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The Kinematic Interaction Of The Forefoot And
Rearfoot During The Stance Phase Of Running Gait

By

Raymond M. Fredericksen

A Thesis

Submitted to

Michigan State University

in partial fulfillment of the requirements
for the degree of

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Department Of Biomechanics

1990

ABSTRACT

THE KINEMATIC INTERACTION OF THE FOREFOOT AND
REARFOOT DURING THE STANCE PHASE OF RUNNING GAIT

By

Raymond M. Fredericksen

The purpose of this study was to develop a method to describe the kinematics of the foot during the stance phase of running. In order to integrate positional data from targets placed on the skin over boney landmarks on the foot and lower leg with ground reaction forces, a subject was filmed running over a force plate. Utilizing a joint coordinate system of analysis, the functional interaction of forefoot and rearfoot motion, during the stance phase of running gait was analyzed.

The foot was modeled as a three link system, comprised of the tibia, calcaneus, and the first metatarsal ray. An experimental method was performed to obtain the three-dimensional kinematic data of the model during foot contact phase of running gait. The functional relationship between the forefoot and rearfoot was analyzed. These data have applications to diagnostics and the evaluation of pathological gait, prescription of orthotic devices, and for development of footwear designs.

DEDICATION

The author would like to dedicate this thesis to all of the people who continually harassed and prodded me to complete it. Without their constant encouragement I would still be "so close" to finishing this project. And to my dog Elle for her constant companionship during periods of procrastination and her ever willingness to play fetch the ball.

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I. INTRODUCTION

The human foot comprises 25% of all the bones in the body. There are twenty-eight bones in the foot, including the tibial and fibular sesmoid bones. The skeletal structure of the foot has thirty-three joints and is supported by one hundred seven ligaments. Movement of the foot is initiated by the innervation of over thirty muscles, including those which originate in the lower leg (Gray, 1973), (Figure 1).

The two major functions of the foot are to provide a foundation of support and balance for the body and to transfer the body's weight forward during human locomotion. The human foot is a complex but adaptable structure, capable of supporting the body's weight during walking as well as supporting dynamic forces well above body weight in activities such as running or jumping.

The motions of the foot have been described as pronation and supination. These motions involve synchronous rotations of the ankle, subtalar, and midtarsal joint complexes of the foot. Pronation involves simultaneous eversion, dorsiflexion, and lateral rotation. Supination involves simultaneous inversion, plantar flexion, and medial rotation. These motions are complex three-dimensional rotations which occur in oblique planes.

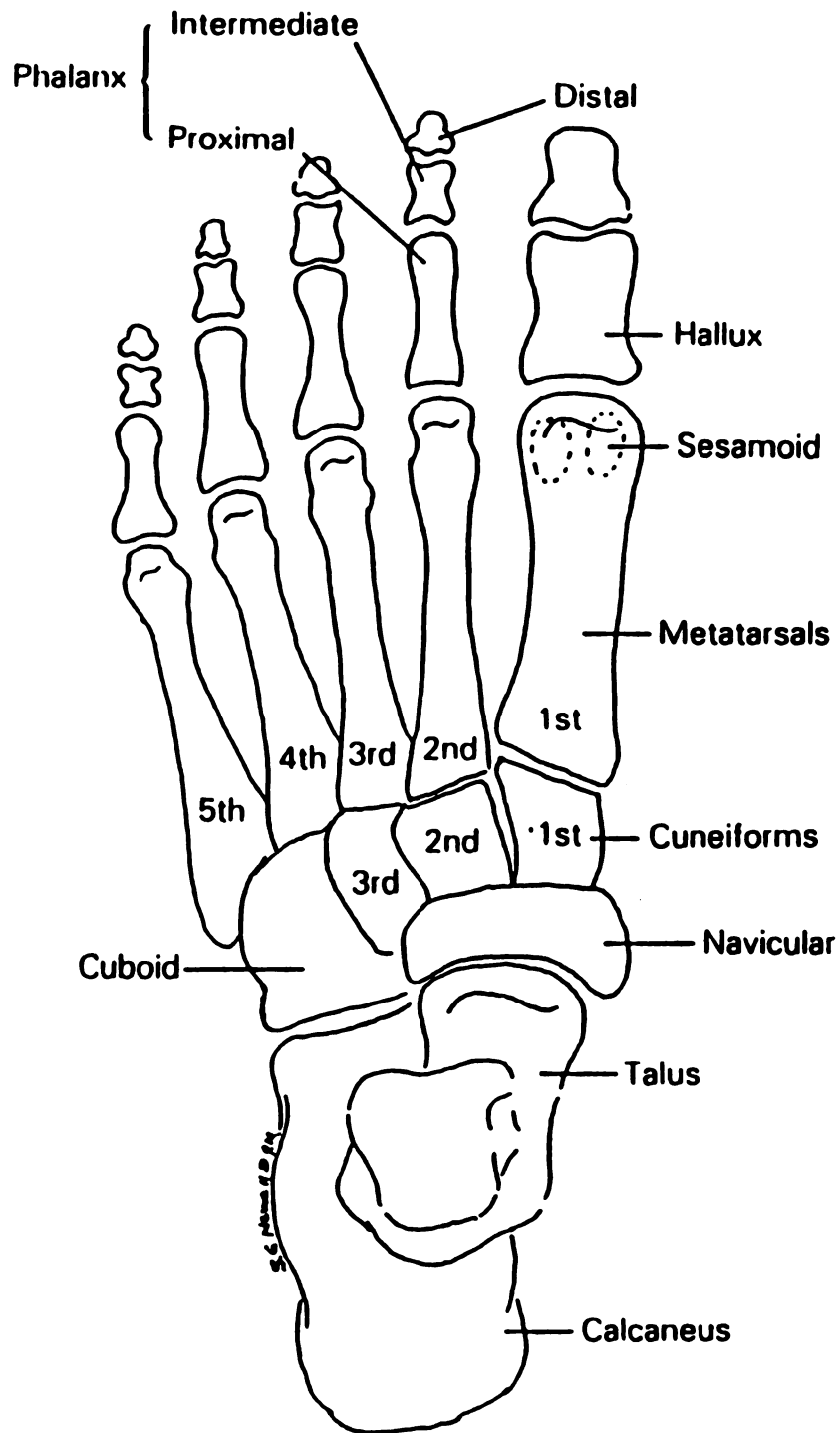


Figure 1. Skeletal Anatomy of the Human Foot.

Measurement and classification of foot motion is extremely important to the clinician in treatment of gait pathologies and prescription of orthotics. Analytical methods, which accurately describe the motion of the foot would provide valuable tools to evaluate variations in footwear design.

Although a direct cause and effect has not been established, maximum pronation and excessive rate of pronation has been correlated with overuse injuries. Messier and Pittala (1988), in a study on the etiology of running injuries, found a correlation between excessive range and rate of pronation and certain overuse injuries. They also found that greater maximum pronation and rate of pronation occurred when running in soft midsole running shoes.

Adaptation of the foot involves the ability to pronate and supinate through a range and sequence of movements that will not result in injury or pathology. However, measures of dynamic pronation and supination have proved difficult to obtain, evaluate and quantify.

Previous dynamic investigations which have studied foot motion during gait have focused primarily on the ankle joint, i.e., motion between the lower leg and calcaneus. However, pronation and supination also can be influenced by motion of the forefoot or, specifically, the position of the bones distal to the midtarsal joint.

Cadaveric studies and clinical evaluations have provided valuable information regarding foot structure and motion. Sarrafian (1983) identified a functional interaction between the joint complexes of the foot located both proximally and distally to the midtarsal joint. However, these studies do not describe the dynamic motion of the foot.

This study provided a method to describe the functional interaction of the rearfoot and forefoot during the stance phase of running gait. While the method utilized in this study is easily adapted to all aspects of human locomotion, an example of running gait was used to demonstrate the versatility of the model. This method has significant application to the clinician in evaluating gait pathology and orthotic prescription, and to the shoe designer in order to evaluate variations in footwear design.

II. LITERATURE SURVEY

Static assessment of foot joint range of motion is routinely conducted by the clinician to determine and classify foot structure and pathologies. This examination is done as a non-weight bearing procedure and does not reflect motions of the foot during the stance phase of gait. Within the literature early studies examined the range of motion of the various joints of the foot by inserting metal pins into cadveric foot specimens and measuring the displacement upon a single plane.

Root, O'Brien, and Weed, (1977), in a classical podiatric text, "Normal And Abnormal Function Of The Foot", suggested that the individual bones of the tarsus and metatarsus function as joint complexes. He identified the functional joint complexes of the foot to be the ankle joint, the subtalar joint, the midtarsal joint, and the metatarsophalangeal joint.

The ankle joint

The ankle joint is described as a hinge joint, comprised of the talus, situated in a mortise, between the malleolus of the tibia and the fibula bones of the lower leg. The primary motion occurs in the sagittal plane and is described as dorsiflexion and plantarflexion. The normal ranges of ankle joint motion reported are 10-20 degrees of

dorsiflexion and 25-35 degrees of plantarflexion. There is considerable variation in ankle joint motion between individuals due to differences in the inclination of the talus with respect to the lower leg and in the conical shape of the trochlea (Inman, 1976), (Figure 2).

Because of the inclination and shape of the talus, Inman (1976) and Sarrafian (1983), suggested that the obliquity of the ankle joint would cause an internal or external rotation of the leg when the foot is in contact with the ground. When the foot as a whole moves relative to the leg, the talus moves as a part of the foot. When the foot is fixed against the ground in movements such as walking or running, the ankle joint complex transversely rotates and the talus functions as part of the lower leg. The amount of rotation varied with the degree of obliquity to the lower leg and the amount of dorsi-plantarflexion occurring at the upper ankle joint.

The talus is the only bone of the seven bones comprising the tarsus of the foot, which articulates with the bones of the lower leg. During foot contact, all of the body's weight is transmitted through the talus to the other bones of the foot (Hontas, et al., 1986). Several authors (Inman, 1976; Hontas, et al., 1986; Perry, 1983) have suggested that it is the interaction of the talus and the calcaneus, through the action of the subtalar joint complex, which functions to reduce rotary stress at the ankle joint.

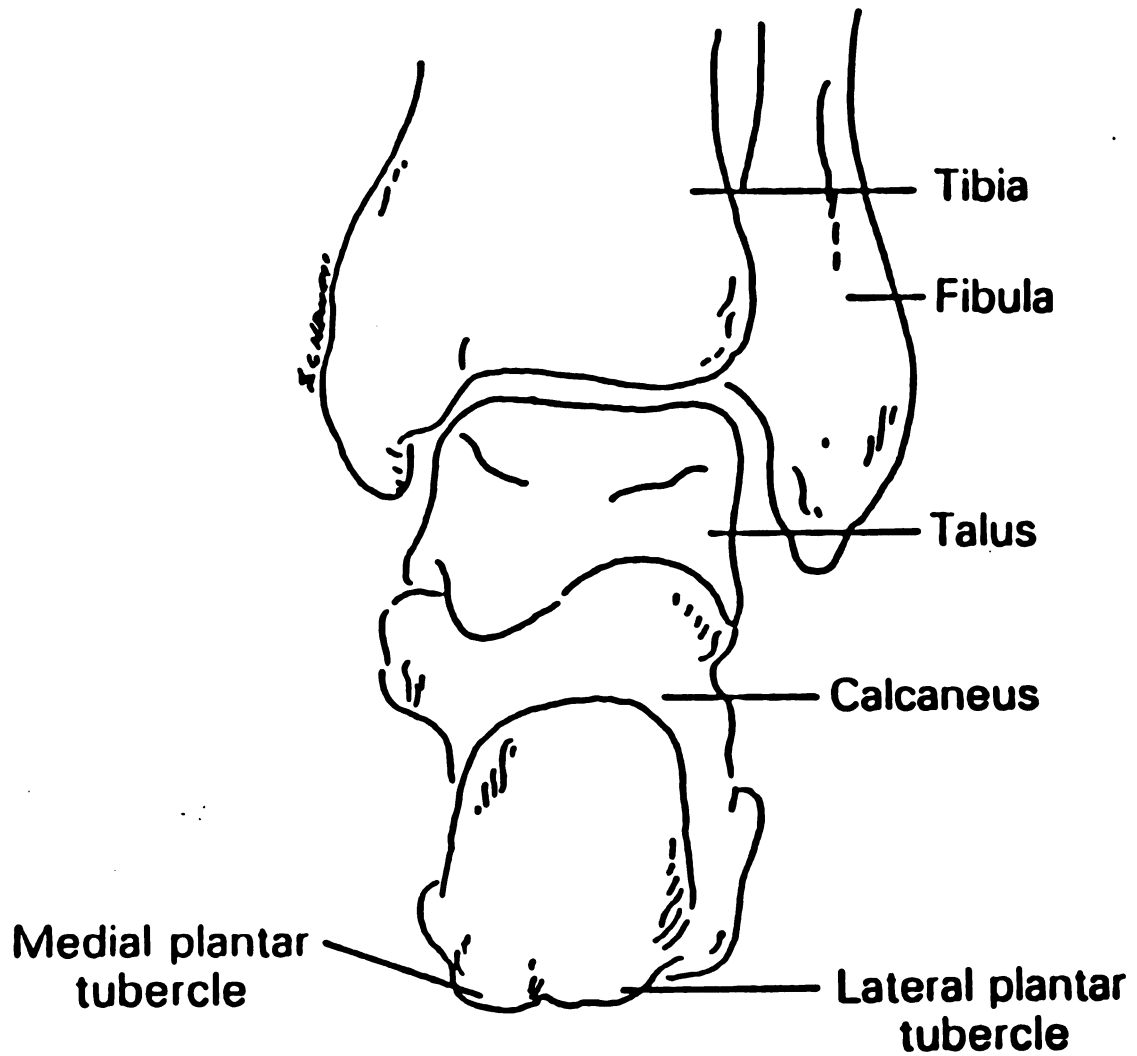


Figure 2. Anatomical Arrangement of Ankle Joint Complex.

Hicks (1953) classified all movements of the foot as rotations. He felt that the talo-calcaneal joint was primarily responsible for the motions of dorsiflexion and plantarflexion.

Proctor and Paul (1982) felt that the ankle joint was comprised of two principle joint systems, the talocrural or upper ankle, and the subtalar joint or lower ankle. The lower ankle joint or subtalar joint also was viewed as a uniaxial joint permitting the motions of inversion and eversion of the calcaneus relative to the talus (Root, et al., 1977; Inman, 1976; Proctor, et al., 1982). Proctor, et al. examined a compensatory interaction between the upper and lower ankle joints. When the range of motion is limited in one of these joint complexes, the other joint complex compensate with greater range of motion (Figure 3).

While the primary motion of the upper ankle joint is flexion and extension, Root, et al. (1977) felt that these motions were accompanied by corresponding lateral and medial rotations. Because of the conical shape of the talus, being wider anteriorly than posteriorly, dorsiflexion at the upper ankle joint tends to laterally rotate the foot, whereas plantarflexion results in medial rotation.

While joint range of motion varied greatly between subjects, Sammarco, Frankel, and Nordin (1980), and Root, et al. (1977) agreed that the minimal range of motion at the ankle joint for normal ambulation is 10 degrees of dorsiflexion and 20 degrees of plantarflexion. Total range

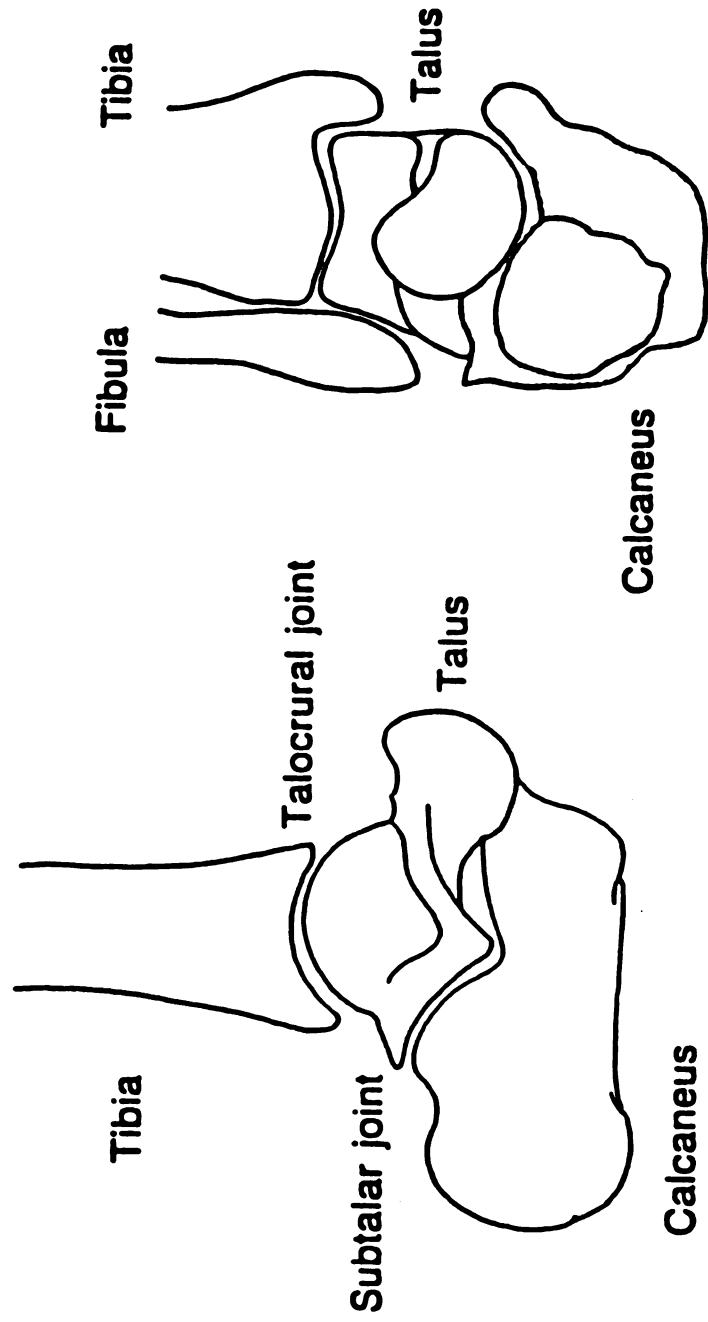


Figure 3. Anatomical Relationship of the Ankle, Subtalar, Joint, and Midtarsal Joint Complexes.

of motion at the ankle joint in the sagittal plane is reported to be 45 degrees, with 10-20 degrees determined to be dorsiflexion and 25-35 degrees plantarflexion.

The subtalar joint

The subtalar joint or lower ankle joint is comprised of the articulation between the talus and calcaneus. Motion at this joint has been described by a number of authors (Manter, 1941; Root, et al., 1977; Sarraffian, 1983) as a combination of gliding and angular rotation movements.

One of the first studies to analyze the motion at the subtalar joint was conducted by Manter (1941). A universal clamp was attached to a cadaveric foot specimen. Metal rods were then inserted at predetermined locations through the talus. The calcaneus was articulated until all of the metal rods circumscribed arcs in one plane when the subtalar joint was moved. Manter (1941) theorized the motion of the subtalar joint would be analagous to the helical angle of a screw.

Using similar methods of analysis as Manter's (1941), Hicks (1953), Root, et al., (1977), and Inman (1969) argued that the motion of the subtalar joint was more like a mitered hinge; the vertical component represented by the lower leg and the horizontal component by the foot. They theorized that internal rotation of the leg would result in

pronation of the foot and that external rotation of the leg would cause the foot to supinate (Figure 4).

While the position of the talus on the calcaneus allows for motion in all three planes, movement on the talus is viewed in a closed kinetic chain as pronation and supination (Kirby, 1987). Also, it must be noted that the alignment of the lower leg, talus, and calcaneus, vary greatly between individuals and changes in this alignment would account for the wide variations in motion reported at these joints between individuals (DuVries, 1973). To date, the functional anatomy of the subtalar joint remains unclear.

A major factor for this obscurity lies in the interrelationship of the upper ankle joint and the subtalar joint. Wright, et al., (1964) described the ankle and subtalar joint complexes as a universal joint, functioning together as a single unit. In this description, the talus is the center piece of the universal joint. The upper segment is comprised of the mortise created by the tibia and fibula on the trochlear surface of the talus. The lower segment corresponds to the calcaneus, navicular, and cuboid bones, which grip the talus from below. Wright also felt that variations in the obliquity of the ankle joint and in the inclination of the subtalar joint would result in different movement patterns between individuals. For example, a person with a more mobile flat foot would have an alignment of the subtalar joint which was more horizontal than an individual without flat feet, resulting in greater

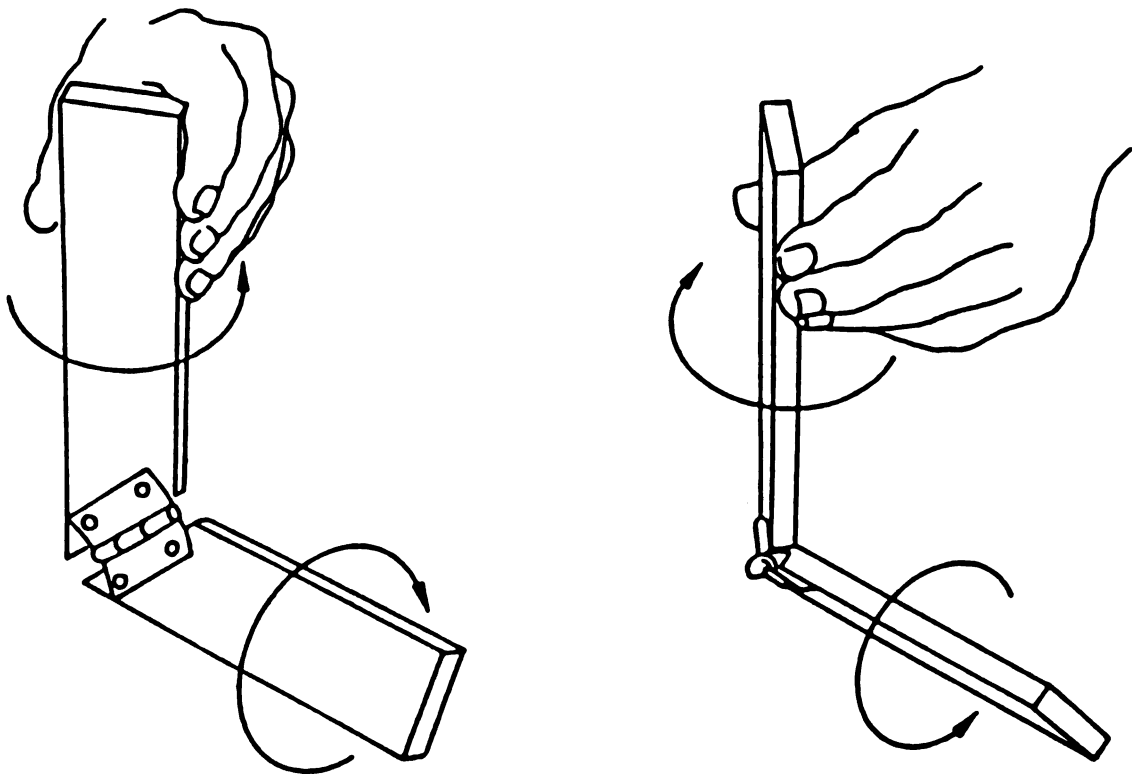


Figure 4. Mitered Hinge Motion of Subtalar Joint.

subtalar joint motion (Hlavac, 1977). Clinically, the average range of motion at the subtalar joint is 20 degrees of inversion and about 10 degrees of eversion (Wright, 1964).

The midtarsal joint

The midtarsal joint, also referred to as the transverse tarsal joint, or Choparts' joint, is a midfoot joint complex. It is comprised of the talus and navicular articulation on the medial side and the calcaneus and cuboid on the lateral aspect of the foot. Although the navicular and cuboid bones are not rigidly attached, any relative motion between them is considered minor and it is generally accepted in the literature that they move in unison (Manter, 1941; Sarrafian, 1983).

The motion described at the midtarsal joint is termed inversion and eversion. Roots' conviction was that the parallel alignment of the navicular and cuboid bones provided primarily this inversion and eversion of the forefoot. He felt that the forefoot would evert or invert as pronation or supination of the rearfoot occurred respectively (Root, et al., 1977).

The importance of the midtarsal joint articulation is demonstrated during the support phase of gait in transmitting rotational motion from the rearfoot to the forefoot (Hicks, 1953). Hicks defined the rearfoot as the tarsal bones proximal to the midtarsal joint complex and the

forefoot as the bones of the foot distal to the midtarsal articulation.

Hicks, (1953) and Elftman, (1960) observed a functional locking and unlocking of the midtarsal joint during the stance phase of gait. Hicks (1953) observed that when the calcaneus was everted, a relative rotation of the forefoot occurred. Likewise, when the calcaneus was inverted and the forefoot loaded, such as in standing tip-toed, the midfoot would convert to a rigid, "high-arched" structure.

Elftman (1960) suggested that the midtarsal joint represented "a clear division between the calcaneus and talus behind and the remainder of the foot in front". Motion of the midtarsal joint, like the subtalar joint, is also described as inversion and eversion. He also felt that motion at the midtarsal joint was a combined movement of the talo-navicular joint and the calcaneo-cuboid joint. When the foot is in a fully pronated position, the navicular and cuboid bones would lie parallel to each other, in a supinated position the two bones would be more vertically aligned. He concluded that because of the anatomical structure of the ankle bones, an interaction of the midtarsal and subtalar joint must also exist.

Manter (1941) agreed with Elftman (1960) that motion of the subtalar joint and midtarsal joint were interrelated and that these rotations occurred simultaneously. In other words, pronation at the subtalar joint would result in eversion at the midtarsal joint (Figure 5).

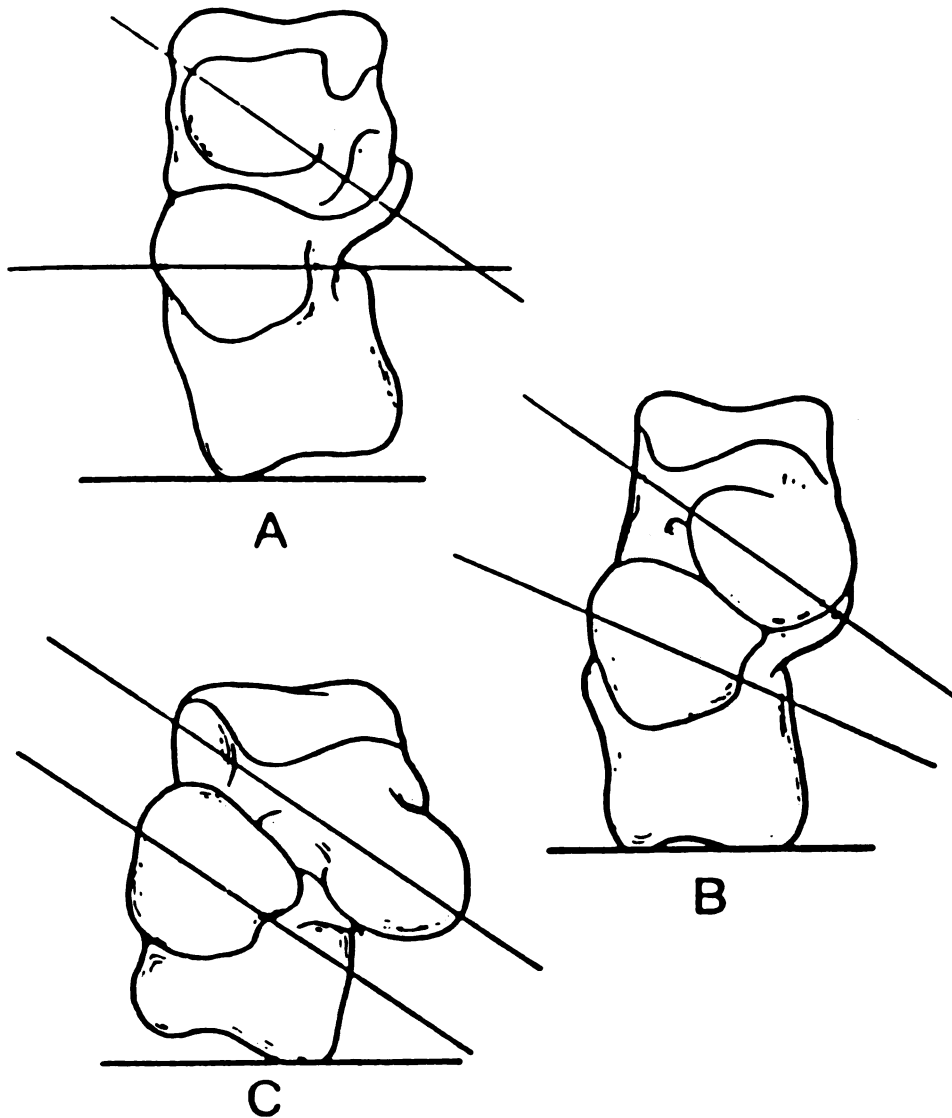


Figure 5. Alignments of Midtarsal Joint When the Rearfoot is
A. Supinated, B. Neutral, C. Pronated.

The normal range of motion at the midtarsal joint is small, although the degree of movement will increase as a result of decreased movement at the subtalar joint or ankle joint. The action of the midtarsal joint is controlled by movement at the subtalar joint. As the subtalar joint is moved through its range of motion from supination to maximum pronation, the amount of motion at the midtarsal joint increases (Mann, 1975). The functional significance of the midtarsal joint is demonstrated when the foot is required to support the body's weight during the stance phase of motion.

Hicks (1953) identified a functional relationship during the stance phase between the rearfoot and the forefoot, with motion occurring at the midtarsal joint inconjunction with the subtalar joint.

Clinical attempts to limit subtalar joint range of motion usually depend upon subsequent stabilization of the midtarsal joint (Burns, Burns, and Burns, 1979).

The midfoot region

The midfoot region of the foot is comprised of the three medial metatarsal bones which articulate relative to the three respective cunieform bones, and the fourth and fifth metatarsals which articulate with the cuboid bone.

Because these joints are anatomically interlocked and held securely in place by ligaments, little or no motion occurs at these articulations (Mann, 1975).

The metatarsal rays

The first metatarsal ray is composed of the medial cuneiform bone and the first metatarsal bone. Kelikian (1965), in a study involving over 200 foot specimens, demonstrated that the first metatarsal and the medial cuneiform bone function as one unit. Attempts to dislodge the metatarso-cuneiform articulation proved unsuccessful, with no movement occurring between the bones. It was also felt that little or no movement occurred in the articulations between adjacent metatarsals and cuneiform bones.

Root, et al. (1977) identified the first metatarsal ray as the principal indicator of forefoot motion. They also felt that movement of the first metatarsal and medial cuneiform bone moved together. The first metatarsal ray is capable of tri-planar motion although most of its motion occurs in the frontal and sagittal planes.

The primary motions of the first metatarsal ray are described as dorsiflexion and plantarflexion with concurrent inversion and eversion. The amount of dorsi-plantarflexion of the first metatarsal ray is about equal to the amount of inversion-eversion motion. Dorsiflexion of the first metatarsal ray as described by Hicks (1953) and later by Schuster (1979) is discussed in relationship to the rearfoot rather than the second metatarsal. Likewise, eversion of the first metatarsal is described relative to vertical, not to the second metatarsal.

D'Amico and Schuster (1979) refuted the idea of a functional twist of the first metatarsal ray relative to subtalar joint eversion, as described by Hicks (1953) and Root, et al. (1977). Rather, D'Amico and Schuster proposed that in the subtalar joint, eversion was synonymous with dorsiflexion and eversion of the first metatarsal ray.

The minimum range of first metatarsal ray dorsiplantarflexion movement necessary for normal locomotion is not known. Root, et al. (1977) felt that dorsiflexion of the first ray was probably not necessary during normal gait as long as adequate range of motion was obtained at the midtarsal joint to allow for sufficient forefoot inversion. Forefoot inversion occurs to compensate for the amount of rearfoot eversion that occurs with subtalar joint pronation. When the midtarsal joint cannot compensate for rearfoot eversion, first metatarsal ray dorsiflexion is essential.

Hicks (1953), demonstrated that the shape of the arch was affected by movement of the metatarsal rays. Moving the first ray up or down resulted in a successive decrease in mobility of the lesser rays.

Most authors, Root, et al. (1977); Sarrafian, (1983); and Hicks, (1953), agreed that motion of the second, third, and fourth metatarsal rays is confined primarily to dorsiflexion and plantarflexion, in the sagittal plane. Movement of the central rays is limited due to their "locked" configuration at the tarsal joints. During stance

phase the entire tarsometatarsal complex moves in response to movement at the subtalar and midtarsal joints.

The fifth metatarsal ray consists of the fifth metatarsal bone only. The fifth ray is capable of triplane movement, but does not have the range of motion as does the first metatarsal ray (Root, et al., 1977; Hicks, 1953). The primary motions of the fifth ray are inversion-eversion, and dorsi-plantarflexion. The amount of adduction and abduction, (medial-lateral rotation), is small. The minimum range of fifth metatarsal ray motion necessary for normal human locomotion is not known, nor is its function well understood (Root, et al., 1977; Hicks, 1953).

The metatarsophalangeal joints

The metatarsophalangeal joints are comprised of articulations between each of the five metatarsal bones and the proximal phalangeal bone of each digit. The primary motions of the metatarsophalangeal joints are dorsi-plantarflexion and medial-lateral rotation. During normal locomotion there is no inversion-eversion in the frontal plane. Since the hallux is stabilized against the ground, inversion-eversion would tend to sublux the joint (Root, et al., 1977).

Hicks (1953) identified the importance of sagittal plane motion of the first metatarsophalangeal joint for normal locomotion. During stance phase, as weight is transferred to the ball of the foot, there occurs

simultaneous plantarflexion of the first metatarsal ray with extension of the hallux, which results in inversion at the subtalar joint. He felt that such motion would result in a functional shortening of the plantar aponeurosis, much like a "windlass", thereby raising the arch (Figure 6).

The minimum range of motion of hallux dorsiflexion at the first metatarsophalangeal joint (MPJ) necessary for normal locomotion is about 65-75 degrees. The range of adduction-abduction motion appears to have no functional significance during locomotion.

Motion at the lesser metatarsophalangeal joints is comparable to motion of the first MPJ. Dorsiflexion of the phalanges in excess of 20-30 degrees requires plantarflexion of the lesser rays. The range of motion necessary during propulsion is slightly less than 65 degrees (Root, et al., 1977; Mann, 1975).

Interaction of joint complexes

There is clearly a lack of agreement in the literature concerning the description of foot joint motion. Further complicating this problem is the fact that the motions at the joints of the ankle and foot are coupled so that several motions occur simultaneously. During human locomotion, motions at the ankle, subtalar, midtarsal, and metatarsophalangeal joints, are all interrelated.

Hicks, (1953); Root, et al., (1977); Mann, (1975); Sarrafian, (1983) and Inman, (1976) described the

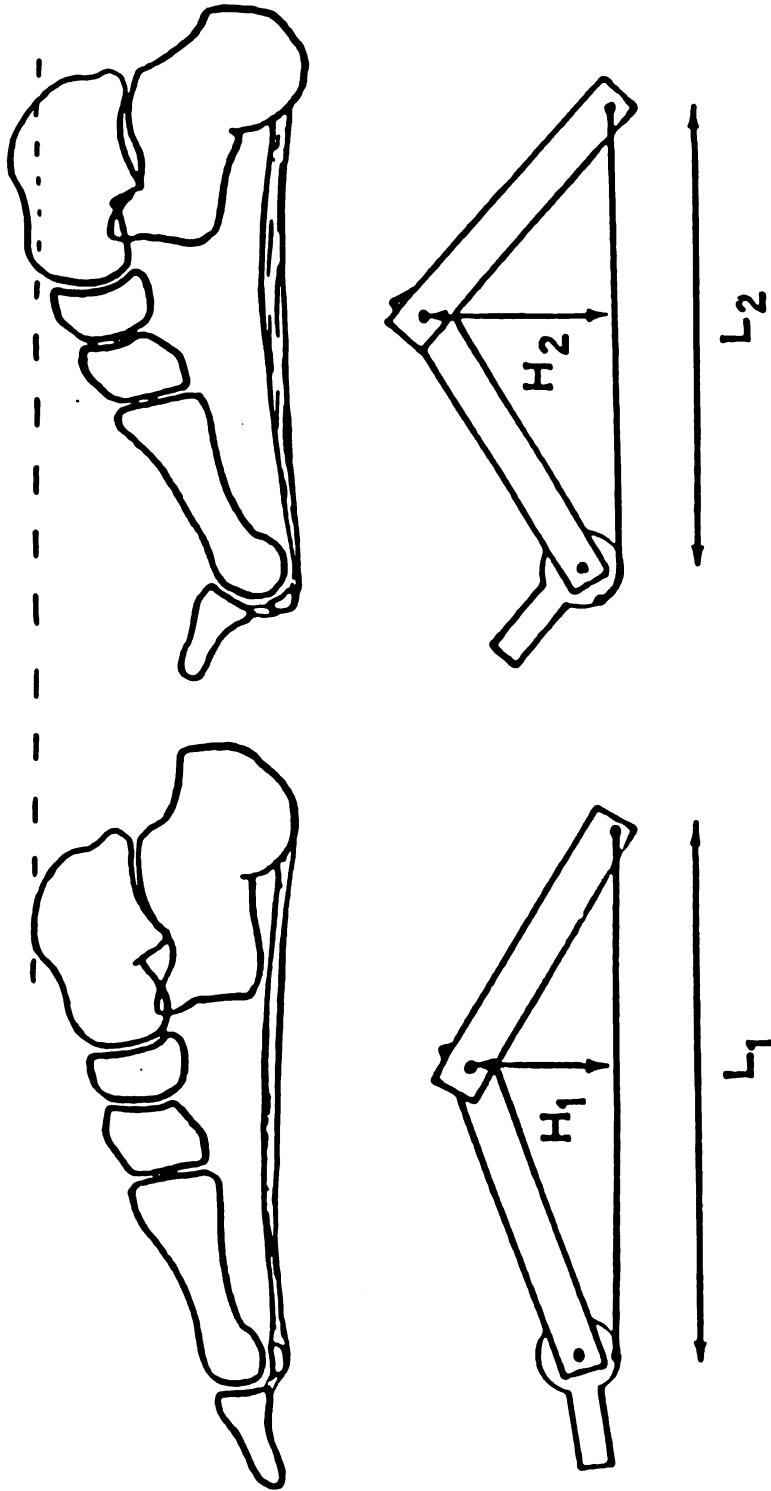


Figure 6. "Windlass", Arch Raising Mechanism of the 1st Metatarsal Ray.

combination of ankle and foot joint motion as pronation or supination. Pronation and supination imply a combination of movements that involve both the rearfoot and forefoot.

Pronation is defined as a combination of dorsiflexion of the ankle, eversion of the calcaneus, and abduction or lateral rotation, of the forefoot. Supination, is defined as the reversal of these rotations, comprised of plantarflexion of the ankle joint, inversion of the calcaneus, and adduction, or medial rotation of the forefoot.

Displacements of the individual bones comprising joints of the foot and ankle have been determined. During locomotion, the individual bones move in unison as joint complexes. However, among researchers there is great variation regarding the joint ranges of motion.

Average values help develop a greater understanding of the basic relationships between the major joint complexes of the foot and ankle. Small differences in the anatomical arrangement of the bones of the foot and ankle account for some of the distinct differences in gait patterns observed between subjects.

While such descriptive studies as have been presented provide invaluable information regarding the functional anatomy of the foot, they do not describe the actual motion of the foot under dynamic circumstances.

Due to the running boom during the 1970's and into the 80's, as the preferred physical fitness activity and with it, a subsequent escalation in running related injuries, the

ability to quantify gait patterns became increasingly important to the clinician and researcher. Excessive movement of the subtalar joint during foot contact while running has been associated with many overuse running injuries (Brody, 1980; Messier, et al., 1988; Clement, 1981; and Subotnick, 1989).

The most common method employed to evaluate dynamic foot motion during the contact phase of gait is termed rearfoot movement analysis. This method involves high speed cinematography from a rear view to measure the change in the angle between the calcaneus and the lower leg, in the frontal plane (Clarke, Frederick, and Hamill, 1984; Nigg, 1986; and Edington, 1990), (Figure 7). These researchers believed that since eversion of the foot is a component of the motion of pronation, the angle of eversion measured during gait would be a reliable indicator of the pronation occurring during the stance phase of the run.

This rearfoot movement analysis has been the predominate technique employed to measure foot motion during the contact phase of gait for the past ten years. These measurements have led to significant development and innovations of orthotic devices and footwear design (Edington, 1990). However, two-dimensional analysis does not provide a complete or accurate description of the motion during the contact phase of gait. Soutas-Little, Beavis, Verstraete, and Markus, (1987) contended that film images in

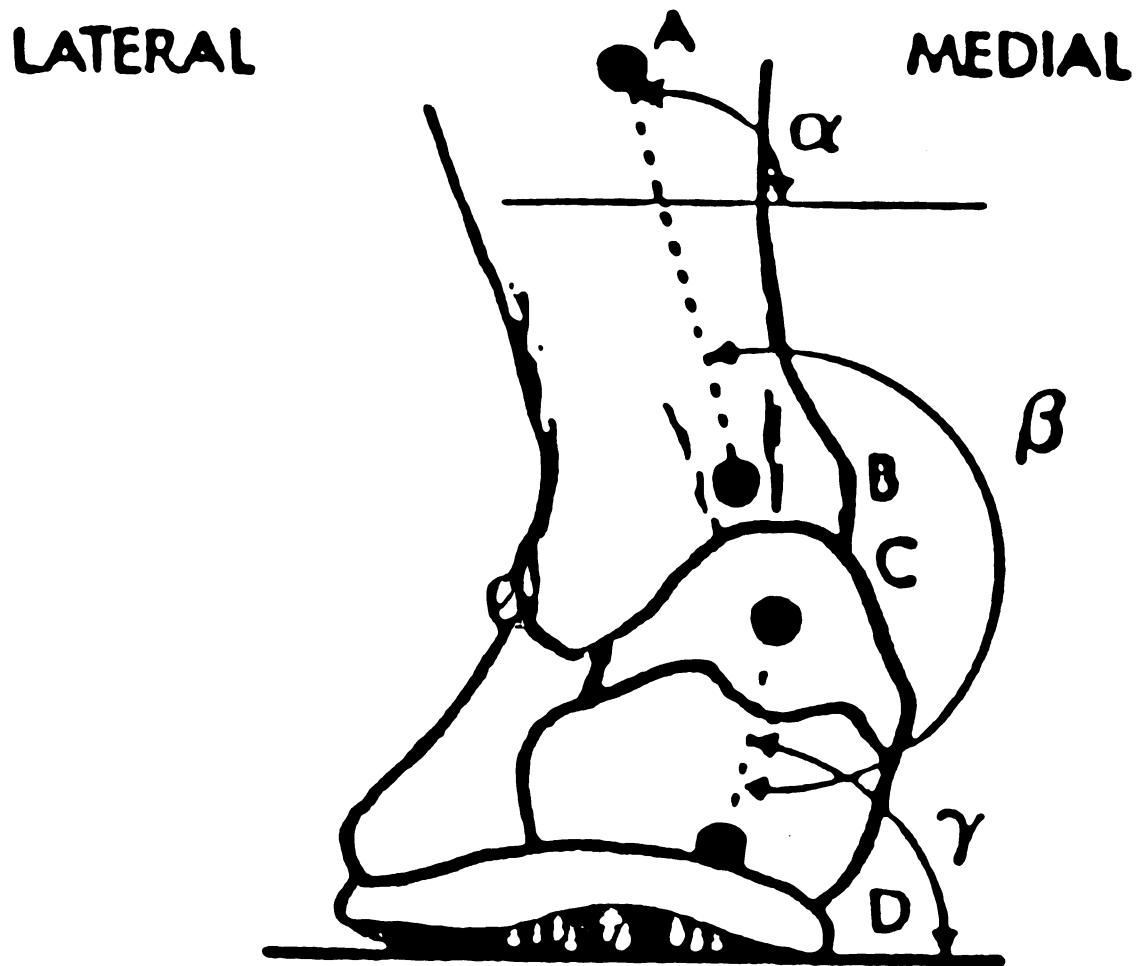


Figure 7. Illustration of the markers at the rear part of a left leg and foot.

a vertical plane are distorted except when the subject's foot, is parallel to the vertical plane of the camera.

More recently, such techniques involving three dimensional cinematography have been employed which provide a complete description of the motion of the foot during the contact phase, without reference to a laboratory coordinate system. A study, conducted by Engsberg and Andrews, (1987), indicated that the measurement of inversion-eversion does not provide an accurate description of ankle joint motion.

These kinematic techniques allow for a three dimensional description of the motion of joints proximal to the midtarsal joint. Employing a "joint coordinate analysis technique" (Soutas-Little, et al., 1987) to the forefoot, interactions of the forefoot and rearfoot can be described.

III. Experimental Methods

An experimental protocol was established to obtain motion data of the foot and ankle for a normal contact while running. This protocol and the analytical methods will be presented in this section. Positional data of the targets, affixed to the lower leg and foot, were obtained utilizing two LOCAM motor driven 16mm cine-cameras, with a filming speed of 100 fps. The cameras were positioned anteriorly and medially to the right leg to obtain an unobstructed view of the right foot during the contact phase of running gait. The included angle between the focal axes of the two cameras was approximately 60 degrees. The motion system was calibrated using a twelve control point calibration structure enclosing a volume one-half meter square and one meter high. This provided an overdetermined system for determining the coefficients for the direct linear transformation matrices (Walton, 1981).

The subject for this study was a 27 year old male runner with a training background of over ten years. Qualitative analysis of the lateral view film record identified the subject as a heel striker at foot contact.

A running shoe with a modified upper construction was worn by the subject. This allowed for the adherence of 1/4" felt, sphere-shaped targets, directly to the skin surface at

palpatable boney landmarks on the lower shank and foot. The subject was targeted on the anterior-medial surface of the lower shank, calcaneus, and the forefoot; to establish local body coordinates.

Triad one was attached to the lower aspect of the tibia, with the first target on the medial aspect, the second target positioned distally to the first in vertical alignment along the tibial shaft. The third target was placed on the anterior border of the tibia between the first two targets.

The rearfoot was represented by a triad of targets placed on the medial aspect of the calcaneus. Targets one and two were aligned vertically at a medial posterior line of the calcaneus, and target three was positioned at the sustentaculum tali of the calcaneus, between the other two targets.

The first metatarsal ray was chosen as the forefoot local body coordinate since the motion of the first ray is often used by the clinician to evaluate forefoot mobility. The third triad was positioned in a similar arrangement upon the surface of the first metatarsal ray of the forefoot. Targets one and two were placed in vertical alignment distal to the calcaneal-navicular joint. The third target was placed at the distal head of the first metatarsal bone between targets one and two (Figure 8).

Prior to filming the subject, a calibration structure was placed in the field of view of the two cameras and

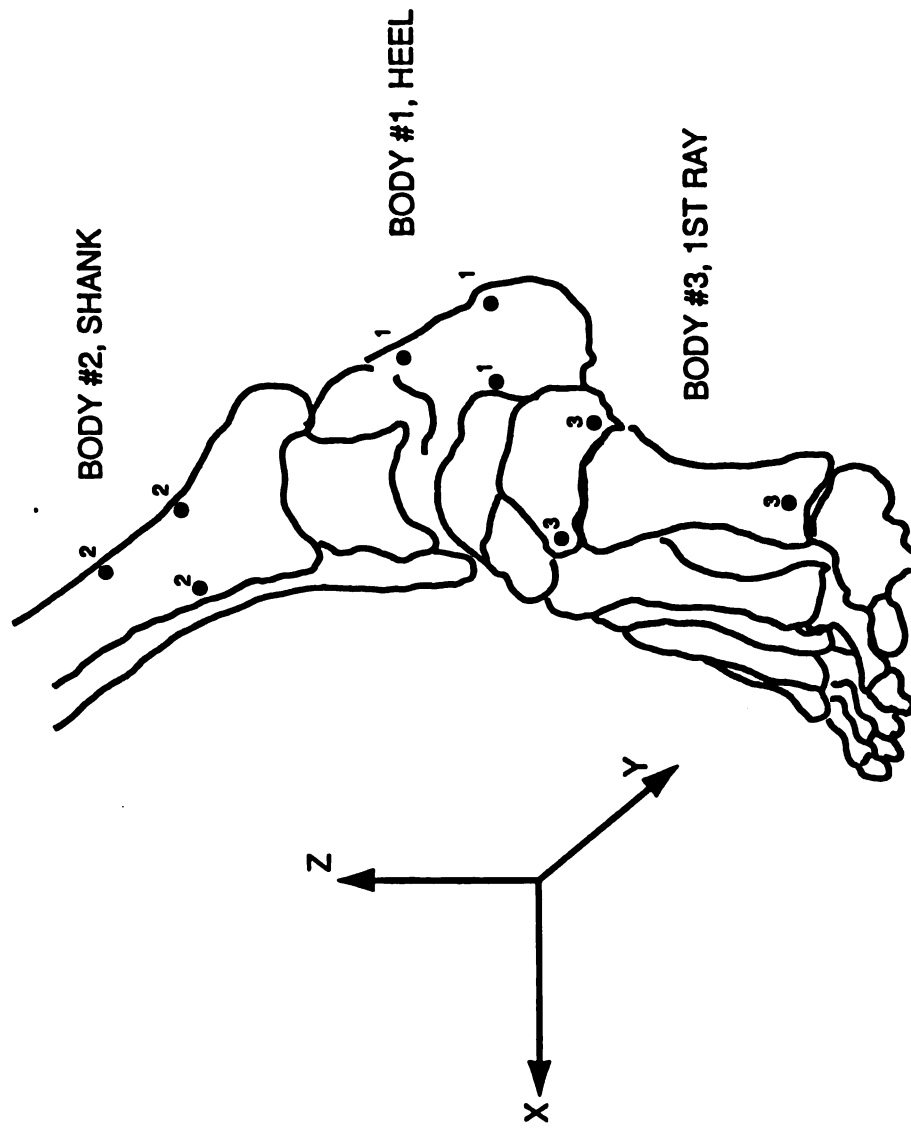


Figure 8.

ANATOMICAL TARGETS FOR FOOT AND SHANK (RIGHT FOOT)

filmed. The calibration structure contained twelve spherical targets, whose three-dimensional coordinates were known. The calibration structure provided the necessary transformation constants to determine the three-dimensional coordinates of the local body targets attached to the subject. The subject was first filmed while standing in an upright and erect position upon the forceplate in the target view of both cameras. The standing position data served as the "zero reference" for all dynamic data collected for the subject.

After a brief warmup and practice period, the subject was instructed to run as "naturally" as possible through a target area within the field of view of both cameras. A forceplate served to identify the target area. Although full foot contact upon the forceplate was not necessary for this kinematic study, three corners of the forceplate were targeted and served to define laboratory space. Placement of the calibration structure upon the forceplate was slightly rotated and these forceplate targets provided the necessary information for the transformation matrix to reorient it with lab space.

The film was then processed and spliced in preparation for the digitization procedure. Two-dimensional positional coordinates were obtained from each camera view film record, utilizing an ALTEK Datatab rear projection system for film digitization in conjunction with an IBM-PC computer.

The twelve targets of the calibration structure and the targets placed at the three corners of the forceplate were digitized to define the global and laboratory coordinate systems. The nine targets comprising the triads on the calcaneus, lower tibia, and the first metatarsal ray of the subject, were also digitized to obtain the two dimensional position data for each target.

The same digitizing sequence was used for the subject while standing and while running. The entire foot contact phase of gait for the subject running, was digitized frame by frame, as well as ten frames prior to and after foot contact.

After use of a direct linear transformation technique, the three-dimensional local body coordinate positions for the targets comprising the triads attached to the subject's lower leg, ankle, and foot were determined using vector cross products (Figure 9). The local body coordinate positions of each of the triads were then used to determine ankle and foot rotations employing a joint coordinate method of analysis as described by Grood and Suntay, (1982) and later applied to the ankle joint by Soutas-Little, et al., (1987). This method employs a set of non-orthogonal body segment reference axes, from which angular displacements about these axes can be determined. These rotations of one targeted rigid body relative to another describe the motion of the joint complex in between.

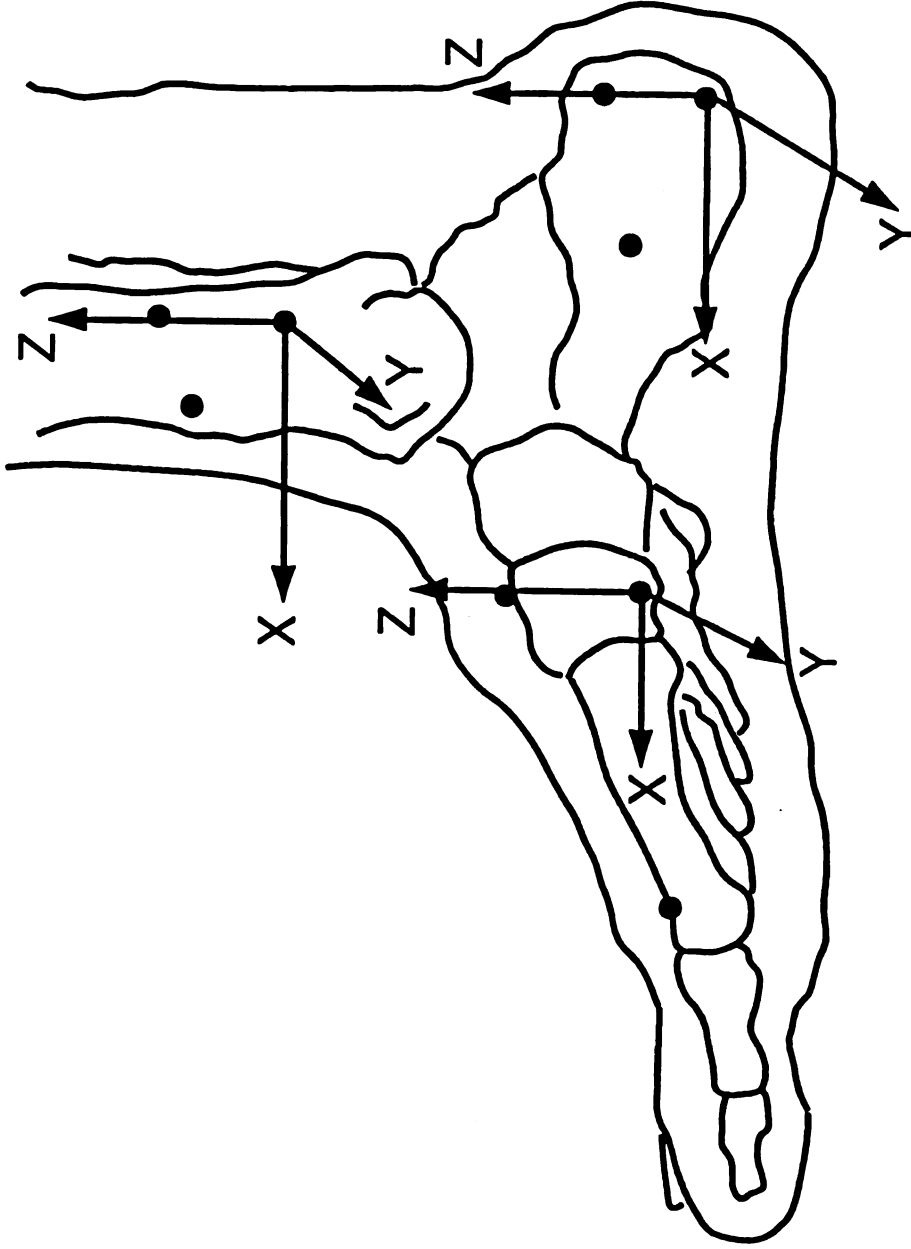


Figure 9.

LOCAL BODY COORDINATES

Following data collection the data were encoded and transferred to a Prime mainframe computer located in the Case Center for CAD/CAM in the College of Engineering on the Michigan State University campus for analysis. The two-dimensional data obtained from each camera view were then synchronized and combined, utilizing a computer program designed to locate the three-dimensional location of each target.

The local body coordinate positions of each of the triads were then processed using a computer program to determine ankle and foot rotations based on a joint coordinate method of analysis as described by Grood and Suntay, (1982) and later applied to the ankle joint by Soutas-Little, et al., (1987). This program computes a set of non-orthogonal body segment reference axes, from which angular displacements about these axes can be determined. These rotations of one targeted rigid body relative to another describe the motion of the joint complex in between.

Angular rotations obtained from the tibial-calcaneal joint coordinate system described the motion of the upper ankle joint and subtalar joint complexes. Rotations obtained from the calcaneal-first metatarsal ray, joint coordinate system were descriptive of the midtarsal joint and subtalar joint complexes. The laboratory coordinate system was assumed to coincide with the hallux when it was in contact with the ground. This was a measure of first metatarsophalangeal joint motion when the hallux

was in contact with the ground. Prior to foot contact, and after toe off when the hallux was not in contact with the ground, this system tracked the spacial orientation of the first ray. Utilizing this model, motions at the functional joint complexes of the foot and ankle, and their interactions were analyzed.

A joint coordinate system could be constructed from any two local body coordinate systems attached to corresponding rigid bodies in the model. A straight line segment was drawn between the two rear targets of the proximal rigid body link of each local body coordinate system in the model. A unit vector was then formed which corresponds to a vertical axis, Z (Figures 10 and 11). This unit vector was formed by,

$$\hat{iz} = AB/|AB| \quad (\text{equation 1}).$$

A perpendicular axis was then formed from the cross product of this Z unit vector with a line segment drawn from targets A to C .

$$\bar{Q} = \hat{iz} \times AC \text{ and } \bar{Q} = Q/|Q| \quad (\text{equation 2}).$$

The third orthogonal unit vector was established by the cross product of the two perpendicular unit vectors.

$$\bar{R} = \bar{Q} \times \hat{iz} \quad (\text{equation 3}).$$

Figure 10.

ANKLE JOINT COORDINATE SYSTEM

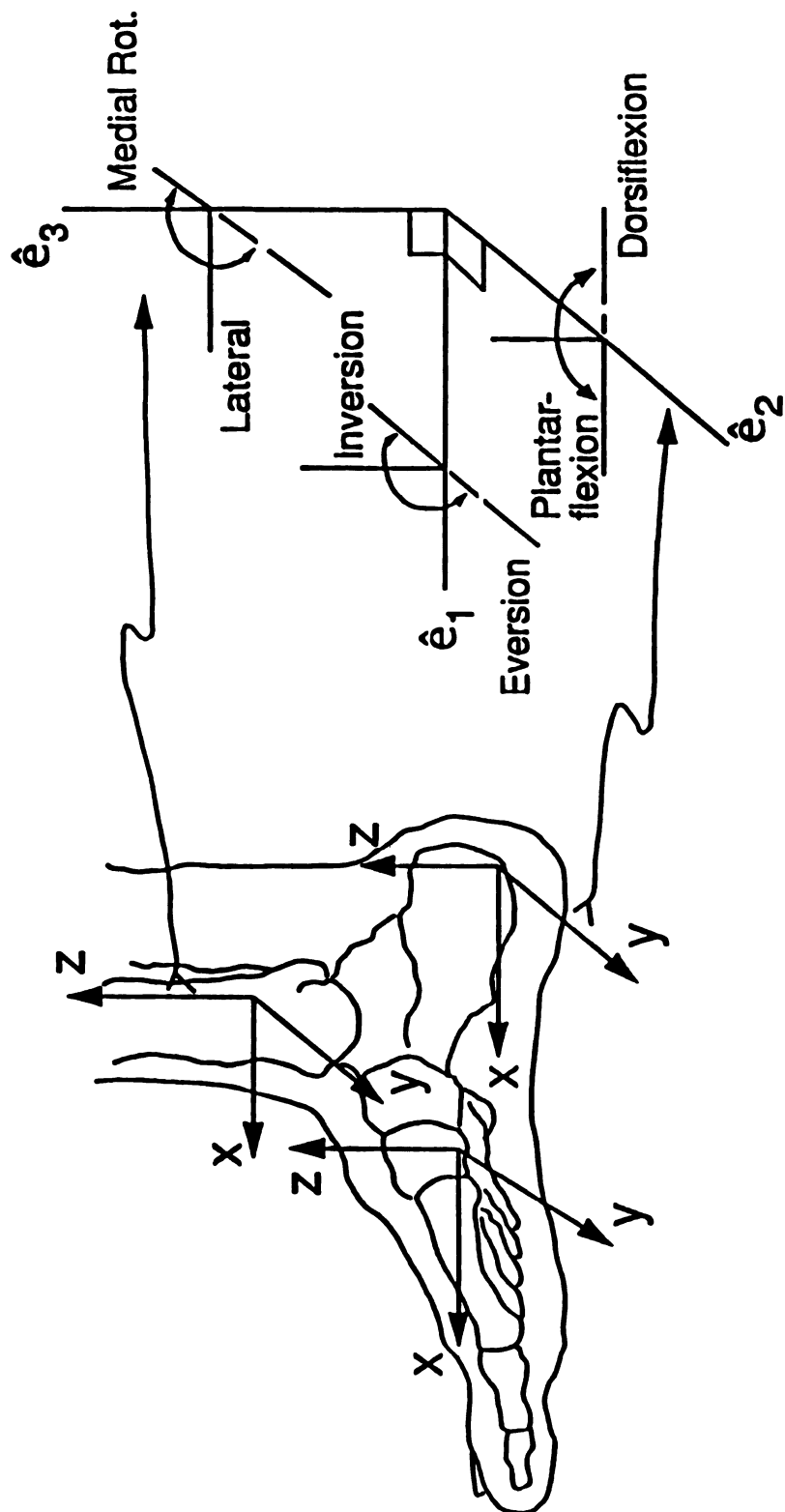
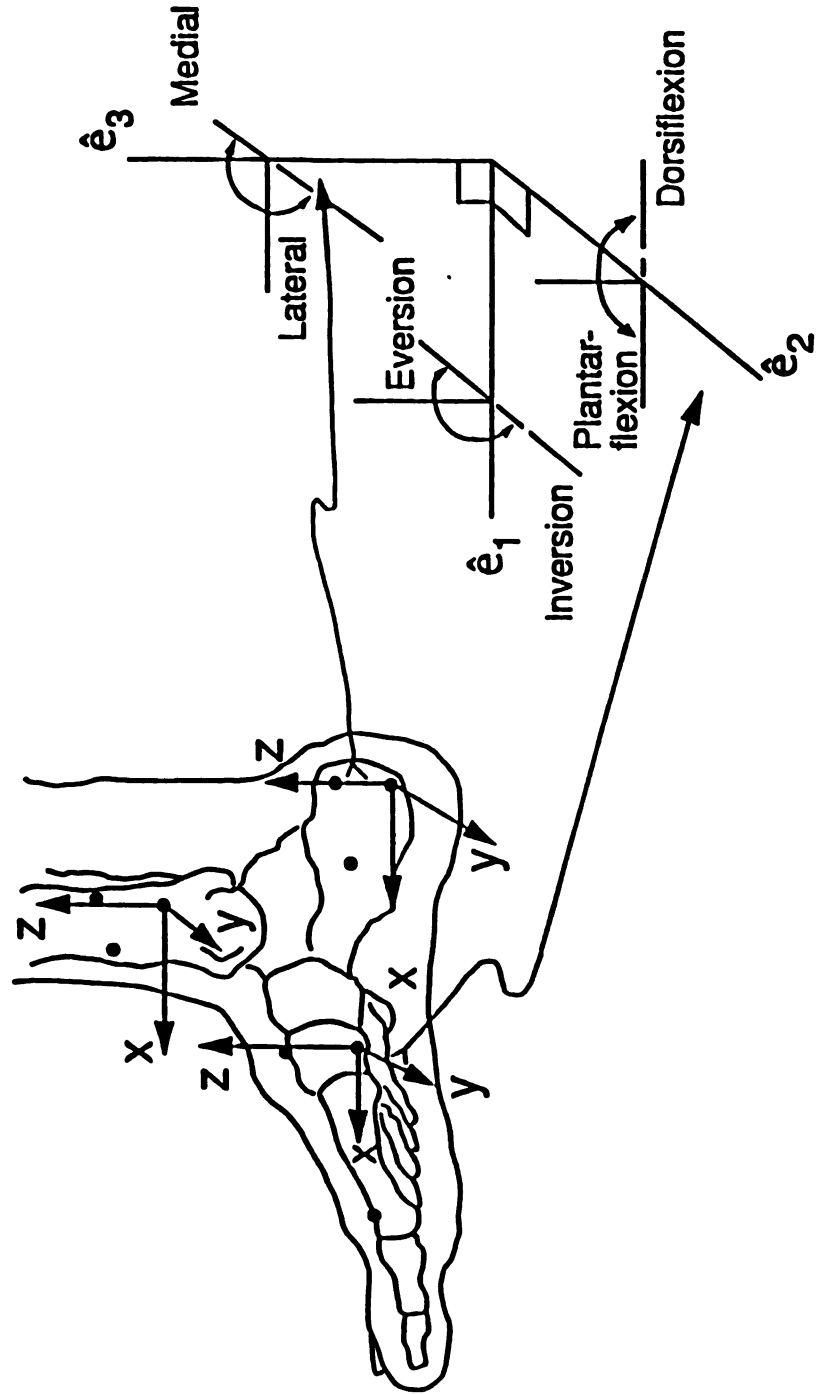


Figure 11.
MIDTARSAL JOINT COORDINATE SYSTEM



The local body coordinate systems of each rigid link were then rotated to correspond with the subject's standing data using the transpose of the standing positional matrix.

IV. Results and Discussion

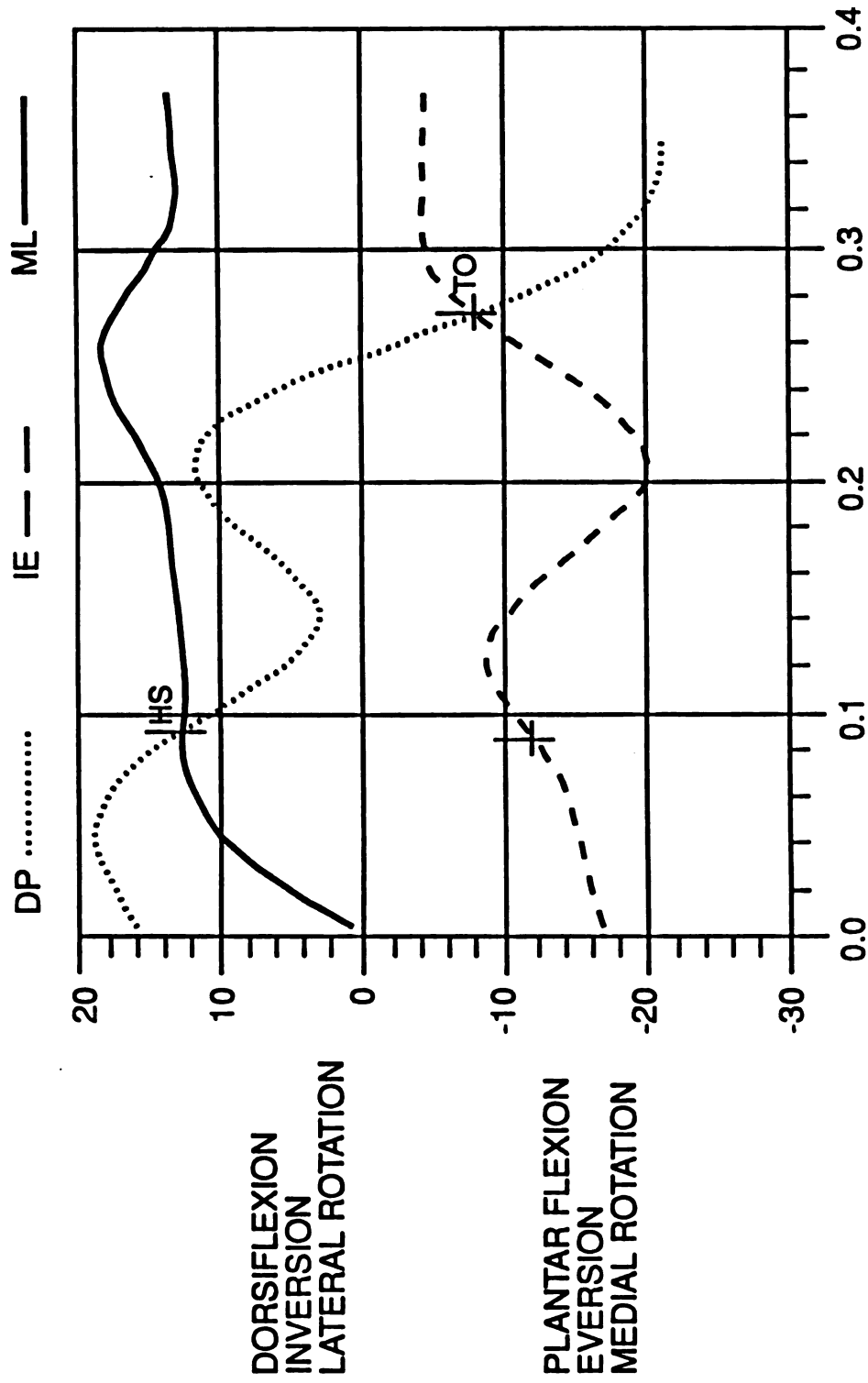
Utilizing the experimental and analytical methods just described, three-dimensional rotations between any two rigid body links in the model could be determined. These rotations described the motion occurring at the joint complex between the rigid body links. Results of the experimental data collection are presented in the following section.

Angular displacement and velocity graphs presented describe motion between the shank and the calcaneus, and between the first metatarsal ray and the calcaneus. Angular displacements between the tibia and the calcaneus describe motion occurring at the ankle-subtalar joint complex, while displacements between the first metatarsal ray and the calcaneus describe motion occurring at the midtarsal joint complex. When the head of the first metatarsal was in contact with the ground from the flat foot period of stance phase until toe off, the hallux assumed to coincide with the laboratory coordinate system. During this time from the flat foot position to toe off, angular displacements calculated between the first metatarsal ray and the laboratory coordinate system measured the motion occurring at the first metatarsophalangeal joint.

The motions of inversion and eversion occurred at the subtalar joint. These motions occurred in the frontal plane and involved a rotation about the $\hat{e}_1$ axis of the joint coordinate system. The primary motions which occurred at the ankle joint were dorsiflexion and plantarflexion. These displacements occurred in the sagittal plane and involved a rotation about the $\hat{e}_2$ axis of the joint coordinate system. The motions of medial and lateral rotation occur in the transverse plane and involve rotation about the $\hat{e}_3$ axis of the joint coordinate system.

The combination of these rotations about the $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$ axes described the motions of pronation and supination. Motion occurring at the ankle-subtalar joint complex often is referred to as rearfoot movement. Motion occurring at the midtarsal joint complex often is described as forefoot motion since it involves movement of the metatarsal rays (Hicks, 1953; Elftman, 1960). An illustration of rearfoot motion occurring at the ankle-subtalar joint complex is presented by the angular displacement graphs in Figure 12.

The total foot contact time occurred over a period of 180ms. Immediately following foot contact the rearfoot joint complex inverted and plantarflexed slightly as the foot stabilized against the ground. The rearfoot then rapidly pronated in order to attenuate the impact associated with footstrike. The rearfoot complex everted through an angle of 10 degrees and dorsiflexed 9 degrees during the



Rearfoot Angular Displacements

Figure 12.

first 110ms of the contact phase. The rearfoot complex was also laterally rotated during this same time period.

From this point in the contact phase until toe off the rearfoot joint complex supinated. The rearfoot inverted 12 degrees, and plantarflexed 23 degrees until toecoff. During this period the rearfoot continued to laterally rotate, reaching a maximum angle of 6 degrees after 160ms of foot stance. During the last 20ms of contact the rearfoot medially rotated through an angle of 3 degrees. The general trends and magnitudes of these displacement angles compared favorably to results reported in the literature by Engsberg, et al., (1987) and Soutas-Little, et al., (1987).

Contact with the ground progressed from the lateral to medial side of the foot. The foot flat position occurred as all five metatarsals heads contacted the ground at the same time (Sarrafian, 1983).

As the forefoot contacted the ground, the rearfoot exhibited a pronation sequence of motion as described above. Sarrafian, (1983) suggested that motion at the midtarsal joint complex during this period would compensate for rearfoot pronation by relative supination at this joint complex. From heel lift until toe off as the load is shifted to the metatarsal heads, the rearfoot joint complexes supinate. The forefoot exhibits a pronation twist relative to the rearfoot during this period.

Angular displacement of the rearfoot relative to the forefoot was analyzed by establishing a joint coordinate

system for the first metatarsal ray relative to the calcaneus. This was representative of motion occurring at the midtarsal joint complex and reflects compensatory motion occurring at the ankle-subtalar joint complexes. An example of the angular displacements between the first metatarsal ray relative to the calcaneus was presented in Figure 13.

Following the foot flat position, the first metatarsal ray everted through an angle of 8 degrees during the first 80ms of contact. Concurrently, the first metatarsal ray dorsiflexed 10 degrees and laterally rotated 11 degrees with the peak displacement angle occurring at 85ms and 90ms, respectively.

As the rearfoot again supinates, the sequence of motion of the first metatarsal ray reversed directions. The first metatarsal ray inverted 4 degrees, plantarflexed 9 degrees, and medially rotated 6 degrees relative to the calcaneus bone. This movement pattern of the first metatarsal ray compared with Sarrafian's (1983) description of the pronatory and supinatory mechanism of the foot. To this author's knowledge, no dynamic description of forefoot kinematics has been reported in the literature. An illustration of the position of the foot at midstance is presented in Figure 14.

The described joint coordinate method of analysis was also utilized to measure the amount of flexion occurring at the metatarsophalangeal joint. By constructing a joint coordinate system between the first metatarsal ray and the

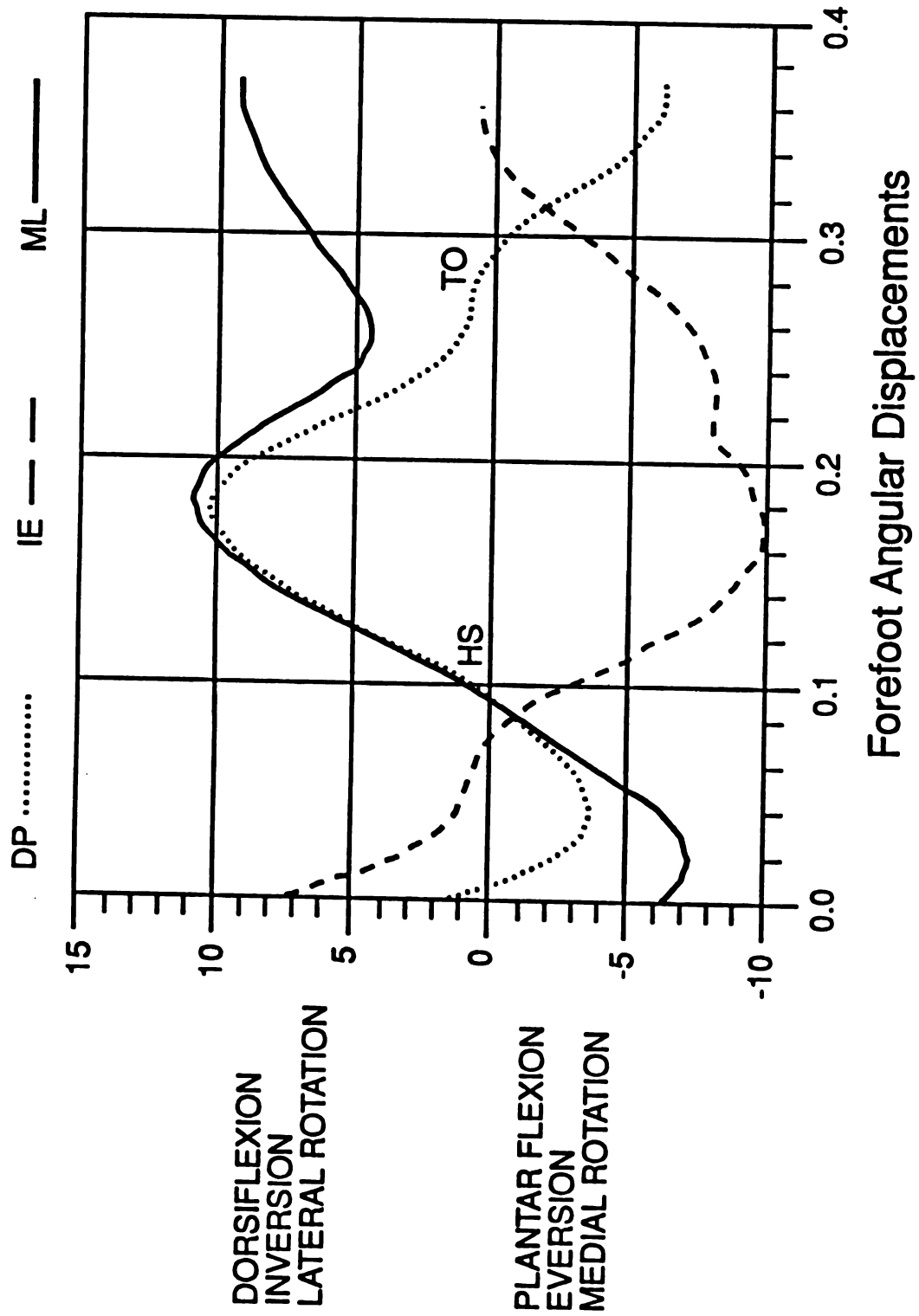


Figure 13.



Figure 14. Position of the Foot at Midstance.

laboratory coordinate system, the spacial orientation of the first ray was determined. When the hallux or great toe was in contact with the ground, it was assumed to coincide with the longitudinal axis in lab space. The displacement angle about the $\hat{e}_2$ axis of the joint coordinate system, was a measure of the amount of dorsi-plantarflexion occurring at the metatarsophalangeal joint. The primary motion at the first MPJ during stance phase was dorsi-plantarflexion. Transverse and frontal plane rotations were insignificant at the metatarsophalangeal joint.

At foot contact the first metatarsal ray was positioned 25 degrees relative to the horizontal axis of the laboratory coordinate system. At midstance the position of the first metatarsal ray was in alignment with the horizontal axis. At this point during the contact cycle, the hallux was in full contact with the ground and the first metatarsal ray was fully pronated and in zero alignment with respect to the long axis of the foot. From midstance to toe off, the first metatarsal continued to dorsiflex with respect to the horizontal axis. At toe off the first metatarsal ray was dorsiflexed 40 degrees relative to the horizontal axis of the laboratory coordinate system.

By differentiating the angular displacement data, the angular velocities were plotted to provide a description of the interactions of the forefoot and rearfoot joint complexes. Angular velocity curves for the forefoot and rearfoot joint complexes are presented in Figures 15 and 16.

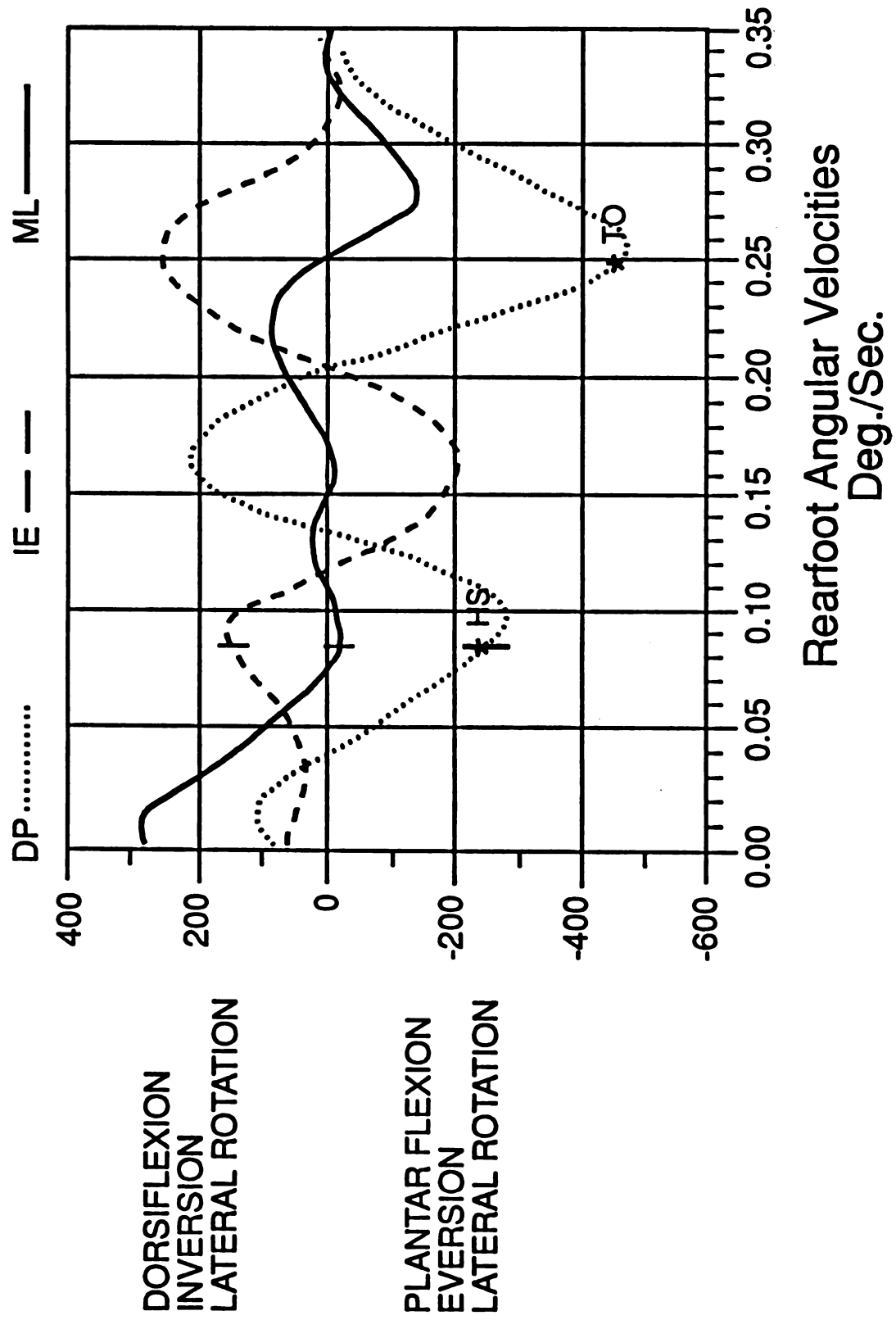


Figure 15.

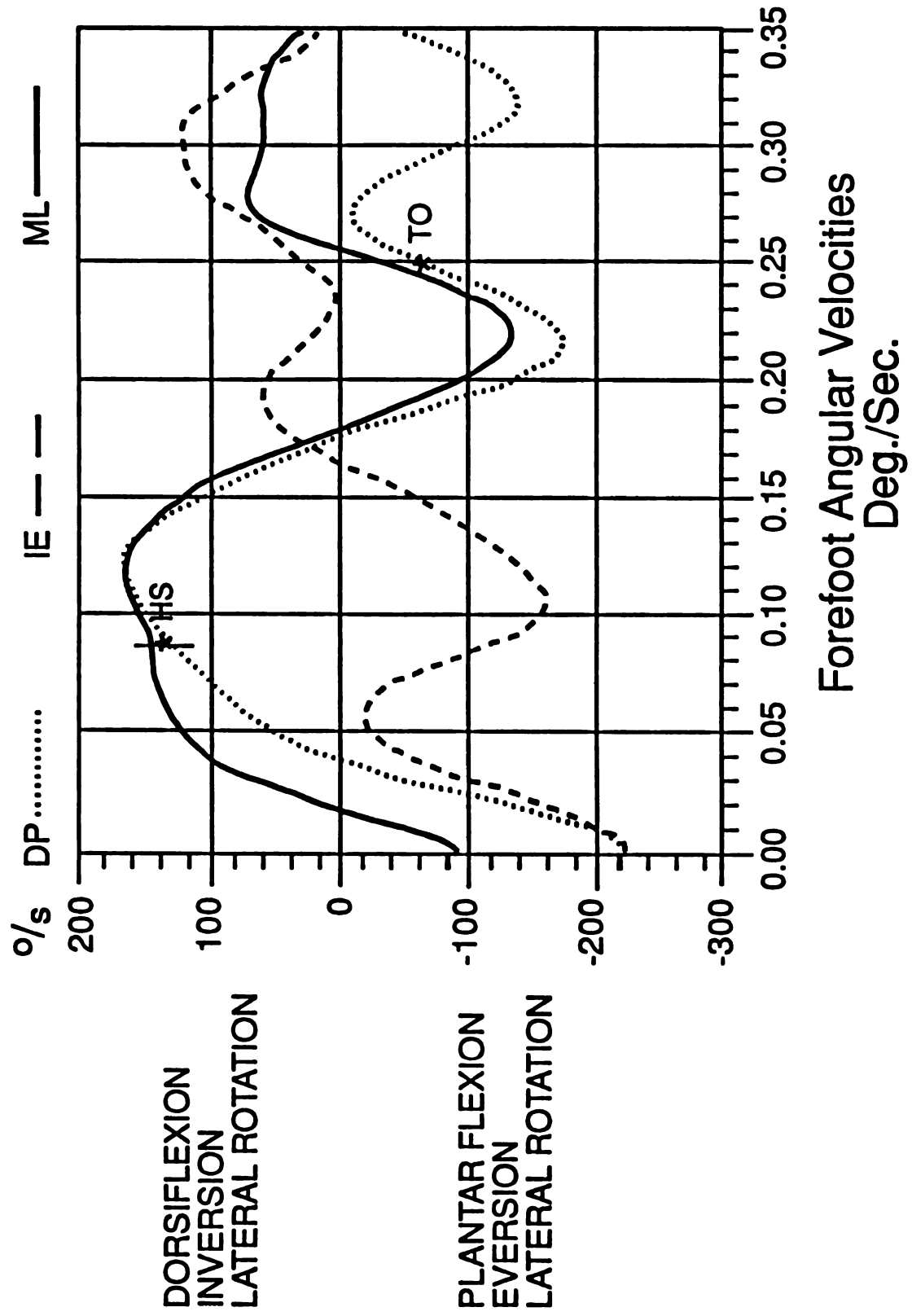


Figure 16.

After the initial contact when the foot is flat and stable against the ground, the rearfoot joint complexes pronated rapidly in order to attenuate impact shock. The maximum angular velocity for both eversion and dorsiflexion was 200 degrees per second, occurring 75 milliseconds into the contact period. The rates of these rotations then decrease until 110 milliseconds, at which time the rearfoot began to supinate. The rearfoot complex laterally rotated throughout the contact period. The maximum angular velocity of lateral rotation in this case was 100 degrees per second and occurred at 160 milliseconds of foot contact.

Following the foot flat position, the forefoot everted, dorsiflexed, and laterally rotated at the midtarsal joint in response to the pronatory motion occurring at the subtalar and ankle joint complexes. The peak angular velocity for each respective rotation was 160 degrees per second and occurred at approximately 30 milliseconds following the foot flat position. From this point until approximately 85 milliseconds, the angular velocities decreased to zero, at which point the foot began to supinate. The discrepancies between the peak angular velocities and their time of occurrence were explained by Sarrafian's (1983) theory of a supinatory twist of the forefoot relative to the rearfoot during this period of stance.

As the contralateral limb swung forward, the body's weight shifted forward onto the ball of the foot of the support limb. From 110 milliseconds until toe off the

rearfoot joint complex supinated. The peak angular velocity of inversion and plantarflexion both occurred at toe off. The high magnitudes of these angular velocities; 225 degrees per second for inversion and 460 degrees per second for plantarflexion indicates a powerful toe off during this phase of foot contact.

The forefoot also was supinating at the midtarsal joint complex during this phase from 110 ms until toe off of the contact period. The peak angular velocity of inversion during this phase was 60 degrees per second and occurred at 100 milliseconds into the contact. From this point until toe off, the angular velocity of inversion decreased to zero.

Concurrently, the forefoot plantarflexed and medially rotated during the toe off phase. The peak angular velocity of plantarflexion reached 180 degrees per second at 130 milliseconds of foot contact. The maximum velocity of medial rotation was 120 degrees per second and also occurred at 130 milliseconds. The angular velocity of plantarflexion and medial rotation both decreased to approximately 60 degrees per second at toe off.

Once again, the discrepancies in the peak angular velocities and their occurrence between the rearfoot and forefoot were attributed to the functional interaction of the joint complexes. The high arched rigid position of the foot, necessary for efficient propulsion, was obtained when the ankle and subtalar joints were supinated. The midtarsal

joint also was supinated, but in order for the foot to remain plantigrade, the forefoot must apply a pronatory twist to the ground (Sarrafian 1983).

The trends and magnitudes of the rearfoot angular velocity curves compare favorably to results reported by Soutas-Little, et al., (1987) in a study on ankle joint kinematics while running. However, to the knowledge of this author there was no reference in the literature regarding three-dimensional angular velocities of the forefoot.

V. Conclusions

The foot functions to balance, support, and propel the weight of the body forward during the contact phase of gait. This is accomplished by functional interactions of the ankle, subtalar, midtarsal, and metatarsophalangeal joints of the foot. The purpose of this study was to develop a method to analyze the kinematic interaction of the functional joint complexes of the foot during the stance phase of running gait.

At foot strike, a runner will land with a vertical ground reaction force of approximately two to three times his or her body weight. Ground reaction forces are transmitted through the talus bone of the ankle joint during foot contact and are attenuated through rotations at the functional joint complexes of the foot. The results from this study supported the theory of a functional interaction of the joint complexes. The rearfoot and forefoot joint complexes interact in a pronatory motion from foot contact until midstance. This pronation motion involves eversion, dorsiflexion, and lateral rotation at the ankle and subtalar joint complexes. The metatarsus also everts, dorsiflexes, and laterally rotates at the midtarsal joint complex as the arch flattens during pronation. However, in order for the foot to remain plantigrade, a relative supinatory twist is

applied by the forefoot. The subtalar joint is then allowed to pronate through a greater time period in order to attenuate impact shock.

During the toe off phase, as the body's weight was shifted to the metatarsals and phalanges, the rearfoot joint complexes supinated. Supination involves inversion, plantarflexion, and medial rotation. The forefoot also inverts, plantarflexes, and medially rotates. However, since the metatarsals take on increasing load during toe off a relative pronatory twist is imparted by the forefoot. This twist places the foot in a high arch rigid position which is necessary for efficient toe off.

Excessive or abnormal pronation has been attributed to many of the overuse injuries associated with running (Brody, (1980) and Messier, et al. (1988) Most of the dynamic studies in the literature have used two-dimensional cinematography techniques to track a projected angle in the frontal plane. This projected angle is formed by lines drawn on the posterior lower shank and calcaneus. This angle provides an estimate of the amount of eversion or inversion occurring in the frontal plane, but does not depict the total relative motion of the ankle joint. The few studies in the literature which have utilized three-dimensional techniques have focused on the relative motion of the ankle joint. These techniques are unable to assess relative motion of rigid bodies distal to the midtarsal joint. Variations in forefoot position such as a varus or

valgus condition, can not be evaluated to provide a complete kinematic description of the contact phase of gait.

By targeting a rigid body distal to the midtarsal joint, a description of the relative motion of the forefoot and rearfoot can be obtained. A joint coordinate analysis was constructed to measure the relative motion between the tibia and the calcaneus, and between the first metatarsal ray and the calcaneus.

This study described a method to analyze the three-dimensional kinematics of the foot during the contact phase of the run. Quantitative data were obtained to describe the functional interaction of the forefoot and rearfoot. These data have applications for diagnosis of foot pathology and for prescription of orthotic devices. This methodology also has application as an investigative tool for development and assessment of footwear designs.

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