works independent of the forefoot or rearfoot motion. Therefore, arch height classification is of little use for the prediction of the rotational axis of the foot during static and dynamic stance.

There are two main abnormalities of the rearfoot region of the human foot. The first is termed rearfoot valgus. This condition occurs when there is excessive tibial valgum and/or subtalar joint valgum, which is to say that the tibia will be more medial at the proximal end than the distal end. The second abnormality is known as rearfoot varus. This is a condition in which there is excessive tibial rotation medially and the subtalar joint rotates laterally [14].

The forefoot is more prone to abnormalities since there are more bones that work in concert with each other and the rest of the forefoot region of the body. Forefoot varus exists when the medial aspect of the forefoot is lower than the lateral aspect of the forefoot [14]. Forefoot valgus exists when the lateral aspect of the forefoot is lower than the medial aspect. Other abnormalities that can occur in the forefoot include hallux abducto valgus, Morton's toe, and a hypermobile first ray. Hallux abducto valgus is a condition in which the great toe is angled toward the other toes of the foot and the metatarsophalangeal joint is more medial. This can cause an impaired gait because the first and second toes of the foot control the majority of the pressure during the toe off phase of gait [14]. Morton's toe is a condition in which the great toe is shorter than the second toe. This can also affect gait because the second toe becomes the last point of contact during the toe off phase of gait. The last condition in which the first ray is hypermobile can cause the foot to become more pronated during toe off and will consequently affect the gait cycle.

More recently, a type of measurement named the valgus index has made resurgence in the podiatric management world. The valgus index is a measurement that is a highly reliable and reproducible measure of medial malleolar shift as a person is in the standing position. In scientific terms, it is "...the frontal-plane spatial displacement of the ankle joint relative to the supporting surface area of the heel" [17]. The first observation of the valgus index in research was used by Rose in 1951 [18] to measure flatfootedness in children. This measurement has remained a high quality standard for measuring the position of the foot. In order to determine the valgus index of the rearfoot, a subject must create an imprint on a sheet of paper, most commonly by ink. A clinician then measures the distance between the two malleoli by making marks directly under the most lateral aspect of each malleoli. The distance from the lateral malleoli and the malleoli bisection are then compared to the distance of the calcaneal bisection and the lateral malleoli and computed in an equation. The equation is shown as $VI= [(LA-LF)/LM] x100$; where VI is the valgus index, LA is the distance between lateral malleolus and malleoli bisection, LF is the distance between lateral malleolus and foot bisection, and LM is the distance between lateral malleolus and medial malleolus (Figure 2.2).

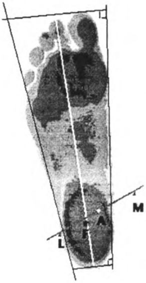
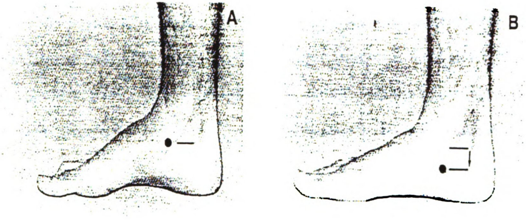


Figure 2.2 Valgus Index Calculation- VI= [(LA-LF)/LM] x 100; LA is the distance between lateral malleoli and malleolar bisection, LF is the distance between lateral malleoli and foot bisection, LM is the distance between lateral malleoli and medial malleoli.

The higher the valgus index the more pronated and consequently flatter the foot. An advantage to valgus indexing is that it does not look at what type of foot a person has, simply where the malleoli line up according to the calcaneus. There have been no studies produced that set a standard for what a normal valgus index should be. The positive effect of this type of measurement is that the interrater reliability has been shown to be within ± 2° within three successive measurements [19].

When a person places pressure on his or her foot, the navicular bone immediately adjacent to the medial longitudinal arch tends to come closer to the surface of the ground. This is known as navicular drop. In the first step, a measurement is taken from the height of the navicular in a subtalar neutral position. The subject is then placed in a full weight-bearing position that is comfortable to him or her. The height of the navicular in relation to the ground is again taken and the difference in height is noted (Figure 2.3). A drop of approximately 10mm is acceptable, but more than 15 mm is excessive and termed abnormal foot pronation, according to Brody [20]. The problem that arises with the measurement of navicular drop is the interrrater reliability. Mueller [21] found that navicular drop measurement had poor-to moderate intratester reliability and poor intertester reliability.



<u>Figure 2.3.</u> Navicular drop weight-bearing (A), and non-weight-bearing (B)

Ratios of soft tissue height at the medial longitudinal arch and foot length have also been measures of the functions of the foot. This is done to see if there is enough height of the arch so that when the foot is placed in a weight-bearing position that the arch is not completely compromised and the foot is completely flat. Kaufman et al. [4] examined the ratio of the navicular height to the length of the foot to determine what is known as the bony arch index. This index is used to analyze the arch height from a solid structure point instead of basing measurements on the soft tissue of the arch. In this procedure, the foot length is taken from the most posterior point on the calcaneus to the most posterior point of the metatarsophalangeal joints of the forefoot. The navicular height is measured in the standing position from the inferior most point of the palpable navicular area. This technique was adopted because of the association of bony arch index to the risk of developing an overuse injury [2].

The amount of mechanical stress on a structure has also been suggested to relate to the pathology of the respective structure [22, 23]. Researchers have named this the tissue stress approach of explaining pathologies [24]. Along with these pathologies, there have been ideas that certain types of feet can promote pathologies. Root et al. [8] proposed a link between subtalar joint pronation and hallux abducto valgus suggesting that persons that have an everted and abducted great toe will walk more on the insides of their foot than persons with a more normally placed great toe.

The position of the forefoot measurement is a controversy as well. Different researchers have used the idea of the anatomical middle of the foot for the axis of rotation simply because it is the middle. Other researchers have found that most of the axes of rotation flow through the second metatarsal head. Two studies have agreed that with barefoot ambulation there is greatest pressure under the second metatarsal head [25, 26]. Soames and Clark found the mean peak pressures to be greatest under the first and second metatarsal heads, with the least under the third, fourth and fifth metatarsal heads [27]. Even when the heel height is increased, it was still determined that the average peak pressure remained under the second metatarsal [28].

Center of Pressure theory

Many researchers look at foot motion in a two dimensional manner and simplify the process of analyzing the data, rather than looking in all three planes of motion. Joint motion is a rotational moment rather than a linear force. A rotational moment is a force created by a structure, acting through a distance, in which there is movement in all three planes, rather than just a straight forward motion. In order to calculate the rotational moment of the subtalar joint, the magnitude of force, its location and the distance from the line of action of the force must be known [5]. When this information is available and the moment is known, researchers can use the concept of rotational equilibrium to determine the stresses placed on the anatomical structures. When the foot is completely on the ground, all points in contact will have a force or pressure applied to them. These forces can be averaged to find a single force that is equal to the sum of the magnitudes of each individual force placed on the foot. This is said to be the center of pressure of the foot at the current time. Sandor [5] defines the center of pressure as; "...the point at which there is no moment from all of the applied forces". This is to say that the foot is "not moving" because the ground reaction forces equal the pressure or forces applied by the foot and the body attached to it. Another term for this is equilibrium. This theory has been verified by a study that was performed by Hicks [3], in which a pin was used to find a point on a cadaveric foot placed on a board where the board/foot complex balanced and there was no rotation about the pin (Figure 2.4).

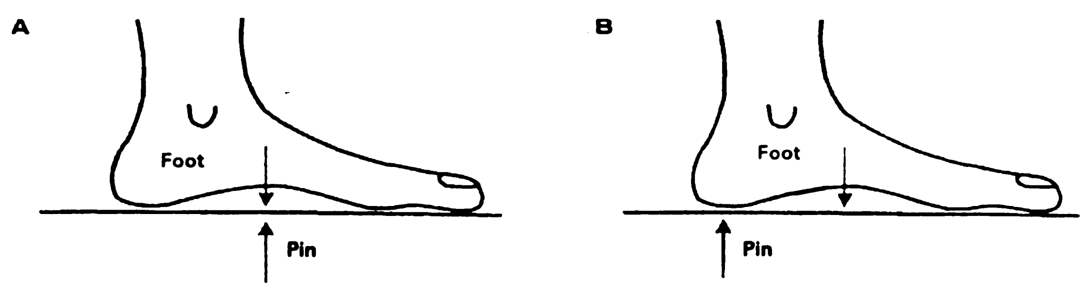


Figure 2.4. Center of pressure moment as seen by position of the pin in relation to the foot. Equilibrium is seen in A, but not in B.

This center of pressure can also be calculated through an (x,y) coordinate system. First, the center of pressure must be found in the x, or anteroposterior, direction, and then in the y, or mediolateral, direction. This is accomplished through using a force plate. A force plate collects data through foil strain gauges attached to proprietary cells. What this means is that gauges within the force plate send messages to cells in an amplifier, which are collected and entered into equations. The first equation that is used calculates the ground reaction force (GRF), which is a force created in an equal and opposite direction to the force created by the foot. This equation is seen as:

$$GRF= (Fx^2+Fy^2+Fz^2)^{1/2}$$

Where Fx, Fy, and Fz are the individual components of force in each direction

Once this is completed, the exact location of the center of pressureis identified using the moments of each direction (Mx, My, and Mz). The following equations show how the exact coordinates are located:

$$X= -My/Fz$$
$$Y= Mx/Fz$$

The center of pressure calculation has become a popular tool because no matter what the foot type or its abnormality, a center of pressure will always be created when the foot is in contact with the ground.

When a person is walking, his or her center of pressure of the foot is always changing. This is because during the gait cycle different parts of the foot are in contact with the ground. During the heel strike phase, only the heel is in contact. As the cycle progresses, the forefoot comes in contact with the ground and the heel is raised off the ground. During gait, while the center of pressure is ever moving, a line that marks the different centers of pressure is produced. This line helps researchers determine other moments that are produced about the foot other than just the vertical moments. Lateral moments can be created about this line that causes the foot to ambulate in a pronated, inverted manner or a supinated, everted manner. This concept is called rotational moments and the line that is created by the centers of pressure is aptly termed the axis of rotation. During gait, the foot is trying to reach rotational equilibrium or have no net moment about the axis. Center of pressure also ties together the concepts of forefoot movement and rearfoot movement.

Subtalar positioning for finding axis of rotation

Looking at the subtalar joint will also have an effect on the axis of rotation of the foot. Kirby theorized that a foot with a more medially deviated subtalar joint is more likely to have a pronation moment acting upon the foot, while a more laterally deviated subtalar joint axis is more likely to produce a supination moment on the foot [29, 30]. In theory then, a center of pressure will be created more laterally for a foot with a medially deviated subtalar joint. Also, a medial center of pressure will be created for a laterally deviated subtalar joint.

A subtalar joint with a medially deviated center of pressure will be in a supination moment from the ground reaction forces and for rotational equilibrium to be attained, something in the body must produce a pronation moment. Fuller [31] theorizes that one of the possible solutions of the pronation moment may be the end range of motion created by the joint capsule or ligaments that cross the subtalar joint. He also goes on to say that the peroneus brevis muscle, which is located on the lateral aspect of the lower leg and has primary concern with extending and abducting the foot, may also contribute to the pronation moment creating equilibrium and this may also be an answer to why people experience peroneal tendonitis.

Conversely, a subtalar joint with a laterally deviated center of pressure will be in a pronation moment from the ground reaction forces. For rotational equilibrium to be attained, structures in the body must produce a supination moment. Fuller theorizes that structures such as the floor of the sinus tarsi, the plantar fascia and various muscles within the lower leg help to produce this moment [31]. The muscles that could be included in the supination moment include the tibialis posterior, flexor digitorum longus and tibialis anterior [32]. All of these structures have been identified in athletes with overuse injuries. The plantar fascia can become inflammed if too much stress is placed on it or it is not flexible. Also, the muscles that help create this moment are susceptible to anterior compartment syndrome, or shin splints.

Sneyers et al. [33] examined the plantar pressure patterns of runners and the influence of foot malalignment. Their study concluded that foot type did not influence the lateromedial load distribution underneath the heel, but the midfoot was affected by foot type. People with pes cavus feet had a relative force impulse that was significantly lower than "normal" feet. This means that they did not use their midfoot as much during dynamic stance phases. Also, no matter what foot type the subject had, there was no change in the relative loads under the second and third metatarsal heads. Although, subjects with a pes cavus condition placed more of a load on the forefoot as compared to the "normal" group. All of these conditions may be reduced, if not eliminated, with the help of an orthotic device bringing the axis of rotation towards a neutral state.

Gait Patterns

Running and walking are considered to be a learned skill because it takes time, practice and acquired skills to perform the motion of movement. Along with the practice of the skills needed to walk and run there is an efficiency factor. Hoshikawa [34] performed a study in the early 1970's that measured the efficiency of runners and found that muscular activity for an excellent runner is less than that of a poor runner. This means that the better a runner is the more efficient they are, and consequently they use less energy in the muscles. No matter who is performing this skill, either walking or running, there are some standard events that must occur to endure locomotion. The six elements that Subotnick [14] defined are overall action, body angle, arm swing, foot placement, rear leg lift and length of stride. In other words, every one of these elements is compiled in a person's gait pattern.

More specifically, the gait pattern can be broken down into six phases. The first phase is heel contact. This is when the foot that is non-supportive of the body is in a downward motion and the calcaneus makes initial contact with the ground. For example, this is when the right foot makes initial contact with the ground via the calcaneus. The second phase is mid-stance, when both feet are in contact with the ground and the forefoot of the right foot connects with the ground. Shortly after mid-stance, heel off of the right foot occurs. This is when the calcaneus comes off of the ground and the forefoot of the right foot is supporting the body. The second to last phase of gait is the toe-off. This is the phase that propels the body forwards. The last phase is then the swing phase of gait. This is when the right foot is not in contact with the ground. While the right foot is not in contact with the ground, the left foot is performing the previously mentioned phases of gait. In an unaffected gait, the right foot will begin the heel contact phase when the left foot is about at the heel off phase [14].

There are differences between running and walking. Walking consists of two components, a single and a double leg stance phase. The single stance phase is when the opposite foot is in the swing phase of its cycle, while the double stance phase will occur when one foot is in heel contact until it reaches mid-stance. Running still has the same amount of phases, but instead of having both a single and double stance phase, there is a single support phase and a double floating phase, where no foot is in contact with the ground. Another difference between walking and running is the pressure produced by the body when the foot is in contact with the ground. Normal, steady walking produces a force that is 1.2 to 1.5 times the mass of the body. Running, on the other hand, can create up to three times as much force as the bodyweight [14]. The last variation between walking and running is the duration of each phase. Running is a quicker motion than walking and hence, the phases of running are shorter than that of walking.

Orthotic Device Usage to Correct Foot Abnormalities and Pathologies

The preceding measurements are ways to find abnormalities in the feet of humans. Now that the abnormalities have been discovered, what does a clinician such as an athletic trainer or physical therapist do to solve the problem? Clinicians and Podiatrists have found that with the appropriate material, orthotic devices that fit into a person's shoe can be created to compensate for the abnormalities and bring the foot into a more stable position. The stable position is a location in which the different aspects of the foot are creating the least amount of pressure on the foot. Ker et al. [35] showed that the foot is the initial shock-absorbing device of the body; therefore an orthotic device supporting this structure will benefit the entire body. This suggests that a person with a higher than normal arch, or pes cavus, which is consequently more rigid and less flexible, will need more support for shock absorption than one with a normal arch. In this instance an orthotic device with a higher, firmer arch mold is used. On the other hand a person with pes planus, or flat arches, will benefit from a less severe arch support arising from a milder orthotic device. His or her foot will be more flexible and can handle more of the shock absorption, but will still require some support.

Another reason for orthotic device usage is excessive rearfoot movements, such as excessive inversion and eversion. Clark et al. [36] suggested that excessive eversion of the rearfoot can lead to injuries to the lower leg, including peroneal tendonitis, anterior tibial stress syndrome and medial tibial stress syndrome. To correct this problem, there are two avenues that could be pursued. The first is using an orthotic device that places a larger amount of material, or a post, on the medial aspect of the rearfoot. This is proposed to stop excessive eversion by creating a "block" for the foot and not allowing it to move into the everted state. The other idea that has been implemented in a more generic manner is the concept of a heel cup. A heel cup is used in orthotic devices to "cradle" the rearfoot and not allow it to move in either direction excessively. The optimal depth of the heel cup for reducing rearfoot motion has yet to be established.

The whole foot can have an abnormal stance as well. As described earlier in this literature review, there are two total foot conditions known as a pronated or supinated foot. A pronated foot will have an axis of rotation that will deviate laterally from "normal," while a supinated foot's axis of rotation will deviate medially. To fix either of these problems, the clinician must build an orthotic device that posts a lift on the correct side in order to alleviate the problem. A person with excessive pronation will require a posting on the medial aspect of the foot in order to restore the axis of rotation to an acceptable position, whereas a person with excessive supination will require a posting on the lateral aspect of the orthotic device. Both of these postings will be dependent upon how excessively pronated or supinated the subject's foot is.

As more is being determined about the feet and their interaction with the closed chain actions of the human body, more will be proposed for solving each of these problems. Orthotic devices play an integral role in this process and can be bought for a general condition such as a pronated foot or a rearfoot with excessive motion or they can be custom made for a specific subject's feet. Custom orthotics are the most accurate way to fix many foot and lower leg problems that arise, but they are also labor and cost intensive. To create a custom orthotic device, a skilled technician takes a mold of the subject's foot and has to "build" an orthotic device complementary to the subject's foot. On the flipside, a general orthotic may not serve the specific purpose a subject's needs, in order to solve his or her problem. Overall, orthotics have proven to be a positive solution for foot pathologies. With continuing advancements in technology and understanding the gait process of individuals as individuals, instead of in a general manner, more problems can be overcome.

Chapter 3: Methods

This study consisted of ten male subjects, picked from a volunteer group consisting solely of students from a Midwestern university's kinesiology department. The subjects were of varying size, stature and age, and were free from any major pathologies or abnormalities in the lower extremities, especially the feet.

Each subject was instructed as to what the study entailed and required to sign a document of consent in order to participate in the data collection process before it began. The subject matter of the study was made fully understandable and an information sheet stating all of the steps that were followed was given to the subject upon completion of the letter of consent.

The first measurement taken was height of the subject. For this procedure a tape measure was fixed to a wall with zero being placed at the floor/wall intersection. The measurement increased as the tape measure rose up the wall. The barefoot subject was placed with his back against the wall, feet shoulder width apart and a measurement taken from the crown of the head, according to what the tape measure read. The next step, weight measurement, was conducted on a certified digital scale to ensure minimal human error by misreading the scale. After completing these two steps, the subject's dominant foot was determined by writing hand. Immediately following this, the subject's dominant foot was measured for a static reading.

The subject was positioned standing comfortably with feet shoulder width apart, and knees slightly bent in a comfortable fashion. The dominant foot was placed on top of a piece of Pressurestat paper and static measurements were taken from this position. Pressurestat paper is a graphed piece of paper that is an accurate indicator of foot placement because it leaves a graphite imprint on the paper of the exact placement of all of the foot landmarks. As the subject is standing with his dominant foot on the graph paper, three landmarks were determined for reference to the measurements taken. The first landmark position that was used was the second metatarsophalangeal (MTP) joint. This point is where the second metatarsal joins with the first phalange of the second toe. A mark was placed on the Pressurestat paper as to where on the graph the foot imprint was located.

The next points determined on the paper were the lateral and medial malleoli. To determine this, a carpenter's square was used to ensure that the mark placed on the paper was placed exactly parallel to the distal most point of the malleoli. Once these two points were marked on the Pressurestat paper, the midpoint of the two was determined by using a straight-edged ruler and measuring the distance between the two and dividing it. This point was used as the posterior point of the rotational axis. Once the defined anterior and posterior points of the rotational axis were determined, then a line was drawn connecting the two with a ruler. This line served as the hypothetical rotational axis produced from static stance of the subject.

The next step of this study consisted of dynamic movement of the subject across a force platform. This section was where the collection of force and moment data was completed. An AMTI LG6-4-1 Biomechanics Platform (force platform) has been previously installed in the indoor track of a local athletic club and was used to collect this data. The force platform collected data at a sampling rate of 600Hz and an AMTI SGA6-4 Signal Conditioner/Amplifier (AMTI, Inc.), with a gain set of 1000, automatically transferred the data to an Excel spreadsheet on an attached computer. Atop of the force platform another piece of Pressurestat paper was fixed to determine foot placement as the subject walked across the platform. The data collection was of the subject walking across the platform with the dominant foot at an average leisurely pace in order to simulate normal walking patterns. This procedure was repeated as many times as needed so that the subject felt comfortable with his walking pattern while the dominant foot struck the force platform (Figure 3.1).

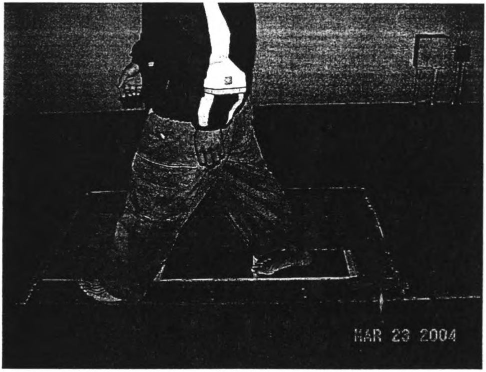


Figure 3.1 Subject walking across Forceplate/Pressurestat paper

Once five successful trials were completed, the subject had then completed his part of the study. From here, nine landmarks were determined on the Pressurestat paper through visual observation so that an outline of the foot was produced around the axis of rotation created by the force platform. These landmarks are the posterior center of the calcaneus, the abductor hallucus maximus, the distal head of the first phalange (great toe), the distal head of the fifth phalange (small toe), the abductor digiti minimi and four points on the lateral border of the foot. These points were useful in creating an image of the foot. The disadvantage of the force platform is that it did not produce an image of the foot; rather it just created an axis of the center of pressures of the foot as it completed a support phase of gait. The positive correlation between the two pieces of equipment is that the force platform and the Pressurestat paper both have a graphical system built in each one and could be correlated so that the axis produced by the Pressurestat paper could be superimposed onto the image created by the force plate image in an Excel spreadsheet.

To ensure that the measurements from the two pieces of equipment were in exact coordinates, the measurements from the Pressurestat paper were entered into a formula to equate to the force plate readings. The x-coordinate, in centimeters, was subtracted from 30.48 cm (a number determined to correctly coordinate from the center of the force plate to the accurate corner of the force plate). The y-coordinate, in centimeters, was determined by subtracting 60.96 cm from the measured coordinate (a number determined to correctly coordinate from the center of the force plate to the accurate corner of the force plate). Once this was entered into the Excel spreadsheet (Microsoft XP edition), an accurate location of the foot on the force plate was produced. To determine the angle of the dynamic axis of rotation, a marker was needed as a reference. This marker was created by a two step process. The first step was to determine the bisection of the foot. This was done by using a technique already determined by Song. A line was created along the edge of the medial border and another was created along the lateral border. Two perpendicular lines at the forefoot most point and the rearfoot most point were created from the medial border line and projected to the lateral border line[37]. The midpoint of each of these lines was connected to one another to create the bisection of the foot. Immediately following this, a line that was perpendicular to the bisection line was created on the rear aspect of the foot. This line served as the base for the angle created by the dynamic axis of rotation. This created an angle that was measured on the great toe side using a protractor and compared to the angle produced during the static measurement process. Examples of this are seen in figures 3.2 and 3.3. In these figures, the imprint of the foot is seen, as well as the baseline created by a line perpendicular to the bisection of the foot. The line created in figure 3.2 is a connection of the determined rear point from the modified valgus index procedure and the connection of the middle of the second metatarsophalangeal joint. The line created in figure 3.3 is a connection of the first point of heel strike and the last point just prior to toe off on the ball of the foot.

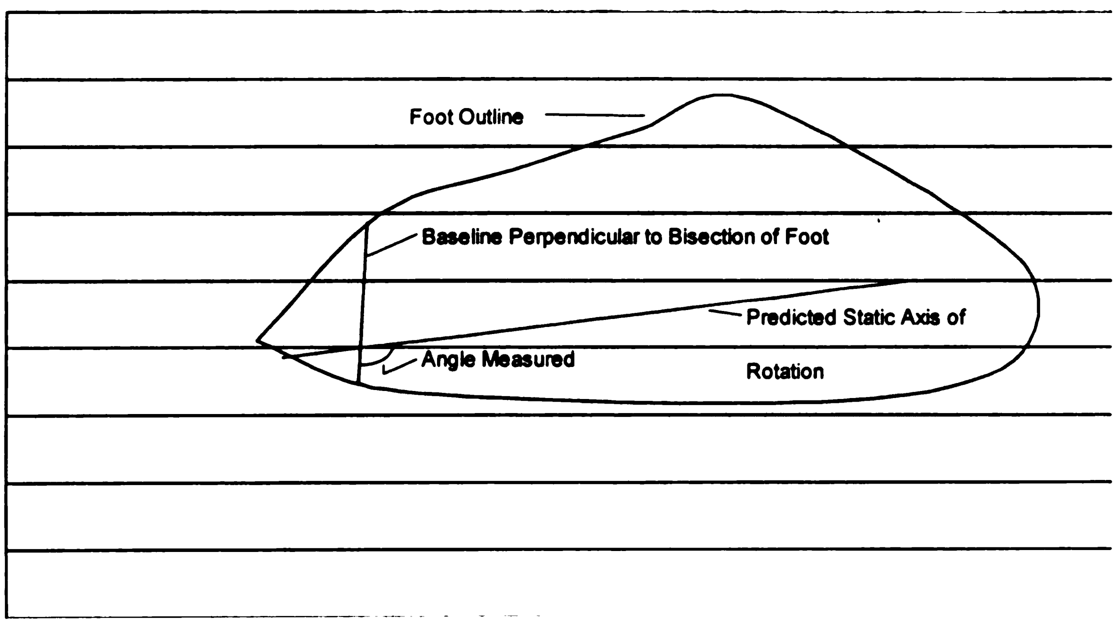
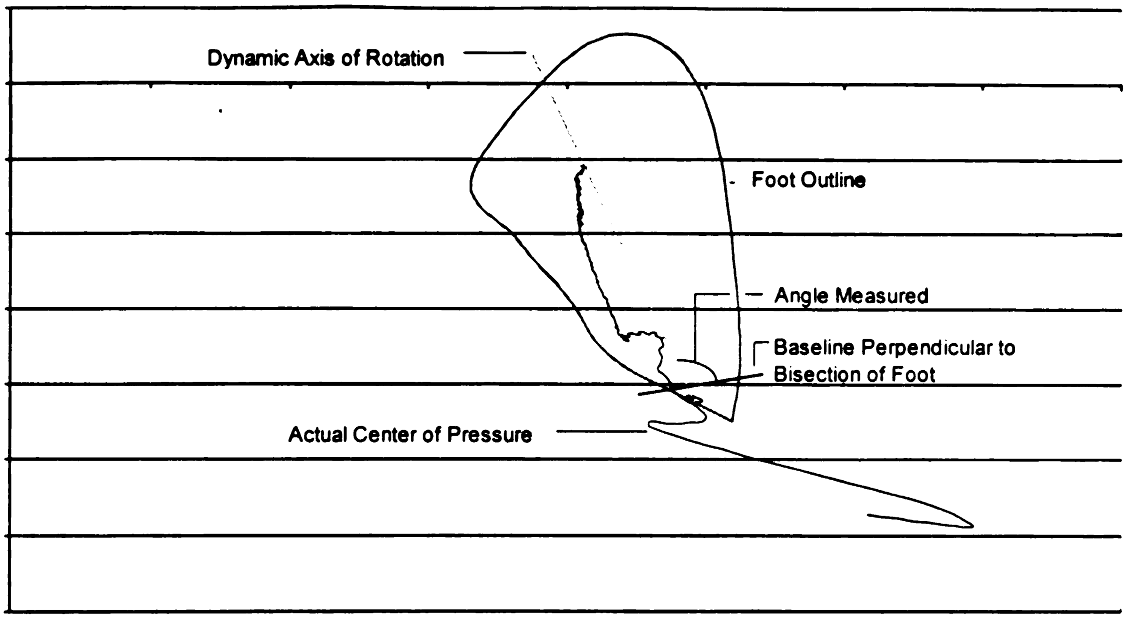


Figure 3.2 Static Measurement (subject 1)



<u>Figure 3.3 Actual Dynamic Reading of Force Plate Measurement (subject 1 trial 1)</u>

Results of each subject trials can be seen in Appendix A.

Chapter 4: Analysis of Results

Subject Demographics

Ten male subjects were used to complete this study. Their average age was 24.1 years old, with an average height of 177.04 cm and an average body mass of 84.34 kg. Table 4.1 outlines the specific traits for each of the subjects.

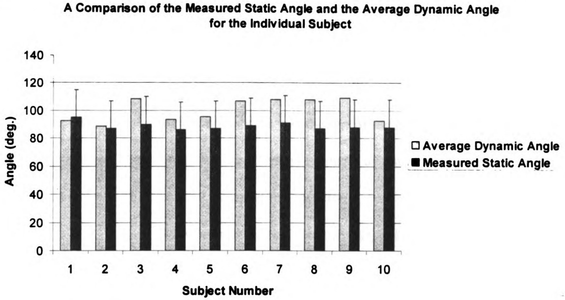
Table 4.1 Subject Demographics

Subject #	Age (Yrs)	Height (cm)	Body Mass (kg)	Dominant Foot
1	24	175.26	81.65	Right
2	25	182.88	92.08	Left
3	24	177.8	78.03	Right
4	28	172.72	99.02	Right
5	25	180.34	79.84	Right
6	23	170.18	65.32	Right
7	23	175.26	102.51	Left
8	23	177.8	82.10	Right
9	22	177.8	83.92	Right
10	24	180.34	78.93	Right

Individual Results

Each subject completed at least three and no more than five successful trials. Following the trials, the points were then plotted using an Excel spreadsheet graph and the angles were then measured manually using a protractor by the researcher. The trial angles were then averaged for the individual subject and compared with his measured static angle. A comparison is shown in Table 4.2.

Table 4.2 **Comparison of Measured Static Angle and Average Dynamic Angle**



Statistical Analysis

Separate T tests were used to look at the data. The first test looked at the average angles for each subject combined to create one single average dynamic angle for the entire group, and one single average static angle for the entire group. These two numbers were then compared using a paired samples T test through SPSS computer software (SPSS 10.0, SPSS Inc. 1999). The results of this test showed a mean value of -12.38 degrees, with a standard deviation of 9.66 degrees. A 95% confidence interval showed the lower limit to be -19.29 degrees and an upper limit of -5.47 degrees. The test revealed a significant difference ($p < .05$) between the static measured angle and the dynamic calculated angle. This indicates that there is a difference between the measured static angle and the actual dynamic axis of rotation.

The second test took a look at all of the trials as an average of the whole group, but the highest and lowest points were taken out of the equation for each subject. The data showed a mean of -14.08 degrees and a standard deviation of 11.01 degrees, which is very similar to the first paired T test as well. The 95% confidence interval had a lower limit of -23.28 degrees and an upper limit of -4.88 degrees. The p-value for this test still revealed a significant difference ($p<.05$) between the static measurement and the dynamic calculated axis.

The third step to the analysis of data was the use of the body mass index (BMI). The BMI is a measure that takes a look at relative density of mass of a person's body to their height and can be calculated by using the equation:

$$BMI = \text{body mass (kg)}/\text{Stature } (m^2)$$ [38]

The basis for this analysis used 26.0 as the cut-off marker for data collection. This number, 26.0, was used because it was the median number among the entire group. All of the subjects with a BMI lower than 26.0 were placed into one group (group A)and those subjects with a BMI of 26.0 and over were placed into a second group (group B). Group A had a mean of -8.53 degrees and a standard deviation of 10.43 degrees. The 95% confidence interval had a lower limit of -21.48 degrees and an upper limit of 4.42 degrees. The test results showed that there was a significant difference ($p<.05$) between the static measurement and the dynamic calculated axis. Group B had a mean of -16.67 degrees and a standard deviation of 9.40 degrees. The 95% confidence interval had a lower limit of -28.34 degrees and an upper limit of -5.00 degrees. The test results showed that there was no significant difference ($p>.05$) between the static measurement and the dynamic calculated axis of rotation.

Chapter 5: Discussion

The purpose of this study was to determine the dynamic axis of rotation of the foot through a static measurement that has been modified from previous research. Although this was not exactly achieved, there was some direction accomplished.

Sources of Measurement Error

The data collected showed that there is a significant difference between the static measurement technique that was devised and the actual dynamic axis of rotation determined by the force plate calculations. This could be due to many factors that could be classified into mathematical and human error. The mathematical errors may be due to insufficient research into the different types of measurement of the foot. Possibilities that may provide more precise measurement may include looking at length of the foot, width of the foot, and height of the structures of the foot. The length and width of the foot may provide an idea of the stability of the foot. If a foot is shorter and wider, then the base of the foot is more stable than a longer, thinner foot. This may be a large factor in the variance of data because specific foot sizes were not utilized. Looking at the structural pieces of the foot may also benefit the accuracy of the measurement. As Nachbauer theorized, the higher the arch, the more unstable the foot [16]. This may also be a key factor in the stability of the walking pattern across the force plate. Another structural piece that may need closer attention is the height of the navicular drop. Mueller looked specifically at how much it moves in the determination of the amount of pronation a foot has[21], but if it is tied in with other measuring techniques, then it may be a beneficial feature of determining the static axis of rotation.

One of the major factors that caused the most difficulty in determining the relevance of the study was the fact that the dynamic readings taken by the force plate showed a great deal of variance. For any given subject, there was a difference of up to 25° among trials (Appendix A, subject 3- trials 3 and 4). This shows the variance of how much a person's step can change every time the foot is laid down to create ambulation. Also, looking at Appendix A, we see that there is a large amount of variance in the standard deviation of each subjects' trials. This reinforces the idea that each step that is taken by the subject is capable of a wide amount of variation. This error was manipulated by throwing out the highs and lows of each subject and there was still a similar amount of variance within the results of each analysis. Even with an average of more trials, there will likely be a greater chance of variance and a greater standard of deviation.

Human error may also be a factor in creating a significant difference between the two measures. The force plate that was used is set into an indoor track with a slight drop-off just before landing on the force plate. This may have caused a feeling of unsteadiness to the subject when he was walking onto it. The slight elevation change would not feel ordinary to the subject and make his step atypical. We tried to minimize this problem as best as possible by allowing the subject multiple practice trials so that he could be as comfortable as possible prior to collecting data. Another human error that may have been created is a stress for the subject that he may not step exactly on the force plate in the desired position. This would cause the subject to either lengthen or shorten his step as he neared the force plate and thereby changing the axis of rotation, through an uneven center of pressure map. To minimize skewed data, we allowed the subject multiple trials even during the data collection if they felt that the trial didn't feel natural. Along with the correct length of a subject's stride is the placement of the foot on the force plate. The subject may also have stepped on the very edge of the force plate distorting the data just slightly. Stepping on the edge of the force plate would cause the lateral border of the foot to receive less pressure than normal, thus shifting the center of pressure medially until just before toe off. This factor was easily seen by the computer and if it occurred, the trial was thrown out and another was completed in its place. Another source of human error may be caused by the graphical determination of the axis of rotation angle. The angle was determined by finding the bisection of the foot and creating a line perpendicular to it. The axis of rotation was then measured from that baseline and recorded. Using a method of bisection that was tested by Song should have minimized the error. The last form of human error that may exist is the placement of the PressureStat paper onto the force plate. The edges of the paper were to be lined up with the edges of the force plate. This makes the assumption that the edges of each component, the force plate and the PressureStat paper, are identical, therefore creating an identical graph. This may not be true because the edges may not have lined up exactly or been placed incorrectly by the researcher. In order to diminish any error by incorrect placement, the paper was taped onto the force plate according to lining up the edge of the paper with the edge of the force plate.

Clinical Implications

Currently, there is not enough research available about this topic to promote a definitive finding. This study and related research provide useful background for clinicians working with correcting patient postural control and gait problems mainly because there is a need for an inexpensive way to determine the axis of rotation. Once this is determined, orthotic devices will have a better chance to be fitted to a person's foot while keeping the expense of fitting and manufacturing reasonable. It is important to note that the equipment that is currently available is very technical and valid, but is expensive and beyond what a typical clinic would have in their budget for orthotic fitting.

Considerations for the Future

Research should be continued to break down the different aspects of the foot in order to determine a valid measurement process for the axis of rotation. Some areas that require more specific direction include the forefoot placement and the heel strike placement. In the forefoot, there is some controversy as to where the greatest point of force is placed [25, 27], but if a measurement process could determine the specific point for each subject, then there would be no room for disagreement. Along with the forefoot dilemma, the point of heel strike is another aspect that needs further clarification. The anatomical middle of the heel is the logical point where the heel strikes, but it fails to take into consideration how the lower leg interacts with the foot during that time. Rose's [18] suggestion of using the valgus index to determine the rearfoot valgus is excellent, but needs further clarification to be translated into where the first point of contact of the heel occurs during the gait process.

Upon clarification of these two main points the process for predicting the axis of rotation will be more valid and will greatly enhance the understanding of foot needs.

Limitations to the Study

The study is accurate in measuring techniques determined by previous research, but there were some limitations to the study. The first limitation was from the size and diversity of the subjects. With only 10 male subjects, there was not enough numbers to decide if the averages were abnormal, or normal. Some of the subjects tested were closer to the predicted static axis than others. If there were more subjects tested then the abnormalities may have been less prevalent.

The track that was used had a slight anomaly in the fact that it had a minor elevation change as the subject walked onto the force plate. This can be avoided in future studies when a runway is built with the force plate at an even height.

The last limitation to the study was the fact that this is a new topic that has little research to back it. With future studies, the idea of the axis of rotation will become clearer and more improved so that a valid predicted measurement will mimic the actual dynamic axis of rotation.

Conclusion

In conclusion, the proposed static measurement technique did not match up to the actual dynamic axis of rotation, but a process was created so that it may be continued until a solution has been found. This solution will make a great impact on the world of custom orthotic fitting because it will allow more people to break down the way they walk and find corrections to their gate problems at a less expensive cost. Cost is a major reason that doctors and clinicians don't prescribe custom orthotics for their patients. Either insurance companies won't pay for it and the patient doesn't want to spend the money or availability of equipment to test the foot is not available because the clinic can't afford it. In the future, I hope to see more studies researching this topic to find a solution.

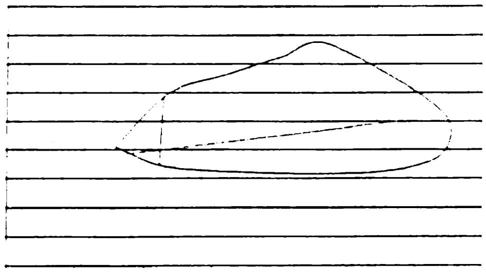
The motive behind why this needs to be determined is so that a clinician can produce a quick and less expensive image of the dynamic axis of rotation to determine the considerations that need to be made when a set of custom orthotics are created for a customer. There are technological devices that can determine this, but they are expensive and require a considerable amount of education to run. With the success of this method, clinicians will be able to measure a patient's foot and have an accurate determination of what is needed.

Appendix A

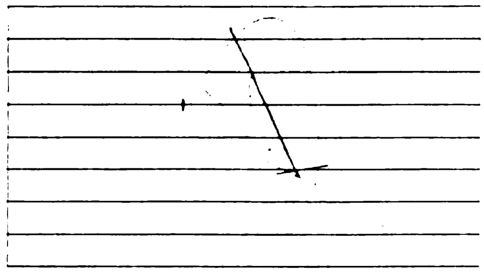
Angle Analysis	Static Angle		Tr 1	Tr 2	Tr 3	Tr 4	Tr 5	Tr 6	Avg	St. Dev
Subject 1	101		99	94	100	100	92		97	3.7
Subject 2	92		92	86	101	91	93		92.6	5.4
Subject 3	90		98	111	97	122	115		108.6	10.8
Subject 4	83		95	103	93	104	92		97.4	5.6
Subject 5	88		97	99	91	101	103		98.2	4.6
Subject 6	87		100	117	111	110	115		110.6	6.5
Subject 7	90		118	121	111	108	99		111.4	8.6
Subject 8	87		110	116	112	98	117		110.6	7.6
Subject 9	90		113	75	111				99.7	21.3
Subject 10	88				93	87	95	100	93.8	5.3

Subject 1

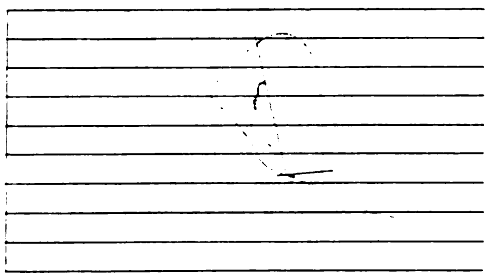
Static



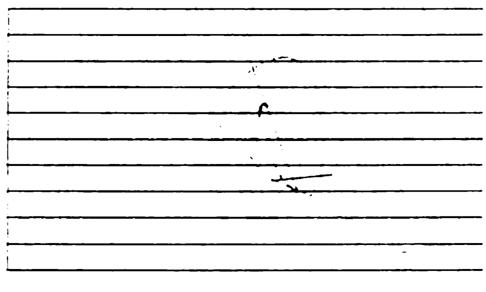
Trial 1



Trial 2



Trial 3



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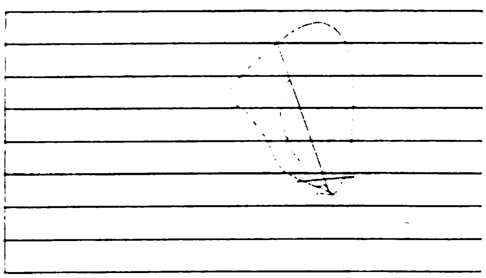
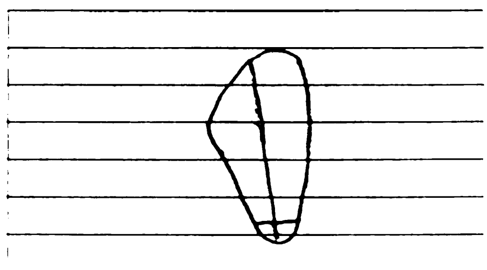
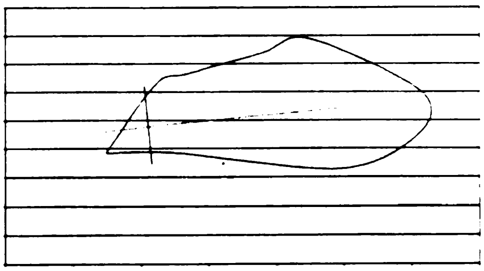


Trial 5



Subject 2

Static



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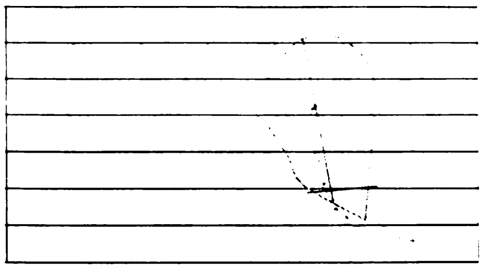

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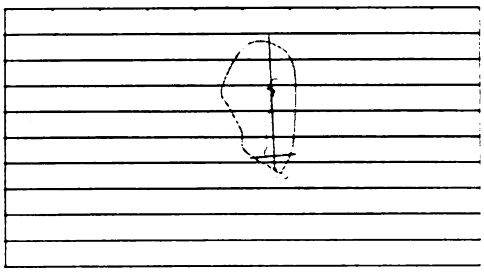

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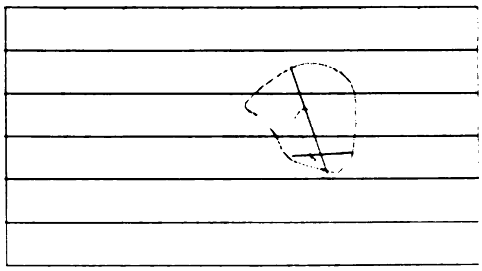

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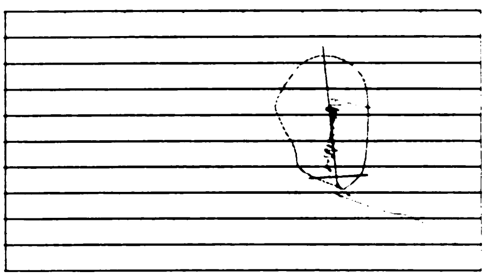

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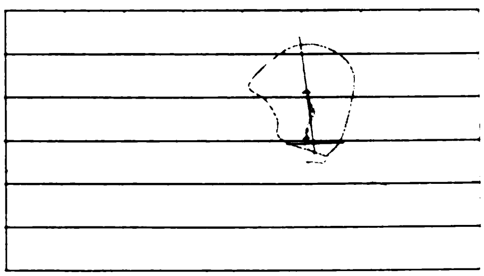
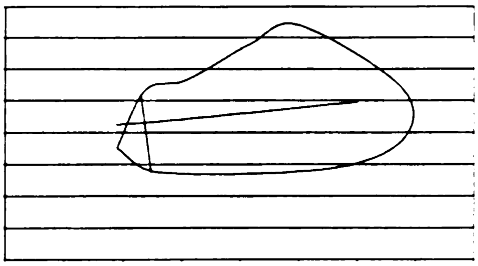


Subject 3

Static



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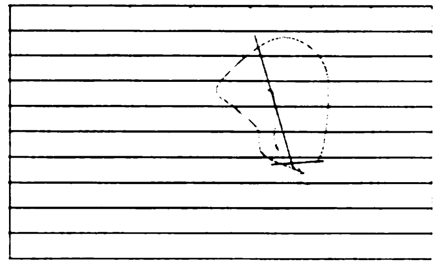

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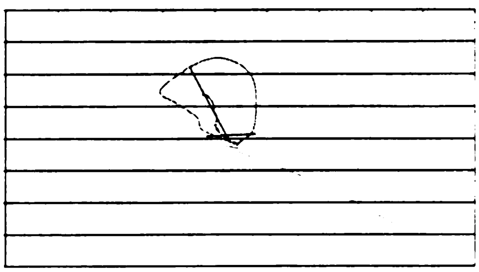

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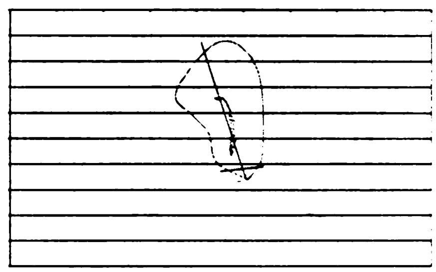

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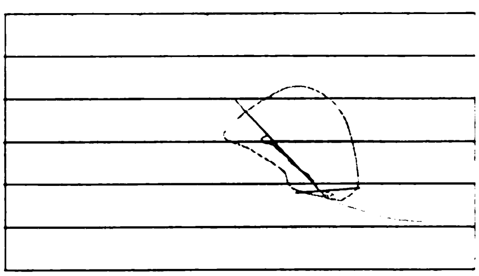

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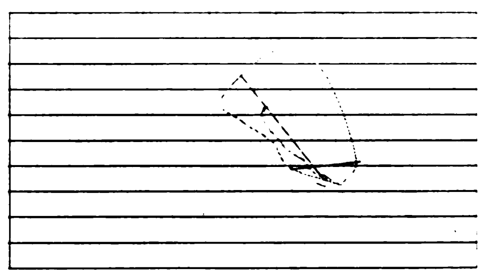

Subject 4

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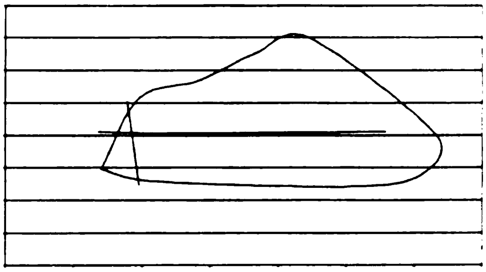

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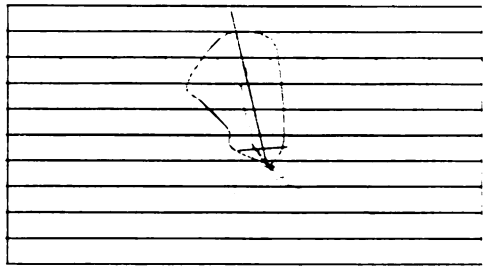

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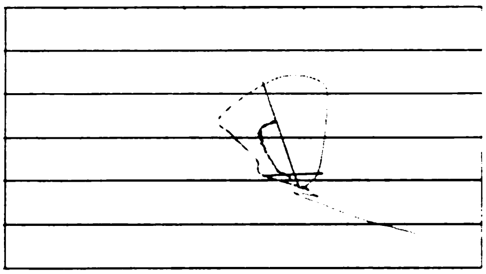

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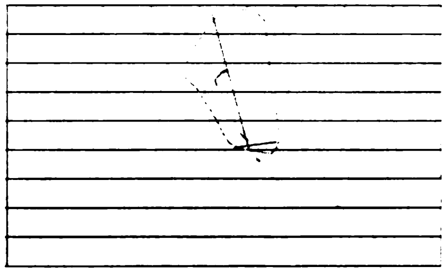

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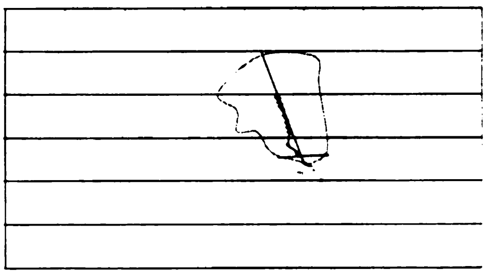

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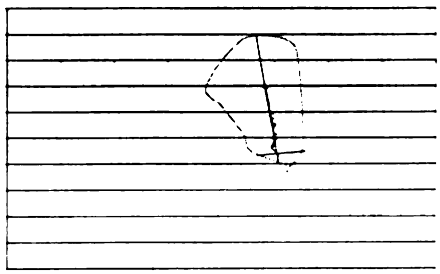
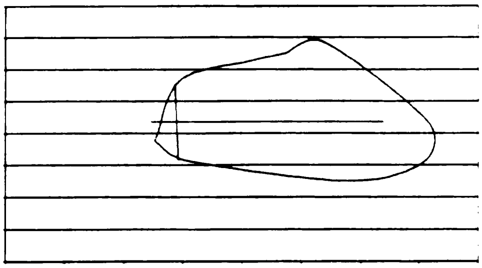
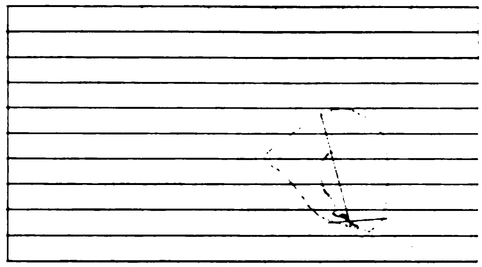


Subject 5

Static



Trial 1



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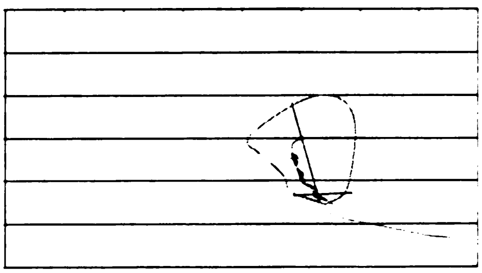

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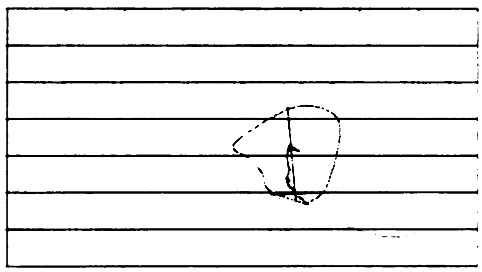
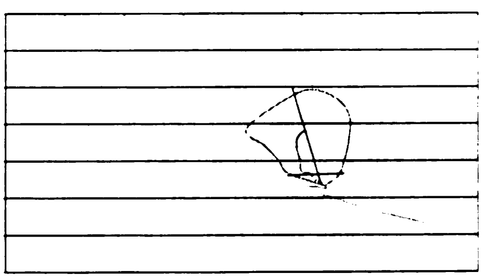


Trial 4



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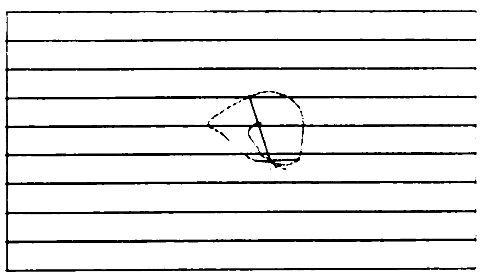

Subject 6

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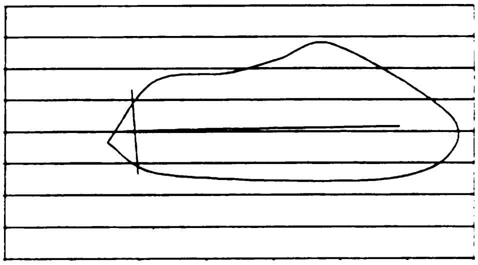

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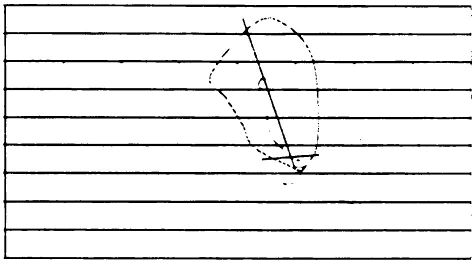

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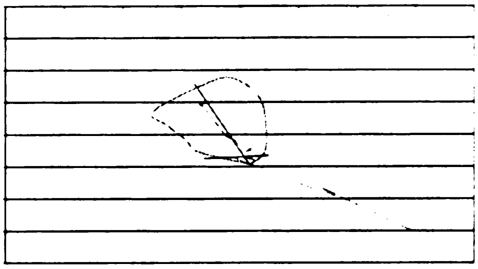

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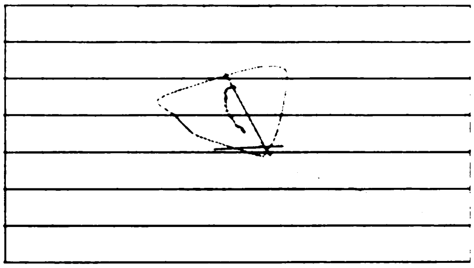

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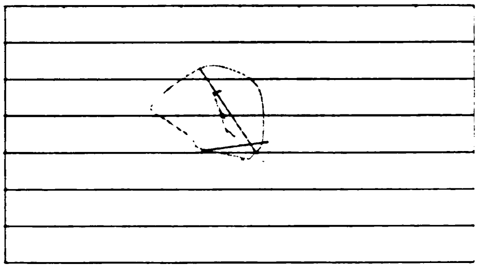

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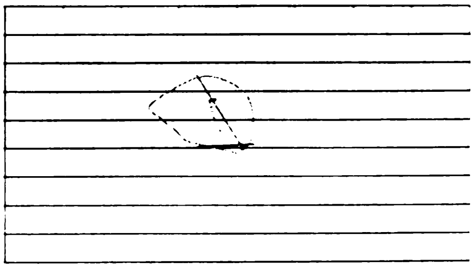

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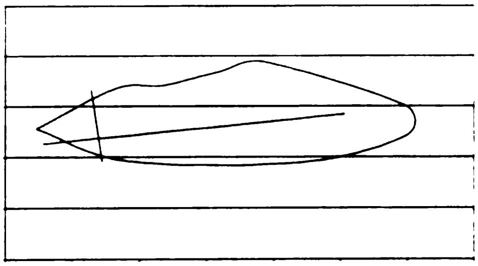

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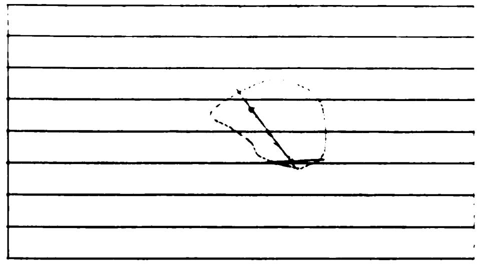

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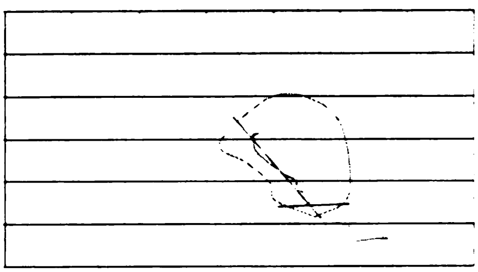

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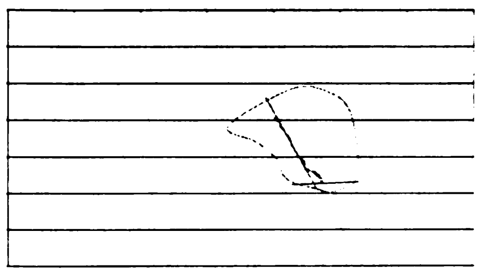

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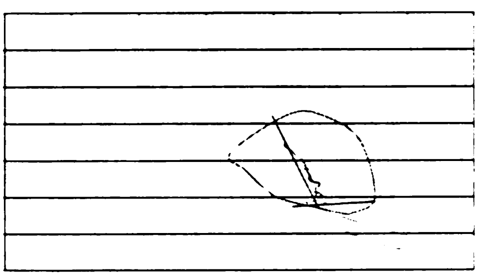

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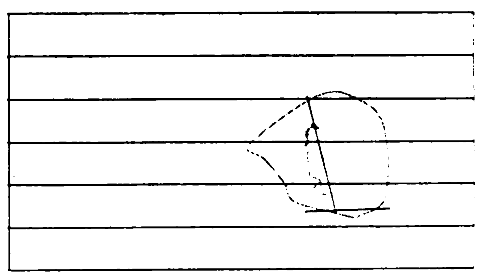

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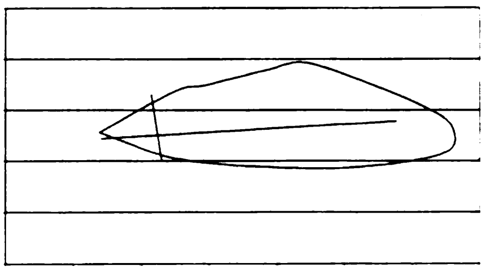

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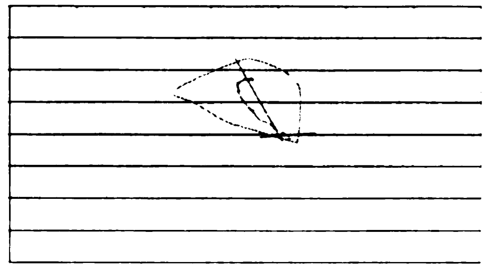

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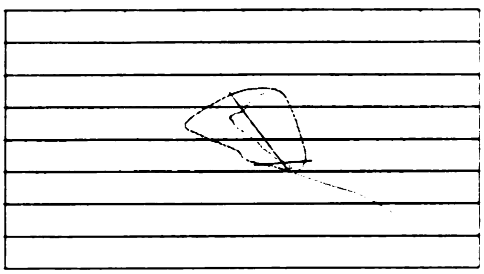

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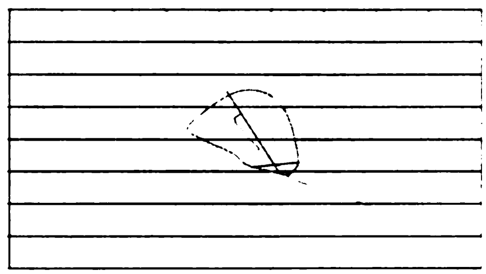

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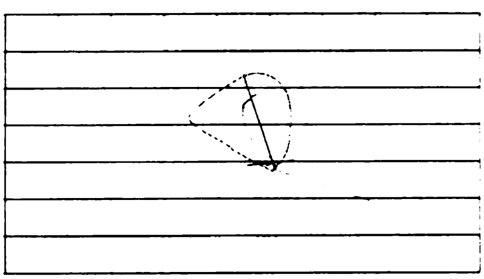

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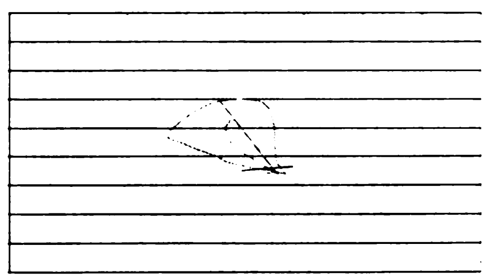
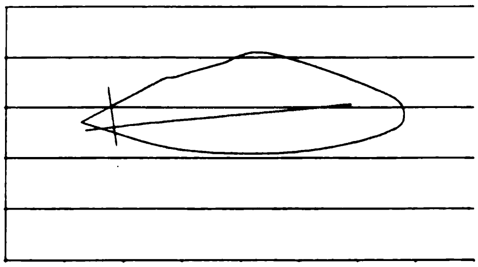


Subject 9

Static



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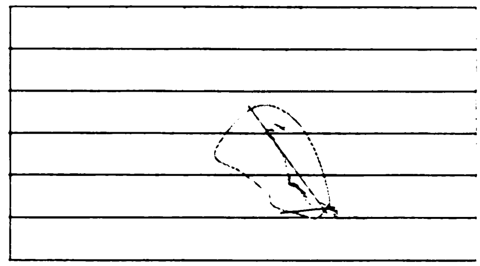

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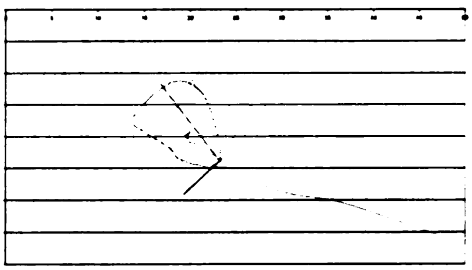

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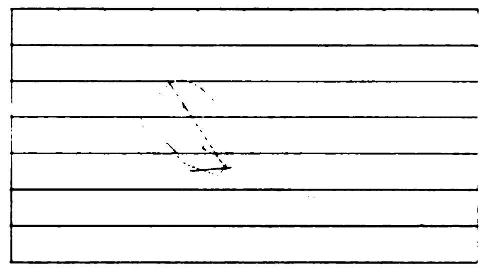
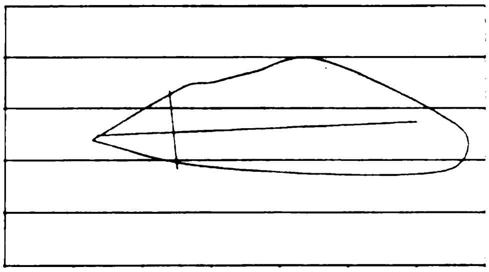


Subject 10

Static



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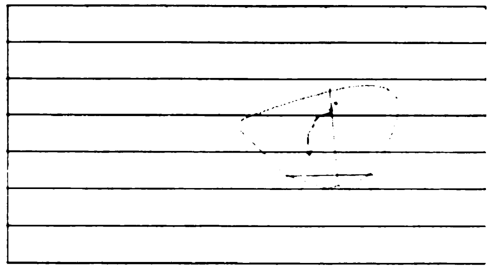

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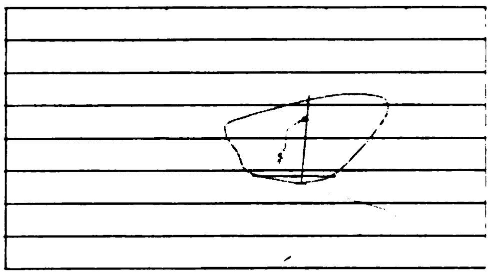

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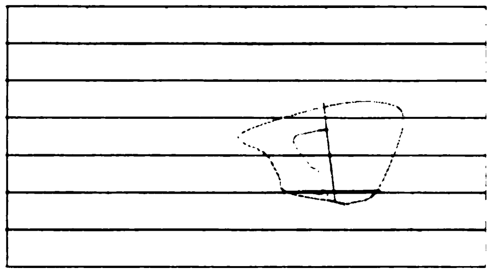
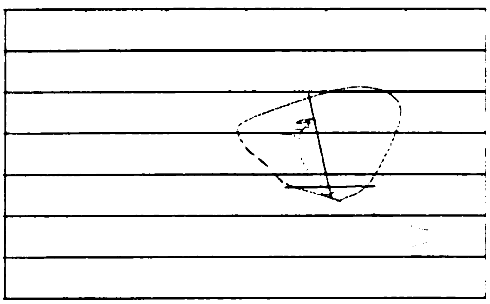


Trial 6



Consent Form for study of the static measurement as a predictor to the dynamic axis of rotation of the human foot.

For questions regarding this study, please contact:
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Principle Researcher
Department of Kinesiology
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East Lansing, MI 48824
517-214-6013
brattabr@msu.edu

For questions regarding your rights as a research participant, please contact:
Peter Vasilenko
Chair Person
Committee on Research Involving Humans
Michigan State University
202 Olds Hall
East Lansing, MI 48824
517-355-2180
UCRIHS@msu.edu

Dear Subject:

My name is Brian Bratta, ATC, CSCS, graduate athletic training student at Michigan State University. I am conducting a research study entitled, "Static Measurement as a Predictor to the Dynamic Axis of Rotation of the Human Foot." This study is being conducted under the direct supervision of John Powell, Phd, ATC, Assistant Professor at Michigan State University. The purpose of this study is to create a more effective, less expensive manner in which to analyze a person's foot structure in order to determine placement of material for a custom orthotic device used within a shoe.

Participation in this study will be voluntary and will consist of measuring your foot from a relaxed stance and performing a comfortable walk on a track in order to determine foot placement during gait. The measuring of the foot will be done while standing on a piece of ink paper. The walking will consist of you walking barefoot across a force plate embedded in the track. This will be at a leisurely pace and without any instrumentation or devices on your body. All of the measurements will be taken on ink paper underneath your foot and will not leave any residue or markings on your feet. The complete measurement process should not take more than 1 hour.

The measurements of the foot will remain confidential, as your name will not be placed on the data, rather an identification number representing your data will be used. The only people that will be privileged to know the your name will be the principal researcher and a technician collecting the computer data. Your privacy will be kept confidential and protected to the maximum extent allowable by law.

Participation in this study is completely voluntary and you may discontinue your involvement at any time. Questions concerning participation in this study should be directed to Brian Bratta, ATC, CSCS, graduate athletic training student (517) 214-6013, or brattabr@msu.edu. Additional questions concerning the rights' of the subjects in this study can be addressed by Peter Vasilenko, PhD, Michigan State University's chair of the Committee on Research Involving Human Subjects at (517) 355-2180, or UCRIHS@msu.edu. Questions regarding the supervision of the study may be directed to John Powell, Phd, ATC, (517) 432-5018, or Powellj4@msu.edu.

Informed Consent:

By completing this section, you are giving your informed consent to participate in this study.

I have read and agree to participate in this study as describe in the above paragraphs.

____
Please Print Your Name

____________________ ________________
Your Signature *Date*

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