ACCURACY OF THE PEAK™ TWO AND THREE-DIMENSIONAL VIDEOGRAPHY ANALYSIS FOR A REARFOOT MODEL.

by

Andrew M. Glaves

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Allied Health Professions, Division of Physical Therapy.

Chapel Hill

1993

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1993

3. REPORT TYPE AND DATES COVERED
THESIS/~~DISSERTATION~~

4. TITLE AND SUBTITLE
Accuracy of te Peak(TM) Two and Three-Dimensional Videography Analysis for a Rearfoot Model.

5. FUNDING NUMBERS

6. AUTHOR(S)
Andrew M. Glaves

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AFIT Student Attending: Univ of North Carolina

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/CI/CIA- 93-061

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DEPARTMENT OF THE AIR FORCE
AFIT/CI
2950 P STREET
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release IAW 190-1
Distribution Unlimited
MICHAEL M. BRICKER, SMSgt, USAF
Chief Administration

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER OF PAGES
36

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

ACCURACY OF THE PEAK™ TWO AND THREE-DIMENSIONAL VIDEOGRAPHY ANALYSIS FOR A REARFOOT MODEL

by

Andrew M. Glaves

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Allied Health Professions, Division of Physical Therapy

Chapel Hill

1993

Approved by:

Advisor

Reader

Reader

ABSTRACT

ANDREW M. GLAVES. Accuracy of the Peak™ Two and Three-Dimensional Videography Analysis for a Rearfoot Model. (Under the direction of CAROL A. GIULIANI Ph.D., P. T.)

The purpose of this study was to determine the accuracy of the Peak™ 2D and 3D video analysis systems for measuring static model angles. A model, representing the right rearfoot, was constructed from a squared and leveled piece of wood and a goniometer. The goniometer was rotated clockwise or counter-clockwise in the frontal plane to simulate eversion or inversion of the shank relative to the calcaneus. The entire model was also rotated clockwise or counter-clockwise in either the transverse or sagittal planes. Three video cameras, two for 3D analysis and one for 2D analysis, simultaneously recorded fifty-one different positions of the rearfoot model. Special attention was given to field size (0.75 meters) and distance between markers for recording the 51 conditions. A repeated measures ANOVA and Tukey's HSD detected significant difference of the inversion/eversion angle between methods: Actual angles, 2D Joint angles, and 3D Segmental angles. There was a significant difference between Actual angle and 2D Joint angle and 2D Joint and 3D Segmental angle. The greatest absolute differences for 2D Joint angles occurred when the model was rotated 30 degrees in the transverse plane. These 12 conditions of 30 degree transverse rotations were significantly different than the other 39 conditions. Separate ANOVA's were applied to each group (n = 12, n = 39). 3D was significantly better than 2D for the 12 conditions of 30 degree transverse plane rotations, however there was no difference among 2D and 3D values for all other conditions (n = 39). For the 51 conditions, the mean absolute error between Actual and 2D was 0.74 and Actual and 3D was 0.81 degrees. The mean absolute error, for the 39 conditions, between Actual and 2D was 0.52 and Actual and 3D was 0.95 degrees. For the 12 conditions, the mean absolute error between Actual and 2D was 1.41 and Actual and 3D was 0.38 degrees. These results suggest that within the limited out of plane movement tested in this study 2D video analysis was as accurate as 3D video analysis. For a rearfoot model, movement greater than 20 degrees in the transverse plane required 3D analysis to minimize error.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Carol Giuliani for her assistance and patience during this investigation and during my academic endeavors at the University of North Carolina. I also would like to express my appreciation to my other thesis committee members, Michael Gross and Dan Hooker for their contributions to this investigation.

To my wife, Jill Glaves, thank you for your support, encouragement, and love throughout the years.

Special thanks to the United States Air Force, for the opportunity to continue my education.

INTRODUCTION

Although videography is used frequently to evaluate human movement in physical therapy research, very few studies have examined the accuracy of three-dimensional (3D) and two-dimensional (2D) analysis systems. In one study Soutas-Little et al.[1] examined differences between 2D and 3D analysis of rearfoot inversion and eversion angles, concluding that 3D is more accurate. Because of this study and the inherent error in 2D analysis of movement out-of-plane, assumptions may exist that 3D is inherently better than 2D, and that 2D analysis has too much error to produce valid results for human movement. The current study will test these assumptions by comparing the accuracy of the Peak™ 2D and 3D system of motion analysis to measured angles of a rearfoot model.

This is an important issue for investigators studying movement because if 3D analysis is significantly better than 2D analysis at calculating rearfoot angles, then past studies of the rearfoot, using 2D video analysis, may not be valid. On the other hand, if 2D video analysis is as accurate as 3D analysis then researchers may need to question whether the extra expense and system setup time for 3D analysis are necessary. Two-dimensional analysis within some limitations of out-of-plane human movement may be valid. These limitations will be explored in this study.

Another area affecting the accuracy of kinematic measurement that was not addressed in the literature reviewed by this researcher is the effect of field size and the distance between markers. The importance of calculating field size and distance between markers is that angular measurement error can be reduced by minimizing field size and maximizing distance between markers. Considering the limitation of marker placement on the calcaneal segment, the error introduced by field size and marker distance may significantly affect measurement accuracy.

REVIEW OF LITERATURE

Because the emphasis of this study is on measurement of rearfoot movement, in this literature review I will discuss the biomechanics and anatomy of the subtalar joint. I will also review the research studies on three-dimensional videographic analysis, including my own pilot work in this area, and the effect of field size on the accuracy of angular measurement.

Anatomy of the Subtalar Joint

The subtalar joint is a composite joint formed by two to three separate plane articulations between the talus superiorly and the calcaneus inferiorly. The posterior subtalar joint articulation is the largest and is formed by a concave facet on the talus and a convex facet on the calcaneus.[2] The smaller anterior articulation (some individuals have a middle articulation) is formed by a convex facet(s) on the neck of the talus and concave facet(s) on the calcaneus.[3] Bruckner[4], states that the subtalar joint with two articular facets demonstrates subtalar axis angles less than forty-two degrees to the horizontal in the sagittal plane and may have greater mobility. She reported that subtalar joints with three articular facets had subtalar joint axis angles greater than forty-two degrees to the horizontal in the sagittal plane and decreased joint mobility.[4] Understanding this joint arrangement is important when assessing the arthrokinematics of the subtalar joint.

A tarsal canal is formed by the concave grooves on the inferior surface of the talus and superior surface of the calcaneus. This tarsal canal divides the subtalar joint into two separate joint cavities. While the posterior articulation has its own joint capsule, the anterior and middle articulations share a joint capsule with the talonavicular joint.[2]

There are seven major ligaments that help support the subtalar joint. Four of these attach directly to the talus and the calcaneus. They are the medial, lateral, posterior, and interosseous talocalcaneal ligaments. The deltoid and the calcaneofibular ligaments also help support the subtalar joint.[3, 5, 6, 7]

The prime movers that produce movement at the subtalar joint are the tibialis posterior for inversion and the peroneus longus and the peroneus brevis for eversion.[3, 5] The tibialis anterior is listed as an invertor at the subtalar joint, but EMG studies show that it is only an invertor when the subtalar joint is in complete eversion.[8] The tibialis posterior is the prime mover for subtalar inversion, and it is the only muscle of subtalar inversion/eversion that has an attachment to the joint.[5]

The subtalar joint is a diarthrodial; subtype, arthrodial synovial joint. Its structure allows gliding movement. Some investigators classify the subtalar joint as a ginglymus, or hinge joint[9], or as a uniaxial joint.

Subtalar Joint Kinematics and Kinetics

Movement at the subtalar joint is complex because of the multiple articulations and the triplaner axis. The axis of motion of the subtalar joint is oriented downward, posteriorly, and laterally. When viewed sagittally, the axis is approximately forty-five degrees from the true horizontal; and a transverse view, of a right subtalar joint, demonstrates that the axis is rotated approximately twenty degrees counter-clockwise from the long axis of the foot. [10, 11, 12, 13]

The motion at the subtalar joint is sometimes described as movement in the frontal plane. However, the true axis of the subtalar joint is not perpendicular to this cardinal plane, and motion that occurs at the subtalar joint passes through all three cardinal planes. This motion is called a triplaner motion.[13] Some authors refer to the movements at the subtalar joint as pronation and supination. The most common way to measure subtalar motion is with a goniometer placed on the posterior surface of the calcaneus, however, measuring in this manner allows only an assessment of the eversion and inversion component of pronation and supination.[13] Oatis[13] recommends that the motions of pronation and supination be descriptive of their component triplaner motions. Pronation involves dorsiflexion, adduction, and eversion of the foot and ankle. Supination involves plantarflexion, abduction, and inversion of the foot and ankie.[13, 14]

Closed Kinetic Chain Movement of the Subtalar Joint

When the foot is fixed by the ground, the superincumbent weight above it functions in a closed kinetic chain.[11, 15, 16] When this is the case, movement of the foot will cause movement of the connecting segments (e.g., tibia and fibula, femur, and ipsilateral hemipelvis). The triplaner motion that occurs at the subtalar joint is then transmitted to the shank. Pronation with the foot fixed will result in shank internal rotation, medial deviation, and forward inclination; and supination at the foot and ankle produces the opposite effect.

The combination movements described earlier, pronation and supination, are very important during the stance phase of gait. "Pronation occurs in the stance phase of gait to allow for shock absorption, ground terrain changes, and equilibrium."[11] At heel strike, 80 percent of the body weight is directly over the calcaneus.[11] The calcaneus is in slight inversion at heel strike.[16]

There are four major forces acting on the foot at heel strike or toe strike. The forces are compression, rotation, anterior shear, and medial shear.[11] Normal pronation is required to lessen these forces. Pronation is initiated at heel strike and controlled by an eccentric contraction of the supinators. Supination begins at approximately the first fifteen percent of the gait cycle allowing a rigid lever system to be set up by locking the bones of the foot and ankle. In turn, this rigid lever system allows for muscle pulley systems to function normally. Supination of the foot results from several mechanisms. From toe strike to push-off, the extrinsic muscles of the foot initiate supination. EMG studies show that the gastrocnemius, soleus, posterior tibialis, flexor digitorum longus, and the flexor hallucis longus become more active as superincumbent body weight passes over the forefoot.[11] Supination also occurs because the shank externally rotates as the contralateral limb swings through. The subtalar joint initiates supination by inversion of the calcaneus. The midtarsal joints' axes cross or become incongruent with each other with supination of the subtalar joint. The crossing of the axes of the two joints is sometimes referred to as locking of the joints. "This locking mechanism occurs when the cuboid and the navicular are perpendicular to each other."[11] Now the bones can act as rigid levers and allow a more efficient pull of the peroneus longus and the posterior tibialis. This synergistic contraction of the two muscle groups will stabilize the mid-foot and the first ray.[11]

Ground Reaction Forces During Gait

Vertical force plate data demonstrate that, during walking, initial impact is approximately 70 to 80 percent of body weight and increases to 110 to 115 percent of body weight during the first 0.2 seconds of the stance phase.[8, 16] In contrast, running and jogging demonstrate vertical forces approximately 275 percent of body weight during the first 0.2 seconds of stance.[12] Medial-lateral and fore-aft shear forces remain relatively the same from walking, to jogging, to running.[12] Mann[12] reports that some investigators estimate the force at the ankle during initial contact, during running, at approximately ten times body weight. Mann[12] describes a one hundred and fifty pound person walking with a stride length of 2.5 feet for one mile, as applying 127 tons of force to the feet. If the same person ran a mile with a stride length of 4.5 feet, the force would increase to 220 tons. Clearly if the ground reaction forces are not attenuated by the foot and ankle, then significant pathology may result in the lower quarter.

Not many subtalar joint reaction studies have been conducted because the subtalar joint does not demonstrate the osteoarthritic changes that the knee and hip joints do.[8] Seirig and Arvikar calculated subtalar joint reaction forces during walking. Peak resultant forces in the posterior articulation were 2.8 times the body weight and in the anterior facet were 2.4 times body weight. Peaks for both articulations occurred late in the stance phase of gait. Using a mathematical model, they also calculated the talocrural joint reaction forces of 5.2 times body weight. Burdett calculated that joint reaction forces during running (4.47 meters/second) were 2.5 times greater than during walking.[8]

Subtalar Joint Kinematics With Abnormal Subtalar Motion

The most common intrinsic deformity causing excess pronation is forefoot varus.[17, 18] Forefoot varus is described as inversion of the forefoot relative to the rear foot with the subtalar joint in neutral. This forefoot deformity may be compensated with increased pronation (increased eversion at the subtalar joint) to position the first ray on the ground. This compensation increases the time that the foot and ankle are in pronation during stance phase, and requires increased eccentric contraction from the posterior tibialis to control the subtalar eversion. This increases the total amount of force that must be produced by the posterior tibialis during the stance phase. Also, this repeated excess of eversion at the subtalar joint could ultimately compromise the non-contractile tissues that support the subtalar joint.

Forefoot valgus is eversion of the forefoot in relation to the rear foot with the subtalar joint in neutral.[17, 18] The kinematics of the subtalar joint with forefoot valgus is inversion of the calcaneus on the talus (foot and ankle maintains a supinated position), allowing the lateral aspect of the foot to contact the floor. This lack of pronation during the stance phase may reduce the amount of vertical force that is dissipated, and also decreases tibial internal rotation.

Pathology Related to Abnormal Subtalar Motion

Increased eversion, during initial contact or stance phase of gait, at the subtalar joint requires the posterior tibialis to produce greater or more prolonged eccentric forces. Because the posterior tibialis has a large attachment to the interosseous membrane, this greater eccentric contraction creates increased forces on the interosseous membrane and, in turn, irritates the periosteum of the tibia. This repeated force may create what is commonly called "shin splints". The repeated forces can also create overuse injuries to the distal attachment of the posterior tibialis and or its tendon sheath as it passes around the medial malleolus. The longer eccentric forces present during excess pronation during the stance phase of gait can create extreme stresses on the plantar fascia.[18]

Decreased pronation, or the calcaneus remaining neutral or slightly inverted, during stance phase of gait can create any number of pathologies. Without the shock absorbing effect of pronation, increased vertical forces (ground reaction forces) are transmitted to the knee, hip, and sacroiliac joints of the lower limb girdle.

The subtalar joint serves an extremely important function in the normal foot during gait. It allows for shock absorption, transverse rotation of the shank, adjustment to ground terrain changes, and equilibrium. The subtalar joint also serves an important function in compensating for primary structural foot deformities.[18]

Rearfoot movement

The total available range of motion of the subtalar joint is difficult to assess because of its complex triplaner motion that is compounded by the variability in the inclination of the subtalar axis. Norkin and Levangie [2] state that the available range of calcaneal eversion is 10 degrees and inversion is 20 degrees. Oatis[13] reports inversion values from 5 to 50 degrees and eversion values of 5 to 26 degrees. Such variability of values among investigators may be due to poor intertester reliability[19], significant differences between right and left feet on the same person[20], and the position in which the person was tested in (e.g., non-weight bearing versus weight bearing).[15] Root et al.[21] state that normal locomotion requires a minimum of 4 to 6 degrees functional movement of inversion and eversion, with a minimum total range of 8 to 12 degrees frontal plane motion at the subtalar joint required for locomotion. Additional movement by the shank could affect subtalar movement. Levens et at.[22] reported transverse tibial rotation that ranged from 13.4 degrees to 25.6 degrees in twenty-six normal males during self selected velocity.

Although there is some range of agreement on the available subtalar range of motion, Elveru et al.[20] demonstrated very poor reliability for intertester goniometric measurement (ICCs of .32 for inversion and .17 for eversion for intertester measurements). Intratester goniometric measurement ICCs were moderately reliable at .74 and .75 for inversion and eversion respectively. If we accept the small subtalar joint values of movement reported by Norkin and Levangie, Root et al., and Oatis then it is easy to see that there is little room for introducing error. Measurement errors of +/- 5 degrees may be larger than the movement occurring at the joint. Any study of the movement at this joint requires careful measurement to minimize error.

Considering the number of studies conducted using video analysis systems and the inferences made from the results, no systematic studies have been performed examining the factors that influence accurate and reliable measurements. Recent investigations by many researchers[23-31] have attempted to quantify rearfoot movement for one reason or another using cinematographic or videographic analysis. However, after close review of the articles I noticed that all of the investigators failed to report the distance between the markers positioned on the calcaneus or posterior aspect of the shoe and the field size in which the data was collected. According to the Peak Performance Motion Measurement Systems (Peak) manual , marker size, field size, and the distance separating markers, are factors that influence resolution, centroid calculations, and computed angular values.[32] Many studies draw conclusions on 2D and 3D measurement of human motion without establishing the accuracy of the method and equipment or system.

ACCURACY OF VIDEOGRAPHIC ANALYSIS

Recently, Vander Linden et al.[33] reported good reproducibility and accuracy for angular measurements obtained from a static model with the Motion Analysis System

(MAS). The MAS is a passive, 3D videography system that use reflective markers to track limb segments and calculate X, Y, and Z coordinates. Vander Linden et al. tested the MAS under both static and dynamic conditions. For the static evaluation they placed 2.5 cm reflective markers at the axis and both ends of the 24 cm arms of a clear plastic goniometer. Seventeen different angles were recorded in three spatial locations. They concluded that the reproducibility and accuracy for the MAS were very high (ICC [1,1] .99), and reported the greatest error at the angle of 180 degrees. Their speculation for this error was that as the angle approached 180 degrees its cosine approached one. Because small changes in the acute angles result in small changes in the cosine, the computer software was limited in its ability to resolve small differences in angles.[33] The dynamic test involved placing two 2.5 cm passive reflective markers 178.5 mm apart on a rigid wooden bar. The wooden bar was placed at several locations within the calibration frame and recorded. They also attached the same wooden bar to the lateral aspect of the lower leg of a human subject. The reflective markers were recorded by the cameras as the subject walked at a self-selected speed. Their objective was to evaluate the systems reliability for measuring the distance between the two markers. They reported a within-trial variability range from 1.39 to 3.04 mm for the wooden bar and 2.16 to 2.58 mm for the wooden bar attached to the leg.

Scholz [34] investigated the reliability and validity of the Waterloo Spatial Motion Analysis Recording Technique (WATSMART) three-dimensional system, under both static and dynamic conditions. The WATSMART calculates 3D coordinates from light emitting diodes attached to the subject. For the static experiment infrared light emitting diodes (IREDs) were placed on the axis and at the end of the movement and stationary arm of a goniometer. Sholz evaluated twelve angles in three different spatial locations. Reported ICCs for all three locations were greater than .99, however there was a systematic error that increased as the plane of the goniometer was rotated forty-five degrees from the optical axis of the cameras. For the dynamic experiment a robotic arm was fitted with IREDs and programmed to repeat a defined movement in three different spatial locations. Scholz reports that the ICCs for portions of each trajectory ranged from .20 to .99. He determined that unwanted light reflections during certain phases of movement caused the low reliability. Scholz concluded that reliable and valid results can be obtained from this motion analysis system if precautions are taken to reduce unwanted light reflections.

What was not reported by both of these researchers was the effect that field size and distance between markers have on the analysis systems ability to accurately calculate segment angles. In both studies the distance between markers was sufficiently large that any deviation in calculating the centroid of the markers would result in very small angular measurement error. Videographic analysis of the rearfoot would require much smaller distances between markers than the authors reported.

The field size was not reported in either study. There is an inverse square relationship between field size and the number of millimeters per pixel (e.g., in a two meter field each pixel equals 4 mm, one meter field each pixel equals 2 mm...). This difference in millimeters per pixel has a direct effect on the video analysis system's ability to calculate angular measurements accurately. Investigators cannot assume that they can achieve similar ICC values as the above authors reported without knowledge of the field size and marker distance.

DEFINITION OF TERMS

Calcaneus = Stationary arm of large goniometer

Eversion = Shank (mobile arm of goniometer) rotated clockwise relative to the calcaneus.

Inversion = Shank rotated counter-clockwise relative to the calcaneus.

Joint Angle Calculations = Peak system program option for 2D and 3D that calculates angles relative to the horizontal.

Peak = Peak Performance Motion Measurement Systems

Segmental Angle Calculations = Peak system program option for 3D that calculated angles between two segments (shank and calcaneus).

Shank = Mobile arm of large goniometer.

PILOT STUDIES

In a pilot study, Glaves, Moutoux, and Giuliani[35] reported on the accuracy of 2D and 3D videography analysis and the effects of field size and relative distance between markers on angular measurement. To investigate measurement of rearfoot movement the investigators constructed a model of the rearfoot. Model dimensions and marker distance represented actual measurements of the rearfoot. Their first question addressed whether the Peak™ 3D video analysis system was more accurate at calculating inversion and eversion angles rotated out of the frontal plane than the 2D system. For the first experiment, the authors videotaped the model at 14 different angles of inversion and eversion for 2D and 3D analysis. The field size for experiment one was slightly over one meter. Results of their first experiment indicated that there was more error in the calcaneus segment than the shank segment. This finding led to a second question, does the field size and distance between markers have an effect on the accuracy of angular measurement made by the Peak™ system.

An ANOVA was computed for four computations of the inversion/eversion angle: model, 2-D joint angle, 3-D joint angle, and 3-D segmental angles. There was no significant difference among computations ($F = .671$, $df = 3,39$, $p > .05$). Individual ANOVA's and ICC's (3,1) comparing the model angle to each type of angle computation were; 2D joint angle = .9121, 3D joint angle =.8413, and 3D segmental angle =.8056. The mean absolute differences from the model angle for each computation were: 2D joint = 1.72^0, 3D joint $=2.89^0$, and 3D segmental $=2.26^0$. These results suggest that there was no difference between 2D and 3D Peak™ video analysis angle computation for the conditions investigated. However, the ICC values suggest greatest validity for the 2D measurements. The authors observed that the calcaneal angle calculations in reference to vertical for 2D and 3D measurements were highly variable and that the shank angle variability was minimal.

This error and variability of the calcaneal angle calculations lead the authors to ask how field size and relative distance between markers effects accuracy of angular measurement with the Peak™ system. In a second experiment the model of the calcaneus was recorded in 2 meter, 1 meter and 0.5 meter field sizes. In a one meter field each pixel is equal to 2 mm. If the analysis system chooses a centroid one pixel right or left of true center this would introduce significant error. For example, if the calcaneal markers were 29 mm apart and the system is off one pixel or 2 mm this would equal an angular measurement error of 3.9 degrees. This error becomes quite significant if you accept that the subtalar joint only has 4 to 6 degrees of inversion or eversion during locomotion. The results (Table 1) indicate that field size has an effect on the number of millimeters per pixel resolution, mean standard deviation, and range of angles calculated. For the 2 meter field the mean standard deviation was 10.87, the range was 32 degrees, and the number of millimeters per pixel was 4 to 1. The 1 meter field had a mean standard deviation of 1.34, the range was 4.2 degrees, and the number of millimeters per pixel was 2 to 1. In the 0.5 meter field the mean standard deviation was 0.23, the range was 0.7 degrees, and the millimeter per pixel was 1 to 1.

Results of experiment one suggest that the 2D angle calculations may be as accurate as 3D angle calculations within given limits of out of plane movement. Results for experiment two suggest that the distance between reflective markers affects the accuracy of the Peak™ angle computations, the relative distance between markers is affected by the field size and therefore the accuracy of the Peak™ system. These preliminary findings suggested that investigators using video motion analysis may be able to minimize error and develop more accurate methods of measurement by attending to marker distance and field size. Control of these factors that affect relative marker distances may provide rearfoot inversion and eversion measurements as accurately with 2D as with 3D measurement. In fact, error introduced by field size and marker distance may be more in 3D than 2D because the error in each camera view will be added in the 3D calculation. Considering the time and cost of 3D analysis continued investigation on this area is warranted.

STATEMENT OF THE PROBLEM

The purpose of this study is to determine the accuracy of the Peak™ three-dimensional videography analysis and Peak two-dimensional videography analysis systems for measured angles of a static model of the rearfoot.

NULL HYPOTHESIS

The Peak™ 2D video analysis is as accurate as the 3D video analysis system for calculating segmental angles of rearfoot inversion/eversion when the model is rotated within selected ranges in the transverse and sagittal planes.

METHOD

A model, representing the right rearfoot, was constructed of a single piece of wood and two goniometers (Figure 1). The wood base piece measured 50 mm by 75 mm by 300 mm. The base piece was planed and then measured for squareness using a carpenter's square and level. The larger goniometer, which represented the shank and calcaneal segments of the rearfoot, was attached to one end of the wood base piece. The stationary arm of the goniometer represented the calcaneus segment and the mobile arm represented the shank segment. This larger gonimeter was used to simulate positions of eversion and inversion of the shank relative to the calcaneus. Care was taken that the gonimeter was attached to the exact center of the base piece end. A second smaller gonimeter was attached to the bottom of the base piece at the same end of the larger gonimeter. The smaller goniometer was used to accurately position the model in either clockwise or counter-clockwise rotations in the transverse plane (toe-in or toe-out positions). Rotations in the sagittal plane were calculated using trigonometric functions. The rotations of the model in the sagittal plane were secured using a wood wedge (Figure 2).

EQUIPMENT

A model, representing the right rearfoot, was used for this experiment. Four spheres, 14 millimeters in diameter and covered with reflective tape, were used as the passive retroreflective markers used on the model. Two Panasonic Digital 5000 videocameras with Genlock systems were used to receive the 3D images. The 3D images were recorded by a Panasonic AG 1960 and Panasonic AG 6300 video cassette recorders. The 2D images were recorded by an AG 180 camcorder. Three studio lamps were positioned to create maximum lighting on the model. The Peak Performance Technologies three-dimensional calibration frame was used to create the three-dimensional space required by the Peak™ software. A metal meter stick was used to measure the field size that was recorded. Index cards, three inches by five inches, were marked with large numbers from one to fifty-one. The numbers corresponding to the condition were recorded in the viewing field.

FIELD SET UP

The two D5000 cameras (cameras 1 and 2) and the AG 180 (camera 3) were set up as indicated in Figure 3. The studio lamps were placed as close as possible to each camera and directed toward the model. Cameras 1 and 2, the two used for 3D analysis, were genlocked so that when recording both cameras were recording on field A or field B simultaneously. Cameras 1 and 2 were properly connected to the VCRs using coaxial cable. Camera 3 recorded directly onto VHS tape and its tape was used for 2D analysis. At this time, the calibration frame, needed for 3D analysis, was placed in the field and centered and leveled so that eight markers on the calibration frame were visible in the field of view. The field of view for each camera was 0.75 meters. This field size was the smallest that could be achieved and still get the minimum number of spheres on the calibration frame in view.

To minimize perspective error for 2D the model was placed on the center of a table (height = 456.25 mm) and camera 3 (2D) was leveled on a tripod with the center 625 mm from the floor, orthogonal to the frontal plane of the model. Four plastic marker spheres (14 mm in diameter) covered with reflective tape, were placed on the vertical axis of the stationary and mobile arms of the goniometer representing the rearfoot (Figure 1). Each cameras' foci, iris, zoom, and white balance were adjusted for the best possible image.

The model was recorded for fifty-one different positions, combinations representative of inversion, eversion, clockwise and counter clockwise rotation in the transverse plane, and clockwise and counter clockwise rotation in the sagittal plane (Table 2). These positions were chosen because they represented normal values of rearfoot motion with normal transverse and sagittal plane rotations, and they represented the limits of rearfoot motion with extremes in transverse plane rotation. The model was not able to be positioned with combinations of eversion/inversion, transverse plane rotations, and sagittal plane rotations simultaneously as may occur with human movement.

DATA COLLECTION AND ANALYSIS

Using the Peak Performance Motion Measurement system (version 2.0 software), all three video tapes were analyzed. For 3D, the calibration frame was digitized in accordance with the Peak manual instructions (pg. 11-6).[32] The Peak calculated coordinates for these digitized points. The computed 3D values had standard errors that ranged from 0.00 - 0.044 mm for camera 1 and 0.00 - 0.86 mm for camera 2. Average mean square errors for position ranged from 0.41 - 1.17 mm, and, according to Peak technicians, this amount of error is well within accepted limits.[36]

The relative inversion\eversion angle between the shank and the calcaneus was calculated using the segmental angle option (3D Segmental angle). This angle is calculated using the intersecting angle of the two lines formed by the shank and calcaneus segments (Figure 4). For comparison, I also set up angle calculations for the shank and calcaneus segments relative to the horizontal (2D Joint angle). In order to obtain the relative inversion\eversion angle from the angles referenced to horizontal, the appropriate subtraction of angles was performed (Figure 4).

The same one hundred fields of each trial in both 2D and 3D were digitized using the automatic data capture module of the Peak. The initial digitized frame was indicated by a tap of the reference card in the field at the beginning of each condition. All data were processed through a Low Pass Butterworth filter at 6 Hz.

The independent variable in this investigation was the method of measurement. This variable had three methods: Actual angle, 2D Joint angle calculations, and 3D Segmental angle calculations. The dependent variable was the mean angular measurement of the 100 digitized fields. Absolute errors between Actual and 2D Joint and Actual and 3D Segmental angles were computed. Intraclass correlation coefficients were computed comparing Actual and 2D Joint and Actual and 3D Segmental angles.

RESULTS

The 2D joint angle calculations of inversion\eversion for 51 conditions demonstrated a mean absolute error of 0.74 degrees from the actual inversion\eversion angles of the model. The 3D segmental angle calculations demonstrated a mean absolute error of 0.81 degrees from the actual inversion\eversion angles. The standard deviations were 0.63 and 0.67 for 2D joint and 3D segmental angles, respectively (Table 3).

A one-way analysis of variance with repeated measures was computed amongst the three methods; Actual angle, 2D Joint angle, and 3D Segmental angle (Table 4). The ANOVA computed significant differences between conditions ($F = 6.615$; $df = 2,100$; $p < .05$). Tukey's Honestly-Significant-Difference post hoc analysis (Table 5) revealed the difference between conditions occurred between Actual angle and 2D Joint angle and between 2D Joint angle and 3D Segmental angle ($p < .05$). The mean of the 2D Joint angles demonstrated a difference of 0.43 degrees less than the Actual mean and the 3D Segmental angles demonstrated a difference of 0.11 degrees greater than the Actual mean. Individual Intraclass Correlation Coefficients (3, 1; $df = 50$) were calculated to compare Actual angles to each type of angle computation and were as follows: 2D joint angle = .99 and 3D segmental angle = .99.

The absolute greatest difference from Actual angle and 2D joint angle was 2.34 degrees (condition 43) and Actual angle and 3D segmental was 2.75 degrees (condition 17). The greatest 2D Joint angular measurement error was occurring most often when the model was rotated 30 degrees in the transverse plane. To determine f it was the 30 degree transverse plane rotations that made a significant difference the 12 conditions that represented 30 degrees of rotation in the transverse plane were deleted from the data set and an ANOVA on the remaining 39 conditions was calculated (Table 6). The ANOVA indicated that there was no significant difference among the conditions ($F = 1.287$; $df = 2, 76$; $p > .05$). The mean differences from actual angles to 2D joint angles was 0.54 degrees and 3D segmental angles 0.95 degrees. The standard deviations for the two groups were 0.42 and 0.7 respectively (Table 7). The Individual Intraclass Correlation Coefficients (3,1; $df = 38$) calculated comparing the actual angles to each type of angle computation were; 2D joint angle = .99 and 3D segmental angle = .99.

The 2D Joint angle calculations, for the 12 conditions of 30 degree rotation in the transverse plane, demonstrated a mean absolute error of 1.41 degrees and the 3D Segmental angle calculations demonstrated a mean absolute error of 0.38 degrees. The standard deviations were 0.78 for 2D Joint and 0.26 for 3D Segmental angle calculations (Table 7).

A one factor, repeated measures ANOVA was computed for the 12 conditions of 30 degrees of rotation in the transverse plane (Table 8). This was done to determine if it was the 30 degree rotations in the transverse plane that differed significantly. There was a significant difference among the three methods (F = 24.508; df = 2, 22; $p < .0001$). Tukey's Honestly-Significant-Difference post hoc analysis (Table 9) revealed the differences between conditions occurred between conditions Actual angle and 2D joint angle, 2D joint angle and 3D segmental angle ($p < .05$). The 2D Joint angle mean demonstrated a difference of 1.41 degrees less than the Actual angle mean and the 3D Segmental angle mean demonstrated a difference of 0.01 degrees less than the Actual mean. There was no significant difference between the group Actual angle and 3D segmental angle. Individual Intraclass Correlation Coefficients (3,1; df = 11) comparing the Actual angle to each type of angle computation were; 2D joint angle = .98 and 3D segmental angle = .99.

DISCUSSION

Results from the one way ANOVA and the post hoc analysis of the three angle measurements (all 51 conditions) indicates that there was a significant difference between Actual angle and 2D Joint angle and 2D Joint angle and 3D Segmental angle computations. There was no significant difference between Actual angle and 3D Segmental angle conditions. The Intraclass Correlation Coefficients showed that both angle computations were valid. What appears to be a contradiction between the ANOVA and the high Intraclass Correlation Coefficients actually demonstrates that there is a high degree of agreement but not necessarily an absence of statistically significant differences. Scanning the absolute differences between Actual angles, 2D joint and 3D segmental angles a pattern developed. The greatest differences were occurring when the model was rotated 30 degrees clockwise and counter-clockwise in the transverse plane. The range of angular error for 2D Joint was 0.0 to 2.34 degrees but 3D Segmental was only 0.04 to 0.81 degrees. There may be circumstances when 2.34 degrees of error is not acceptable in the study of rearfoot eversion and inversion. The angular measurement errors prompted a computation of a oneway ANOVA with the 30 degree transverse plane rotations deleted from the data set. This was done to see if it was the 30 degree transverse plane rotations that made a significant difference among the groups. The one way ANOVA of the 39 conditions indicated that there was no significant difference between the angular measurements.

To determine if it was the 30 degree rotations that made a significant difference an ANOVA was computed using the twelve conditions. The ANOVA and post hoc analysis demonstrated that there was a significant difference between Actual and 2D Joint and 2D Joint and 3D Segmental angle. There was no significant difference between Actual and 3D segmental angles.

The error for the 2D Joint angle computations when rotated 30 degrees in the transverse plane may be due to the projection errors that Soutas-Little et al. eluded to in their article.[1] They felt that the segments measured about a laboratory axis in 2D analysis had the potential for error secondary to projection onto a plane. They stated that this potential error would be compounded during medial and lateral foot rotations and plantar and dorsiflexion. It is important to note that the rotations in the sagittal plane, some were up to 30 degrees, did not make a significant difference among the methods in this study.

In the pilot study by Glaves et al.[35], significant error was noticed in calculating the calcaneal angles relative to vertical in a 1.25 meter field size. It was calculated that in a 1.25 meter field size each pixel equaled 2.5 mm. When the relative distance between the calcaneal markers was 29 mm this presented a potential angular measurement error of 4.9 degrees. The potential measurement error for the calcaneal segment in the 0.75 meter field size used was 2.8 degrees. The 0.75 meter field size played an important role in minimizing error. The mean angular measurement error for the 2D Joint angle calcaneus segment was 0.57 degrees and the standard deviation was 0.9. The decreased field size improved the overall accuracy of calculating the calcaneal segment.

For all the conditions up to and including 20 degrees of rotation in the transverse plane there was no significant difference between 2D and 3D videography analysis. It appears that even the rotations up to 30 degrees in the sagittal plane do not make a significant difference in measurement error. It is important to consider that the planar rotations chosen for this study are only a few possible movement permutations of rearfoot movement. This study did not evaluate the combination of all rearfoot movements that may be seen in human locomotion (e.g. plantarflexion at the talocrural joint, subtalar inversion, and toe-out).

For those persons considering using 2D videography analysis versus 3D analysis, for studying the rearfoot, they should consider what possible maximum rotations they might encounter out of the orthogonal plane. If the rotations are no greater than 20 degrees in the transverse plane and the segments remain perpendicular to each other then it would be reasonable to consider using 2D videography analysis. The relative ease of setup for 2D videography analysis versus 3D analysis would make it more desirable.

One point to consider is that spherical markers were used as opposed to flat, circular markers frequently used in 2D videography analysis. Spherical markers do not change shape when rotated out of the orthogonal plane. Flat markers may become ovoid when rotated out of plane thus affecting centroid calculating by videography analysis systems.

LIMITATIONS

One limitation to this study was that a static model was used and that motion analysis implies dynamic analysis. Further studies need to be done to assess the accuracy of the Peak™ 2D and 3D analysis system for dynamics. Also, this was a model and not a human subject knowing full well the variability of the human anatomy. Another limitation to this study was that only the component planar rotations of rearfoot movement were evaluated and not the combination of planar rotations. With human rearfoot movement analysis there is a possibility that there would be sagittal plane rotations between the calcaneal and shank segments as well as sagittal plane rotation of the entire lower leg, there may also be transverse plane rotation of one segment on the other or of the entire lower leg occurring simultaneously. A final limitation in this study was the distance between calcaneal markers. The distance chosen for marker placement was determined by measurement made on several average subjects, (176.25 cm in height), 29 mm was the distance for the tallest male. This distance may not be the standard distance used in rearfoot studies, however, from the review of literature it is not readily apparent how marker distance is determined.

CONCLUSION

The Peak™ 3D videography analysis is more accurate than the 2D analysis at calculating inversion/eversion angles on a static model rotated greater than 20 degrees in the transverse plane.

The Peak™ 2D videography analysis is as accurate as the 3D analysis in calculating inversion/eversion angles on a static model rotated no more than 20 degrees in the transverse plane when the two segments remain perpendicular to one another in the sagittal plane. The 2D analysis is also as accurate as 3D analysis in calculating inversion/eversion angles on a static model rotated up to 30 degrees in the sagittal plane.

Accuracy of both 2D and 3D Peak™ analysis needs to be studied on a dynamic model and human movement.

There is a need for estimating error based on marker size, distance between markers, and field size for each experiment. It is not sufficient to site another study and assume that your data is as accurate.

REFERENCES

1. Soutas-Little RW, Beavis GC, Verstraete MC, Markus TL: Analysis of Foot Motion During Running Using Joint Coordinate System. Med Sci Sports Exerc 19(3): 285-293, 1987

2. Norkin C, Levangie P: Joint Structure and Function: A Comprehensive Analysis. Second Edition, 342-46, 1983

3. Riegger CL: Anatomy of the Ankle and Foot. Phys Ther 68:1802-1814, 1988

4. Bruckner J: Variations in the Human Subtalar Joint. J Ortho Sports Phys Ther 8:489-494, 1987

5. Moore KL: Clinically Oriented Anatomy. Second Edition, 1985

6. Heilman AE, Braly G, Bishop JO, Noble PC, Tullos HS: An Anatomic Study of Subtalar Instability. Foot and Ankle 10:224-228, 1990

7. Stormont DM, Morrey BF, An K, Cass JR: Stability of the Loaded Ankle: Relation Between Articular Restraint and Primary and Secondary Static Restraints. Am J Sports Med 13:295-300, 1985

8. Rodgers MM: Dynamic Biomechanics of the Normal Foot and Ankle During Walking and Running. J Am Phys Ther Assoc 68:1822-1829, 1988

9. Scott SH, Winter DA: Talocrural and Talocalcaneal Joint Kinematics and Kinetics During the Stance Phase of Walking. J Biomechanics 24:743-752, 1991

10. Brown LP, Yavorsky P: Locomotor Biomechanics and Pathomechanics: A Review. J. Ortho Sports Phys Ther 9:3-10, 1987

11. Donatelli R: Normal Biomechanics of the Foot and Ankle. J Ortho Sports Phys Ther 7:91-95, 1985

12. Mann RA: Biomechanics of Running. AAOS Symposium on the Foot and Leg in Running Sports. 1-29, 1980

13. Oatis CA: Biomechanics of the Foot and Ankle Under Static Conditions. Phys Ther. 68:1815-1821, 1988

14. Lundberg A, Svenson OK, Bylund C, Goldie I, Selvik G: Kinematics of the Ankle/Foot Complex-Part 2: Pronation and Supination. Foot and Ankle 9:248-253, 1989

15. Lattanza L, Gray GW, Kantner RM: Closed Versus Open Kinematic Chain Measurements of Subtalar Joint Eversion: Implications for Clinical Practice. J Ortho Sports Phys Ther 9:310-314, 1988

16. Cavanagh PR: The Shoe-Ground Interface in Running. AAOS Symposium on the Foot and Leg in Running Sports. 30-44, 1980

17. Donatelli R: Abnormal Biomechanics of the Foot and Ankle. J Ortho Sports Phys Ther 9:11-16, 1988

18. Tiberio D: Pathomechanics of Structural Foot Deformities. Phys Ther 68:1840-1849, 1988

19. Elveru RA, Rothstein JM, Lamb RL: Goniometric Reliability in a Clinical Setting: Subtalar and Ankle Joint Measurements. Phys Ther. 68:672-677, 1988

20. Greene TA, Hillman SK: Bilateral Inversion-Eversion Range of Motion Comparisons Among College Athletes. J Ortho Sports Phys Ther 11:543-546, 1990

21. Root ML, Orien WP, Weed JH: Normal and Abnormal Function of the Foot. Clinical Biomechanics Vol. II, First Edition, 1977

22. Levens AS, Berkeley CE, Inman VT, et al: Transverse Rotation of the Segments of the Lower Extremity in Locomotion. J Bone Joint Surg 30A:859-872, 1948.

23. Kepple TM, Stanhope SJ, Lohmann KN, Roman NL: A Video-Based Technique for Measuring Ankle-Subtalar Motion During Stance. J Biomed Eng 12:273-280, 1990.

24. Reinschmidt C, Stacoff A, Stussi E: Heel Movement Within a Court Shoe. Med Sci Sports Exerc 24:1390-1395, 1992.

25. Stacoff A, Reinschmidt C, Stussi E: The Movement of the Heel Within a Running Shoe. Med Sci Sports Exerc 24:695-701, 1992.

26. Novick A, Kelley DL: Position and Movement Changes of the Foot with Orthotic Intervention during the Loading Response of Gait. J Ortho Sports Phys Ther 11:301-312, 1990.

27. Smith LS, Clarke TE, Hamill CL, Santopietro F: The Effects of Soft and Semi-rigid Orthoses upon Rearfoot Movement in Running. J Am Pod Med Assoc 76:227-233, 1986

28. Clarke TE, Frederick EC, Hamill CL: The Effects of Shoe Design Parameters on Rearfoot Control in Running. Med Sci Sports Exerc 15:376-381, 1983

29. Engsberg JR, Andrews JG: Kinematic Analysis of theTalocalcaneal/Talocrural Joint During Running Support. Med Sci Sports Exerc 19:275-284,1987

30. Stacoff A, Kalin X, Stussi E: The Effects of Shoes on the Torsion and Rearfoot Motion in Running. Med Sci Sports Exerc 23:482-490, 1991

31. Simpson KJ, Shewokis PA, Alduwaisan S, Reeves KT: Factors Influencing Rearfoot Kinematics During a Rapid Lateral braking Movement. Med Sci Sports Exerc 24:586-594, 1992

32. Peak Performance Motion Measurement Systems (version 1.7), Englewood, CO., Peak Performance Technologies Inc., 1990

33. Vander Linden DW, Carlson SJ, Hubbard RL: Reproducibility and Accuracy of Angle Measurements Obtained Under Static Conditions with the Motion Analysis Video System. Phys Ther. 72: 300-5, 1992

34. Scholz JP: Reliability and Validity of the WATSMART Three-dimensional Optoelectric Motion Analysis System. Phys Ther. 69: 679-89, 1989

35. Glaves AM, Moutoux M, Giuliani CA: Accuracy of the Peak™ Two and Three-Dimensional Videography Analysis for an Ankle Model. Unpublished pilot study. Poster presentation at Combined Sections Meeting 6 February 1993

36. Personal correspondence with Peak™ service technician John Porter.

TABLE 1. Variability of Calcaneal Angles in Reference to Vertical (different fields of view).

Field Size	Mean SD	Range	Pixel:Distance
2 meter	10.8753	32 degrees	1:4mm
1 meter	1.3435	4.2 degrees	1:2mm
0.5 meter	0.2273	.7 degrees	1:1mm

TABLE 2. Position of right rearfoot model for each condition.

CONDITIONS	INVERSION (degrees)	EVERSION (degrees)	TRANSVERSE PLANE ROTATIONS (degrees)	SAGITTAL PLANE ROTATIONS (degrees)
1	0	0	0	0
2		5	0	0
3		5	10 CW	0
4		5	10 CCW	0
5		5	20 CW	0
6		5	20 CCW	0
7		5	30 CW	0
8		5	30 CCW	0
9	5		0	0
10	5		10 CW	0
11	5		10 CCW	0
12	5		20 CW	0
13	5		20 CCW	0
14	5		30 CW	0
15	5		30 CCW	0
16		10	0	0
17		10	10 CW	0
18		10	10 CCW	0
19		10	20 CW	0
20		10	20 CCW	0
21		10	30 CW	0
22		10	30 CCW	0
23	10		0	0
24	10		10 CW	0
25	10		10 CCW	0
26	10		20 CW	0
27	10		20 CCW	0
28	10		30 CW	0
29	10		30 CCW	0
30		15	0	0
31		15	10 CW	0
32		15	10 CCW	0
33		15	20 CW	0
34		15	20 CCW	0
35		15	30 CW	0
36		15	30 CCW	0
37	15		0	0
38	15		10 CW	0
39	15		10 CCW	0
40	15		20 CW	0
41	15		20 CCW	0
42	15		30 CW	0
43	15		30 CCW	0
44		5	0	10 CCW
45	5		0	10 CCW
46		5	0	15 CCW
47	5		0	15 CCW
48		5	0	20 CW
49	5		0	20 CW
50		5	0	30 CW
51	5		0	30 CW

CW = Clockwise, CCW = Counter Clockwise

TABLE 3. Computed angular measurements, mean absolute error, and standard deviations for 2D Joint and 3D Segmental angle calculations.

CONDITION	ACTUAL ANGLE inversion/eversion	2D JOINT ANGLE	*	3D SEGMENTAL ANGLE	**
1	180	179.98	.02	178.22	1.23
2	5	5.17	.17	5.22	.22
3	5	4.03	.97	7.49	2.49
4	5	4.9	.1	3.91	1.09
5	5	4.32	.68	7.28	2.28
6	5	4.78	.22	4.28	.72
7	5	5	0	5.04	.04
8	5	4.54	.46	5.16	.16
9	5	5.36	.36	6.05	1.05
10	5	5.43	.43	4.17	.83
11	5	4.44	.56	5.36	.36
12	5	5.05	.05	6.69	1.69
13	5	4.52	.48	5.12	.12
14	5	3.8	1.2	5.34	.34
15	5	3.79	1.21	4.68	.32
16	10	10.1	.1	9.06	.94
17	10	9.64	.36	12.75	2.75
18	10	9.49	.51	8.54	1.46
19	10	9.21	.79	10.48	.48
20	10	9.99	.01	10.29	.29
21	10	9.14	.86	10.28	.28
22	10	9.69	.31	9.75	.25
23	10	9.68	.32	9.09	.91
24	10	9.42	.58	8.39	1.61
25	10	9.61	.39	10.71	.71
26	10	9.89	.11	9.59	.41
27	10	8.49	1.51	10.02	.02
28	10	7.91	2.09	9.86	.14
29	10	7.95	2.05	9.82	.18
30	15	15.80	.80	15.39	.39
31	15	15.63	.63	16.13	1.13
32	15	14.62	.38	14.04	.96
33	15	13.99	1.01	16.81	1.81
34	15	15.15	.15	14.70	.30
35	15	12.87	2.13	14.19	.81
36	15	13.40	1.60	14.34	.66
37	15	15.30	.30	14.82	.18
38	15	14.35	.65	13.48	1.52
39	15	14.90	.10	15.51	.51
40	15	14.52	.48	14.31	.69
41	15	13.57	1.43	15.33	.33
42	15	12.83	2.17	15.61	.61
43	15	12.66	2.34	15.77	.77
44	5	4.38	.62	5.58	.58
45	5	6.04	1.04	5.32	.32
46	5	4.81	.19	4.69	.31
47	5	6.15	1.15	4.79	.21
48	5	4.18	.82	4.01	.99
49	5	6.06	1.06	6.82	1.82
50	5	6.53	1.53	3.75	1.25
51	5	4.92	.08	6.93	1.93
MEAN	12.549	12.117	.74	12.657	.81
SD	24.277	24.301	.63	24.085	67

* Absolute difference between Actual and 2D Joint Angle

** Absolute difference between Actual and 3D Segmental Angle

TABLE 4. One factor ANOVA-Repeated measures for Actual, 2D Joint, and 3D Segmental angles for all 51 conditions.

	df:	SS:	MS:	F-test:	P value:
Between subjects	50	87937.51	1758.75		
Within subjects	102	71.213	.698		
treatments	2	8.321	4.161	6.615	.002
residual	100	62.892	.629		
Total	152	88008.723			

TABLE 5. Tukey's Honestly-Significant-Difference Test. 3 levels of the independent variable (Act, 2D Jt., 3D Seg.) for 51 conditions.

	3DSEG 12.66	ACT 12.55	2DJT 12.12
3DSEG	----	0.11	0.54*
ACT		----	0.43*
2DJT			----

*$p < 0.05$ ($Q_{cv} = 0.40$)

3DSEG = 3D Segmental angle calculation

ACT = Actual angle

2DJT = 2D Joint angle calculation

TABLE 6. One factor ANOVA-Repeated measures for Actual, 2D Joint, and 3D Segmental angles without the 30 degree rotations in the transverse plane (39 conditions).

Source:	df:	SS:	MS:	F-test:	P value:
Between subjects	38	86994.768	2289.336		
Within subjects	78	49.72	.637		
treatments	2	1.628	.814	1.287	.2821
residual	76	48.092	.633		
Total	116	87044.488			

TABLE 7. Computed angular measurements, mean absolute error, and standard deviations for 2 groups of conditions (n = 12, n =39).

CONDITION	ACTUAL ANGLE inversion/eversion	2D JOINT ANGLE	*	3D SEGMENTAL ANGLE	**
1	180	179.98	.02	178.22	1.23
2	5	5.17	.17	5.22	.22
3	5	4.03	.97	7.49	2.49
4	5	4.9	.1	3.91	1.09
5	5	4.32	.68	7.28	2.28
6	5	4.78	.22	4.28	.72
+7	5	5	0	5.04	.04
+8	5	4.54	.46	5.16	.16
9	5	5.36	.36	6.05	1.05
10	5	5.43	.43	4.17	.83
11	5	4.44	.56	5.36	.36
12	5	5.05	.05	6.69	1.69
13	5	4.52	.48	5.12	.12
+14	5	3.8	1.2	5.34	.34
+15	5	3.79	1.21	4.68	.32
16	10	10.1	.1	9.06	.94
17	10	9.64	.36	12.75	2.75
18	10	9.49	.51	8.54	1.46
19	10	9.21	.79	10.48	.48
20	10	9.99	.01	10.29	.29
+21	10	9.14	.86	10.28	.28
+22	10	9.69	.31	9.75	.25
23	10	9.68	.32	9.09	.91
24	10	9.42	.58	8.39	1.61
25	10	9.61	.39	10.71	.71
26	10	9.89	.11	9.59	.41
27	10	8.49	1.51	10.02	.02
+28	10	7.91	2.09	9.86	.14
+29	10	7.95	2.05	9.82	.18
30	15	15.80	.80	15.39	.39
31	15	15.63	.63	16.13	1.13
32	15	14.62	.38	14.04	.96
33	15	13.99	1.01	16.81	1.81
34	15	15.15	.15	14.70	.30
+35	15	12.87	2.13	14.19	.81
+36	15	13.40	1.60	14.34	.66
37	15	15.30	.30	14.82	.18
38	15	14.35	.65	13.48	1.52
39	15	14.90	.10	15.51	.51
40	15	14.52	.48	14.31	.69
41	15	13.57	1.43	15.33	.33
+42	15	12.83	2.17	15.61	.61
+43	15	12.66	2.34	15.77	.77
44	5	4.38	.62	5.58	.58
45	5	6.04	1.04	5.32	.32
46	5	4.81	.19	4.69	.31
47	5	6.15	1.15	4.79	.21
48	5	4.18	.82	4.01	.99
49	5	6.06	1.06	6.82	1.82
50	5	6.53	1.53	3.75	1.25
51	5	4.92	.08	6.93	1.93
N=12 MEAN	10.00	8.587	1.41	9.987	0.38
SD	4.264	3.794	0.78	4.258	0.26
N=39 MEAN	13.333	13.19	.542	13.479	.946
SD	27.705	27.712	.423	27.479	0.70

† 30 degrees of rotation in the transverse plane (n = 12)

* Absolute difference between Actual and 2D Joint angle

**Absolute difference between Actual and 3D Segmental angle

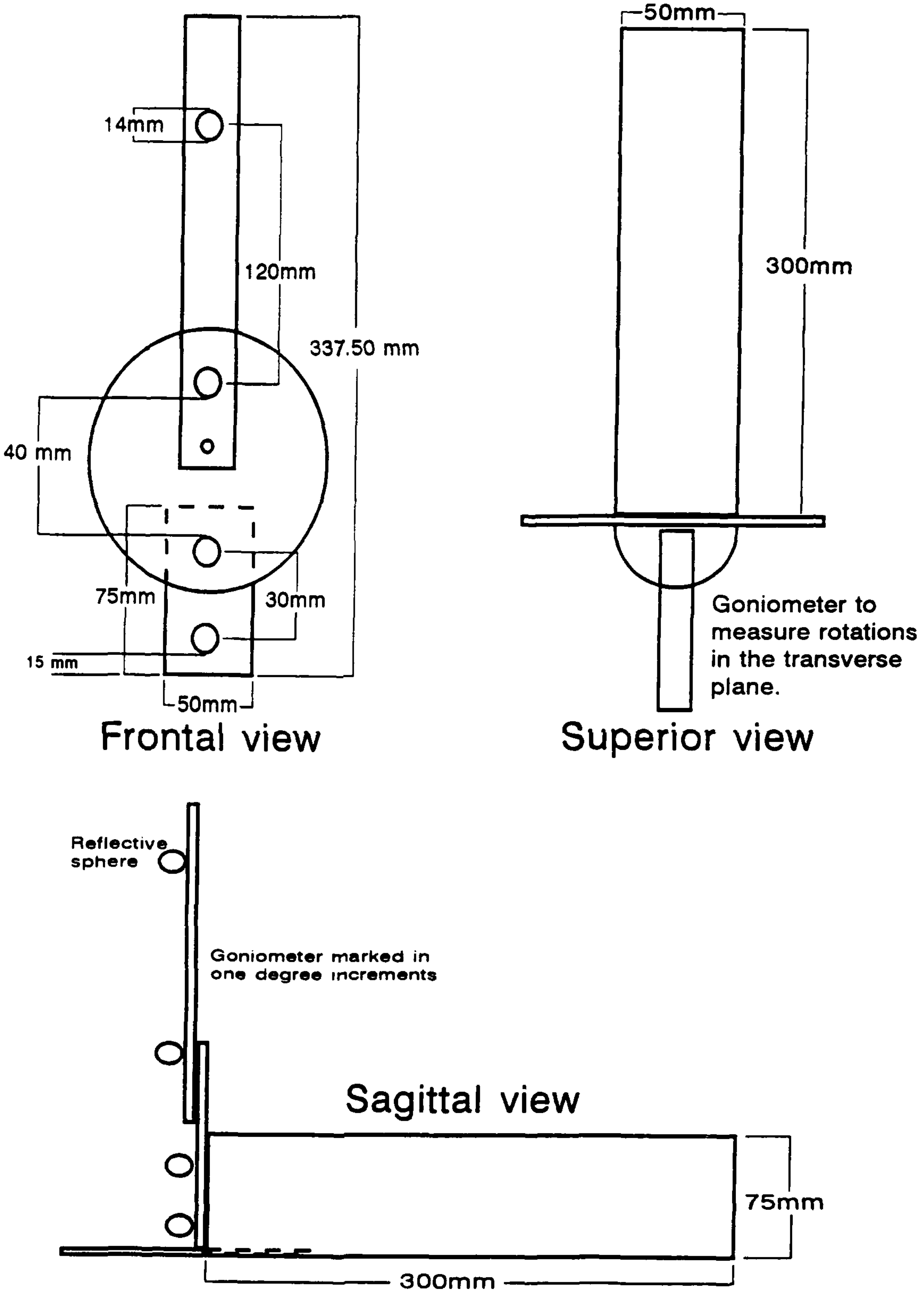
TABLE 8. One factor ANOVA-Repeated measures for Actual, 2D Joint, and 3D Segmental angles for the 12 conditions with 30 degrees of rotation in the transverse plane (conditions 7, 8, 14, 15, 21, 22, 28, 29, 35, 36, 42, 43).

Source:	df:	SS:	MS:	F-test:	P value
Between subjects	11	546.37	49.67		
Within subjects	24	21.492	.896		
treatments	2	14.834	7.417	24.508	.0001
residual	22	6.658	.303		
Total	35	567.862			

TABLE 9. Tukey's Honestly-Significant-Difference Test. 3 levels of the independent variable (Act., 3D Seg., 2D Jt.) for 12 conditions.

	ACT 10.00	3DSEG 9.99	2DJT 8.59
ACT	----	0.01	1.41*
3DSEG		----	1.40*
2DJT			----

*$p < 0.05$ ($Q_{cv} = 0.97$)
ACT = Actual angle
3DSEG = 3D Segmental angle calculation
2DJT = 2D Joint angle calculation

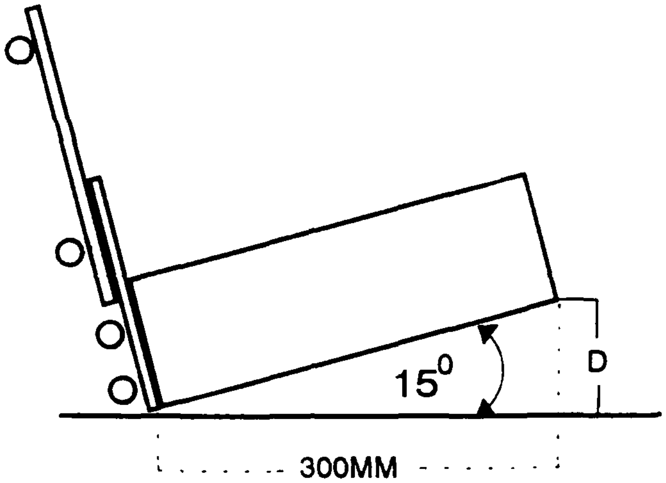

Frontal view

Superior view

Sagittal view

FIGURE 1. Right rearfoot model.

*not to scale



15 degree counter-clockwise
rotation in the sagittal plane.

Sin 15 = D/300
300 * .2588 = 77.65
D = 77.65 mm

FIGURE 2. Calculation of sagittal plane rotations.

*not to scale

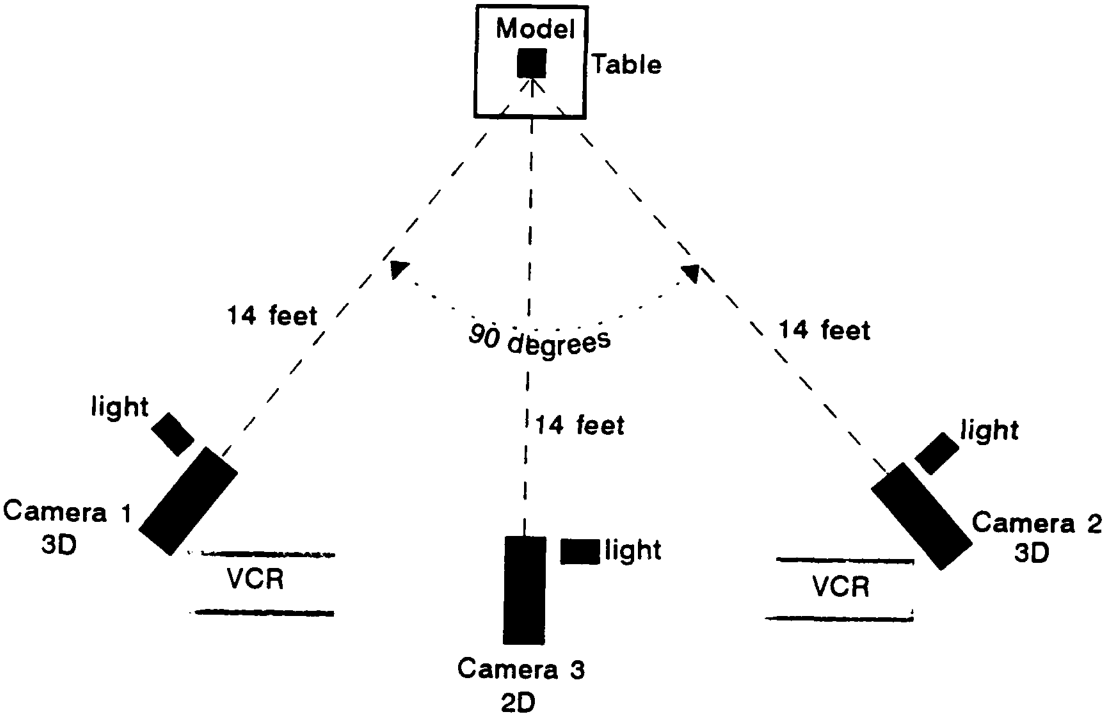
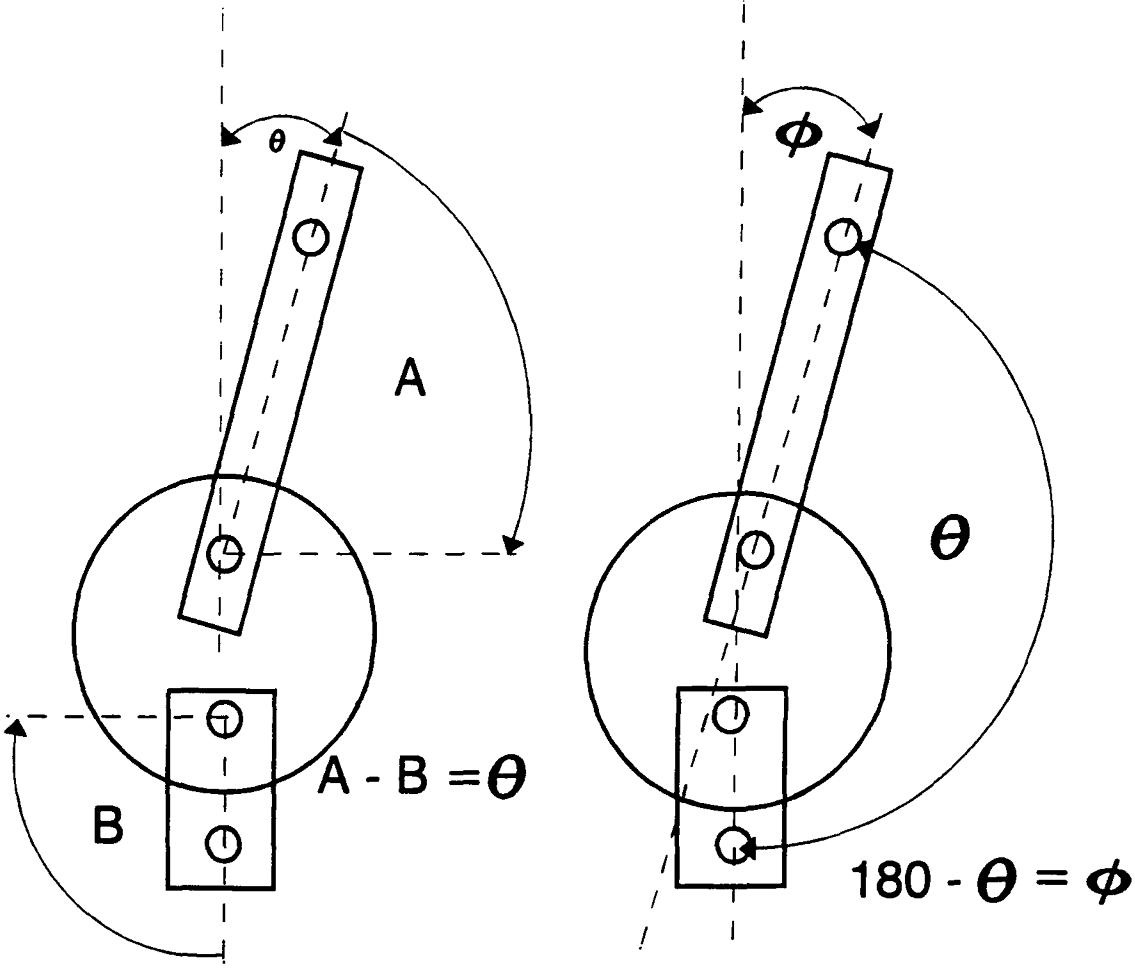


FIGURE 3. Field set up.
*not to scale



2D Joint angle calculation

3D Segmental angle calculation

FIGURE 4. Joint angle and Segmental angle calculations.