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# Potential relationships between lower extremity structural alignment and toe angle during static and dynamic activities

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**Potential Relationships Between Lower Extremity Structural Alignment and Toe Angle During Static and Dynamic Activities**

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## ABSTRACT

**Background:** The influence of lower extremity structural alignment on foot progression angle (FPA) and toe-out angle (TOA) has been measured, however foot structure has not been included in this analysis. No studies to our knowledge have assessed the influence of lower quarter structure on standing toe-out angle or during dynamic tasks such as squatting.

**Purpose:** The purpose of this study was to assess the potential influence of longitudinal arch angle (LAA) and weight-bearing dorsiflexion in addition to passive hip internal rotation (HIR) and thigh foot angle (TFA) on the following activities: standing TOA, FPA (walking TOA), forward arm squat TOA, and barbell back squat TOA.

**Study Design:** Controlled laboratory study.

**Methods:** A total of 37 participants (19 male; 18 female) who lacked a history of lower extremity injury were recruited from the University of Tennessee at Chattanooga. Each participant reported a score of seven or greater on the Tegner activity scale and had previous experience with squatting tasks. The following measurements were taken for each participant: height, weight, hip internal rotation, thigh foot angle, longitudinal arch angle, weight-bearing dorsiflexion, hip width, static toe-out angle and stance width; toe-out angle, stance width and squat depth during a forward arm squat; toe-out angle, stance width and squat depth during a barbell back squat; standing hip height, and foot progression angle.

**Results:** HIR exhibited a significant correlation with TOA/FPA in each of the four models: static stance TOA, FPA, forward arm squat TOA, and barbell back squat TOA. HIR alone explained 15% and 24% of the variance associated with standing TOA and FPA, respectively. HIR and TFA explained 25% of the variance associated with TOA in a forward arm squat. HIR, TFA, and LAA explained 43% of the variance associated with TOA in a barbell back squat. On average,

participants exhibited a positive TOA and FPA. Furthermore, average stance width and TOA increased from standing TOA to forward arm squat TOA to barbell back squat TOA.

**Conclusion:** HIR was the most consistent structural predictor for TOA and FPA. Thigh foot angle was influential during a forward arm and barbell back squat.  LAA was only associated with TOA during a barbell back squat which may be explained by participants naturally preparing for a loaded movement. Ankle dorsiflexion does not appear to influence TOA/FPA.

**Clinical Relevance:** This study provides data on a specific population of young adult athletes. It shows that a positive TOA and FPA is widely preferred among participants, and stance width and TOA adapts to the task performed. Foot arch height is not a predictor of TOA or FPA and does not need to be included in an analysis of FPA. Finally, due to the overwhelming preference of a positive TOA during squatting tasks, clinicians and researchers alike should consider having participants squat in a natural, preferred stance.

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# I. INTRODUCTION

## Introduction

Foot toe-out angle (TOA) can serve as an important measure for clinicians and athletes alike. Foot progression angle (FPA) is a variation of TOA that describes foot placement during normal gait while TOA is a static measure. A positive TOA/FPA describes a foot that is turned outward, whereas a negative TOA/FPA describes a foot that is turned inward. Research shows that most individuals' preferential stance exhibits a positive TOA (McIlroy and Maki 1997). Furthermore, many studies show that this toe-out stance is still present during normal walking gait (Seber, Hazer et al. 2000, Cibulka, Winters et al. 2016, Hudson 2016). Structurally, Cibulka et al. (2016) demonstrated a significant negative correlation between hip internal rotation (HIR) and FPA, and a positive correlation between tibiofemoral torsion and FPA. Hudson (2016) demonstrated a similar relationship between tibial torsion and FPA, however he also demonstrated offsetting torsions (defined as external tibial torsion in conjunction with femoral antetorsion) more often than basic probability would suggest, showing it is the interaction of multiple structures, and not just one structure, that leads to the position of preferred TOA.

Limited ankle dorsiflexion (ADF) can inhibit one's ability to complete a proper squat. Limited dorsiflexion minimizes the proper movement in the sagittal plane as the ankle joint approaches end range early in the squat. This results in a forward leaning trunk in an attempt to reach proper squat depth, or other compensations in the frontal or transverse planes such as subtalar joint pronation or knee valgus (Macrum, Bell et al. 2012). Proper dorsiflexion measures rule out the possibility of limited dorsiflexion affecting the squat, therefore if excessive pronation occurs during the squat movement, other structural influences may be indicated.

Previous studies have neglected to examine joint structures distal to the ankle when studying TOA/FPA. It is known that foot pronation can potentially lead to obligatory internal rotation at the hip, knee, and ankle (Gross 1995). Pronation is a triplanar motion composed of dorsiflexion, abduction, and eversion.  First used by Dahle et al. (Dahle, Mueller et al. 1991) longitudinal arch angle (LAA) is a weight-bearing clinical measure of foot pronation, and therefore potentially a surrogate measure of TOA as well. LAA is defined as "the angle formed by two vectors- one passing through the midpoint of the medial malleolus to the navicular tuberosity and the other passing through the midpoint of the medial aspect of the first metatarsal head to the navicular tuberosity" (McPoil and Cornwall 2005).

TOA is also an area of interest during the squat movement. Extreme TOA is undesirable as it may promote dysfunctional patella tracking (Myer, Kushner et al. 2014), however a slight TOA may be necessary for stability and proper lower extremity alignment. A back squat is often used in training to increase power and determine a one rep max threshold for an individual (Brown 2007). In a study assessing powerlifters during a back squat competition, Escamilla et al. (2001) demonstrated increasing TOA as stance width increased. An increased stance width may be associated with balance during a loaded activity, and the increased TOA may have been present to compensate and provide proper patella tracking. A forward arm squat is often used clinically and is preffered during the rehabilitation process as it helps remove stress from the knees during the squat movement (Lahti, Hegyi et al. 2019). However, studies assessing squat performance using a forward arm squat often instruct participants to squat with their feet facing forward, which may influence the natural squat movement (Lamontagne, Kennedy et al. 2009, Lamontagne, Brisson et al. 2011, Bagwell, Snibbe et al. 2016, Diamond, Bennell et al. 2017).

The purpose of our study was to include weight-bearing ankle dorsiflexion and LAA measures along with hip internal rotation (HIR) and thigh foot angle (TFA) in efforts to predict preferred TOA/FPA for four different activities: standing TOA, FPA, forward arm squat TOA, and barbell back squat TOA. It was hypothesized that ankle dorsiflexion and LAA would add significantly to the regression model for all four activities.

# II. REVIEW OF LITERATURE

## Introduction

This literature review primarily focused on clinical measures related to the torsional profile of the lower extremity. A section on the relevance of a forward arm squat and barbell back squat to TOA was also included. This literature review will end with a brief review of multiple regression.

## Hip Internal Rotation

Hip internal rotation (HIR) has been of interest in multiple studies regarding TOA and FPA (Seber, Hazer et al. 2000, Cibulka, Winters et al. 2016, Hudson 2016). Cibulka et al. (2016) attempted to use clinical measures of hip internal rotation ("as a proxy measurement for femoral torsion") and tibiofemoral torsion to try to predict FPA in healthy individuals. Using the passive hip internal rotation range of motion tests, Cibulka et al. demonstrated an average HIR of 41.2° and a moderate negative correlation to FPA (r= -0.40). Other studies have demonstrated varying degrees of correlation between HIR and FPA (Seber, Hazer et al. 2000, Hudson 2016); however this could be due to a difference in methodology or subject population. In general, it is accepted that larger HIR leads to a smaller TOA.

HIR may also have a negative influence on squat depth during a deep squat. Studies conducted on participants with femoroacetabular impingement (FAI) show that the FAI participants cannot squat as deep as healthy controls (Lamontagne, Brisson et al. 2011, Bagwell, Snibbe et al. 2016). It is known that symptoms of FAI are exacerbated during hip flexion and internal rotation (Ganz, Parvizi et al. 2003, Beck, Kalhor et al. 2005). Therefore, diminished squat depth is likely due to limited hip internal rotation during a deep squat as a result of participants guarding against abutment or reaching bony abutment itself (Bagwell, Snibbe et al.

2016). Therefore, in addition to its influence on TOA/FPA, HIR measurements are necessary to reveal potential confounding variables during the squat task.

**Thigh Foot Angle**

Thigh foot angle (TFA) is a measure of tibial torsion taken with the participant in a prone position with the knee flexed to 90°. Cibulka et al. (2016) reported using this method and demonstrated an average TFA of 17° (range= 4-31.3°) in a subject population consisting of 60 subjects (41 female, 19 male) with an average age of 26.7 $\pm$ 10.9 years. Various correlations of TFA/tibial torsion to FPA/TOA are reported in other studies but this is likely due to a difference in methodology or subject population (Radler, Kranzl et al. 2010, Hudson 2016). Nearly every study reports a wide range of tibial torsion values, which may inaccurately influence the averages produced, however a larger TFA is generally associated with a larger TOA/FPA.

**Ankle Weight-bearing Dorsiflexion**

Limited dorsiflexion can alter the mechanics of a squat by restricting the sagittal plane motion of both the ankle and knee. This can lead to an increase in compensatory motions in the frontal or transverse planes, which may produce increasing pressures on the subtalar joint, patellofemoral joint, and the anterior cruciate ligament. (Tiberio 1987, Macrum, Bell et al. 2012, Dill, Begalle et al. 2014). These excessive transverse and frontal plane movements such as subtalar joint pronation and knee valgus must be addressed to find the underlying reason for compensation in order to reduce the risk of injury. Rabin and Kozol (2017) examined both an overhead squat and a forward arm squat to determine their possibility as screening measures for individuals who have limited ankle dorsiflexion during weight-bearing. They demonstrated that a successfully completed overhead squat to full knee flexion without the individuals raising their heels off the floor had a 100% sensitivity to detect individuals with limited ankle dorsiflexion. However due to the difficulty of this task by having to maintain the arms overhead, only individuals with high dorsiflexion range of motion were able to complete this task. An easier forward arm squat demonstrated good specificity (0.87) and may be helpful to use for those who were unable to complete the overhead squat task. If the participant was not able to complete either movement, limited ankle dorsiflexion was likely present.

Dorsiflexion is an important measurement for our study due to the compensatory actions such as subtalar joint pronation and knee valgus that could occur as a result of limited dorsiflexion (Macrum, Bell et al. 2012). We are interested to see if limited dorsiflexion is accompanied by compensation with TOA as well. Furthermore, if a participant was not able to complete a deep squat, we could assess the influence of dorsiflexion range of motion and decide if it were a dorsiflexion flexibility or structural issue that kept the participant from completing a proper deep squat.

**Longitudinal Arch Angle**

Longitudinal arch angle (LAA) was first used by Dahle et al. (1991) to classify foot types into categories of pronation, supination, or neutral. They defined LAA as the angle formed from vectors of three bony landmarks on the medial foot- the medial malleolus, the navicular tuberosity, and the first metatarsal head- during a weight-bearing stance. Since Dahle, LAA has been used both as a visual and a numerical measurement for foot pronation. In their study of 63 subjects (57 male) with an age range of 18-30 years old, Jonson and Gross (1997) found an average weight-bearing LAA of 141.6° and 146.5° for males and females, respectively. They defined a pronated foot as exhibiting a LAA less than 130° and a supinated foot as exhibiting greater than 150°. A LAA in between these numbers was considered neutral (Jonson and Gross 1997).

Excessive pronation during midstance may cause a compensatory internal rotation of the femur. This rotation then puts excessive stress on the lateral portion of the patellofemoral joint when the tibiofemoral joint nears extension. This may begin to elicit pain in the patellofemoral joint, especially if anteversion of the femur is present (Tiberio 1987). Furthermore, a very low longitudinal arch angle is associated with the condition commonly known as ‘flat feet’ and can lead to pronation and an “increased angle of gait” (Lee, Vanore et al. 2005). More research is needed to determine if structural deformities such as abnormal lower extremity rotational profiles cause pronation and lead to flat feet, or if flat feet cause pronation and lead to structural deformities. McPoil and Cornwall (2005) determined that “the static measurement of the longitudinal arch angle is highly predictive of the dynamic posture of the foot that occurs during the midstance phase of walking.” This is important because studies have shown that maximum pronation is reached at, or just after, the midstance phase (Pierrynowski and Smith 1996, McPoil and Cornwall 2005).

**Barbell Back Squat**

Squats are an essential movement used from athletes looking to improve strength to therapists working on rehabilitation with patients. A positive TOA and wide stance has been associated with back squats (Escamilla, Francisco et al. 2000, Lahti, Hegyi et al. 2019). In a study examining kinematics and kinetics of powerlifters during a barbell back-squat competition, Escamillia et al. (2000) demonstrated that the “middle stance” group exhibited a stance ranging from 121-153% of the competitor’s shoulder width, and the groups (narrow, middle, and wide) exhibited increasingly larger toe-out angles during the squats. This incrementally larger TOA may be present to help promote proper patella tracking during a wider stance (Myer, Kushner et al. 2014).

**Forward Arm Squat**

Despite the common use of the back squat among athletes, a forward arm squat may be the preferred squat in a clinical setting because it promotes a hip dominant squat by leaning the trunk forward which places the line of gravity more anterior to the hip and thus closer to the knee joint. In doing so, stress is removed from the knees which is typically desired for patients early in the ACL reconstruction rehabilitation pathway or for athletes who suffer from anterior knee pain (Lahti, Hegyi et al. 2019). In recent studies, a forward arm squat has been used to identify structural abnormalities in participants specifically exhibiting femoroacetabular impingement syndrome (Lamontagne, Kennedy et al. 2009, Lamontagne, Brisson et al. 2011, Bagwell, Snibbe et al. 2016, Diamond, Bennell et al. 2017). FAI occurs when the head and/or neck of the femur does not properly sit within the acetabulum of the hip which causes a painful abutment of the femur against the acetabulum. This is usually exacerbated when the hip is flexed and internally rotated (Ganz, Parvizi et al. 2003, Beck, Kalhor et al. 2005). Studies have described the potential compensations that FAI participants may exhibit during a deep squat, however the participants are consistently instructed to squat with their feet facing forward (Lamontagne, Kennedy et al. 2009, Lamontagne, Brisson et al. 2011, Bagwell, Snibbe et al. 2016, Diamond, Bennell et al. 2017). This is presumably to control for variation within subjects, however as mentioned above, multiple studies have shown that participants naturally prefer a positive TOA/FPA. If participants will functionally squat with a positive TOA outside of the clinic, then these screenings could potentially be used to find 'real-world' functional deficits and asses the client while they are in a natural, preferred position. Furthermore, this natural TOA/FPA is likely influenced by structural alignment, and we believe participants should not be constrained to a non-natural stance during these studies because the constrained stance may conceal information regarding the participant's lower extremity structural alignment.

**Multiple Regression**

A multiple linear regression analysis will be used in this study to determine each variable's possible influence on the resulting TOA/FPA for each of the four activities (static stance, walking gait, forward arm squat and barbell back squat). A multiple regression analysis is a statistical technique that allows one to analyze the potential influence of multiple independent variables on a dependent variable of interest (Carter, Lubinsky et al. 2011). The analysis produces an equation in the form of y= mx + b, where the “y” is the TOA/FPA and the “x” is the independent variable(s) associated with the model. In addition, an R-squared value can be calculated to indicate the percentage of variance explained by the regression model. Variables in the final model consist of those that make a statistically significant contribution.

# III. MATERIALS AND METHODS

## Participants

A total of 37 participants were recruited from students at the University of Tennessee at Chattanooga (UTC) via word of mouth. Prior to participating in this study, participants were provided with an informed consent document (Appendix A). Participants were given a brief oral overview of its content and were also encouraged to read over the document themselves. Contents of this study were approved by the University of Tennessee at Chattanooga Institutional Review Board.

Participants were excluded from the study if they met any of the exclusion criteria as follows: A score lower than seven on the Tegner Activity Scale (Appendix B), lack of prior squat training, any history of lower extremity major injury (fractures, ligament tears, tendon ruptures, etc.), or any history of lower extremity minor injury within the last six months, defined as forced time away from sport for more than three days.

## Procedures

Data was collected by two researchers: a third year Doctor of Physical Therapy (DPT) student and a senior undergraduate Exercise Science major. The DPT student was responsible for positioning and instructing participants for the measures, whereas the undergraduate student collected pictures and video of the measures for later analyzation on ImageJ software (https://imagej.nih.gov/ij/). A small notepad denoting the subject's number was placed in the background of each photo to ensure file organization for each participant. Data collection was supervised by a professor in the Physical Therapy department with expertise in lower quarter structure. The following measurements were taken: height, weight, hip internal rotation, thigh foot angle, longitudinal arch angle, weight-bearing dorsiflexion, hip width, static toe angle and stance width; toe angle, stance width and squat depth during a forward arm squat; toe angle, stance width and squat depth during a barbell back squat; standing hip height, and foot progression angle.

**Baseline Measures**

After participants had reviewed and signed the informed consent, their sport history for both high school and college were recorded on the data collection sheet (Appendix C) in order to ensure a Tegner activity level greater than seven. Next, participants were instructed to remove their shoes and step on a balance beam scale for height and weight measures. All subsequent measures were conducted on the right side only unless otherwise noted.

**Hip Internal Rotation**

Participants were instructed to lay prone on a treatment table approximately 60 cm above the ground and relax. The DPT student then flexed the participant's right knee at 90° while stabilizing the contralateral pelvis with his right hand. Next, the DPT student internally rotated the participant's right hip to a passive end range. This position was held momentarily while the undergraduate student captured a still image (Appendix D). This process was then repeated two more times for a total of three pictures of the participant's passive hip internal rotation range of motion. The camera was positioned 1.3 meters behind the treatment table, and at the approximate midpoint height of the participant's knee.

In ImageJ, the angle tool was used to quantify the participant's hip internal rotation. The first ray of the angle was a vertical line meeting the vertex of the angle at center of the knee joint. The second ray bisected the tibia extending through the midpoint of the ankle joint (ie, malleoli). This process was repeated for each image three times resulting in three separate measures of hip internal rotation.

**Thigh Foot Angle**

Following the hip internal rotation measurement, the participant was instructed to sit up on the table to allow the DPT student to attach reflective markers on the participant's right medial and lateral malleoli. Once these were secure, the participant was instructed to lay prone on a mat situated on the ground. Again, the participant was instructed to relax and flex their right knee to a 90° angle. At this point, the camera was attached to a tripod 170 cm high looking down on the participant's lower extremity. A bubble level was used to ensure that the camera was level relative to the floor.  This position was held momentarily while the undergraduate student captured a still image (Appendix E).  In between each captured image, the DPT student extended the participant's knee and brought it back to a flexed angle of 90° at the knee. The DPT student also ensured that the ankle joint remained at 90° to minimize potential variation between the pictures. A total of three images were taken.

For each image, Microsoft Paint (Microsoft; Redmond, WA) was used to draw a straight line between the medial and lateral malleoli markers on each image. Then the ImageJ angle tool was again used to measure tibial torsion. A vertical line was drawn bisecting the thigh to create the first ray of the angle. The next ray was created by following the line created on Microsoft Paint. This angle formed was the complement angle from the actual thigh foot angle. Therefore, the angle measured was subtracted from 90° to achieve the measurement for the participant's TFA. This process was repeated for all three images.

**Ankle Weight-Bearing Dorsiflexion**

Next, the DPT student made a mark on the anterior aspect of the tibia 15 cm below the tibial tuberosity to aid in the measurement of weight-bearing ankle dorsiflexion. Participants were instructed to face the wall in a staggered stance with their right foot forward. The participants were then instructed to move the right knee forward to touch the wall while maintaining heel contact with the ground. The participants were allowed as many adjustments as needed to find the correct distance, and the DPT student lightly palpated the participant's heel to ensure it remained in contact with the ground. The IOS Compass app on an iPhone (Apple; Cupertino, CA) was used to measure the tibial segment in space relative to the floor to serve as a surrogate measure of ankle dorsiflexion. Before each measurement, the app was zeroed out while the phone was against a level wall to establish a vertical baseline. The midline of the phone was placed 15 cm below the tibial tuberosity for each measurement. Three measurements were taken, and the phone was recalibrated to the vertical baseline between each measurement.

**Longitudinal Arch Angle**

The medial malleolus marker from the thigh foot angle measurement was removed. Next, the participant was instructed to stand while the DPT student palpated the bony landmarks of the medial malleolus, navicular head, and 1st metatarsal head and denoted them with an Expo marker. The participant was then instructed to stand in a staggered stance with their right foot forward. They then were told to shift their weight onto their right foot by coming forward onto their left toe to simulate midstance when walking. At this point, an image was captured with the camera at ground level, 65 cm away from the participant (Appendix F). The participant was instructed to step their right foot back even with their left foot to reset in between each photo. A total of three images were taken.

The angle tool in ImageJ was used to quantify the participant's longitudinal arch angle. The vertex of the angle was located at the navicular head, with the first ray bisecting the marking on the medial malleolus and the second ray bisecting the marker on the 1st metatarsal head. This process was repeated for each image, for a total of three measures per participant.

## Hip Width

Next, the participants were instructed to stand in front of the DPT student for a hip width measurement. The DPT student palpated each participant's right and left anterior superior iliac spines and used an anthropometer sliding calipers (Model 61291, Lafeyette Instruments, Lafeyette, IN) to measure this width to a tenth of a centimeter.  Hip width was defined as the distance between these two bony landmarks.

## Toe Out Angle Measures

### *Static Stance*

After the hip width measurement, participants were instructed to stand on a piece of butcher paper (46 x 70 cm) secured to the floor. Participants were instructed to look straight ahead, march in place, and then stand comfortably on the butcher paper. At that point, the DPT student placed a mark on the butcher paper at the end of the second toe and at the mid-section of the heel, while also tracing the heel with the marker. After the position of both feet had been recorded, the participant was allowed to step off the butcher paper.

The markings on the butcher paper were used to determine participant's stance width and toe out angle. Stance width was defined as the distance between the midsection of both heels, as measured with a standard meter stick. Furthermore, foot placement from the bottom of the butcher paper was measured to account for potential staggered foot placement during the static stance. Toe angle was measured by drawing a straight line from the midsection of the heel to the marking of the second toe. A perpendicular line from the bottom of the butcher paper drawn using a 90° square tool provided a vertical line next to the line denoting the foot's placement and was used to complete the angle. This angle was measured using a standard 12-inch universal goniometer.

*Forward Arm Squat*

Once the static stance measure was completed, the researchers switched out the butcher papers (46 x 80 cm) and secured a new, non-marked butcher paper to the floor. At this time, if they had not already done so, the participants were instructed to change into their spandex shorts. The DPT student then placed reflective markers on the right greater trochanteric head, lateral femoral condyle, and lateral malleolus. The participant was instructed to complete five consecutive squats “as deep as you can go, with your arms forward, and without your heels coming off of the ground” while standing on the butcher paper. The participant was allowed as many practice squats as needed until they were comfortable completing the movement. The same markings were made on the butcher paper as were made during the static stance once the five squats were completed. A second researcher positioned the camera on a tripod at approximately mid-thigh height on the frontal plane for each participant. A bubble level was used to ensure the camera was level on three dimensions, and a video was taken to capture all five squats. Once the researchers collected the video and made the proper foot placement markings, the participant was allowed to step off the butcher paper.

The markings on the butcher paper were used to determine the stance width and toe out angle in the same way as described above with the static stance butcher paper. The middle three squats (squats 2-4) were used for data analyzation on ImageJ. A marking one-meter high on an adjacent wall allowed the researchers to “set scale” on ImageJ and determine the participant’s hip height and squat depth. With the scale set according to the meter measurement on the wall, a vertical line was drawn from the reflective marker on the greater trochanteric head to the floor, and then measured to determine the participant's standing hip height. Squat depth was measured by taking a still image of the video at the participant's maximum depth during squats 2-4. Once the image was captured, researchers drew a vertical line on ImageJ from the greater trochanteric head to the floor to measure the depth of the squat (Appendix G). Squat depth was then reported as a ratio of greater trochanteric head height at the point of maximum squat depth to greater trochanteric head height at normal stance.

*Barbell Back Squat*

Once the forward arm squat procedures were completed, the researchers flipped over the butcher paper and secured it to the floor. The participants were again instructed to complete five consecutive squats "as deep as you can go, without your heels coming off of the ground" while standing on the butcher paper, however this time they held a 122cm (ie, 4 feet) dowel rod on their shoulders as they would a barbell during a back squat (Myer, Kushner et al. 2014) (Appendix H). The procedures and measurements taken during the barbell back squat were the same as the procedures and measurements described above during the forward arm squat.

**Foot Progression Angle**

Next, the participants walked along a GaitRite mat (GaitRite; Franklin, NJ) to measure their foot progression angle. A GaitRite mat is a pressure-sensitive mat used to gather foot placement and gait data during a normal walking phase. The length of the GaitRite mat was approximately 15feet. Participants were told to walk with a normal gait, while staring at an 'x' on the wall at the end of the hallway, and to continue walking with their normal gait until they reached another marking on the floor one meter past the end of the mat. Once the participants reached the second marking denoting the end of a walk, they returned to their starting position at the front of the mat. Participants repeated walks until the GaitRite system had collected sufficient data for five different walks. The GaitRite system collected walking TOA data to the tenth of a degree for each step and this was averaged for each participant to provide an FPA average measure.

**Statistical Analysis**

Descriptive statistics for the main variables of interest (TOA, HIR, TFA, and ADF, and LAA) included in the regression models were calculated. LAA, HIR, TFA, and ADF were measured three times and averaged for each participant. Each variable was analyzed using box plots and normal probability plots to assess for any potential outliers. Next, a check of influential observations was performed with variables that were significantly correlated with TOA or FPA. Cook's distance, studentized residuals, and leverage plots were used to determine whether there were any influential observations. If no influential observations were detected, then all observations were included in the final regression model. At this point, a check for collinearity between variables was performed by assessing the variable influence factor and collinearity diagnostics. If collinearity was detected, the collinear variable was removed from the regression model. SAS software (version 9.4, Cary, NC) was used to calculate the model of best fit. This model was determined using all possible regressions and based on $R^2$, using Mallow's Cp as a criterion.

# IV. RESULTS

## Participants

The study involved 37 participants (19 males, 18 females) with a mean age of 23.1 years old (SD= 2.3). The participants' mean height was 1.70 meters (SD= 0.1) and mean weight was 70.8 kilograms (SD= 13.5). All participants scored a seven or higher on the Tegner activity scale. Descriptive data for each participant is listed in Appendix D. Toe-out angle and foot progression angle averages are listed in Table 1. Participants consistently exhibited a positive TOA. Furthermore, stance width and TOA increased as participants moved from a static stance to a forward arm squat stance to a barbell back squat stance. Average anatomical descriptive statistics are listed in Table 2.

**Table 1. Average and Standard Deviation Toe-Out Angle and Stance Width for Static and Dynamic Activities**

| | **Left Foot (°)** | **Right Foot (°)** | **Stance Width (cm)** |
|---|---|---|---|
| Static Stance | 8.6 (5.2) | 9.6 (5.0) | 19.9 (4.5) |
| Forward Arm Squat | 12.5 (6.6) | 14.7 (6.6) | 32.9 (6.9) |
| Barbell Back Squat | 14.2 (6.7) | 17.6 (7.1) | 38.2 (7.4) |
| Foot Progression Angle | 3.5 (5.3) | 6.1 (5.7) | n/a |

**Table 2. Averages and Standard Deviations for All Anatomical Structural Measures**

| Longitudinal Arch Angle (°) | Hip Internal Rotation (°) | Thigh Foot Angle (°) | Ankle Dorsiflexion (°) |
|---|---|---|---|
| 141.7 (8.6) | 36.5 (9.4) | 20.8 (5.9) | 39.8 (6.4) |

## Regression Models

### *FPA*

The FPA data set did not contain any statistical outliers, however one participant was not included in the correlation analysis due to insufficient data related to their FPA, resulting in an analysis of 36 participants. HIR exhibited a significant inverse correlation with walking FPA (Table 2). In the regression model, the model of best fit included only HIR ($p = 0.003$):

$$FPA= -0.30*HIR + 16.8$$

This model explained approximately 24% of the variance associated with FPA during walking (r-squared= 0.24, adjusted r-squared= 0.22, Cp= 0.94). The negative correlation between FPA and HIR suggests that as HIR measurements increased, FPA decreased while walking.

**Table 3. Walking Foot Progression Angle Correlation**

| | | FPA | LAA | HIR | TFA | ADF |
|---|---|---|---|---|---|---|
| FPA | r | 1.000 | <0.001 | -0.488 | 0.217 | -0.15 |
| | p | | 1.000 | 0.003 | 0.205 | 0.383 |
| LAA | r | <0.001 | 1.000 | 0.002 | 0.258 | -0.085 |
| | p | 1.000 | | 0.993 | 0.128 | 0.624 |
| HIR | r | -0.488 | 0.002 | 1.000 | -0.027 | 0.371 |
| | p | 0.003 | 0.993 | | 0.875 | 0.026 |
| TFA | r | 0.217 | 0.258 | -0.027 | 1.000 | 0.007 |
| | p | 0.205 | 0.128 | 0.875 | | 0.966 |
| ADF | r | -0.15 | -0.085 | 0.371 | 0.007 | 1.000 |
| | p | 0.383 | 0.624 | 0.026 | 0.966 | |

FPA= foot progression angle, LAA= longitudinal arch angle, HIR= hip internal rotation, TFA= thigh foot angle, ADF= ankle dorsiflexion

*Standing Toe-Out Angle*

The standing toe-out angle (TOA) data set did not contain any statistical outliers, and all observations were included in the correlation analysis. Hip internal rotation (HIR) exhibited a significant inverse correlation with TOA (Table 4). In the regression analysis, the model of best fit included only HIR ($p = 0.017$):

$$TOA = -0.21 * HIR + 17.2$$

This model explained approximately 15% of the variance with TOA during static stance (r-squared= 0.15, adjusted r-squared= 0.13, Cp= 7.32). The negative correlation between TOA and HIR suggests that as HIR measurements increased, TOA decreased during static stance.

**Table 4. Standing Toe-Out Angle Correlation**

| | | TOA | LAA | HIR | TFA | ADF |
|---|---|---|---|---|---|---|
| TOA | r | 1.000 | -0.141 | -0.390 | 0.282 | 0.076 |
| | p | | 0.404 | 0.017 | 0.091 | 0.654 |
| LAA | r | -0.141 | 1.000 | -0.006 | 0.244 | -0.078 |
| | p | 0.404 | | 0.970 | 0.146 | 0.646 |
| HIR | r | -0.390 | -0.006 | 1.000 | 0.009 | 0.340 |
| | p | 0.017 | 0.970 | | 0.959 | 0.039 |
| TFA | r | 0.282 | 0.244 | 0.009 | 1.000 | -0.018 |
| | p | 0.091 | 0.146 | 0.959 | | 0.915 |
| ADF | r | 0.076 | -0.078 | 0.340 | -0.018 | 1.000 |
| | p | 0.654 | 0.646 | 0.039 | 0.915 | |

FPA= foot progression angle, LAA= longitudinal arch angle, HIR= hip internal rotation, TFA= thigh foot angle, ADF= ankle dorsiflexion

*Forward Arm Squat Toe-Out Angle*

The forward arm squat toe-out angle data set did not contain any statistical outliers, and all observations were included in the correlation analysis. HIR exhibited a significant inverse correlation with forward arm squat TOA, while thigh foot angle (TFA) exhibited a significant positive correlation with forward arm squat TOA (Table 5). In the regression model, the model of best fit included both HIR (p= 0.029) and TFA (p= 0.035):

$$TOA = 0.40*TFA - 0.26*HIR + 15.8$$

This model explained approximately 25% of the variance associated with TOA during a forward arm squat (r-squared= 0.25, adjusted r-squared= 0.21, Cp= 3.79). The negative correlation between TOA and HIR suggests that as HIR measurements increased, TOA decreased during a forward arm squat. The positive correlation between TOA and TFA suggests that as TFA measurements increased, TOA increased during a forward arm squat.

**Table 5. Forward Arm Squat Toe-Out Angle Correlation**

| | | TOA | LAA | HIR | TFA | ADF |
|---|---|---|---|---|---|---|
| TOA | r | 1.000 | -0.140 | -0.360 | 0.347 | -0.049 |
| | p | | 0.407 | 0.029 | 0.035 | 0.775 |
| LAA | r | -0.140 | 1.000 | -0.006 | 0.244 | -0.078 |
| | p | 0.407 | | 0.970 | 0.146 | 0.646 |
| HIR | r | -0.360 | -0.006 | 1.000 | 0.009 | 0.340 |
| | p | 0.029 | 0.970 | | 0.959 | 0.039 |
| TFA | r | 0.347 | 0.244 | 0.009 | 1.000 | -0.018 |
| | p | 0.035 | 0.146 | 0.959 | | 0.915 |
| ADF | r | -0.049 | -0.078 | 0.340 | -0.018 | 1.000 |
| | p | 0.775 | 0.646 | 0.039 | 0.915 | |

FPA= foot progression angle, LAA= longitudinal arch angle, HIR= hip internal rotation, TFA= thigh foot angle, ADF= ankle dorsiflexion

*Barbell Back Squat Toe-Out Angle*

The barbell back squat toe-out angle data set did not contain any statistical outliers, and all observations were included in the correlation analysis. HIR exhibited a significant inverse correlation with barbell back squat TOA, while TFA exhibited a significant positive correlation with barbell back squat TOA (Table 6). Longitudinal arch angle (LAA) exhibited a negative correlation with barbell back squat TOA, however did not reach statistical significance ($p > 0.05$). In the regression model, the model of best fit included HIR ($p = 0.019$), TFA ($p = 0.031$), and LAA ($p = 0.08$):

$$\text{TOA: } 0.56*\text{TFA} - 0.30*\text{HIR} - 0.34*\text{LAA} + 64.5$$

This model explained approximately 43% of the variance associated with TOA during a barbell back squat (r-squared= 0.43, adjusted r-squared= 0.38, Cp= 4.76). The negative correlation of both HIR and LAA suggests that as HIR and LAA measurements increased, TOA decreased during a barbell back squat. While the LAA correlation did not reach statistical significance by itself, it provided a substantial contribution to the regression model when coupled with HIR and TFA. The positive correlation between TOA and TFA suggests that as TFA measurements increased, TOA increased during a barbell back squat.

**Table 6. Barbell Back Squat Toe-Out Angle Correlation**

| | | TOA | LAA | HIR | TFA | ADF |
|---|---|---|---|---|---|---|
| TOA | r | 1.000 | -0.292 | -0.384 | 0.356 | -0.271 |
| | p | | 0.080 | 0.019 | 0.031 | 0.105 |
| LAA | r | -0.292 | 1.000 | -0.006 | 0.244 | -0.078 |
| | p | 0.080 | | 0.970 | 0.146 | 0.646 |
| HIR | r | -0.384 | -0.006 | 1.000 | 0.009 | 0.340 |
| | p | 0.019 | 0.970 | | 0.959 | 0.039 |
| TFA | r | 0.356 | 0.244 | 0.009 | 1.000 | -0.018 |
| | p | 0.031 | 0.146 | 0.959 | | 0.915 |
| ADF | r | -0.271 | -0.078 | 0.340 | -0.018 | 1.000 |
| | p | 0.105 | 0.646 | 0.039 | 0.915 | |

FPA= foot progression angle, LAA= longitudinal arch angle, HIR= hip internal rotation, TFA= thigh foot angle, ADF= ankle dorsiflexion

## V. DISCUSSION

The purpose of our study was to examine the influence of lower extremity structure on FPA, standing TOA, forward arm squat TOA, and barbell back squat TOA. We had hypothesized that LAA would be a significant predictor for each regression model, but this hypothesis was only partially supported as LAA was only included in the final model for the barbell back squat. We had also hypothesized that ADF would be a significant predictor for each regression model, but this hypothesis was rejected as ADF was not included in any of the models. HIR served as the best predictor for FPA and TOA during all activities, and was accompanied by TFA during a forward arm squat, and TFA and LAA during a barbell back squat.

**FPA**

Our participants exhibited an average FPA of 3.5° and 6.1° for their left and right feet, respectively. Cibulka et al. (2016) demonstrated similar measures of FPA in their study, noting an average FPA of 3.3° in their population of 60 participants (41 female and 19 male) who were on average 26.7 $\pm$ 10.9 years old. It should be noted however, that their female participants exhibited an average FPA of 1.4°, lowering their total average FPA. Furthermore, our participants, who were widely right-foot dominant, had 2.6° greater FPA on their right compared to their left side. Cibulka randomized the measurements to analyze only the left foot for 30 participants and only the right foot for the other 30 participants. If Cibulka's participants were widely right-foot dominant as well, this could provide another explanation of why Cibulka reported a lower FPA than what we demonstrated in our subjects. Hudson et al. (2016) also reported a comparable FPA of 4.5° in their study of 102 participants (59 females and 43 males) who were on average 29.1 years old, ranging from 19-69. Further research is needed to assess the influence of foot dominance and sex on FPA and TOA.

According to our model, HIR was the only significant variable in our model that explained approximately 24% of the variance associated with FPA. Cibulka et al. (2016) demonstrated that HIR along with TFA explained 41% of the variance in FPA, but did not specify the proportion attributed to HIR alone. The Pearson *r* value for their HIR was -0.40 compared to our value of -0.48, so most likely the percent of variance explained was similar between studies. Cibulka reported a slightly higher average of HIR of 41.2° compared to our study average of 36.5°. However, this discrepancy may be attributed to the large percentage of females (approximately 68%) in Cibulka's study. The average HIR for males in their study was 33.5°, while the average for females was 42.8°. These numbers are very similar to our averages for males and females, which were 30.9° and 42.5°, respectively. Our results, however, did not include TFA in our final model. The TFA values in Cibulka's study were slightly lower (average 16.9 $\pm$ 6.1°) compared to our values (average 20.8 $\pm$ 5.9°), but variability was similar. Therefore, the lack of variance explained in our study could also be linked to limb dominance. Finally, ADF and LAA were not included in the final regression model suggesting that neither variable had influence on FPA. It should be noted that ADF was assessed with the knee bent, which is more of a direct measure of ankle range of motion and/or soleus muscle length, compared to gastrocnemius muscle length. Therefore, assessment of ADF length with the knee extended may have better explained FPA. LAA was hypothesized to be associated with FPA; however, the task of walking itself, which is a general forward motion of the body, may override structural considerations.

**Standing TOA**

Our participants exhibited an average standing TOA of 8.6° and 9.6° for their left and right feet respectively. McIlroy and Maki (1997) studied natural static stance TOA in a total of 262 participants, which included a subgroup of 81 "young adult" participants (average age of 29 ± 11 years) similar to the age of our participants. The young adults exhibited an average TOA of 11.6 ± 8.9°, measured from the center of the heel to the great toe. A measurement using the great toe theoretically would provide a smaller TOA than a measurement from the second toe. Despite this difference in methods, McIlroy and Maki's average measurements were still larger than our measurements. McIlroy and Maki reported larger variability within their study, which may be attributed to their subject population or influential structural alignment, which was not reported. However, their results are in agreeance with our results which suggest that a preferred, natural stance often exhibits a positive TOA. Our study helps confirm this research and provides TOA data for a more specific population.

In terms of the regression model, similar to FPA, only HIR was demonstrated to be a significant predictor, explaining 15% of the variance in standing TOA. Despite the fact that Cibulka et al. (2016) demonstrated that TFA was associated with walking FPA, TFA does not appear to be significantly related to standing TOA. In addition, neither ADF nor LAA seem related to standing TOA, suggesting that other factors (eg, balance) play a role in the TOA associated with standing.

**Forward Arm Squat TOA**

Our participants exhibited an average TOA of 12.5° and 14.7° for their left and right feet respectively during a forward arm squat. We are unaware of any other study determining natural TOA for the forward arm squat. According to our model, HIR and TFA explained approximately 25% of the variance associated with TOA during a forward arm squat. Hudson

(2016) helps explain the potential offsetting capabilities of HIR and TFA. He suggests that in participants with low HIR, TFA can be used to help predict FPA. This is clinically relevant because a large TFA can be ‘hidden’ by excessive HIR during a dynamic movement, i.e. walking. Furthermore, Radler et al. (2010) highlights the importance of “a considerable dynamic influence of mechanisms, especially in the hip, that should be considered when evaluating torsional profile” in relation to FPA. However during a static stance (such as the one adopted during a squat), these mechanisms used to compensate for structural rotation are not possible (Radler, Kranzl et al. 2010), therefore bringing TFA into relevance during static stance activity. Furthermore, while the stance itself is static, the movement of a squat cannot be considered static due to a changing center of mass. From this perspective, a wider TOA associated with the forward arm squat provides a more stable base during the dynamic activity than compared to normal posture adopted during a truly static activity. Again, neither ADF nor LAA were significantly related to forward arm squat TOA, suggesting that other factors (eg, balance) play a role in the TOA associated with a forward arm squat.

**Barbell Back Squat TOA**

Our participants exhibited an average TOA of 14.2° and 17.6° for their left and right feet respectively during a barbell back squat. Escamilla et al. (2000) demonstrated that Olympic weightlifters who stood with a similar stance width had a toe angle of 20 $\pm$ 5°. Their values are slightly greater than our values, used the midpoint of the foot vs the 2$^{nd}$ toe. According to our model HIR, TFA, and LAA explained approximately 43% of the variance associated with TOA during a barbell back squat. As mentioned above, a forward arm squat is normally used in a clinical setting whereas a barbell back squat is a common movement in the athletic training realm. A forward arm squat is an easier movement as the arms act as a counter balance during the squat. Our participants exhibited a wider stance and larger TOA when completing a barbell back squat when compared to a forward arm squat, which may be a compensatory strategy to increase their base of support to provide balance during this movement.

LAA contributed to this model even though it was not significant during the forward arm squat. All of our participants had a history of squat training, and we believe that the increase in TOA and stance width is associated with the participants naturally preparing for a heavier load, which is typical of a barbell back squat, even though back squats for the study were performed with a light dowel. Lower LAA can help explain the increased TOA due to pronation of the subtalar joint. Pronation puts the subtalar joint at its end range, and we believe that this may be done to stiffen what is naturally a supple foot in order to prepare for the increase in load. This pronation is not evident during the forward arm squat because no load is associated with completing a forward arm squat. Again, ADF did not contribute significantly to the model of best fit for the barbell back squat.

**Limitations and Suggestions for Future Research**

A limitation of this study was that participants completed the activities barefoot and were not supported in terms of the arch and heel elevation, which is typical of a tennis shoe and especially of a squat/weightlifting shoe. Furthermore, this study only measured structural alignment, whereas flexibility, range of motion, and strength also likely influence toe angle. Additionally, ankle dorsiflexion measurements were taken with the knee flexed. This may have measured ankle and soleus flexibility while inhibiting gastrocnemius tightness from influencing TOA as it might with the knee straight, and therefore may have affected the relationship between TOA and dorsiflexion, especially in regard to standing TOA. Our participants all exhibited an extensive history of athletic participation, and while our gender spread was close to equal (19 males; 18 females), all of our participants were right foot dominant. Our participants exhibited a substantially larger TOA/FPA on their right foot compared to their left. We suggest that future research measure participants bilaterally and examine the influence of athletic participation and foot dominance on natural TOA/FPA. Finally, further research should be conducted in regard to the depth of squat and joint contribution in relation to preferred TOA during a squatting task.

**Conclusion**

Our study examined the influence of four main variables: HIR, TFA, LAA, and ADF on FPA and standing TOA, forward arm squat TOA, and barbell back squat TOA. We demonstrated HIR as the strongest stand-alone structural predictor for FPA and TOA, while TFA helps explain variation in TOA for forward arm and barbell back squats. We also demonstrated that LAA was only associated with the TOA for the barbell back squat, which may be explained by participants naturally preparing for a loaded movement. ADF does not appear to be related to toe out positions for static or dynamic activities.

## LIST OF REFERENCES

Bagwell, J. J., J. Snibbe, M. Gerhardt and C. M. Powers (2016). "Hip kinematics and kinetics in persons with and without cam femoroacetabular impingement during a deep squat task." Clin Biomech (Bristol, Avon) **31**: 87-92.

Beck, M., M. Kalhor, M. Leunig and R. Ganz (2005). "Hip morphology influences the pattern of damage to the acetabular cartilage." The Journal of Bone and Joint Surgery.

Brown, L. E. (2007). Strength Training: National Strength and Conditioning Association. Colorado Springs, Colorado, National Strength and Conditioning Association.

Carter, R. E., J. Lubinsky and E. Domholdt (2011). Rehabilitation Research: Principles and Applications, Fourth Edition. St. Louis, Missouri, Elsevier Saunders.

Cibulka, M. T., K. Winters, T. Kampwerth, B. McAfee, L. Payne, T. Roeckenhaus and S. A. Ross (2016). "Predicting Foot Progression Angle during Gait Using Two Clinical Measures in Healthy Adults, a Preliminary Study." Int J Sports Phys Ther **11**(3): 400-408.

Dahle, L. K., M. J. Mueller, A. Delitto and J. E. Diamond (1991). "Visual assessment of foot type and relationship of foot type to lower extremity injury." J Orthop Sports Phys Ther **14**(2): 70-74.

Diamond, L. E., K. L. Bennell, T. V. Wrigley, R. S. Hinman, J. O'Donnell and P. W. Hodges (2017). "Squatting Biomechanics in Individuals with Symptomatic Femoroacetabular Impingement." Med Sci Sports Exerc **49**(8): 1520-1529.

Dill, K. E., R. L. Begalle, B. S. Frank, S. M. Zinder and D. A. Padua (2014). "Altered knee and ankle kinematics during squatting in those with limited weight-bearing-lunge ankle-dorsiflexion range of motion." J Athl Train **49**(6): 723-732.

Escamilla, R. F., A. C. Francisco, G. S. Fleisig, S. W. Barrentine, C. M. Welch, A. V. Kayes, K. P. Speer and J. R. Andrews (2000). "A three-dimensional biomechanical analysis of sumo and conventional style deadlifts." Med Sci Sports Exerc **32**(7): 1265-1275.

Ganz, R., J. Parvizi, M. Beck, M. Leunig, H. Notzli and K. A. Siebenrock (2003). "Femoroacetabular impingement: a cause for osteoarthritis of the hip." Clin Orthop Relat Res(417): 112-120.

Gross, M. T. (1995). "Lower quarter screening for skeletal malalignment--suggestions for orthotics and shoewear." J Orthop Sports Phys Ther **21**(6): 389-405.

Hudson, D. (2016). "The rotational profile: A study of lower limb axial torsion, hip rotation, and the foot progression angle in healthy adults." Gait Posture **49**: 426-430.

Jonson, S. R. and M. T. Gross (1997). "Intraexaminer reliability, interexaminer reliability, and mean values for nine lower extremity skeletal measures in healthy naval midshipmen." J Orthop Sports Phys Ther **25**(4): 253-263.

Lahti, J., A. Hegyi, A. D. Vigotsky and J. P. Ahtiainen (2019). "Effects of barbell back squat stance width on sagittal and frontal hip and knee kinetics." Scand J Med Sci Sports **29**(1): 44-54.

Lamontagne, M., N. Brisson, M. J. Kennedy and P. E. Beaule (2011). "Preoperative and postoperative lower-extremity joint and pelvic kinematics during maximal squatting of patients with cam femoro-acetabular impingement." J Bone Joint Surg Am **93 Suppl 2**: 40-45.

Lamontagne, M., M. J. Kennedy and P. E. Beaule (2009). "The effect of cam FAI on hip and pelvic motion during maximum squat." Clin Orthop Relat Res **467**(3): 645-650.

Lee, M. S., J. V. Vanore, J. L. Thomas, A. R. Catanzariti, G. Kogler, S. R. Kravitz, S. J. Miller, S. C. Gassen and P. Clinical Practice Guideline Adult Flatfoot (2005). "Diagnosis and treatment of adult flatfoot." J Foot Ankle Surg **44**(2): 78-113.

Macrum, E., D. R. Bell, M. Boling, M. Lewek and D. Padua (2012). "Effect of limiting ankle-dorsiflexion range of motion on lower extremity kinematics and muscle-activation patterns during a squat." J Sport Rehabil **21**(2): 144-150.

McIlroy, W. E. and B. E. Maki (1997). "Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing." Clin Biomech (Bristol, Avon) **12**(1): 66-70.

McPoil, T. G. and M. W. Cornwall (2005). "Use of the longitudinal arch angle to predict dynamic foot posture in walking." J Am Podiatr Med Assoc **95**(2): 114-120.

Myer, G. D., A. M. Kushner, J. L. Brent, B. J. Schoenfeld, J. Hugentobler, R. S. Lloyd, A. Vermeil, D. A. Chu, J. Harbin and S. M. McGill (2014). "The back squat: A proposed assessment of functional deficits and technical factors that limit performance." Strength Cond J **36**(6): 4-27.

Pierrynowski, M. R. and S. B. Smith (1996). "Rear foot inversion/eversion during gait relative to the subtalar joint neutral position." Foot Ankle Int **17**(7): 406-412.

Radler, C., A. Kranzl, H. M. Manner, M. Hoglinger, R. Ganger and F. Grill (2010). "Torsional profile versus gait analysis: consistency between the anatomic torsion and the resulting gait pattern in patients with rotational malalignment of the lower extremity." Gait Posture **32**(3): 405-410.

Seber, S., B. Hazer, N. Kose, E. Gokturk, I. Gunal and A. Turgut (2000). "Rotational profile of the lower extremity and foot progression angle: computerized tomographic examination of 50 male adults." Arch Orthop Trauma Surg **120**(5-6): 255-258.

Tiberio, D. (1987). "The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model." J Orthop Sports Phys Ther **9**(4): 160-165.

# APPENDICES

**Appendix A. Informed Consent Form**

INFORMED CONSENT FORM

UNIVERSITY OF TENNESSEE AT CHATTANOOGA
PROTOCOL TITLE: *Possible Relationships between Lower Extremity Structural Alignment and Toe Angle in Squatting and Walking*

**Principal Investigator:** Jeremiah Tate, PT, PhD
**UTC Department:** Physical Therapy
**Phone number:**(423) 425-5710

**Co-Investigators:** Mark Britt
Tyler Trew, SPT

Please read this consent document carefully before you decide to participate in this study.

<u>Purpose of the research study:</u>

This is a research study designed to contribute to general knowledge. The purpose of this research study is to attempt to create a prediction model to determine the potential relationships between lower extremity structural alignment and toe angle during static and dynamic activities.

You have been invited to participate in the study because you are an adult between the ages of 18 and 45 who is a recreational athlete in sports involving running and cutting. In addition, you are familiar with squat training from previous experience. You should not participate in this study if you have had a previous lower extremity fracture and/or surgery, or have suffered a lower extremity injury in the past 6 month that limited your activity for more than 2 weeks.

<u>What you will be asked to do in the study:</u>

Your participation will involve evaluation of your right lower extremity alignment through different measurements in sitting, standing, and lying. First, your height and weight will be measured using a standard clinical scale. You will then lay down on your stomach on an examination table. A researcher will stabilize your hip while they bend your knee and gently rotate your hip to end range. At this point, another researcher will take a picture of your leg in this position. You will remain in this position while the researcher palpates the side of your hip and positions you for another picture. Next, the researchers will apply small, reflective balls on both sides of your ankles with tape and then take photos on your feet while lying on your stomach with your knees bent.

You will then be asked to stand up with your feet in a staggered stance with the front knee slightly bent. A researcher will mark three marks on your feet with an Expo marker and pictures will be taken of the inside of your ankles while in a staggered stance. You will then walk towards a wall and again assume a staggered stance position. This time, you will bend your front knee and attempt to touch the wall with your kneecap. You will be asked to slide your foot back until you cannot touch the wall without your heel coming up off the floor. At the point, a researcher will place a smartphone on the front of your lower leg to get an angle measurement. Next, you will stand in a relaxed position, and a researcher will locate your hip bones and measure the distance between your hips.

You will then be asked to stand on butcher paper in relaxed positon. At this point, a researcher will mark the positions of your heels and $2^{nd}$ toes. You will then have reflective markers placed on the outside of your ankles, knees, and hips. You will then practice doing a squat holding a wooden stick behind your head and then practice a squat with your arms held out front at shoulder level. After you get comfortable with these squats, you will complete 5 repetitions while standing on butcher paper and at the end of the $5^{th}$ squat your foot positions will again be marked on the paper. Videos will be taken during the squats to measure the depth of the squat. Lastly, you will be asked to walk on a mat that will measure your foot position while walking.

<u>Time required</u>:

*30 minutes*

<u>Risks and Benefits</u>:

The risks of the study could be slight muscle soreness in the lower extremities associated with squatting. Because you have familiarity with squatting, this risk should be minimal. The potential benefits of the study include general knowledge about structural alignment and an awareness of your preferred foot placement during standing and walking.

<u>Incentive or Compensation:</u>

In case of injury: All types of research involve possible risk, some including the risk of personal injury. In spite of all precautions, you might develop complications from participating in this study. If such complications arise, you should seek medical assistance at UTC Student Health Services, but any costs associated with the treatment will be the participant's responsibility. The University of Tennessee at Chattanooga has not set aside funds to compensate you for any such complications or injuries, or for related medical care. However, by signing this form, you do not waive any of your legal rights.

No incentives will be offered to the participants in this study.

**OR**

There are no incentives and you will not be paid for your participation.

<u>Video recording and photographing of study participants/activities</u>

I understand that I will be photographed and videotaped by the researchers during this study. You have the right to refuse to allow photographs and/or video to be taken. Please select one of the following options:

I consent to photographs/video recordings: Yes _______ No _______

Confidentiality:

Your identity will be kept confidential to the extent provided by law. Your identity will be kept confidential by using coded numbers to identify your information after data collection. Personal information will be secured in a password protected file and all consent forms and paperwork will be stored in the primary investigator's office in a locked file cabinet. Photos and video files will be uploaded by the researchers to a university owned computer that is password protected and will be locked up behind closed doors when not in use. The principal investigator and co-investigators will be the only individuals who have access to this data. Identifiers might be removed from the information, and after such removal, the information could be used for future research studies or distributed without additional informed consent. Any hard copies of consent forms and other documents related to the study will be shredded 3 years after the completion of the study. De-identified photo or video data files will be kept indefinitely.

Voluntary participation:

You will be excluded from the study if you are younger than 18 years old. Your participation in this study is completely voluntary. Should you elect to discontinue participation, any information already collected will be discarded. There is no penalty or loss of benefit for choosing not to participate.

Right to withdraw from the study:

You have the right to withdraw from the study at any time without consequence or penalty.

Whom to contact if you have questions about the study:
If you have any questions or concerns regarding the information provided here, please contact Dr. Jeremiah Tate through the Physical Therapy Department in the University of Tennessee at Chattanooga, at (423) 425-5710 or Jeremiah-Tate@utc.edu.

If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you may contact Dr. Amy Doolittle, Chair of the UTC Institutional Review Board at (423) 425-5563. This research protocol has been approved by the UTC Institutional Review Board. Additional contact information is available at www.utc.edu/irb.

Agreement:

If you wish to participate in this study, please sign the form below. A signature will indicate agreement to participate.

Participant's Name: (Print) ____________________________________________

Signature _________________________________ (Date) ________________

## Appendix B. Tegner Activity Scale

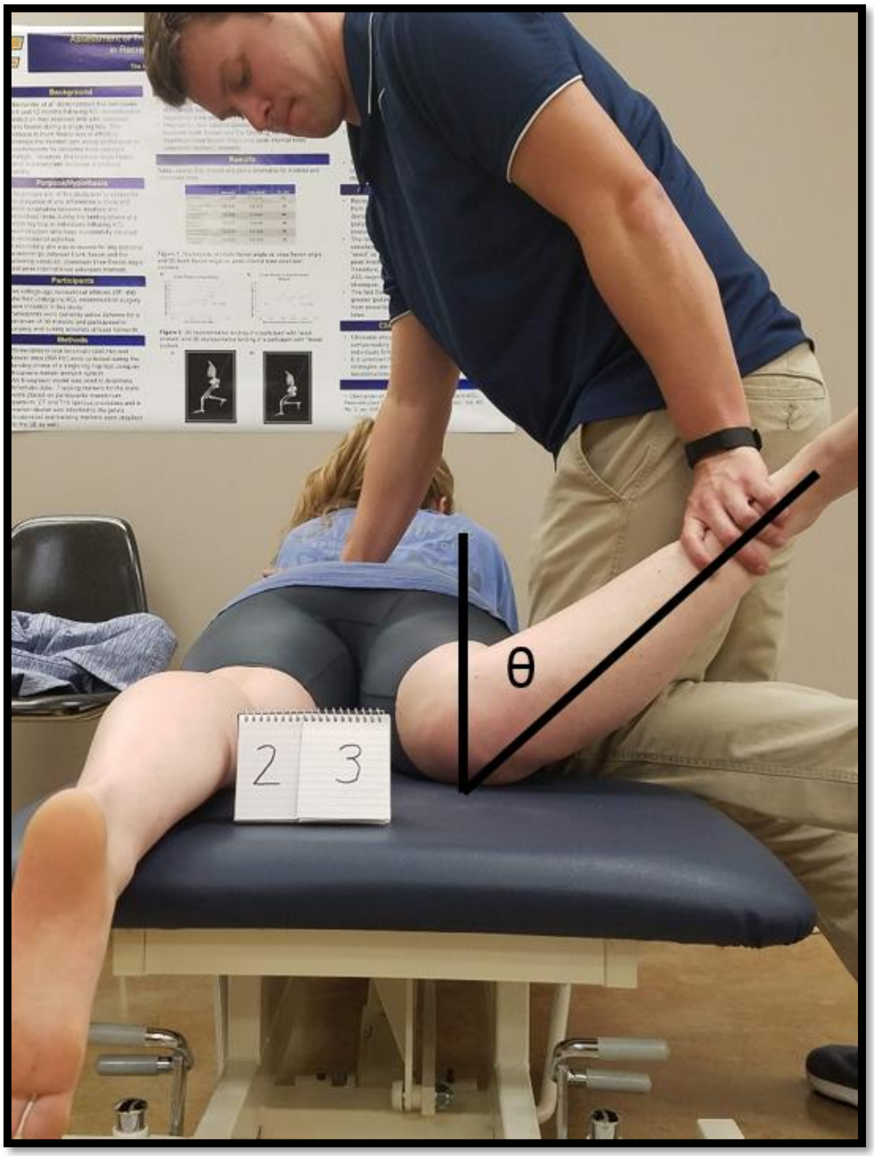
Please indicate below the **HIGHEST** level of activity that you are able to participate in **CURRENTLY**.

- ☐ Level 10 — Competitive sports-soccer, football, rugby (national elite)
- ☐ Level 9 — Competitive sports-soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball
- ☐ Level 8 — Competitive sports-racquetball, squash or badminton, track and field athletics (jumping, etc.), downhill skiing
- ☐ Level 7 — Competitive sports-tennis, running, motorcars speedway, handball<br>Recreational sports-soccer, football, rugby, ice-hockey, basketball, squash, racquetball, running
- ☐ Level 6 — Recreational sports-tennis and badminton, handball, racquetball, downhill skiing, jogging at least 5 x per week
- ☐ Level 5 — Work-heavy labor (construction, etc.)<br>Competitive sports-cycling, cross-country skiing<br>Recreational sports-jogging on uneven ground at least twice weekly
- ☐ Level 4 — Work-moderately heavy labor (e.g. truck driving, etc.)<br>Recreational sports-cycling, cross-country skiing, jogging on even ground at least twice weekly
- ☐ Level 3 — Work-light labor (nursing, etc.)<br>Competitive and recreational sports-swimming, walking in forest possible
- ☐ Level 2 — Walking on uneven ground possible, but impossible to back pack or hike
- ☐ Level 1 — Work-sedentary (secretarial, etc.)
- ☐ Level 0 — Sick leave or disability pension because of knee problems

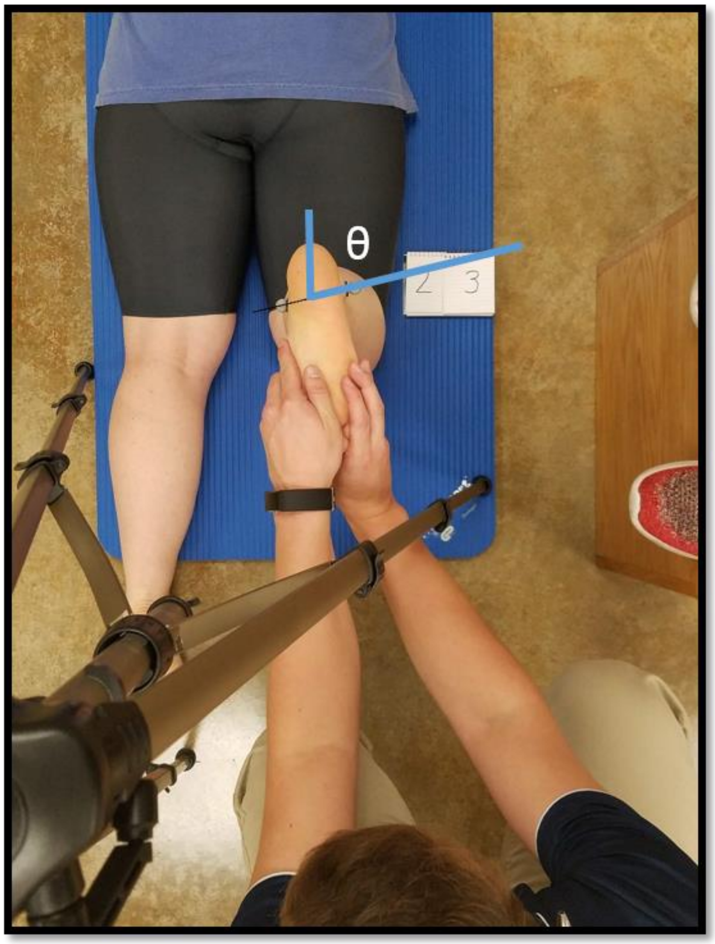
**Appendix C. Data Collection Sheet**

| | |
|---|---|
| **Sport History** | **HS:**<br>**College:** |
| **Height** | |
| **Weight** | |
| **Tegner Activity Level** | |
| **Hip Internal Rotation** | **Picture 1 ____ 2 ____ 3 ____** |
| **Femoral Torsion** | **Picture 1 ____ 2 ____ 3 ____** |
| **Thigh foot angle** | **Picture 1 ____ 2 ____ 3 ____** |
| **Longitudinal Arch Angle** | **Picture 1 ____ 2 ____ 3 ____** |
| | |
| **Weight-bearing Dorsiflexion** | **Measure 1 _____ 2 _____ 3 _____** |
| **Hip width (ASIS to ASIS)** | **___________ mm** |
| **Static Toe Angle** | **___________ degrees** |
| **Toe Angle- Forward Arm Squat** | **___________ degrees** |
| **Toe Angle- Barbell Back Squat** | **___________ degrees** |
| **Standing hip height** | **___________ mm** |
| **Squat Depth- Forward Arm Squat** | **___________ mm _______/________ = %** |
| **Squat Depth- Barbell Back Squat** | **___________ mm _______/________ = %** |
| **Foot Progression Angle** | **1 ____ 2 ____ 3 _____ 4 _____ 5 ______** |

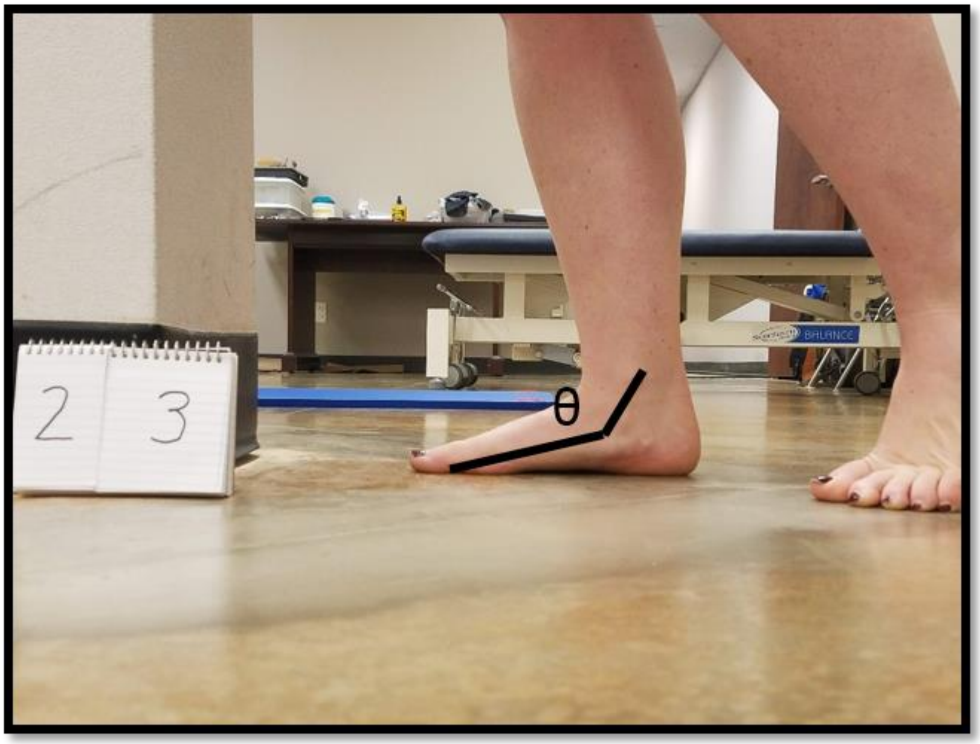
**Appendix D.  Hip Internal Rotation Measurement**



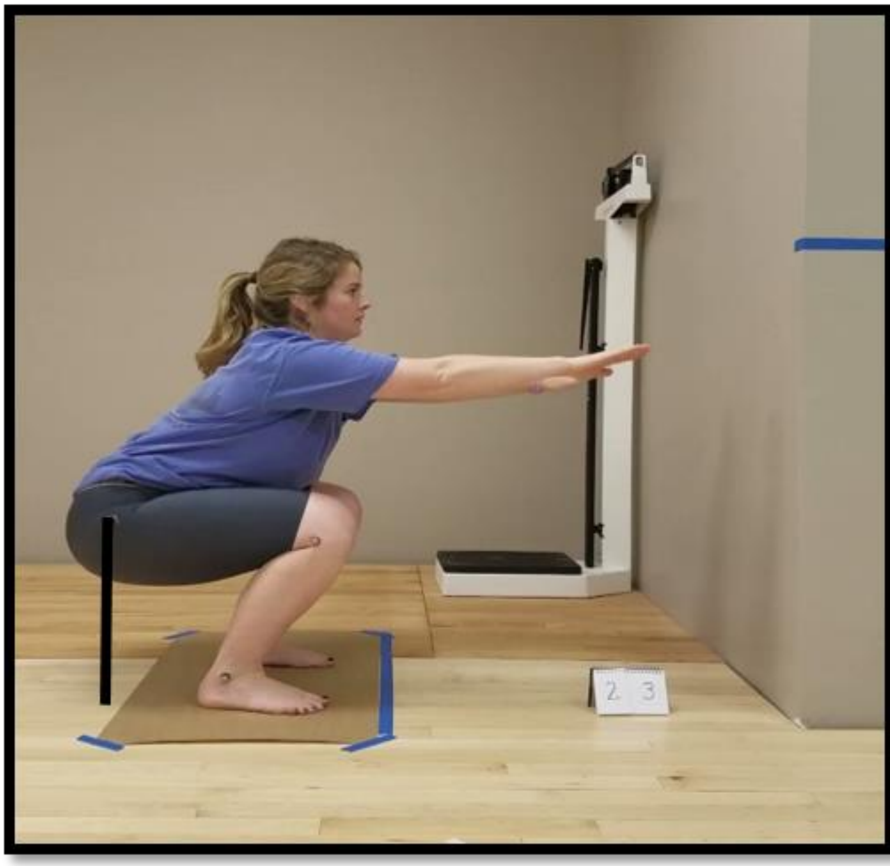
**Appendix E.  Thigh Foot Angle Measurement**



**Appendix F. Longitudinal Arch Angle Measurement**



## Appendix G. Forward Arm Squat Measurement



**Appendix H. Barbell Back Squat Measurement**