AN ABSTRACT OF THE DISSERTATION OF

Kim Hannigan-Downs for the degree of Doctor of Philosophy in Human Performance presented on June 11, 2004.

Title: Radiographic Validation and Reliability of Selected Measures of Pronation and Biomechanical Analyses of Tarsal Navicular Displacement under Static and Dynamic Loading Conditions.

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Abstract approved: _____

Rod A. Harter

The navicular drop test (NDT), Feiss' line (FL) and standing foot angle (SFA) are clinical tests used to estimate the amount of pronation via inferior displacement of the tarsal navicular. Thirty-two patients (female and male, ages 18-65) who sought medical treatment for lower extremity pathologies participated in the study that assessed the reliability and validity of the NDT and the FL. The NDT and FL tests had moderate to good ($r = 0.608 - 0.885$) positive correlation values, with the exception of the FL change in position value ($r = -.091$). The intra-examiner reliability results showed good to excellent consistency for all measures of the NDT and FL tests (ICC = 0.817 – 0.939). The inter-examiner reliability measures were poor to moderate for the FL test of pronation (ICC = 0.425 – 0.742), while the reliability for the NDT was moderate to good (ICC = 0.686 - 0.886). These findings suggest that the validity of the NDT was moderate, and that the FL test was questionable. The intra-examiner reliability was strong for both the NDT and FL tests.

Forty-six (23 women, 23 men) subjects participated in the study that evaluated the relationship between two static clinical tests (NDT and SFA) of pronation and three-dimensional movement of the bones of the foot. Poor to moderate positive relationships were observed ($p < .05$) between the NDT and the dynamic navicular movement during the walking and running conditions (Spearman's rho = 0.340 and 0.397, respectively). We observed that each of the regression models used to explain dynamic navicular movement during walking, running, and drop landing were statistically significant ($p < 0.05$). The explained variance of the dynamic navicular drop for the running condition was the largest ($R^2 = .531$), while the model for walking showed the least explained variance ($R^2 = .289$). The explained variance for dynamic SFA was the greatest for the walking condition ($R^2 = .373$), while the model for drop landing had the least explained variance ($R^2 = .330$). This research supports the continued use of the NDT as an indicator of dynamic navicular displacement, but questions the use of the SFA measurement.

Radiographic Validation and Reliability of Selected Measures of Pronation and Biomechanical Analysis of Tarsal Navicular Displacement under Static and Dynamic Loading Conditions

by

Kim Hannigan-Downs

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Kim Hannigan-Downs, Author

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CONTRIBUTION OF AUTHORS

For the paper Radiographic validation and reliability of selected clinical measures of pronation:

Dr. Rod Harter was instrumental in the design, analysis of results and editing of this manuscript.

For the paper Biomechanical analysis of tarsal navicular displacement under static and dynamic loading conditions:

Dr. Gerald Smith and Dr. Rod Harter were involved in the design of the project. Dr. Rod Harter assisted with the interpretation and editing of the manuscript.

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Chapter 1

INTRODUCTION

In an effort to better understand the etiology of lower extremity injuries, researchers have long studied the form and structure of the human foot. [1-12] The foot is an anatomically complex structure whose functions include roles as a compliant shock absorber, static and dynamic base of support, and rigid lever arm. [1,12] The repetitive loading that the foot undergoes during physical activity and activities of daily living frequently results in foot injuries and overuse conditions. [11,24-31,43,45,46,50,51,65,68]

During gait, the subtalar joint pronates which causes forward displacement of the navicular and the talus. [17] This movement, in addition to the parallel alignment of the transtarsal joint, produces a supple forefoot, thus providing the ability to adjust to uneven surfaces. If excessive pronation occurs in the foot, the soft tissues supporting the transtarsal joint and medial longitudinal arch experience abnormal stress. The abnormal stresses may lead to injury.

The measure of pronation is difficult due to the intricacy of the movement. Root et al. [1] assessed pronation by measuring the calcaneal position, the subtalar neutral position, and the range of motion at the subtalar joint with a goniometer.

Their technique of measuring pronation [1] remains in use today despite the publication of several studies which have reported open kinetic chain goniometric subtalar measurements to be unreliable (inter-examiner) with reported ICC values ranging from 0.00 to 0.27. [32-34]

As a result, closed chain techniques such as the navicular drop test, Feiss' line and standing foot angle have gained greater acceptance among clinicians. [2,3,24,26-28,30-35,37,40,43,51,76] These measurements are static tests that are relatively easy to obtain in the clinical setting when compared to a time consuming and expensive three-dimensional biomechanical analysis.

The navicular drop test and Feiss' line have been used in the clinical setting for more than three decades as measurements of pronation. [2,3,32-34,40,41] Descriptions of both of these special tests can be found in current editions of orthopedic physical assessment texts used by certified athletic trainers, physical therapists, and others. [35,37,76] However, there are no published reports of these clinical tests being validated. When the reliability of the navicular drop test has been assessed, the results have varied. Intratester reliability values ranged from ICC = 0.61-0.96 (1.92 -2.57 mm). [33,40-41] Therefore, a study of the navicular drop test and Feiss' line was necessary to determine if these two measurements accurately and reliably indicate navicular sagittal plane movement.

There is no published evidence of the validity of the standing foot angle, but one study evaluated the intertester reliability of the measure and reported an intraclass correlation coefficient of 0.69. [24] Twenty-five members of an amateur folk dance

troupe (20 females; 5 males), who ranged in age from 16 to 25 years, participated in the study.

Unfortunately, static measurements (open or closed kinetic chain) taken on a single plane do not fully capture the complexity of triplanar pronation, nor do they take into account the effect(s) of the forces placed upon the foot during different locomotion activities. Therefore it is important from a practical (time and cost) perspective to determine if the static clinical tests of pronation are reflective of what occurs dynamically.

The results of these investigations are presented in two manuscripts within the dissertation. Chapter 2 contains the study titled, "Radiographic validation and reliability of selected clinical tests of pronation" to be submitted to *Clinical Orthopaedics and Related Research* for publication. The purposes of the study presented in Chapter 2 were to: (a) employ radiographic imaging techniques to determine the validity of the navicular drop test and Feiss' line measurements in normal and injured limbs and, (b) to establish the intra-examiner and inter-examiner reliability and standard error of measurement (SEM) for these clinical tests. The radiographic images, weight bearing and non-weight bearing, served as the criterion measure against which the clinical tests were compared. The measurements obtained by two certified athletic trainers were utilized to quantify both intratester and intertester reliability. Table 1.1 summarizes the parameters of interest and the dependent variables.

Evaluative Parameters	Dependent Variables
Inferior navicular displacement (relative to the floor)	Navicular drop test
Inferior navicular displacement (relative to Feiss' line)	Feiss' line measurement
Radiographic images	Inferior navicular displacement

Table 1.1 Dependent variables of the radiographic study.

The manuscript titled, "Biomechanical analysis of tarsal navicular displacement under static and dynamic loading conditions" is found in Chapter 3 and will be submitted to the journal, *Foot and Ankle International*, for publication. The purposes of this study were: (a) to perform the navicular drop test and the standing foot angle in normal, apparently healthy men and women and compare these values to the three-dimensional displacement values for the navicular bone during the experimental conditions of walking, running and drop landing (stepping off of a 38 cm box); and (b) to identify a regression equation that can be used to predict the dynamic movement of pronation of the foot from selected static measures. Table 1.2 lists the evaluative parameters and the specific dependent variables for each.

Evaluative Parameters	Dependent Variables
Self-Reported Questionnaire	1. Body Weight 2. Foot Length 3. Arch type 4. Foot type 5. Age
Goniometric measurements	1. Passive dorsiflexion 2. OKC Passive inversion 3. OKC Passive eversion
Clinical tests of pronation	1. Navicular drop test 2. Standing foot angle
3-D Kinematics	1. Maximum vertical displacement of the navicular tubercle 2. Maximum mediolateral displacement of the navicular tubercle 3. Maximum rearfoot angle (eversion) 4. Maximum standing foot angle 5. Minimum standing foot angle

Note: OKC = open kinetic chain

Table 1.2 Dependent variables in the biomechanical analysis of pronation study.

Chapter 2

Radiographic Validation and Reliability of Selected Clinical Measures of Pronation

by

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ABSTRACT

Abnormal pronation of the foot has been associated with a wide range of injuries in the lower extremity. The navicular drop test (NDT) and Feiss' line (FL) are two clinical tests used to estimate the amount of pronation via transcutaneous measurement of the inferior displacement of the tarsal navicular. Although widely used in clinical practice for decades, no published record of validation for these special tests exists. The purposes of this study were: (a) to employ radiographic imaging techniques to determine the validity of the NDT and FL measurements in normal and injured limbs, and (b) to establish the intra-examiner and inter-examiner reliability and standard error of measurement (SEM) for these clinical tests. Thirty-two patients (female and male, ages 18-65) who sought medical treatment for lower extremity pathologies were recruited to participate in the study. As part of the diagnostic evaluation ordered by their physician, 16 subjects had non-weight bearing and weight-bearing radiographs taken of the feet of their symptomatic and asymptomatic limbs. Radiopaque markers were placed on the medial malleolus of the tibia, navicular tubercle, and head of the first metatarsal to facilitate the calculation of the NDT and FL (Figure 2.1). Displacement of the navicular, as calculated from the radiographs, served as the criterion measure for validation of the clinical tests, and was compared with the NDT and FL test results using interclass correlation statistical analyses

(Pearson r, $\alpha = .05$). Repeated measurements of NDT and FL on different days by the same certified athletic trainer, and same day comparisons between two certified athletic trainers will be used to calculate intraclass correlation coefficients [ICC (2,1)] and the SEM. The NDT and FL tests had moderate to good ($r = 0.608 - 0.885$) positive correlation values, with the exception of the FL change in position value ($r = -.091$). The intra-examiner reliability results showed good to excellent consistency for all measures of the NDT and FL tests (ICC = 0.817 – 0.939). The inter-examiner reliability measures were poor to moderate for the FL test of pronation (ICC = 0.425 – 0.742), while the reliability for the NDT was moderate to good (ICC = 0.686 - 0.886). These findings suggest that the validity of the NDT was moderate, and that the FL test was questionable. The intra-examiner reliability was strong for both the NDT and FL tests, while the inter-examiner reliability was moderate for the NDT and poor for the FL. Therefore, continued use of the NDT as a clinical test of pronation was supported by this study, while the accuracy of the FL test was suspect.

INTRODUCTION

In an effort to better understand the etiology of lower extremity injuries, researchers have long studied the form and structure of the human foot. [1-12] The foot is an anatomically complex structure whose functions include roles as a compliant shock absorber, static and dynamic base of support, and rigid lever arm. [1,12] The repetitive loads that the foot is subjected to in these and other biomechanical roles can lead to a variety of foot injuries and overuse conditions.

Pronation of the foot has been associated with a myriad of sport-related injuries and conditions, and these are not limited to the foot itself, but also involve the shank, knee, hip and low back. [13-20] Achilles tendinitis, metatarsalgia, hallux valgus, tailor's bunion, plantar fasciitis and plantar interdigital neuromas have all been associated with pronation.[1,5,14,17-18] Medial tibial stress syndrome has been linked to abnormal pronation and excessive eccentric loading of the posterior tibialis muscle.[13,15] Two recent studies found that subjects who had incurred an anterior cruciate ligament (ACL) injury had significantly greater subtalar pronation than did the uninjured/control groups.[19-20] Botte[16] linked unilateral structural and functional abnormalities of the pelvis and lumbar spine to foot pathomechanics, and concluded that control of foot function was crucial to the treatment of lumbar injuries.

Excessive pronation as defined by Root et al.[1] is a condition of hypermobility that may lead to numerous injuries of the foot, ankle and lower leg.

These authors assessed pronation by measuring the calcaneal position, the subtalar neutral position, and the range of motion at the subtalar joint. Their technique of measuring pronation[1] remains in use today despite the existence of several studies which have reported open kinetic chain goniometric subtalar measurements to be unreliable (inter-examiner) with reported ICC values ranging from 0.00 to 0.27.[21-23] As a result, closed chain techniques such as the navicular drop test (NDT) and Feiss' line (FL) have gained greater acceptance among clinicians.

Brody[2] is commonly credited as the original proponent of the navicular drop test. However, in 1956 Schuster[24] first proposed the concept of the NDT as a measurement of foot pronation. The NDT is a measure of the change in the height of the navicular relative to the ground when measured in static, closed kinetic chain non-weight bearing and full weight bearing positions.[2] Brody et al.[2] considered NDT results greater than 15 mm to be abnormal, while those $\leq$ 10 mm displacement were defined as normal.

Feiss' line uses three anatomical landmarks (medial malleolus of tibia, navicular tubercle, head of first metatarsal) to evaluate pronation of the foot. Similar to the NDT, inferior displacement of the navicular between closed chain non-weight bearing and full weight bearing positions is of central importance.[25-28] The NDT and FL tests differ in that with FL, the change in navicular position is measured relative to a line connecting the malleolus and first metatarsal, rather

than the ground. A positive FL test is one in which the navicular drops at least two-thirds of its original height.[28]

NDT and FL are currently being utilized by certified athletic trainers, physical therapists and other clinicians to evaluate the degree of pronation, but no evidence of validation for these tests exists. The results of interrater reliability studies of the NDT have been mixed, with ICC values ranging from 0.57 – 0.96. [22-23,29,31-32] Sommer et al.[13] concluded that FL had good interrater reliability, but did not provide interclass correlation coefficients. The validity and the reliability of these two clinical tests, therefore, remain at question.

The purposes of this study were: (a) to employ radiographic imaging techniques to determine the validity of the NDT and FL measurements in normal and injured limbs, and (b) to establish the intra and inter-examiner reliability and standard error of measurement (SEM) for these clinical tests.

METHODS AND PROCEDURES

Subjects

Thirty-two individuals who sought medical evaluation for a foot, ankle, or lower leg pathology participated in the study. Two orthopedic surgeons helped with the recruitment of subjects. Oregon statutes prohibit the use of radiation on human subjects for the sole purpose of research; therefore, symptomatic individuals comprised the subject pool. All subjects were 18 years of age or older, free of decubitus ulcers on both feet, and able to bear 100% of their weight

on the injured limb. Women who were pregnant or breast-feeding were excluded from the study.

Procedures

The first of the two experimental sessions took place in the physician's office where the subjects were prescreened, read the consent document (Appendix C) and provided informed consent prior to participation in the study. When the physician sent the patient for x-rays, the primary researcher accompanied the subject to the facility. While the subject was seated, three adhesive radiopaque encapsulated lead markers, typically used in mammography, were applied to the center of the medial malleolus, the prominence of the navicular tubercle and the center of the first metatarsal head (Figure 2.1).

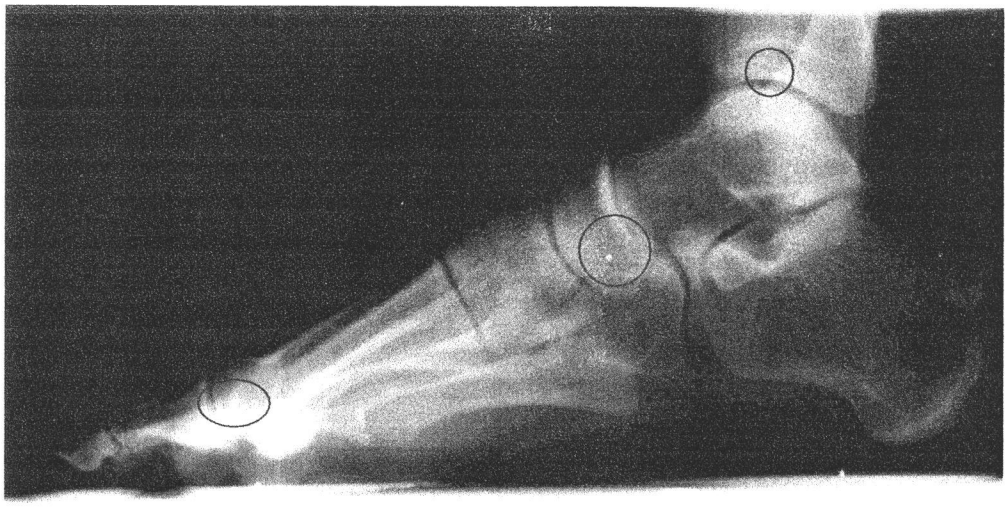

Figure 2.1. Radiographic image showing radio-opaque markers.

The radiology departments at the two clinics had different types of equipment and configurations which made necessary varying subject positions. Therefore, the distance of the x-ray tube lens to the film plane was standardized to 94.5 cm. All radiographic films were taken in the sagittal plane, capturing a mediolateral image of the foot and ankle complex.

In 16 subjects, the unaffected leg was also evaluated, followed by the injured limb. The subject stood so that the uninjured limb was placed in front of the injured limb. The toes of the rear foot were placed on the edge of the platform (wooden box used for weight-bearing x-rays) out of the radiographic field. For safety purposes, the subject was asked to hold onto a stable object, e.g., wall or bar, while standing on the platform. Prior to filming the forward foot, the subject was asked to place as little of their weight as possible on their front foot, but maintain contact to the platform. Using the closed kinetic chain talar congruency method, [32] the subject's forward foot was positioned in subtalar joint neutral.

The first (non-weight bearing) measurement of the NDT was obtained by placing a 7.6 x 12.7 cm index card perpendicular to the floor on the medial aspect of the foot, and marking the position of the navicular tubercle on the card. Next, the initial measurement of FL was performed by holding a straight edge against the medial aspect (through the navicular) of the foot. The distance of the straight edge to the platform was then measured in millimeters.

Radiographic film (24 x 30 cm) located within a plate was placed lateral to the subject's foot/ankle. The distance from the x-ray camera tube to the film plate

was standardized to 94.5 cm according to established protocol for ankle/foot x-rays. The known distance of two screws in the platform, visible on the x-rays, was used as the scaling factor. After the first x-ray, the same procedure was completed again, but the subject was asked to put full weight on the front foot. The second measurement of the NDT was taken by placing the same index card against the medial aspect of the foot and making a second mark on the card at the level of the navicular. Next, the second FL measurement was also made to determine the distance the FL has moved from its initial position. The plate containing unexposed x-ray film was then placed on the lateral aspect of the foot for a full weight-bearing radiograph. Following completion of these procedures, the entire experimental protocol was repeated on the contralateral foot.

Within two weeks of the initial session, the subjects came to the Oregon State University Sports Medicine/Disabilities Research Laboratory for the second testing session. The principal investigator (KHD) and a second clinician (MH), both certified athletic trainers, performed bilateral measures of the NDT and FL tests. The order of clinician measurements was counterbalanced to control for testing order bias. All measurements were taken while the subject was standing on the floor. The previous procedures were followed, but radiographs were not taken in session two, and anatomical landmarks were identified with a grease pen dot rather than encapsulated lead markers. All grease pen marks were thoroughly removed by the first examiner prior to any measurements by the second clinician. In this way, investigators were blinded to the markings and measurements of the

other. Lastly, weight-bearing sagittal and frontal plane 35 mm still photographs were taken as a photographic record of the subject's foot morphology.

A demographic and anthropometric questionnaire (Appendix D) was completed by the subject. The information collected included the subject's name, phone number, age, primary complaint or diagnosis, height, weight, foot size, foot type, and arch type. As the present study was a validity and reliability study, this information was not a factor in the data analysis.

After radiographs were processed by the radiation technicians and evaluated by the physicians, the primary investigator retrieved copies of the films for digitization and analysis. All x-rays were scanned with a digital scanner (Image Reader LE, Campbell, CA) using Desk Scan software (Hewlett Packard, Palo Alto, CA) in which the positions of three lead markers were plotted on a x-y coordinate system. The navicular position on the radiographs taken in non-weight bearing and weight bearing positions were compared to determine the relative displacement of the navicular bone. The inferior movement of the navicular on the radiographs was assessed by measuring the distance of the navicular tubercle marker to the horizontal line constructed after digitization of the locations of the screw heads. These displacement values were compared with the NDT and FL values obtained in session one.

Statistic Analyses

The statistical analyses of the data from this study were conducted as three distinct entities: (a) validation of the NDT and FL tests compared to the criterion measure (radiographic images), (b) intra-examiner reliability of NDT and FL tests, and (c) inter-examiner reliability of the NDT and FL clinical tests.

To determine the validity of both the NDT and FL tests, displacement of the navicular as calculated from radiographic images served as the criterion measure. Pearson product moment correlation coefficients were calculated to evaluate the nature of the relationship between the magnitude of navicular displacement in the radiographs versus NDT and the radiographs versus FL ($\alpha = .05$). While statistically significant correlations were expected, an interclass correlation coefficient of $r \geq .80$ was considered to be the minimum value necessary to conclude that the NDT and FL tests are valid measures.

To assess the intra-examiner reliability of the NDT and FL clinical measures, a repeated measures ANOVA was conducted using the Shrout and Fleiss[34] intraclass correlation coefficient (ICC) formula $_{2,1}$. Specifically, ICC values were calculated for three dependent variables: (a) non-weight bearing position of the tarsal navicular, (b) weight bearing position of the navicular, and (c) magnitude of navicular displacement between non-weight bearing and weight bearing positions. To estimate the precision of these measurements, standard error of measurement (SEM) values were computed. A 95% confidence interval was calculated (mean $\pm$ 1.96 x SEM) for each dependent variable.[35]

To evaluate the inter-examiner reliability of the NDT and FL, a similar analysis as that used for the intra-examiner reliability was used to calculate ICC and SEM values.

RESULTS

Validity evidence for the Feiss' line

The Feiss' line weight bearing and non-weight bearing clinical tests were positively correlated ($p < 0.01$) with measures obtained from the radiographs. The non-weight bearing condition showed a slightly greater correlation coefficient at $r = 0.741$, as compared to the weight bearing measurement at $r = 0.691$. Table 2.1 summarizes the results of the Pearson product moment correlation coefficients and standard error of measurement values between the radiographic and index card measurements for the NDT and FL.

Validity evidence for the navicular drop test

The NDT clinical and radiographic measures demonstrated strong positive correlations among all three measures of navicular height (Table 2.1). The weight-bearing and non-weight bearing NDT measurements were highly correlated ($r = 0.885$ and $r = 0.880$, respectively). The NDT scores, calculated from the non-weight bearing and weight-bearing x-ray and clinical measurements had a correlation of $r = 0.608$ ($p < .01$).

Radiographic Measurements

Card Measurements	fl-nwb[1]	fl–wb[2]	fl-diff[3]	ndt–nwb[4]	ndt-wb[5]	ndt-diff[6]
fl-nwb[1]	.741**	.789**	.180	.487*	.419*	.019
fl-wb[2]	.692**	.691**	.238	.231	.238	-.056
fl-diff[3]	-.031	.022	-.091	.279	.101	.242
ndt-nwb[4]	.319	.354*	.025	.880**	.748**	-.015
ndt-wb[5]	.314	.332	.048	.810**	.885**	-.379*
ndt-diff[6]	-.032	-.010	-.041	.001	-.325	.608**

* = Correlation is significant at the 0.05 level (two-tailed).
** = Correlation is significant at the 0.01 level (two-tailed).

Table 2.1. Pearson product moment correlation matrix.
[1]fl-nwb. Feiss' line – non-weight bearing condition.
[2]fl-wb. Feiss' line – weight-bearing condition.
[3]fl-diff. Feiss' line – difference between non-weight bearing and weight bearing
[4]ndt-nwb. Navicular drop test – non-weight bearing condition.
[5]ndt-wb. Navicular drop test – weight-bearing condition.
[6]ndt-diff. Navicular drop test – difference between NW bearing and WB

Reliability evidence for intra-examiner testing

High inter-examiner coefficients were obtained for FL non-weight bearing ($ICC_{2,1}$ = 0.881 SEM =2.330), weight-bearing ($ICC_{2,1}$ = .9342, SEM = 1.459) and total change in position measurements ($ICC_{2,1}$ = 0.817, SEM = 1.570). The reliability of the NDT was moderate to high ranging from 0.840 (SEM = 1.899) for the total change in position to 0.927 (SEM = 1.680) for the non-weight bearing values. The intra-examiner reliability coefficients are presented in Table 2.2.

Condition	Feiss' line $ICC_{2,1}$ (SEM)	Navicular drop test $ICC_{2,1}$ (SEM)
Non-WB	.881 (2.330)	.927 (1.680)
WB	.934 (1.459)	.939 (1.792)
Difference (=NWB-WB)	.817 (1.570)	.840 (1.899)

Table 2.2. Intra-examiner reliability evidence for Feiss' Line and the Navicular Drop Test.

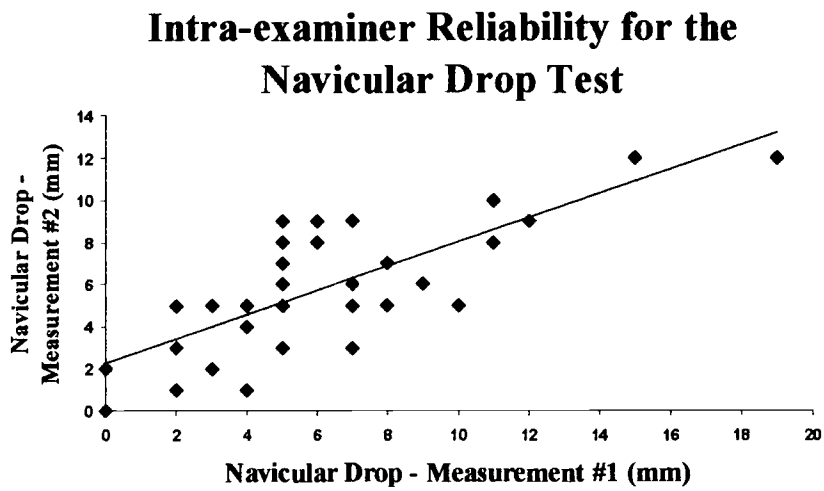

Figure 2.2. Intra-examiner reliability scatterplot for the navicular drop test.

Reliability evidence for inter-examiner testing

The inter-examiner reliability value (Table 2.3) for the FL measurement of the non-weight bearing position was moderate ($ICC_{2,1}$ = 0.743, SEM = 3.490). However, the ICC value for the difference (NWB to WB) was poor ($ICC_{2,1}$ = .425, SEM = 2.620) [Figure 2.3]. High inter-rater reliability was achieved for both the non-weight bearing and weight-bearing testing of the navicular position in the NDT. A comparison of the NDT values obtained by the two examiners revealed an intraclass correlation coefficient of 0.686 (SEM = 3.256).

Condition	Feiss' line $ICC_{2,1}$ (SEM)	Navicular drop test $ICC_{2,1}$ (SEM)
Non-WB	.742 (3.490)	.834 (2.406)
WB	.522 (4.598)	.886 (2.180)
Difference (=NWB-WB)	.425 (2.620)	.686 (3.256)

Table 2.3. Interexaminer reliability evidence for Feiss' Line and the Navicular Drop Test.

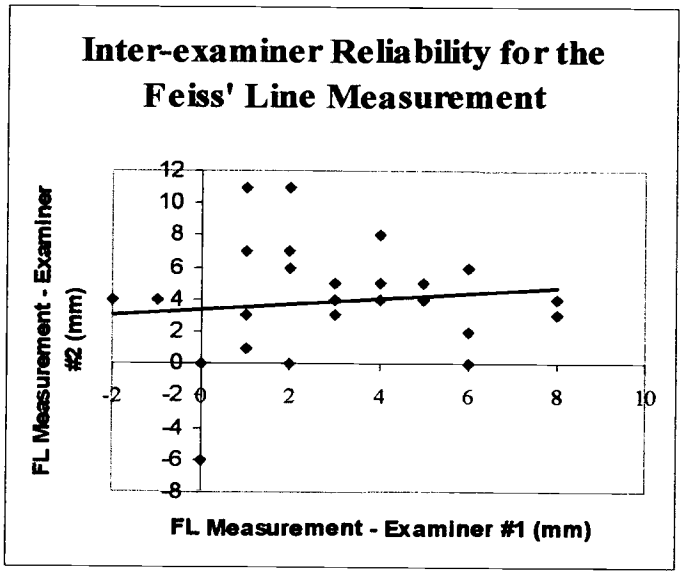

Figure 2.3. Scatter plot of the inter-examiner reliability for Feiss' Line.

DISCUSSION

The navicular drop test and Feiss' line have been used in the clinical setting for more than three decades as a measurement of pronation [3,25-28]. Both of these special tests appear in current editions of orthopedic assessment texts used by certified athletic trainers, physical therapists, and others. [26-28] However, there are

no published reports of this clinical test being validated. When the reliability of the NDT has been assessed, the results have varied.[22-23,27,30-31] Therefore, a validation study of the NDT and Feiss' line was necessary to determine if these two measurements accurately and reliably indicate navicular sagittal plane movement.

The Pearson product moment correlations between the same measurements taken from the radiographic markers and that of the first cards were statistically significant ($p < .01$) at every comparison with the exception of the total change in FL height. The clinical measurements of the weight and non-weight bearing positions of the FL were moderately valid, however the difference between these two positions demonstrated a poor correlation. It is the total change in height of the navicular tubercle in reference to the FL that is utilized in the testing of pronation, therefore the validity of the FL as a measure of true inferior displacement of the tarsal navicular is questionable. The non-weight and weight-bearing FL correlations, however, were not as strong as those seen with the NDT. The NDT measurements for the non-weight and weight bearing positions were statistically significant ($p < .01$). The validity of the NDT test is dependent upon the correct positioning of the subtalar joint and accurate palpation and marking of one bone, the navicular tubercle. There is less room for examiner error with the NDT test as compared to the FL where three anatomical landmarks are required for the measure. Therefore, there was moderate validity, 0.608 ($p < 0.01$) in the

difference between the non-weight bearing and weight-bearing positions of the NDT.

The intra-examiner reliability for the FL measurements was high for the non-weight bearing position ($ICC_{2,1} = 0.881$), high for the weight-bearing position ($ICC_{2,1} = 0.934$) and thus high for the total change in position between the two ($ICC_{2,1} = 0.817$). The high intraclass correlation coefficient for the non-weight bearing condition indicates that the subtalar neutral position was located consistently by the same investigator. Measurements of the weight-bearing position for FL showed tremendous variability between subjects, with some weight-bearing displacements of the navicular displacing in an upward direction. However, the examiner consistency between trials was good, especially in the weight-bearing position.

Loading the foot with body weight compresses the calcaneal fat pad and the metatarsal fat pad, thus lowering the positions of the medial malleolus and the first metatarsal head relative to the ground. Even in a rigid pes cavus foot where the bones of the medial longitudinal arch do not move inferiorly in the sagittal plane, there should still be compression of the fat pads. It is possible that when the subjects were asked to place full weight upon a single foot that instead of collapsing the medial longitudinal arch by placing their weight over the medial metatarsophalangeal joints and the medial calcaneus, they inverted their subtalar joint to maintain a balanced posture. The inverted position places most of the weight on the lateral aspect of the foot, thus raising the medial arch and

subsequent FL landmarks. The factor of balance was addressed with each subject by asking them hold on to the wall or counter top, but some subjects seemed to need more assistance with balance than others. The x-ray platform was 46 cm in height and located on the floor. Although the change in FL position is shown to be consistent ($ICC_{2,1}$ = .817) when testing was performed on different days, the validity of the test has been shown to be suspect, thereby addressing the issue of the practical significance of the FL test.

For the FL test, the change in navicular position is based upon a relative change of the navicular tubercle from the FL as the foot proceeds from a non-weight bearing to a weight-bearing position [26]. According to Starkey [28], a positive FL test is one in which the navicular drops at least two-thirds of its original height. In our sample of subjects, the navicular height of only one individual would be categorized as possessing a positive FL test. Whether the pathology of the subjects within this sample would be associated with excessive pronation is unknown, and not of consequence for the analysis of reliability and validity.

The intra-examiner reliability results for the NDT were moderate to high, and were consistent with previous studies that reported NDT intra-examiner ICC values ranging from 0.61-0.83. [22,29,30,31] The difference between the two conditions (NWB-WB) had an $ICC_{2,1}$ value of 0.840. Similar to the FL measure, the largest value was observed in the weight-bearing position (ICC = .9390). The NDT is considered an indicator of excessive pronation when the total change in

navicular position exceeds 15 mm [2]. Brody[2] defined any measurement of navicular drop that is less than 10 mm as "normal", which leaves NDT values of 11mm to 15 mm undefined in terms of. In the present study, four individuals (11.43 %) exceeded Brody's definition of an abnormal amount of navicular movement while eight (22.86%) fell within the 11-15 mm range. All four feet that demonstrated a 15 mm or greater navicular drop were symptomatic, while only 5 of the 8 feet with NDT values in the 11-15 mm range exhibited symptoms.

The inter-examiner measurements for FL were also consistent with the literature which showed ICC values ranging from 0.57 – 0.96. [22-23,29,31-32] In the present study, the ICC values were poor for the total change in position and the weight-bearing position. However, the non-weight bearing position of the FL had an $ICC_{2,1}$ value of 0.7424. The time spent in practicing prior to the study was designed to familiarize the examiners with the subtalar congruency method. While this position has been speculated to be one of the sources for error in previous studies regarding inter-examiner reliability [23], the ICC value in this study demonstrated moderate consistency between the examiners.

The accuracy of the Feiss' line measurement is dependent upon several important factors, of which the first is the placement of the three lead markers on the skin surface over bony landmarks. When the lead markers were viewed on the radiographs it was evident that the center of the medial malleolus and the first metatarsal head were misplaced approximately 40 % of the time by 1 mm to 4 mm, making the line drawn between the first metatarsal head and the medial

malleolus incorrect. A second factor necessary for an accurate FL measurement is a consistent position from which to take all non-weight or partial weight-bearing measures. A closed kinetic chain subtalar neutral foot position was chosen for this study as the reference or starting position, and the talar congruency method functioned as the means to get to the neutral position. This closed kinetic chain determination of subtalar joint neutral was developed in response to the concern that the measurements taken using open chain goniometry techniques were unreliable [21-23]. The talar congruency method is subjective in that it involves palpating the talar heads and moving the foot through inversion/eversion until the head of the talus is felt equally on both aspects of the ankle joint [1]. The NDT was also dependent on the correct location of the subtalar neutral position for the measurement of the navicular tubercle height, but as described previously, the measurement is dependent upon the only one anatomical landmark. Therefore, it is not surprising that the weight-bearing measures of both tests had higher inter-correlation values than the non-weight bearing measures within the same group. In the full weight-bearing positions the chance for examiner error was reduced. Lastly, the adhesive lead markers are not a 'true' gold standard, because they were subjectively placed onto the medial aspect of the foot by the examiner. To achieve a 'true' a gold standard, radiopaque markers would need to be introduced directly into the bones of the foot at known locations.

Our inter-examiner NDT results ($ICC_{2,1} = 0.686$) were consistent with ICC values reported in previous studies [22,31]. Picciano et al. [22] reported an inter-

examiner reliability value of 0.57, while Sell et al. [31] found the inter-examiner reliability value to be 0.73. The standard error of measurements of these studies was 2.7 mm. and 2.1 mm. respectively, while the SEM in the present study was 2.620 mm. One important difference in the methodologies of these two studies was the experience of the examiner. Picciano et al. utilized two inexperienced physical therapy students who took the measurements while Sell et al. evaluated the NDT with one experienced tester and one who did not have a previous knowledge of the involved tests. The evaluators in Sell's group participated in four, one-hour practice sessions in effort to become consistent with the tests. In the present study, the two examiners were experienced certified athletic trainers who were previously familiar with the two clinical tests but specifically practiced the closed kinetic chain subtalar joint congruency method for use in this study.

Conclusions

Irrespective of the good intra-examiner reliability values, the continued use of Feiss' line as a clinical test is questionable due to the poor accuracy of tracking tarsal navicular sagittal plane movement.

Our findings support the continued use of the navicular drop test as a clinical measure of pronation, but recognize that the accuracy of the NDT is not perfect in describing sagittal plane movement of the navicular. As expected, the intra-examiner test/retest reliability was greater than that observed between two

examiners. These conclusions are similar to other studies which examine both intra and inter-examiner reliability for the NDT test.

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Chapter 3

Biomechanical Analysis of Tarsal Navicular Displacement under Static and Dynamic Loading Conditions

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ABSTRACT

Although widely used in clinical practice, only one study has been located that evaluated the relationship between the static clinical test of the navicular drop and the three-dimensional movement of the rearfoot under the condition of walking.[38] The navicular drop test and standing foot angle are two static clinical tests used to estimate the amount of pronation via transcutaneous measurement of the tarsal navicular. The purposes of this study were to: (a) obtain navicular drop test and the standing foot angle values in a large cross-sectional sample and compare these values to the three-dimensional displacement values for the navicular tubercle during the conditions of walking, running and drop landing and (b) identify a regression equation(s) that can be used to predict the dynamic movement of pronation of the foot from selected static measures. Forty-six subjects (23 women, mean age = 25.6 yrs. $\pm$ 4.9 yrs.; 23 men, mean age = 26.3 yrs. $\pm$ 6.2 yrs.) participated in the study. Four video cameras (Panasonic, Secaucus, New Jersey) were used to capture medial and rearfoot movement as the subjects walked, ran and performed a drop landing. The three dimensional data was analyzed using Peak Performance Motus™ software version 5.0 (Peak Performance Technologies, Englewood, Colorado. The statistical analyses included a Pearson product moment correlation matrix and regression analyses utilizing the Statistical Package for the Social Sciences software, version 11.0.1 (SPSS, Inc., Chicago, Illinois). The critical alpha level for all correlations was set at 0.05. Prior to running the multiple regression analyses with SPSS, we

performed an exploratory "Best Subsets" regression analysis with Minitab, version 13.0 (MINITAB, Inc., State College, Pennsylvania) to determine which predictor variables should be included in each of the six linear regression equations to be calculated with SPSS. Poor to moderate positive relationships were observed ($p < .05$) between the static clinical navicular drop test and dynamic navicular movement measured during the walking and running conditions (Pearson $r = 0.340$ and 0.397, respectively). We observed that each of the regression models used to explain dynamic navicular movement during walking, running, and drop landing were statistically significant ($p < 0.05$). The explained variance of the dynamic navicular drop movement for the running condition was the largest at $R^2 = .531$ while the model for walking (dynamic navicular drop) showed the least explained variance with $R^2 = .289$. The predictor variables that were found to partially explain dynamic navicular drop were different for the walk, run and drop landing conditions. Unlike the prediction equations for dynamic navicular drop, the explanatory variables for dynamic standing foot angle were the same in every regression equation across experimental conditions, e.g., walking, running, drop landing. The specific variables were: passive eversion ROM, ethnicity, passive dorsiflexion ROM, weight and foot length. The explained variance for dynamic standing foot angle was the greatest for the walking condition ($R^2 = .373$) while the model for drop landing had the least explained variance with $R^2 = .330$. Our findings support the continued use of the navicular drop test as an indicator of dynamic navicular

displacement, but suggest that the standing foot angle should not be utilized as an estimate of dynamic pronation.

INTRODUCTION

The human foot is an anatomically complex structure that functions as a shock absorber and base of support for movement. [1,12] The form and structure of the human foot has been extensively studied by researchers and clinicians in order to obtain a more complete understanding of the etiology of lower extremity injuries. [1-23] Repetitive loads that the foot is subjected to during activities of daily living can lead to a variety of overuse conditions and foot injuries. [24-32,43,45,46,49-51,63,68,79-80,85]

Pronation of the foot has been associated with a myriad of sport-related injuries and conditions. These injuries are not limited to the foot itself, but also involve the shank, knee, hip and low back. [24-32,30,43,45,46] Tendinitis, metatarsalgia, hallux valgus, tailor's bunion, plantar fasciitis and plantar interdigital neuromas have all been associated with abnormal pronation.[1,5,28,29] Medial tibial stress syndrome has been linked to abnormal pronation and excessive eccentric loading of the posterior tibialis muscle.[24,26,85] Two recent studies found that subjects who had incurred an anterior cruciate ligament injury had significantly greater amounts of subtalar pronation than did uninjured subjects in the control groups.[30,31] Botte [27] linked unilateral structural and functional abnormalities of the pelvis and lumbar spine to foot pathomechanics, and concluded that control of foot function was crucial to the treatment of lumbar injuries.

Pronation of the foot is a normal, specialized movement that involves plantar flexion of the ankle (talocrural) joint, eversion of the subtalar joint, and abduction of the forefoot. Excessive pronation (Figure 3.1) as defined by Root et al.[1] is a condition of hypermobility that may lead to numerous conditions and injuries of the foot, ankle, lower leg, knee, hip and low back. Root et al. assessed pronation by measuring calcaneal position, subtalar neutral position and the passive range of motion at the subtalar joint when the subject was in open kinetic chain position. The specific open kinetic chain position they employed required the subject to lie prone on a table with his/her feet hanging over the edge. The non-weight bearing technique Root et al. used to measure pronation remains in use today despite reports of inconsistent measurements between examiners. [32-34] As a result, static weight bearing assessment techniques of pronation, such as the navicular drop test [2] and standing foot angle [8,24], have been examined for their reliability and accuracy. [24, 32-34]

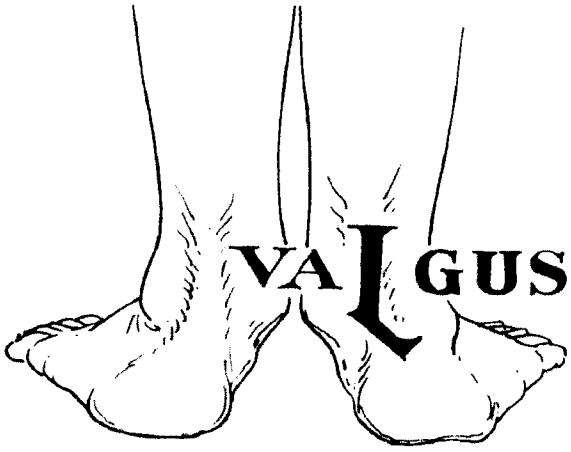

Figure 3.1. Excessive pronation of the foot and the associated valgus (abduction) deformity. (Source: Hoppenfeld, 1979)

The **navicular drop test** is a measurement of foot pronation that is commonly credited to Brody. [2] However, Schuster [39] first proposed the concept in 1956. The navicular drop test is a measure of the change in the height of the navicular tubercle relative to the ground when measured in static, closed kinetic chain, partial weight bearing and full weight bearing positions (Figure 3.2). [2] Brody et al.[2] considered side-to-side differences in navicular drop test results greater than 15 mm to be "abnormal", while those ≤ 10 mm displacement were defined as "normal".

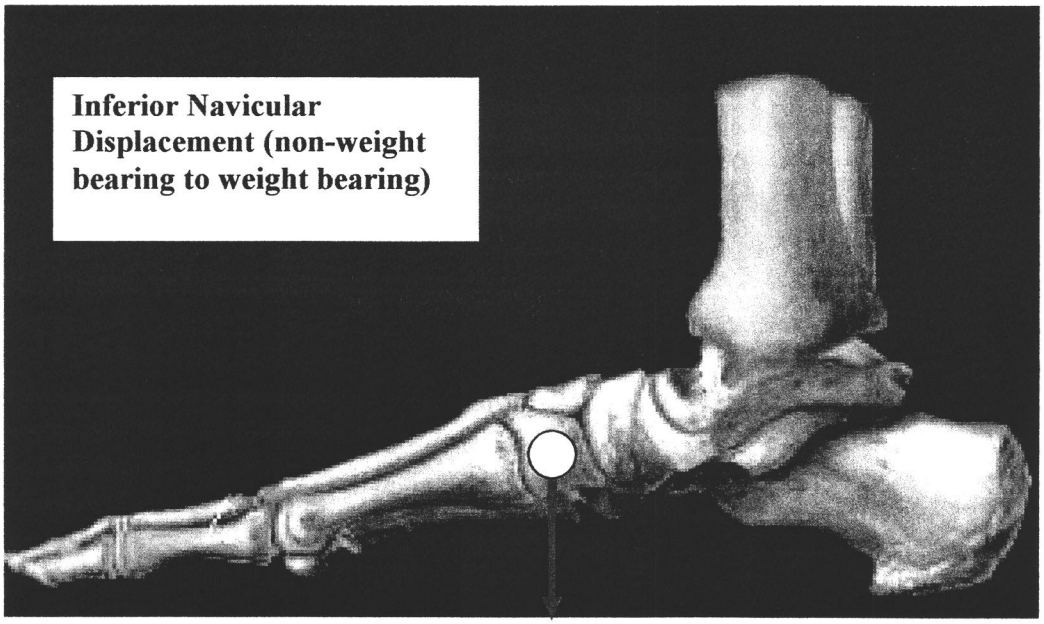

Figure 3.2. Navicular drop test illustration.

The clinical test known as the **standing foot angle** uses three anatomical landmarks to evaluate pronation of the foot. The angle formed between the medial malleolar-navicular tubercle segment and the navicular tubercle-first

metatarsal head segment is the angle assessed in this clinical measurement (Figure 3.3). [8,24] Dahle et al. [8] reported the normal range for standing foot angle to be 120-150°. These authors defined standing foot angles less than 120° as a "pronating foot" while larger angles are indicative of a "supinating foot". Unlike the navicular drop test, there is no definition of what angle constitutes a pathological standing foot angle.

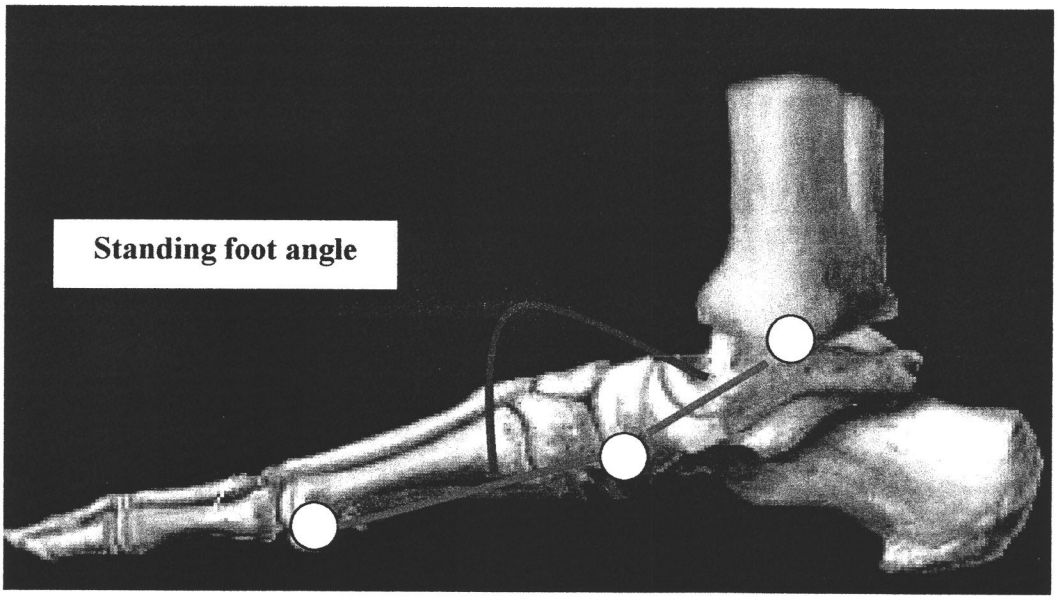

Figure 3.3. Standing foot angle illustration.

Frequently in clinical settings, pronation of the foot is estimated using an open and/or closed kinetic chain static measurement due to the time required and costs associated with obtaining a three-dimensional biomechanical analysis. Unfortunately, uniplanar static measurements do not fully capture the complexity of the foot pronation, nor do they reflect the effects of the forces placed upon the foot during locomotion activities.

Three-dimensional kinematic analysis of the foot and ankle quantifies human motion with greater accuracy than two-dimensional analysis techniques. [59,60] There is limited evidence of the relationship between the static tests and the complex, multi-planar movement of the tarsal navicular during pronation. [61] Cornwall and McPoil [61] reported that navicular tubercle movement during overground walking, as measured by the inferior navicular movement, was highly correlated ($r = 0.94$) with rearfoot motion, as quantified by a (three dimensional) electromagnetic motion analysis system.

Foot length [39,86], foot type [62-64], arch type [1, 65,66,68-70,73,78—84,86] and/or degree of passive dorsiflexion. [24,26,85] are factors that have been associated with the amount of pronation that an individual demonstrates during gait. Arch type and height have been the most extensively studied. [1, 65,66,68-70,73,78—84,86] Nearly 40 years ago Close and Inman [73] reported a greater amount of subtalar joint motion in 'flat feet' as compared to feet with high arches. Many investigators have stated that flat feet are hypermobile, thus disposed to excessive pronation while high-arched feet are inflexible or rigid. [74,75,76] However, in more recent investigations, the variable of arch height has not produced a difference in rearfoot movement. [77,78]

Static measures of pronation continue to be widely utilized in orthopedic and podiatric assessments of lower extremity pathologies. The majority of clinicians operate under the assumption that these measures are inherently valid and reliable indicators of true dynamic motion of the foot. Unfortunately, few studies have

explored the interrelationships between the movements of the bones of the foot under static versus dynamic loads. This lack of information is due, in part, to the technical complexity of the experimental methods required for such an investigation. In an era when evidence-based medicine research findings are revising the standard of care in every medical specialty, this study is of particular importance to this area of clinical practice.

PURPOSE OF THE STUDY

The purpose of this study was to obtain static navicular drop test and standing foot angle measurements in apparently healthy women and men and compare these values with dynamic measurements obtained from three-dimensional kinematic analyses of foot motion during walking at 1.8 m/s^{-1}, running at 3.6 m/s^{-1} and drop landing from a height of 38 cm. A second purpose of the study was to identify one or more regression equations that accurately predict dynamic pronation of the foot from selected static measures for each of the three experimental conditions, e.g., walking, running, drop landing.

METHODS AND PROCEDURES

Subjects

Subjects for the study were recruited from the student population at Oregon State University in Corvallis, Oregon. Sixty apparently healthy

individuals gave their written, informed consent for participation in this study, which was previously approved by the OSU Institutional Review Board for the Protection of Human Subjects. (Appendix E) All subjects were 18 years of age or older, free from current injury involving the lower limbs, at least six months free from previous lower limb injury and at least one year after any surgery to the lower limbs. Every subject was required to possess a heel-toe gait pattern, a trait that permitted the assessment of pronation of the foot occurring early in the stance phase of gait. [1,13,16] . Due to technical difficulties with synchronization of the video cameras that were not apparent until after data collection, the kinematic data from 14 subjects (8 women, 6 men) were lost to further analysis. Complete sets of data from 46 subjects (23 women - 25.6 $\pm$ 4.9 yrs., 163.8 $\pm$ 6.2 cm., 64.7 $\pm$ 7.8 kg.; 23 men - 26.3 yrs. $\pm$ 6.2 yrs., 178.3 cm $\pm$ 9.1 cm, 81 $\pm$ 11.5 kg) were included in this analysis.

Instrumentation

To obtain three-dimensional coordinates of reflective markers that were placed on specific anatomical landmarks on the subject, four video cameras and recorders (Panasonic, Secaucus, New Jersey) that captured 60 fields per second were utilized. Two cameras captured the motion of the three medial markers located on the head of the first metatarsal, navicular tubercle and the medial malleolus of the tibia. The two remaining video cameras recorded motion of the four posterior markers (two on the Achilles tendon and two on the calcaneus).

Each pair of cameras was located approximately 90 degrees with respect to each other, while all four cameras were genlocked to synchronize framing. A computer generated event marker in each video image provided a common point in time from which to synchronize all cameras.

The video recordings of both the rearfoot and medial motion were manually digitized using Peak Performance Motus™ software version 5.0 (Peak Performance Technologies, Englewood, Colorado). A custom-made 51cm x 34 cm x 30 cm calibration structure was used. The 12 control point markers with known locations in three-dimensional space had mean reprediction error of 0.5 mm. Maximum vertical displacement of the navicular tubercle, maximum mediolateral displacement of the navicular tubercle, maximum standing foot angle, minimal standing foot angle, and maximum rearfoot pronation (eversion) were calculated from the three-dimensional position-time data.

A 12.5 cm, 180 degree plastic goniometer (Isokinetics, Inc., North Little Rock, Arkansas) was utilized to assess the static standing foot angle, passive eversion, passive inversion and passive dorsiflexion to the nearest degree.

Two infrared timing sensors (model # 63501R, Lafayette Instrument Company, Lafayette, Indiana) were utilized to verify that subjects maintained the required velocity during the walking and running conditions. The sensors were placed equidistant to the center of the force plate and four meters apart from one another. A schematic diagram of the laboratory experimental set-up is presented in Figure 3.4.

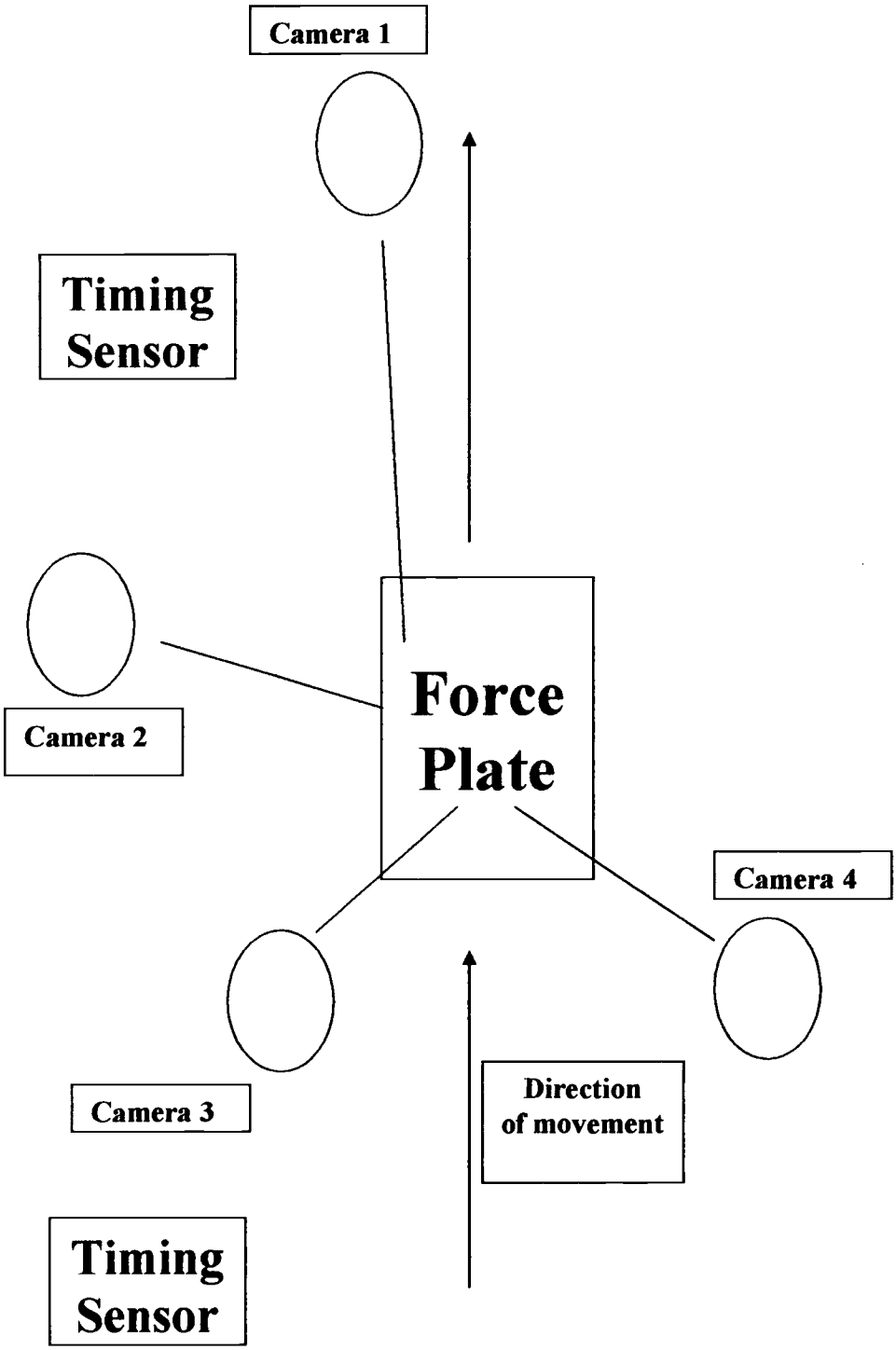

Figure 3.4. Schematic design of experimental laboratory set-up.

Experimental Procedures

Each subject was asked to come to the OSU Biomechanics Laboratory for a single data collection that took approximately 60 minutes to complete. Subjects were required to wear shorts to allow for placement of reflective markers on the skin of the shank and foot. Prior to data collection, each subject completed demographic and anthropometric questionnaires (Appendix F).

After completion of the questionnaire, the same investigator (KHD) measured height, weight, foot length, foot type, arch type and passive range of motion for dorsiflexion, inversion and eversion. In addition, static measurements of the navicular drop test and the standing foot angle were obtained.

To measure the movement of the navicular tubercle during the navicular drop test the subject was asked to stand with his/her right foot approximately two inches in front of the left, placing as little of body weight as possible on the forward foot. The subject was required to maintain a position that kept the plantar surface of the foot in complete contact with the floor. Using the closed kinetic chain talar congruency method described by Picciano et al. [33], the subject's forward foot was positioned in subtalar joint neutral. The first measurement of the navicular drop test was obtained in a non-weight bearing position by placing an index card (7.6 cm x 12.7 cm) perpendicular to the floor on the medial aspect of the foot, and marking the position of the navicular tubercle on the card. The subject was then asked to put full weight on the front foot. The second measurement of the navicular drop test was obtained by placing the same index

card against the medial aspect of the foot and making a second mark on the card at the level of the navicular tubercle during full weight bearing.

The standing foot angle was assessed by a single measurement where the subject was asked to stand on his/her right foot. A goniometer was used to measure the angle between the navicular tubercle and the first metatarsal segment, and the navicular tubercle and medial malleolus segment. [24]

Prior to marker placement for the three-dimensional analysis, each subject was required to warm-up for five minutes on a stationary bike while maintaining a rate of about 80 rpm and a resistance level of 1 to 2 kpm. The subject then performed static stretching exercises for the muscles of the lower extremity, particularly the posterior muscles of the shank. The calf was stretched by pushing the heel to the ground while pushing against the wall (3 repetitions, each held for 12 seconds).

With the subject in a prone position on a table, seven 10 mm diameter retro-reflective markers were placed on the skin over the following bony landmarks of the right limb: center of the medial malleolus, navicular tubercle, center of the first metatarsal head (medial aspect), two on the posterior aspect of the calcaneus, and two on the posterior aspect of the Achilles tendon (Figure 3.5). The markers were held in position with double-sided adhesive tape (Scotch 3M, St. Paul, Minnesota).

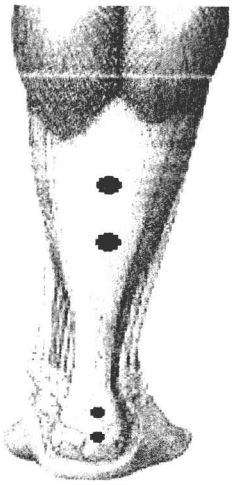

Figure 3.5. Posterior marker placement.

The subject was then positioned with his/her right foot on the force plate to ensure that all markers were clearly visible in the appropriate cameras. Following this procedure the subject practiced walking, running and drop landings on the force plate using a counterbalanced design to control for order bias and muscle fatigue. The required walking (1.8 m/s $^{-1}$) and running speeds (3.6 m/s $^{-1}$) were verified by two timing sensors set four meters apart along the walkway.

Each subject determined the best starting point on the walkway in order to consistently place his/her right foot in the center of the force plate while walking at the required velocity. Once the proper distance had been determined, a mark was taped to the floor so the subject could return to that location for each trial. In addition, the subject was encouraged to walk through the data collection area at the same pace by asking him/her to maintain the walking pace to a location

beyond the second timing sensor. This helped to eliminate any premature slowing of the gait.

A successful walking trial was defined as one in which the subject's gait speed was within $\pm$ 1.5% ($\pm$ 0.03 s) of the required 1.8 m/s $^{-1}$ pace. Five walking trials that met this criterion were recorded for later analysis. [61]

The running condition was initiated by asking the subject to practice running at a rate of 3.6 m/s^{-1}. Using the identical procedure as in the walking trials, each subject was asked to find a starting position that allowed for consistent placement of the right foot on the force plate. A successful running trial was defined as one in which the subject's speed was within $\pm$ 3.0% ($\pm$ 0.03 s) of the required pace. Five running trials that met this criterion were recorded for later analysis.

The drop landing condition consisted of stepping off of a 38 cm box onto the force plate. The sequence of landing and loading of the foot was from the toes to the heel, opposite that of walking and running. The subject was asked to land on his/her right foot and make contact with the heel before touching down on the left foot for balance. A successful drop landing trial was defined as one in which the toe-heel pattern was evident and both feet were completely on the force plate. As with the walking and running conditions, five successful trials were recorded for data reduction and statistical analysis.

Statistical Analysis

To determine the nature of the relationships between selected static measures of pronation and dynamic measures obtained from three-dimensional kinematic analyses of walking, running and drop landing, a Pearson product moment correlation matrix was developed using the Statistical Package for the Social Sciences software, version 11.0.1 (SPSS, Inc., Chicago, Illinois). The critical alpha level for all correlations was set at 0.05.

To effort to identify one or more regression equations that accurately predicted dynamic pronation of the foot during walking, running, drop landing from selected static measures of pronation, we again employed the SPSS software, version 11.0.1.

Prior to running the multiple regression analyses with SPSS, we performed an exploratory "Best Subsets" regression analysis with Minitab, version 13.0 (MINITAB, Inc., State College, Pennsylvania) to determine which predictor variables should be included in each of the six linear regression equations to be calculated with SPSS. The 13 possible predictor variables were: height, weight, gender, ethnicity, age, foot type, arch type, foot length, static navicular drop test, standing foot angle, passive dorsiflexion, passive inversion range of motion and passive eversion range of motion. The Minitab analyses were used to identify a maximum of five predictor variables that resulted in the optimal R^2 value. Given on our sample size and number of predictor variables, we followed the recommendation of Tabachnick and Fidell (1989) and imposed a

limit of no more than five predictor variables for any one regression equation. [88] Statistical significance for all (forward) linear regression analyses with SPSS software was established at $\alpha = 0.05$.

RESULTS

A total of 60 subjects were recruited and completed all aspects of this study. Technical problems with synchronization of the four video cameras used to obtain the kinematic data resulted in incomplete data sets for 14 subjects. As a result, the data from 46 subjects (23 women, 23 men) were included in the analyses. Subject demographic characteristics are summarized in Table 3.1.

Variable	Mean	Standard Deviation	Range
Age	26.0 yrs	5.4	20 to 39 yrs
Height	170.7 cm	10.5	156 to 195 cm
Weight	73.6 kg	13.2	50.9 to 108.2 kg
Navicular Drop Test	4.3 mm	2.4	0 to 9.5 mm
Standing Foot Angle	123.7 deg	8.3	108 to 140 deg
Passive Dorsiflexion ROM	15.9 deg	4.1	8 to 23 deg
Passive Eversion ROM	5.0 deg	1.2	3 to 8 deg
Passive Inversion ROM	16.7 deg	2.9	10 to 22 deg
Foot Length	26.2 cm	2.0 cm	22.9 to 29.7 cm

ROM = range of motion

Table 3.1. Subject Demographic Data (N = 46).

Arch type [1, 65,66,68-70,73,78—84,86] and foot type [62-64] are thought to be related to pronation of the foot . Arch type was classified as either "normal", "pes planus" or "pes cavus", while foot type was described as either "Egyptian", "Morton's", or "Square". [35] The results of these observations and clinical evaluations are presented in Table 3.2.

CATEGORY	SUBJECTS (N = 46)	PERCENT
Ethnicity		
White	36	78.3%
Asian	7	15.3%
Pacific Islander	1	2.2%
Black	1	2.2%
Total	**46**	**100.0%**
Sex:		
Female	23	50.0%
Male	23	50.0%
Total	**46**	**100.0%**
Arch Type		
Normal	23	50.0%
Pes planus	15	32.6%
Pes cavus	8	17.4%
Total	**46**	**100.0%**
Foot Type		
Egyptian	40	87.0%
Morton's	4	8.7%
Square	2	4.3%
Total	**46**	**100.0%**

Table 3.2. Subject Ethnicity, Sex, Arch Type and Foot Type (N = 46).

The three-dimensional motion analysis evaluated two clinical tests of pronation in 46 subjects. Dynamic data evaluating the navicular drop test and the standing foot angle during three conditions (walk, run and drop landing) is presented in Table 3.3.

Variable	Mean	Standard Deviation	Range
Dyn NDT walk	4.8 mm	2.1 mm	1.6 to 10.1 mm
Dyn NDT run	7.0 mm	3.2 mm	1.0 to 13.7 mm
Dyn NDT drop landing	7.4 mm	3.8 mm	2.0 to 15.6 mm
Dyn SFA walk	145.8 deg	12.1 deg	123.9 to 162.9 deg
Dyn SFA run	139.6 deg	11.8 deg	119.4 to 157.1 deg
Dyn SFA drop landing	137.9 deg	11.3 deg	117.2 to 157.9 deg

DynNDT walk = dynamic navicular drop movement during walking; DynNDT run = dynamic navicular drop movement during running; DynNDT drop landing = dynamic navicular drop movement during drop landing; Dyn SFA walk = dynamic standing foot angle during walking; DynSFA run = dynamic standing foot angle during running; DynSFA drop landing = dynamic standing foot angle during drop landing.

Table 3.3. Dynamic Kinematic Data (N = 46).

The presentation of results is divided into two major sections, with both describing the interrelationships among measures of pronation. In the first section, the results of Pearson product moment correlations between static (anthropometric) and dynamic measures of pronation are presented. In the second section, the results of multiple linear regression analyses using anthropometric and static measures of pronation to predict foot motion under the dynamic loading conditions of walking, running and drop landing are presented. Table 3.4 contains a glossary of the abbreviations used for the actual kinematic parameters used in the regression analyses.

Kinematic parameter	Abbreviation
Static navicular drop test	Static NDT
Static standing foot angle measurement	Static SFA
Dynamic navicular drop movement during walking	Dyn#NDT walk
Dynamic navicular drop movement during running	Dyn#NDT run
Dynamic navicular drop movement during drop landing	Dyn#NDT drop landing
Dynamic standing foot angle during walking	Dyn#SFA walk
Dynamic standing foot angle during running	Dyn#SFA run
Dynamic standing foot angle during drop landing	Dyn#SFA drop landing

Table 3.4 Glossary of regression analysis terms

Navicular Drop Test : Static versus Dynamic Measurements

While statistically significant at the $p < 0.05$ level, poor to moderate positive relationships existed between the static, clinical navicular drop test and the dynamic navicular movement during the walking and running conditions (Pearson product moment $r = 0.292$ to 0.359, respectively). The inferior movement of the tarsal navicular during the drop landing condition was also significantly correlated with the static navicular movement (Pearson product moment $r = 0.350$) (Table 3.5).

			Static NDT	Dyn#NDT - walk	Dyn# NDT - run	Dyn# NDT - drop
Pearson product moment	Static NDT	Correlation Coefficient	1.000	.292(*)	.359(*)	.350(*)
		Sig. (2-tailed)	.	.047	.012	.013

* Correlation is significant at the 0.05 level (2-tailed).

Table 3.5. Static versus dynamic navicular drop correlations.

Standing Foot Angle: Static versus Dynamic Measurements

There were no significant relationships between static standing foot angle and the dynamic standing foot angle measured during the walking, running and drop landing conditions ($p > 0.05$) (Table 3.6).

			Static SFA	Dyn# SFA - walk	Dyn# SFA - run	Dyn# SFA - jump
Pearson product moment	Static SFA	Correlation Coefficient	1.000	.040	-.087	-.159
		Sig. (2-tailed)	.	.785	.564	.292

** Correlation is significant at the 0.01 level (2-tailed).

Table 3.6. Static versus dynamic standing foot angle correlations.

MULTILEVEL REGRESSION ANALYSES

Dynamic Navicular Drop

Preliminary data screening to identify the best explanatory variables for dynamic navicular drop was performed using the "best subsets" function available with MINITAB version 13.0 (MINITAB, Inc., State College, Pennsylvania). We had a total of 13 explanatory variables that could be used in the multilevel regression analysis equations. According to Tabachnick and Fidell [88], with a sample size of 46 subjects, no more than five explanatory variables should be included in any multilevel regression equation. The results of the "best subsets" analyses for predicting dynamic navicular drop for the walking, running, and drop landing conditions are presented in Tables 3.7, 3.8 and 3.9, respectively.

Best Subsets	Dynamic Navicular Drop - Walking Condition	R	R^2
Best 1	1. Static navicular drop test	.392	.104
Best 2	1. Static navicular drop test 2. Foot type	.425	.165
Best 3	1. Static navicular drop test 2. Foot type 3. Arch type	.483	.217
Best 4	1. Weight 2. Foot type 3. Arch type 4. Static navicular drop test	.538	.289
Best 5	*Not applicable*		

Table 3.7. Best explanatory variable subsets for walking condition with dynamic navicular drop as the dependent variable.

Best Subsets	Dynamic Navicular Drop - Running Condition	R	R^2
Best 1	1. Arch type	.395	.156
Best 2	1. Foot type 2. Arch type	.522	.272
Best 3	1. Foot type 2. Arch type 3. Passive inversion ROM	.587	.345
Best 4	1. Foot type 2. Arch type 3. Passive dorsiflexion ROM 4. Static navicular drop test	.652	.425
Best 5	1. Foot type 2. Arch type 3. Passive dorsiflexion ROM 4. Static navicular drop test 5. Passive inversion ROM	.729	.531

Table 3.8. Best explanatory variable subsets for running condition with dynamic navicular drop as the dependent variable.

Best Subsets	Dynamic Navicular Drop – Drop Landing Condition	R	R^2
Best 1	1. Static standing foot angle	.379	.144
Best 2	1. Arch type 2. Static navicular drop test	.507	.257
Best 3	1. Arch type 2. Static standing foot angle 3. Static navicular drop test	.559	.312
Best 4	1. Arch type 2. Static standing foot angle 3. Static navicular drop test 4. Age	.597	.357
Best 5	1. Arch type 2. Foot type 3. Age 4. Passive inversion ROM 5. Static navicular drop test	.655	.429

Table 3.9. Best explanatory variable subsets for drop landing condition with dynamic navicular drop as the dependent variable.

The results of the multilevel regression analyses to predict dynamic navicular drop during walking, running, and drop landing are summarized in Tables 3.10, 3.11 and 3.12. We observed that each of the regression models used to explain dynamic navicular movement during walking, running, and drop landing were statistically significant ($p < 0.05$). The explained variance of the model for the running condition was the largest at $R^2 = .531$ while the model for walking showed the least explained variance with $R^2 = .289$. The predictor variables that were found to partially explain dynamic navicular drop were different for the walk, run and drop landing conditions. There were, however,

three common explanatory variables common to all conditions: foot type, arch type, and static navicular drop test.

For walking, the static navicular drop measurement was the explanatory variable that best explained dynamic navicular drop (10.4%, $p < 0.05$). In this regression model, $R = .538$ while $R^2 = .289$ ($p < 0.015$) (Table 3.10).

Parameters	**Regression coefficients**	**Standard Error**
Constant	2.420	1.007
Weight	-.009	.006
Foot type	.386	.181
Pes cavus	-.329	.188
Pes planus	-.218	.144
Static navicular drop test	.068	.032

[a] Total explained variance = 0.289, $p < 0.05$

Table 3.10. Regression coefficients and standard errors from a multilevel regression analysis with the natural log transformed *Dynamic Navicular Drop-Walking* as the dependent variable and weight (kg), foot type and static navicular drop (mm) as explanatory variables.

For the running condition, arch type was the explanatory variable that best explained dynamic navicular drop (15.6%, $p < 0.05$). In this regression equation, $R = .729$ while $R^2 = .531$ ($p < 0.0001$) (Table 3.11).

Parameters	Regression coefficients	Standard Error
Constant	-2.957	2.621
Foot type	3.835	1.094
Pes cavus	-3.505	1.140
Pes planus	-2.719	.862
Passive dorsiflexion ROM	.202	.093
Static navicular drop test	.460	.182
Passive inversion ROM	.173	.131

[a] Total explained variance = 0.531, $p < 0.0001$

Table 3.11. Regression coefficients and standard errors from a multilevel regression analysis *Dynamic Navicular Drop-Running* as the dependent variable and foot type, passive dorsiflexion ROM (deg), static navicular drop (mm) and passive inversion ROM (deg) as explanatory variables.

For the drop landing condition, standing foot angle was the explanatory variable that best explained dynamic navicular drop (14.4%, $p < 0.05$). In this regression model, R = .655 while R^2 = .429 ($p < 0.001$) (Table 3.12).

Parameters	Regression coefficients	Standard Error
Constant	1.686	3.898
Age	-.138	.091
Foot type	2.915	1.431
Pes cavus	-1.855	1.520
Pes planus	-3.571	1.120
Static navicular drop test	.726	.245
Passive inversion ROM	.322	.166

[a] Total explained variance = 0.429, $p < 0.001$

Table 3.12. Regression coefficients and standard errors from a multilevel regression analysis *Dynamic Navicular Drop-Drop Landing* as the dependent variable and age (yrs), foot type, static navicular drop (mm) and passive inversion ROM (deg) as explanatory variables.

Dynamic Standing Foot Angle

We used the identical Minitab preliminary data screening technique previously described to identify the best explanatory variables for the regression equations to predict dynamic standing foot angle. The results of the "best subsets" analyses for predicting dynamic standing foot angle during the walking, running, and drop landing experimental conditions are presented in Tables 3.13, 3.14 and 3.15 respectively.

Best Subsets	Dynamic Standing Foot Angle – Walking Condition	R	R^2
Best 1	1. Passive eversion ROM	.491	.241
Best 2	1. Passive eversion ROM 2. Ethnicity	.550	.302
Best 3	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM	.585	.342
Best 4	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM 4. Weight	.611	.373
Best 5	*Not applicable*		

Table 3.13. Best explanatory variable subsets for walking condition with dynamic standing foot angle as the dependent variable.

Best Subsets	Dynamic Standing Foot Angle – Running Condition	R	R^2
Best 1	1. Passive eversion ROM	.462	.213
Best 2	1. Passive eversion ROM 2. Ethnicity	.511	.261
Best 3	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM	.551	.303
Best 4	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM 4. Weight	.596	.355
Best 5	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM 4. Weight 5. Foot length	.608	.370

Table 3.14. Best explanatory variable subsets for running condition with dynamic standing foot angle as the dependent variable.

Best Subsets	Dynamic Standing Foot Angle – Drop Landing Condition	R	R^2
Best 1	1. Passive eversion ROM	.392	.154
Best 2	1. Passive eversion ROM 2. Ethnicity	.471	.222
Best 3	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM	.503	.253
Best 4	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM 4. Weight	.561	.315
Best 5	1. Passive eversion ROM 2. Ethnicity 3. Passive dorsiflexion ROM 4. Weight 5. Foot length	.574	.330

Table 3.15. Best explanatory variable subsets for drop landing condition with dynamic standing foot angle as the dependent variable.

The results of the multilevel regression analyses to predict dynamic standing foot angle during walking, running, and drop landing are summarized in Tables 3.16, 3.17 and 3.18. All three regression models used to predict dynamic standing foot angle were statistically significant ($p < 0.05$). Unlike the prediction equations for dynamic navicular drop, the explanatory variables for dynamic standing foot angle were the same in every regression equation across experimental conditions, e.g., walking, running, drop landing. The variables were: passive eversion ROM, ethnicity, passive dorsiflexion ROM, weight and foot length. The explained variance was the greatest for the walking condition (R^2

= .373) while the model for drop landing had the least explained variance with R^2 = .330.

Passive eversion range of motion was the explanatory variable that best explained dynamic standing foot angle during walking (24.1%, $p < 0.05$). In this regression model, R = .611 while R^2 = .373 ($p < 0.001$) (Table 3.16).

Parameters	**Regression coefficients**	**Standard Error**
Constant	138.953	14.589
Ethnicity	7.847	3.600
Weight	.078	.055
Passive dorsiflexion ROM	.771	.389
Passive eversion ROM	-4.872	1.245

[a] Total explained variance = 0.373, $p < 0.001$

Table 3.16. Regression coefficients and standard errors from a multilevel regression analysis *Dynamic Standing Foot Angle -Walking* as the dependent variable and ethnicity, weight (kg), passive dorsiflexion ROM (deg), and passive eversion ROM (deg) as explanatory variables.

For the running condition, passive eversion range of motions was the explanatory variable that best explained dynamic static foot angle (21.3%, $p < 0.05$). In this regression equation, R = .608 while R^2 = .370 ($p < 0.002$) (Table 3.17).

Parameters	Regression coefficients	Standard Error
Constant	151.862	29.049
Weight	.155	.079
Ethnicity	6.810	3.575
Foot length	-1.208	1.235
Passive dorsiflexion ROM	.721	.399
Passive eversion ROM	-4.513	1.237

[a] Total explained variance = 0.373, $p < 0.001$

Table 3.17. Regression coefficients and standard errors from a multilevel regression analysis *Dynamic Standing Foot Angle -Running* as the dependent variable and weight (kg), ethnicity, foot length (cm), passive dorsiflexion ROM (deg) and passive eversion ROM (deg) as explanatory variables.

For the drop landing condition, passive eversion range of motion was the explanatory variable that best explained dynamic standing foot angle (15.4%, $p < 0.05$). In this regression model, $R = .575$ while $R^2 = .330$ ($p < 0.005$) (Table 3.18).

Parameters	Regression coefficients	Standard Error
Constant	144.867	28.755
Weight	.157	.078
Ethnicity	7.696	3.538
Foot length	-1.171	1.223
Passive dorsiflexion ROM	.637	.395
Passive eversion ROM	-3.609	1.225

[a] Total explained variance = 0.330, $p < 0.005$

Table 3.18. Regression coefficients and standard errors from a multilevel regression analysis *Dynamic Standing Foot Angle –Drop landing* as the dependent variable and weight (kg), ethnicity, foot length (cm), passive dorsiflexion ROM (deg) and passive eversion ROM (deg) as explanatory variables.

DISCUSSION

The purpose of this study was to obtain static navicular drop test and standing foot angle measurements in 46 healthy women and men and compare these values with dynamic measurements obtained from three-dimensional kinematic analyses of foot motion during walking at 1.8 m/s $^{-1}$, running at 3.6 m/s $^{-1}$ and drop landing from a height of 38 cm. A second purpose was to identify one or more regression equations that accurately predict dynamic pronation of the foot from selected static measures for each of the three experimental conditions, e.g., walking, running, drop landing.

Static versus Dynamic Measures of Pronation

The static navicular drop test values were significantly correlated in the positive direction with the dynamic measures of inferior navicular movement obtained during the walking, running and drop landing experimental conditions. These results are consistent with the conclusions drawn by Cornwall and McPoil (1999), who determined that the navicular drop test was a good indicator of dynamic navicular movement during walking. [42] Cornwall and McPoil observed a dynamic mean maximum vertical displacement for the navicular to be 5.9 ± 2.8 mm and compare favorably to the mean dynamic navicular displacement (4.7 ± 2.1 mm) found in our investigation during the walking condition.

The correlations we observed between the static navicular drop test results and navicular motion quantified during the walking, running and drop landing conditions were low, Pearson's product moment $r = .292$, .359 and .350, respectively. While these values were statistically significant, the correlations were categorized as "poor". [89] Therefore, the utility of clinical navicular drop test as a method of estimating how the navicular responds under the dynamic loads encountered during gait remains in doubt.

The static navicular drop test values were poorly correlated with the dynamic inferior navicular movement measured during drop landings ($r = .350$, $p > .05$). One possible explanation for the lack of a stronger correlation between these measures is the kinematic differences between the dynamic loading of the foot during drop landings compared to walking and running. The loading

sequence of the foot in drop landings is opposite that of the other two conditions, with the toes and metatarsal-phalangeal joints landing first followed by the midfoot and rearfoot. While each subject was asked to touch their heel to the force plate prior to stepping forward, it is possible that the individual's entire body weight was not distributed to the navicular, talus and calcaneus.

A second possible explanation for the low correlations between static and dynamic measures of pronation during drop landings may be attributed to the windlass mechanism. [86] As the metatarsophalangeal joints hyperextend, the plantar fascia, muscles and ligaments supporting the longitudinal arch becomes taut. This tension transforms the foot into a rigid lever for push-off during gait. As the soft tissue becomes taut, there is little movement of the bones being supported by soft tissues, therefore little navicular drop. [86] It is possible that, due to the sequence of the landing (metatarsophalangeal joint hyperextension), that the foot becomes 'stiff' prior to the 'foot flat' position.

We were surprised by the lack of significant correlation between static and dynamic standing foot angle measurements in any of the three experimental conditions. This result could be explained by a number of areas where measurement error may have occurred or it could simply be a poor indicator of navicular movement. This clinical test of pronation requires the identification of three bony landmarks as opposed to a single landmark (navicular drop test). Therefore, a greater chance for error during marker placement exists. The markers used in the three dimensional analyses were located on the surface of the

skin and thus, may be influenced by underlying soft tissue movement. Finally, pronation is a three-dimensional movement and standing foot angle simply assesses movement in a single plane.

The literature on the clinical significance of the standing foot angle is very sparse. Dahle et al. [8] reported the normal range for standing foot angle to be 120 to 150°. Standing foot angles less than 120° are defined, by these authors as a "pronating foot" while larger angles would be indicative of a "supinating foot". Sommer and Vallentyne [24] examined the correlation between foot alignment and medial tibial stress syndrome and found that the group with medial tibial stress syndrome had a mean static standing foot angle of 137 degrees while the control (non-injured group) had a mean static standing foot angle of 145 degrees ($p < 0.0001$).

The navicular drop test, a static measurement, has been shown to be a valid and reliable test of inferior navicular translation when assessed as an individual moves from a non-weight bearing to a weight bearing position. ([32-34,36-38]) No published evidence has been found regarding the validity of the standing foot angle, but Sommer and Vallentyne [24] reported the test to have good intertester reliability (ICC = .69).

In advance of this investigation, the principal investigator (KHD) conducted a pilot study to assess the intratester reliability of the standing foot angle measurement. Static standing foot angle measurements were obtained from 29 feet on two consecutive days, resulting in an "excellent" intratester reliability

($ICC_{2,1}$ = .840, SEM = 4.2 deg). Therefore, the measurement itself can be consistently performed by a single evaluator over time.

Regression Analysis

Pronation of the foot has proven to be a difficult motion to assess due to the multiple joints involved and the uniqueness of the axes around which the motion occurs. [1,5-7,10,12,36,60,73,77] In addition, the cost, equipment, and time associated with three-dimensional motion analysis makes it impractical to utilize in the clinical setting.

Due to the injuries and conditions that are thought to be associated with excessive pronation, several researchers have attempted to identify the anthropometric variables that might influence foot motion. [4,6,8,11,47,63,65-66,70-71,74,77,79,80,82] There have been conflicting reports on the best static measure of pronation. [24,32,33,34,38,40,41,44] Cavanagh et al. [87] did not evaluate pronation, but with a similar purpose, examined 27 foot measurements taken from radiographs in an exploration into peak plantar pressure under the heel and the first metatarsal head. While the measurements themselves were found to be very reliable, only 31% (heel) and 38% (first metatarsal head) of the variance in peak plantar pressure could be explained by the 27 predictor measurements. [87] This landmark study was a poignant indicator of the difficulty in predicting dynamic motion of the foot from static measurements.

Dynamic navicular drop regression equations

The inferior navicular movement, when assessed dynamically, showed the greatest amount of explained variance (R^2=.531) during the running condition and the least during the walking condition (R^2=.291). In previous studies, the ground reaction forces have consistently been dependent upon the tested speed of the gait, e.g., walk, run, with GRFs increasing as the speed of the gait increases. [53-56] Monro et al. [55] observed that the average vertical ground reaction force increased significantly from 1.40 BW at 3.0 m/s^{-1} to 1.70 BW at 5.0 m/s^{-1}. The walking velocity for this study was set at 1.8 m/s^{-1} while the running velocity was 3.8 m/s^{-1}.

There were three common predictor variables in each of the dynamic navicular drop regression equations: foot type, arch type and static navicular drop test. Foot type has been addressed in two studies that evaluated the pressure distribution of the Morton's (Greek) foot structure compared to 'normals' (Egyptian foot). [11,64] The pressure pattern of contact was the same for both, but a significantly greater amount of pressure was found over the second metatarsal-phalangeal joint in the Morton's foot group. Pronation of the foot involves internal rotation of the first metatarsal bone at the metatarsal-phalangeal joint. It seems that this movement would be exacerbated in an individual with a Morton's foot structure and, as a compensatory movement, the external rotation of the talonavicular joint would increase (pronation).

Arch type and static navicular drop are the two most common predictor variables used to assess incidence of foot injury in the current literature. [1, 65,66,68-70,73,78—84,86] Studies by Cowan et al. and Gilaldi et al. both reported that military recruits with low arches had a significantly lower incidence of injury. [79,80] Our results supported the importance of arch height and static navicular drop as indicators of dynamic navicular movement. However, the practical meaning and application of the various explanatory variables in regression equations needs to be explored in future studies. Specifically, factors such as weight and ankle/subtalar joint range of motion can be modified in subjects, while foot type and arch type are factors that cannot be modified.

Standing foot angle regression equations

The angle formed by the intersection of the three bony landmarks of the foot accounted for only 37% of the explained variance during walking and running, and 33% for the drop landing condition. These values are very similar to what Cavanagh et al. observed when predicting foot pressure from multiple radiographic foot measurements. [87]

The predictor variables for standing foot angle in each of the three experimental conditions were the same: passive eversion, ethnicity, passive dorsiflexion, weight, and foot length. We were surprised by the consistency of the variables across all dynamic loading conditions as it was very different from what we observed with the navicular drop test. Further investigation is warranted

for the variable ethnicity due to the small number of individuals that were non-Caucasian. Pronation involves eversion of the subtalar joint, therefore, it follows that the more eversion range of motion an individual has the more pronation they will have. The posterior tibialis muscle inserts on many bones of the foot, but has a primary insertion site on the navicular. With larger amounts of passive dorsiflexion, the stiffness of the posterior tibialis muscle may be diminished due to elongation strain. This may, in turn, allow for greater amounts of inferior navicular movement. Arangio et al. determined that five degrees of pronation, relative to the neutral foot, increases the load to the medial longitudinal arch by 22%, while increasing the moment at the talonavicular joint increases by 47%. (90)

Foot length has been explored in conjunction with arch height by Williams and McClay (2000) as a means of classifying arch type. These authors determined truncated foot length (calcaneus to metatarsal heads) divided by dorsum height to be the most reliable measure of arch height whether the individual is in a weight bearing or non-weight bearing position. Further study needs to be done to determine the extent to which foot length and weight are indicators of the amount of pronation.

Finally, the viscoelastic nature of all human tissues may play a significant role in explaining our observations. Due to these viscoelastic properties, the static and dynamic tissues of the foot respond to increases in loading rate with increased mechanical stiffness and ultimate failure strength. We quantified navicular

displacement and standing foot angle during walking, running and drop landing, experimental conditions that likely had significant differences in loading rate. Unfortunately, the *in vivo* measurement of loading rate and strain rate of the anatomical structures of the foot were beyond the scope of our present study. Therefore, it is difficult to determine if either of the clinical static tests we employed accurately reflect the true physiological loads that the soft tissues encounter during locomotion and drop landings.

Conclusions

The static standing foot angle measurements were poorly correlated with the standing foot angles assessed during the dynamic conditions, e.g., walking, running, drop landing. The best combinations of predictor variables in the regression equations for dynamic standing foot angle explained only 33 to 37% of the common variance. Our results suggest that clinicians not use the static standing foot angle as an evaluation tool for pronation, or at the very least, apply their clinical test results with caution.

Dynamic movement of the navicular was best described by the regression equation formulated for the running condition. This equation, combining the explanatory variables of weight, foot type, arch type, and static navicular drop test, accounted for 53% of the dynamic inferior navicular motion observed. While the running condition regression equation explained more common variance than did the walking and drop landing equations, nearly half (47%) of

the causes of dynamic navicular drop remain unidentified at the conclusion of our study. Thus, the clinical value and practical significance of the three regression equations to predict dynamic navicular motion from static anthropometric variables are unknown, and characterize the inherent risks associated with trying to generalize the results of static tests to dynamic conditions.

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Chapter 4

CONCLUSIONS

Taken on the whole, the findings of these two research studies support the continued use of the navicular drop test as an indicator of dynamic navicular displacement. The strength of the relationship between static and dynamic measures of navicular displacement, while statistically significant, was low to moderate (rho < .40). Future research efforts should employ state-of-the-art three-dimensional motion analysis and diagnostic imaging technology to capture the movement of the foot under dynamic loading conditions, e.g., functional magnetic resonance imaging.

Based upon radiographic measurements, we concluded that the navicular drop test was a valid measurement of inferior navicular displacement as an individual moved from the non-weight bearing to weight-bearing position. Our research also demonstrated that the navicular drop test was highly repeatable between tests and experienced clinicians

In contrast, the Feiss' line measurement was shown not to be a valid measure of navicular movement when explored with radiographs. Therefore, the continued use of this measure as a clinical test of pronation was not supported by our findings.

The static standing foot angle measurements were poorly correlated with the standing foot angles assessed during the dynamic conditions, e.g., walking, running, drop landing. The best combinations of predictor variables in the regression equations for dynamic standing foot angle explained only 33 to 37% of the common variance. Our results suggest that clinicians not use the static standing foot angle as an evaluation tool for pronation, or at the very least, apply their clinical test results with caution

Dynamic movement of the navicular was best described by the regression equation formulated for the running condition. This equation, combining the explanatory variables of weight, foot type, arch type, and static navicular drop test, accounted for 53% of the dynamic inferior navicular motion observed. While the running condition regression equation explained more common variance than did the walking and drop landing equations, nearly half (47%) of the causes of dynamic navicular drop remain unidentified at the conclusion of our study. Thus, the value and practical significance of the three regression equations to predict dynamic navicular motion from static anthropometric variables are unknown.

The results of this dissertation point out the limitations of a regression model that attempts to predict dynamic navicular motion and standing foot angle from static parameters. Simultaneously, this conclusion provides support for further research to identify new dynamic measures of foot function, as well as different static anthropometric variables, that might better explain the kinematics of the foot under dynamic loading conditions.

APPENDICES

APPENDIX A

REVIEW OF LITERATURE

REVIEW OF LITERATURE

In an effort to obtain a more complete understanding of the etiology of lower extremity injuries, researchers have long studied the form and structure of the human foot. [1-12] The foot is an anatomically complex structure that functions as both a compliant shock absorber and rigid lever arm during locomotion. [1,12,13] These paradoxical functions are accomplished through interarticulation of the 26 bones. These 22 joints include the subtalar joint, the talonavicular and the calcaneocuboid joints, the five tarsometatarsal joints, the five metatarsophalangeal joints and nine interphalangeal joints. The foot bones, for the purposes of this literature review, are divided into three functional segments. These are categorized as the hindfoot, comprised of the talus and calcaneus; the midfoot, comprised of the navicular, cuboid and the medial, intermediate and lateral cuneiforms; and the forefoot, comprised of the five metatarsals and 14 phalangeal bones.

HINDFOOT

Anatomy of the subtalar joint

The subtalar joint (STJ) has three plane articulations formed by the talus and calcaneus, but a single axis of movement. The STJ is a primary weight-bearing joint that functions to dampen the rotational forces occurring at the shank.

This articulation is considered to be functionally stable and rarely dislocates due in part to the strong ligamentous support. The talocalcaneal ligament lies within the tarsal canal, the ligamentum cervicis, the medial and lateral collateral ligaments of the ankle, and the posterior and lateral talocalcaneal ligaments combine to give the subtalar joint tremendous stability. The three articulations of the subtalar joint have alternating facets that also serve to limit the movement of the joint. The posterior articulation is formed by a concave facet on the talus and a convex facet on the calcaneus while the anterior and middle articulations (both are much smaller in size) are formed by convex facets on the talus and concave facets on the calcaneus. [13] Subtalar motion is described as triplanar around a single oblique axis that seems to vary greatly among apparently healthy individuals. In 1941, Manter [14] reported the inclination of the subtalar axis to be upward and anterior from the transverse plane an average of 42 degrees (range of 29-47 degrees) and medial from the sagittal plane an average of 16 degrees (range of 8-24 degrees).

In 1989, Lundberg et al. [10] introduced radiopaque markers into the medial bones of the foot (tibia, talus, calcaneus, navicular, medial cuneiform, and first metatarsal) of eight healthy subjects in an effort to determine the influence of pronation and supination on the weight-bearing foot. X-ray exposures were taken and the joint deviations from neutral were calculated. The researchers found that the subtalar axis was not stationary as previously thought. Instead, the position of

the axis varied between 29 and 38 degrees depending upon the position of the talocrural and subtalar joints and the amount of tibial rotation. [10]

Due to the difficulty associated with the invasive in vivo technique employed by Lundberg et al. (1989), McClay and Bray examined the sagittal inclination of the subtalar joint by taking measurements from bony landmarks on 100 plain radiographs. The mean values for the subtalar axis (sagittal plane) varied from 28.7 to 47.7 degrees. These values are similar to those determined by the in vivo and cadaver studies. [15]

Description of supination and pronation in a weight-bearing position

The triplanar movements (axes cross the sagittal, frontal and transverse planes) that occur around the subtalar axis have been termed supination and pronation. When the calcaneus is on the ground in a weight-bearing position it is not free to perform dorsiflexion/plantar flexion or abduction/adduction, therefore pronation consists of eversion of the calcaneus and plantar flexion and adduction of the talus. Supination, in a weight-bearing position, is accomplished by calcaneal inversion, and dorsiflexion and abduction of the talus. Abduction and adduction of the talus are often referred to as medial and lateral rotation due to their longitudinal axis. [16]

Calcaneal range of motion is the movement that is most commonly measured in the complex motions of supination and pronation. Whether the limb is in a weight-bearing or non-weight-bearing position, the calcaneal movements

are the same. [17] Eversion (valgus) movement averages 10° while inversion (varus) movement measures 20°. [1] Supination is considered to be the close-packed position for the subtalar joint while pronation is the position of mobility. The adduction and plantar flexion of the talus when the foot is in a weight-bearing position produces a spreading of the adjacent tarsal bones, therefore pronation range of motion is limited by the ligaments that maintain the talocalcaneal joint as well as those supporting the talonavicular joint. [13]

MIDFOOT

Anatomy of the talonavicular joint

The talonavicular joint, located in the midfoot region, is comprised of the large, convex head of the talus and the concave posterior surface of the navicular. The concavity of the navicular is deepened by three ligaments: (a) the deltoid ligament medially, (b) the plantar calcaneonavicular ("spring") ligament inferiorly, and (c) the bifurcated ligament laterally. [13] The same joint capsule that encompasses the anterior and middle facets of the subtalar joint envelops the talonavicular joint tying the navicular and the calcaneus together structurally. [13]

Definition of the talocalcaneonavicular joint structure

The term talocalcaneonavicular (TCN) joint structure was developed due to the simultaneous movement of the talus on the navicular and calcaneus

(weight-bearing position) and the fact that many ligaments originate on the calcaneus, cross the talus and insert on the navicular. [13] The TCN joint, like the subtalar joint, is triplanar with one degree of movement (pronation and supination) and therefore one axis. The axis is positioned 40° upward and anteriorly and 30° medially and anteriorly. [1,14,18] The TCN is capable of a greater degree of dorsiflexion/plantar flexion than the subtalar joint due to the greater inclination of the axis medially. [13]

Anatomy of the calcaneocuboid joint

A second joint in the midfoot region is the calcaneocuboid articulation. It is classified as a saddle or sellar joint with convex and concave surfaces at right angles to one another. The calcaneocuboid joint has a separate capsule that is strengthened by the bifurcated ligament (calcaneocuboid), the dorsal calcaneocuboid ligament, and the plantar calcaneocuboid ligaments (short and long). The movement produced at this joint is typed as pivotal and is crucial during the push-off phase of gait. [13,17]

Definition of the transverse tarsal joint

The transverse tarsal joint is a term that is used to describe both the talonavicular and the calcaneocuboid joints. There is very little motion between the navicular and the cuboid due primarily to ligamentous attachments. Two independent axes are used to describe transverse tarsal joint movement. The first

axis is longitudinal, sloping upward only slightly from a horizontal position and moving medially. [14,18] Movement around this axis has been described two different ways; (1) rotation around a longitudinal axis in the form of inversion and eversion [16], and (2) a 'screwlike' motion that, in an everted weight-bearing position, turns the navicular in a medial direction and displaces it distally. [14] During pronation, when viewing the right foot from behind, the navicular turns counterclockwise with respect to the calcaneus, and the talus exhibits a clockwise rotation. [14] The second axis of the transverse tarsal joint is classified as an oblique axis that runs nearly parallel to the axis of the talocalcaneonavicular joint. This axis is inclined approximately 52° from the horizontal plane and 57° from the frontal plane creating the following combinations of movement: (a) dorsiflexion and abduction and (b) plantar flexion and adduction. [1,14,18] When the subtalar joint is in pronation, the two axes of the transverse tarsal joint are parallel, unlocking the joint and giving hypermobility to the foot. [19] When the subtalar joint moves into supination, the axes of the transverse tarsal joints are no longer parallel. This creates a rigid foot, mid-stance to toe-off, in order to function as a lever for locomotion. [19] In cases of abnormal pronation and/or severe flatfeet there is an increase in the motion (dorsiflexion and abduction) around this axis.

Closed kinetic chain function

During the stance phase of gait, the transtarsal and subtalar joints are critical for support, balance and locomotion via push-off. Following heel strike, the ankle (talocrural joint) plantar flexes, causing adduction and internal rotation of the tibia and talus. [16,17,19] The subtalar joint pronates which causes forward displacement of the navicular and the talus. [17] Maximum range of motion occurs at the transtarsal joint due to calcaneal eversion and the parallel alignment of the navicular and cuboid. These movements produce a supple forefoot, thus providing the ability to adjust to uneven surfaces. During mid-stance, the tibia externally rotates while the talus abducts and the talocrural joint moves into dorsiflexion. [16,17] Supination occurs at the subtalar joint when the foot begins the push-off phase of gait. This movement stabilizes the cuboid, allowing it to function as a fulcrum for the peroneus longus muscle, which facilitates plantar flexion of the first metatarsal. [16]

Definitions of pronation

Pronation of the foot is a normal specialized movement that involves plantar flexion of the ankle (talocrural) joint, eversion of the subtalar joint, and abduction of the forefoot. During the stance phase of gait, the subtalar joint moves immediately into pronation, accompanied by internal rotation of the tibia and femur. Pronation reaches a maximum at approximately 35 – 45% of the

stance phase. [20] While running, maximum pronation ranges from 8-15° and in walking, 3-10°. [21-23]

Excessive pronation

Root et al. [1] defined excessive pronation as a condition of hypermobility that may lead to numerous conditions and injuries of the foot, ankle, lower leg, knee, hip and low back. [24-31] These authors assessed pronation by measuring calcaneal position, subtalar neutral position and the passive range of motion at the subtalar joint when the subject was in open kinetic chain position, i.e., the subject lay prone on a table with his/her feet hanging over the edge. The non-weight bearing technique that Root et al. used to measure pronation [1] remains in use today despite the existence of several studies that have reported this type of joint measurement to be inconsistent among examiners. [32-34] Of greater significance is the issue of validity. No study has examined the open kinetic chain subtalar neutral position method of measurement (frontal plane) to determine if it accurately depicts the triplanar movement. [35]

In 1993, Picciano et al. [33] examined the intratester and intertester measurement reliabilities of open kinetic chain subtalar joint neutral, closed kinetic chain subtalar joint neutral and the navicular drop test. Two inexperienced physical therapy students performed all of the measurements after participating in a two-hour training session on how to perform the tests. The intratester ICC (± SEM) values for the open kinetic chain subtalar neutral test were very poor, 0.06

($\pm$ 1.81°) and 0.27 ($\pm$ 2.29°) for each of the two testers. The intertester ICC value was even worse at 0.00 ($\pm$ 2.51°). The closed kinetic chain subtalar neutral joint intratester values were 0.14 ($\pm$ 2.46°) and 0.18 ($\pm$ 2.40°) and the intertester correlation coefficient was 0.15 ($\pm$ 2.43°). These results suggest that both open and closed kinetic chain subtalar neutral tests to have poor intratester and intertester reliability. [33] However, the experience of the testers should be considered.

Smith-Oricchio and Harris (1990) evaluated the intertester reliability of a subtalar joint neutral measurement by comparing the results of three testers. [34] Each examiner was a physical therapist that had been involved in orthotic clinics or foot management for a period of one to two years. Therefore, they had more experience with the measurements than those testers in the Picciano et al. [33] study. The ICC value for intertester reliability was 0.60. (NOTE: an ICC of .60 is "moderate") [90] No standard error of measurement values were provided. The authors concluded that the non-weight bearing measurements of calcaneal inversion and eversion had low intertester reliability. [34]

The research by Lundberg et al., [10] not only provided new information regarding the orientation of the subtalar joint axis (discussed previously), but also revealed that the talonavicular joint performed the greatest amount of motion (within the hindfoot complex) during pronation and supination. [10] The Lundberg et al. study is a landmark paper that shifted the focus from subtalar joint movement to talonavicular joint movement when measuring pronation.

Kitaoka et al. (1997) evaluated the relative contributions of various joints of the foot and ankle to pronation, supination, dorsiflexion and plantar flexion. [36] Thirteen normal, fresh-frozen cadaveric specimens were utilized for the study. The three-dimensional movements of the talus, calcaneus, navicular and first metatarsal were monitored using a magnetic tracking system. The authors concluded that when the foot was placed in global pronation, the majority of movement occurred at the metatarsal-navicular level. The next highest area of movement was at the navicular-talar level. No mention was made of the medial cuneiform bone. [36]

Navicular drop test

Due to the poor to moderate intratester and intertester reliability values of the open kinetic chain subtalar neutral position and the new information of the navicular movement, additional static weight bearing assessment techniques of pronation, such as the navicular drop test [2], Feiss' line measurement [37] and standing foot angle [8,24], were developed and examined for their reliability and accuracy. [24,32-34,38] Brody [2] is commonly credited as the original proponent of the navicular drop test. However, Schuster [39] first proposed the concept of the navicular drop test in 1956 as a measurement of foot pronation.

In 1982, Brody, a physician, described his personal evaluation protocol for treating running related injuries and conditions. Part of the paper is devoted to the navicular drop test that Brody described as a practical method for determining the

amount of pronation in the foot. The navicular drop test is a measure of the change in the height of the navicular tubercle relative to the ground when measured in static, closed kinetic chain, partial weight bearing and full weight bearing positions. [2] Brody [2] considered navicular drop test results greater than 15 mm to be abnormal, while those $\leq$ 10 mm displacement were defined as normal. No reliability evidence was reported. [2]

Mueller et al. (1993) evaluated the intratester reliability of the navicular drop measurement in 29 healthy individuals. Only one experienced examiner performed the measurements, obtained on separate days for each subject. Reliability coefficients ranged from 0.78 (1.68 mm) - 0.83 (2.08 mm) for the right and left foot, respectively. [40]

In 1994, Sell et al. evaluated the intertester and intratester reliability of navicular height by using an inclinometer. The intertester ICC value was 0.73 (2.1 mm) and the intratester ICC value was 0.83 (1.7 mm). Thirty subjects were evaluated in this study and the two testers were a physical therapist and a student. Based upon these results, the authors concluded the navicular height test to be a reliable measure of foot pronation and preferable to the traditional open kinetic chain method of subtalar joint movement. [41]

Contrary to the previous studies, Picciano (1993) found the intratester and intertester reliability values for the navicular drop test to be poor to moderate. [33] Two testers performed the measurements on 15 subjects (30 feet). Intratester ICC ($\pm$ SEM) values were determined to be 0.61 ($\pm$ 2.57 mm) and 0.79 ($\pm$ 1.92 mm)

for each of the testers and the intertester reliability was ICC = 0.57 (± 2.72 mm). The explanation for the discrepancy between these results and those of Sell et al. [41] and Mueller et al. [40] may be attributed to the experience of the testers. In this investigation, two inexperienced physical therapy students served as the testers. The students were given an instructional and practice session, but it was only two hours long. [33]

In 1999, Cornwall and McPoil evaluated the displacement of the navicular bone while walking and related the values to those normative navicular drop values previously reported in the literature. [42] Three separate studies reported abnormal NDT values to be 15, 13 and 10 mm of inferior navicular movement. [2,43,40] Using a 3D research electromagnetic tracking system, it was determined that the navicular bone goes through significant medial and vertical displacement during the stance phase of gait. The relative change in height was determined to be 7.9 mm (± 2.5). The authors also found that the time to maximal vertical displacement of the navicular occurred earlier, at 47.8% of the stance phase than that of the maximal medial displacement (53.1%). Thus, the researchers concluded that the navicular drop test is a good indicator of dynamic navicular bone movement. [42]

Vinicombe et al. [44] evaluated the navicular drop and navicular drift tests for intertester and intratester reliability. The navicular drift measurement was proposed by Hylton B. Menz [35] as a practical and quantifiable way to determine transverse plane (medial) movement of the navicular bone during pronation. Five

podiatric physicians with a minimum of three years of postgraduate work served as the testers for 20 apparently healthy subjects. The correlation coefficients for the intratester navicular drop test ranged from 0.44 to 0.91 while the standard error of measurement values ranged from 1.47 to 3.66 mm. The ICC values for the intertester data were between 0.56 and 0.78 with SEM values that ranged from 2.29 to 3.23 mm. The navicular drift showed lower ICC values. Intratester reliability ICC values ranged from 0.44-0.70 (SEM 2.05-2.47 mm) and intertester reliability ICC values ranged from 0.32-0.53 (SEM 1.44-2.24 mm). The authors concluded that both techniques are only moderately reliable and that physicians using these techniques should consider the error associated with the measurements when interpreting the numbers. [44]

Feiss' line measurement

Feiss' line uses three anatomical landmarks, i.e., medial malleolus of tibia, navicular tubercle, head of first metatarsal, to evaluate pronation of the foot. [37] Similar to the navicular drop test, inferior displacement of the navicular between closed chain non-weight bearing and full weight bearing positions is of central importance. The navicular drop and Feiss' line tests differ in that with Feiss' line, the change in navicular position is measured relative to a line connecting the malleolus and first metatarsal, rather than the ground. A positive Feiss' line test is one in which the navicular drops at least two-thirds of its original height. [37]

In 1999, Hannigan-Downs et al. examined the validity and reliability of the navicular drop test and the Feiss' line measurement. Displacement of the navicular as calculated from radiographic images served as the criterion measure. The navicular drop test was found to be both a valid ($r=0.61$) ($p<.01$) and reliable (intratester and intertester) measure of inferior navicular displacement. The ICC value for intratester reliability was 0.84 (SEM = 1.90mm) while the intertester reliability ICC value was 0.67 (SEM = 3.26 mm). The Feiss' line measurement showed a negative correlation with the criterion radiographic measurement ($r = -0.09$) ($p<0.01$). The intertester reliability value for the Feiss' line was 0.52 (SEM = 4.60mm) and the ICC value for intratester reliability was 0.82 (SEM = 1.57mm). Due to the poor correlation value, the authors concluded that the value of the Feiss' line as a true indicator of navicular movement was uncertain despite moderate intratester and intratester ICC values. [38] The Feiss' line measurement was dependent upon the accurate determination of three anatomical landmarks as opposed to the single (navicular tubercle) landmark in the navicular drop test.

Standing foot angle

The clinical test known as the standing foot angle uses three anatomical landmarks to evaluate pronation of the foot. The angle formed between the medial malleolus-navicular tubercle segment and the navicular tubercle-first metatarsal head segment is the angle assessed in this clinical measurement. [8,24]

Dahle et al. [8] reported the normal range for standing foot angle to be 120-150°. Standing foot angles less than 120° are defined, by the authors as a pronating foot while larger angles would be indicative of a supinating foot. Sommer and Vallentyne [24] examined the correlation between standing foot angle and medial tibial stress syndrome and suggested a normal angle of <135° in order to maximize accuracy (sensitivity of 35.6%; specificity of 88.9%). The standing foot angle of the group with medial tibial stress syndrome was 8° less that of the control group (P=0.0001). If a cut-off value of <140° is used then the values of sensitivity and specificity are 71.3% and 69.5% respectively.

Summary of validity and reliability evidence for the clinical tests of pronation

The navicular drop test, a static measurement, has been shown to be a valid and reliable test of inferior navicular translation when assessed as an individual moves from a non-weight bearing to a weight bearing position. [33,34,38,40-42] The only published study that evaluated the Feiss' line measurement found it not to be a valid or reliable measurement of pronation. [38] No published evidence has been located regarding the validity of the standing foot angle, but Sommer and Vallentyne [24] reported the test to have good inter-rater reliability (ICC = .69). The standing foot angle has been described in orthopedic assessment texts, but no evidence has been located regarding the reliability or validity evidence of this test to accurately predict inferior navicular movement. [37]

Injuries related to pronation

Pathological pronation of the foot has been associated with a myriad of sport-related injuries and conditions. These injuries are not limited to the foot itself, but also involve the low back, hip, knee and shank. [24-31,43,45-50] Root et al. described the mechanical relationship between the hip and subtalar joint by stating that laterally rotating the hip results in subtalar joint pronation. [1] In a study by Cibulka et al.,[45] a positive relationship was suggested between unilateral excessive hip lateral rotation and sacroiliac joint dysfunction. The authors concluded that when one hip had more lateral rotation than the other, the patient frequently had a posteriorly tilted innominate. A related study by Rothbart and Estabrook[46] reported that excessive pronation produced pelvic obliquity, thus disrupting the sacroiliac joint. Botte linked unilateral structural and functional abnormalities of the pelvis and lumbar spine to foot pathomechanics, and concluded that control of foot function was crucial to the treatment of lumbar injuries. [27] Subtalar pronation has been associated with a unilateral shortened leg condition. [27,47] Low back pain has been linked to leg length discrepancies, so an association could be drawn between subtalar pronation and back pain. However, there is very little evidence to support this theory. [27]

During excessive pronation, eversion of the subtalar joint causes internal rotation of the tibia. At midstance of gait, the femur begins to externally rotate. If the subtalar joint continues to evert, as it would in excessive pronation, the rotary torques of the femur and tibia are in opposite directions thus creating stress

at the knee joint. Coplan (1989) determined that pronators had an increase in the amount of passive knee rotation when compared to nonpronators. [48] However, this study only evaluated the non-weight bearing position. Tiberio [49] published a theroretical model that provided an explanation as to how excessive pronation may be part of the abnormal mechanics that produces anterior knee pain. Tiberio's theory was supported by Power et al. in an investigation that found a significant increase in the amount of rearfoot varus between injured and non-injured groups. [50]

Three recent studies found that subjects who had incurred an anterior cruciate ligament injury had significantly greater amounts of subtalar pronation than did the uninjured, control groups. [30,31,43] All of the studies used the clinical measure of navicular drop to assess pronation. However, there is conflicting evidence regarding the role of pronation and anterior cruciate ligament injury. [51] In a study by Smith et al. [51] no significant difference was found between the navicular drop test in uninjured and ACL injured groups. The study had a fairly small number of participants in each group, which may have contributed to the lack of significant differences (N=14).

Medial tibial stress syndrome has been linked to abnormal pronation and excessive eccentric loading of the posterior tibialis muscle. [5,24,26,28] The posterior tibialis muscle eccentrically controls the internal rotation of the tibia and subtalar joint pronation during the initial phase of stance. [16] If abnormal pronation occurs at the subtalar joint, excessive tensile forces will be placed upon the posterior

tibialis tendon which originates on the posterior proximal surface of the tibia, fibula and interosseous membrane. The tensile forces may cause pain and inflammation which would then be classified as medial tibial stress syndrome. If this destructive motion occurs over a period of time without intervention, the medial longitudinal arch may collapse and the posterior tibialis tendon may develop tenosynovitis or in the severe case may rupture. [85]

Achilles tendinitis, metatarsalgia, plantar fasciitis and plantar interdigital neuromas have all been associated with abnormal pronation.[1,5,14,17-18] However, recent studies have shown conflicting evidence regarding the role of excessive pronation in metatarsalgia and interdigital neuromas. [25,29] James et al. showed that in 72 patients with pronated feet 15 % had plantar fasciitis and 12% had Achilles tendinitis. [5]

Ground reaction forces

In clinical settings, pronation of the foot is frequently determined using an open or closed kinetic chain static measurement due to the time and costs associated with three-dimensional biomechanical analysis. Unfortunately, static measurements do not fully capture the complexity of the foot pronation, nor do they take into account the effect(s) of the forces placed upon the foot during locomotion activities. In previous gait studies, the magnitude of ground reaction forces have consistently been dependent upon the tested speed of the gait, e.g., walk or run. [52-57] Monro et al. [55] determined that the average vertical ground

reaction force increased significantly from 1.40 BW at 3.0 m/s^{-1} to 1.70 BW at 5.0 m/s^{-1}. During a landing condition, the mean peak vertical ground reaction force was determined to be 4.5 BW (SD = 1.7). [58]

Three-dimensional analysis of foot motion

Three-dimensional analysis of the foot and ankle has been shown to depict human motion with greater accuracy than two-dimensional kinematic analysis. [22,59,60] There is limited evidence of the relationship between the static tests and the complicated, three-dimensional movement of foot pronation. [61] Cornwall and McPoil [61] reported that navicular tubercle movement during over ground walking, as measured by the navicular drop test, was highly correlated (r = .942) with rearfoot motion, as quantified by an electromagnetic motion analysis system.

Possible contributing factors to pronation

The following factors may contribute to the amount of pronation that an individual attains during gait: arch type [1, 63-70], foot length [35], foot type [62], and/or degree of passive dorsiflexion. [72] There are conflicting results regarding the influence of arch height on pronation. Nearly 40 years ago Close and Inman [73] reported a greater amount of subtalar joint motion in 'flat feet' as compared to feet with high arches. Many investigators have stated that flat feet are hypermobile, thus disposed to excessive pronation while high-arched feet are

inflexible or rigid. [74,75,76] However, in more recent investigations, the variable of arch height has not produced a difference in rearfoot movement. [77,78]

Part of the complexity of the arch height question lies in the numerous ways in which the longitudinal arch has been measured. Gilaldi et al. [79] based the subjective assessment of arch height on observation alone. In contrast, Cowan et al. [80] evaluated photographs to quantitatively measure various points on the longitudinal arch. An additional study designed to determine the intertester reliability of the visual assessment of pronation and supination found the reliability value to be 'adequate' at Kappa = 0.724.[8] Nazoczenski et al. [81] utilized radiographs to evaluate the medial longitudinal arch structure in a study that determined low-arched individuals to have a higher eversion to tibial internal rotation ratio. The authors suggested that this might place greater strain on the foot and ankle as compared to the low eversion to internal rotation ratio group (high arches).

Williams and McClay [82] investigated the reliability and validity of several clinical measures used to determine arch height. The subjects were evaluated in a 10% and a 90% weight-bearing position to determine if static measures accurately depicted the dynamic changes that occur in the foot. Lateral radiographs of ten feet were used as the gold standard from which to compare the measurements. The researchers concluded that the most valid and reliable measure of arch height was dorsum height (at 50% of foot length) divided by truncated foot length (calcaneus to metatarsophalangeal joint). [82]

The height of the medial longitudinal arch has been widely investigated due, in large part, to the common thought that an abnormality may be a predisposition to injury. [63,65,75,79,80] In 1985, Subotnick stated that 60% of the population has a normal arch while 20% of the population have a high-arched foot (pes cavus) and 20% have a low-arched foot (pes planus). He concluded that approximately 30% of the patients that he treated in his podiatric office suffered an injury or condition that he attributed to the structural and functional limitations of a cavus foot. [75]

Gilaldi et al. [79] examined stress fractures in the lower extremities of 295 Israeli Army recruits and found that the recruits with low arches were not as prone to develop this injury when compared to either the normal or high-arch group. The classification of arch type was subjective and the article did not contain quantitative definitions of high or low arches. [79]

Cowan et al. [80] found a statistically significant ($p<.05$) increase in the number of athletic-related injuries in United States Army recruits who had high arches (n=49), but showed the low-arched group (n=49) to have relatively few injuries in comparison. The 246 trainees were divided into three groups (high, normal and low arches) and then followed during the twelve weeks of training. In another military study, Kaufman et al. [63], conducted a prospective study of the United States Navy Sea, Air and Land (SEAL) candidates and determined that subjects with either pes cavus or pes planus had nearly twice the incidence of stress fractures when compared to the individuals with a normal arch height. In

contrast, James et al. [5] determined that specific injuries could not be predicted with the structural abnormalities of pronation or supination.

Nigg et al. [83] evaluated whether the measurement of arch height influenced maximal eversion or internal tibial rotation during the stance phase of running and found that no relationship existed on these individual measures. These authors proposed the existence of a functional relationship between arch height and injury because the ratio of the transfer of foot eversion to internal leg rotation increased significantly with increased arch height. Twenty-seven percent of the variation of the transfer of movement was explained by arch height. Nigg et al. suggested that a low ratio of eversion to tibial internal rotation in an individual with a high arch may place more stress on the knee, whereas a high ratio of eversion to tibial internal rotation in an individual with a low arch may place greater strain on the foot and ankle. [83,84]

Several studies have examined the ramifications that the variable of foot length may have on the amount of arch height (pronation). [70,82] Williams and McClay, 2000, normalized foot length to arch height and found that the best measure for both a reliable and valid test was dorsum height divided by truncated foot length. Truncated foot length is a measurement taken from the calcaneus to the first metatarsophalangeal joint. The measurement was developed due to conditions like hallux valgus and pes cavus (claw toes) where the toes have become misaligned or suffer a claw deformity that functions to shorten the foot length. [82] Aquino and Payne, 2001, evaluated the function of the windlass

mechanism in excessively pronated feet. They observed, after taking numerous weight-bearing and non-weight bearing measurements, that three of the clinical assessments were significantly associated with the dynamic windlass mechanism. The three measurements were the position of the forefoot relative to the rearfoot, subtalar joint axis position and navicular drift/foot length ratio. [86]

The anatomical and functional complexity of the foot makes it a difficult body part to assess and treat. However, the injuries that have been associated with excessive pronation exist not only in the foot itself, but up the kinetic chain of the lower extremity. The injuries can be categorized as mild (medial tibial stress disorder) or severe (anterior cruciate ligament ruptures). Therefore, it is essential that the tests used to determine excessive pronation be, not only, valid and reliable measures of subtalar movement, but also easy and inexpensive to perform in a clinical setting.

APPENDIX B

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REFERENCES

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APPENDIX C

INFORMED CONSENT DOCUMENT FOR THE RADIOGRAPHIC STUDY

Appendix C

INFORMED CONSENT DOCUMENT

A. Title: Radiographic Validation and Reliability of Selected Clinical Measures of Pronation

B. Investigators: Kim Hannigan-Downs, M.S., ATC
Rod A. Harter, Ph.D., ATC

C. Purpose: To determine whether measuring the movement of one of the main bones in the foot (navicular) is a valid and reliable way for clinicians to estimate pronation in the foot.

D. Procedures: I understand that as a participant in this study the following things will happen:

1. Pre-study Screening.

a. If I am pregnant or breast-feeding I will not be asked to participate in this study.

a. If I am under the age of 18 I will not be asked to participate in this study.

b. If I am seeing the physician for an injury that prevents me from standing with my full body weight on that leg, I will not be asked to participate in this study.

2. What participants will do during the study.

a. My participation will involve two testing sessions on two different days. The first session will be completed while at the physician's office when my injury is being evaluated. I understand that my doctor has ordered x-rays of the foot of my injured leg to help determine the source of my pain/injury, and x-rays of my uninjured foot for comparative purposes. Each foot will be x-rayed in two positions, first with very little weight borne on my foot, and second taken while I place my full weight on one foot.

b. In a week or less, at my convenience, I agree to come to the Sports Medicine Lab in the Women's Building at OSU to repeat some of the diagnostic tests performed today, none of which involve x-rays.

3. Foreseeable risks or discomforts.

a. I understand that there are risks associated with this study due to exposure to radiation from x-rays. The amount of radiation in one x-ray of my foot/ankle is approximately equivalent to that received from the natural surroundings in Corvallis during one day.

4. Benefits to be expected from the research.

a. I understand that as compensation for my participation, I will receive $25.00 for completing this study. Additionally, the information gained from this research will help to increase the body of knowledge about the bones of the foot in an injury situation.

b. Your insurance will not be billed for x-rays, as these costs will be paid by this study. Depending upon your insurance plan, this benefit may decrease the total cost to you for your medical visit.

5. Alternative procedures or course of treatment.

a. Due to State of Oregon statutes which do not allow for x-rays of humans for the sole purpose of research, the only alternative for this type of study is to utilize individuals who have an injury or have injured their foot in some way.

6. Confidentiality.

a. The results of this investigation may be published, but my name or identity will not ever be revealed. A code number rather than my name will be used to identify the data collected from me as part of this study. The master copy of assigned code numbers will be kept secure by Kim Hannigan-Downs.

7. Compensation for Injury.

a. I understand that Oregon State University does not provide a research subject with compensation or medical treatment in the event the subject is injured as a result of participation in this research project.

G. Voluntary Participation Statement.

1. I understand that my participation in this study is completely voluntary and that I may either refuse to participate or withdraw from the study at any time without penalty. I understand that if I withdraw from the study before it is completed, I will not receive the $25.00 compensation for my participation.

H. If You Have Questions.

1. Further questions about this research study, or research related injuries should be directed to Dr. Rod A. Harter, Langton Hall 226, Oregon State University, Corvallis, Oregon at (541) 737-6801.

2. If I have questions about my rights as a subject participating in this research, or I feel that I have been placed at risk, I can contact the Chair of the Human Subjects Research Review Committee: Research Office, AdS A312, (541) 737-3473.

My signature below indicates that I have read and that I understand the procedures previously described and give my informed and voluntary consent to participate in this study. I understand that I will receive a signed copy of this consent form.

Subject's Signature:_____Date: _____

Subject's Name (printed): _____Phone #:_____

Subject's Present Address:

_____

Street City State Zip code

Signature of investigator:

_____Date_____

APPENDIX D

SUBJECT QUESTIONNAIRE FOR THE RADIOGRAPHIC STUDY

Appendix D

Subject Questionnaire

1. **Name:** _____

2. **Address:**

_____

Street **City,** **State** **Zip Code**

3. **Telephone number(s):**

_____ **(work)**

_____ **(home)**

4. **E-Mail address (if applicable):**_____

5. **Age:** _____ 6. **Sex: F or M (circle your response)**

7. **Height:** _____ 8. **Weight** _____

9. **Primary complaint or physician diagnosis:**_____

Do not fill-in the following information as it will be assessed by the investigator:

10. **Symptomatic limb: Right or Left**

	Right	**Left**
11. **Foot size:**	_____	_____
12. **Foot type:**	**Egyptian**	**Greek**	**Square**
13. **Arch type:**	**Pes planus**	**Normal**	**Supple pes cavus**

Rigid pes cavus

Notes:

_____

_____

_____

APPENDIX E

INFORMED CONSENT DOCUMENT FOR THE BIOMECHANICAL STUDY

Appendix E

INFORMED CONSENT DOCUMENT

A. **Title:** Biomechanical analysis of tarsal navicular displacement under static and dynamic loading conditions.

B. **Investigators:** Kim Hannigan-Downs, M.S., ATC, Doctoral Student
Rod A. Harter, Ph.D., ATC, Associate Professor

C. **Purposes:** There are two purposes to this study. The first is to determine whether the clinical measurements of navicular position, taken when the foot is not moving (static), are indicative of the actual movement that takes place during a dynamic movement such walking, stepping off of a box and running. The second purpose is to determine if a number of static measurements can be put into an equation to accurately predict the dynamic movement of the navicular bone.

D. **Procedures: I understand that as a participant in this study the following things will happen:**

a. Pre-study Screening.
c. I am between the ages of 18 and 40.
d. I am currently free of injury to my hips, legs, ankles and feet.
e. I have been free of injury to my hips, legs, ankles and feet for the past six months.
f. I have not had surgery within the past year on my hips, legs, ankles or feet.

2. **What participants will do during the study.**

a. My participation will involve one testing session that will last approximately one hour. The session will be completed at the Biomechanics Laboratory in the Women's Building on the OSU Campus. Each foot will be measured in two positions, first with very little weight borne on my foot, and second taken while I place my full weight on one foot.

b. After the measurements are taken while I am standing still, I will be asked to walk on level ground, run on level ground, and step off of a box that is 38 centimeters (15 inches) in height onto or across a force plate located on the floor. I will need to complete five successful repetitions of each condition, making sure to stay within a pre-determined pace for the walk and the run conditions.

3. **Foreseeable risks or discomforts.**
   a. I understand that there are risks associated with this study due to the strain placed upon the ligaments, muscles and bones of the foot. Walking and running are common activities of daily living and do not represent any significant risk of injury. When stepping off the box and landing on one foot the stresses to my lower limb will be similar to those experienced when stepping off of a small stepping stool. The risk of injury is minimal with the landing from a 38 cm (15 in.) step, but nonetheless present.

4. **Benefits to be expected from the research.**
   a. The information gained from this research will help to increase the body of knowledge about the movement of the bones of the foot. The long term goal being to predict, from anatomical and biomechanical measurements, risk factors for injury to the foot.
   b. Additionally, the information may help us to prevent injury to the foot by early intervention with orthotics, strength or flexibility training.

E. **Confidentiality.**

1. The results of this investigation may be published, but my name or identity will be kept confidential to the extent permitted by law. A code number rather than my name will be used to identify the data collected from me as part of this study. The master copy of the assigned code numbers will be kept secure by Kim Hannigan-Downs.

F. **Compensation for Injury.**

1. I understand that Oregon State University does not provide a research subject with compensation or medical treatment in the event the subject is injured as a result of participation in this research project.

G. **Voluntary Participation Statement.**

1. I understand that my participation in this study is completely voluntary and that I may either refuse to participate or withdraw from the study at any time without penalty.

H. **If You Have Questions.**

1. Further questions about this research study, or research related injuries should be directed to Kim Hannigan-Downs, 232 Langton Hall, Oregon State University, Corvallis, Oregon at (541) 737-3078 or Dr. Rod A. Harter, Langton Hall 226, Oregon State University, Corvallis, Oregon at (541) 737-6801.
2. If I have questions about my rights as a subject participating in this research, I should contact the IRB Coordinator, OSU Research Office, (541) 737-8008.

My signature below indicates that I have read and that I understand the procedures previously described and give my informed and voluntary consent to participate in this study. I understand that I will receive a signed copy of this consent form.

Subject's Signature:_____ Date: _____

Subject's Name (printed): _____ Phone #:_____

Subject's Present
Address:_____
Street City State Zip code

Signature of investigator:

_____ Date: _____

APPENDIX F

SUBJECT QUESTIONNAIRE FOR THE BIOMECHANICAL STUDY

Appendix F

Subject Questionnaire

1. **Name:** _____

2. **Telephone Numbers:**
_____ **(H) and/or** _____ **(W)**

3. **E-Mail address (if applicable):**
_____

4. **Age:** _____ 5. **Sex: F or M (circle your response)**

6. **Which best describes your racial/ethnic identity? (Please check all that apply.)**

___ **White, European American, Non-Hispanic**
___ **Asian or Asian American**
___ **Black, African American, Non-Hispanic**
___ **Middle Eastern or Middle-Eastern American**
___ **North African or North African-American**
___ **Pacific Islander**
___ **Hispanic or Latino American**
___ **American Indian or Alaskan Native**
___ **If none of the choices apple to you, please use your**
___ **Decline to respond**

Please do not fill-in the following information as it will be assessed by the investigator:

7. **Measured height:** _____ 8. **Measured weight:** _____

	Right	Left
9. **Foot length:**	_____	_____
10. **Foot type:**	_____	_____
11. **Arch type:**	_____	_____
12. **Dorsiflexion (PROM)**	_____	_____

14. Inv/Ever ROM