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An Investigation of the Relationship between Plantar Weight Distribution and the Condition of Osteoarthritic Knees during Quiet Standing

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An Investigation of the Relationship between Plantar Weight Distribution and the Condition of Osteoarthritic Knees during Quiet Standing

A Thesis

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PASSED ___X___ FAILED ________

ABSTRACT

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An Investigation of the Relationship between Plantar Weight Distribution and the Condition of Osteoarthritic Knees during Quiet Standing

Thesis Advisor: Dr. Renee Rogge

Osteoarthritis (OA) is a damaging disease that commonly affects the knee and can impact function of the lower limb. This study examined how plantar weight distribution is related to the changes in knee alignment and various types of joint damage in patients with OA. A force mat was used to measure plantar weight distribution on 37 patients with knee OA, and the internal condition of the knee was evaluated during surgery. Analysis showed a relationship between medial plantar weight distribution and an increase in knee alignment angle (0.20, $p < 0.001$). For the damage models, an indirect relationship was found between medial weight distribution and ACL damage (-0.14, $p=0.029$). No relationship was found for the other types of OA damage. It is reasonable to believe they do exist, however. This study found a connection between weight distribution and alignment, and previous research has shown one between alignment and OA.

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1. INTRODUCTION

1.2 Overview

Osteoarthritis (OA) is the most common joint disease affecting the knee. It is characterized by pain, loss of function, joint space narrowing, and possible limb deformity[1]. The main changes in the knee as a result of OA occur at the articular cartilage, yet there are a wide variety of changes that can occur to the knee either preceding the development of OA or as a result of the degeneration. These include damage to soft tissues such as the ligaments and menisci, along with loss of the accompanying mechanoreceptors needed to maintain joint function[2, 3, 4, 5, 6], misalignment of the mechanical axes and resultant changes in stress[1], and altered weight distribution through the bottom of the foot[7].

These changes currently require many different measurement tools to accurately assess the degree of severity. A single test that could help evaluate any number of these changes would be a valuable finding and addition to the field. Pressure sensors can be used to reliably and accurately determine a subject's static posture, specifically postural sway and weight distribution throughout the bottom of the feet[8]. The changes in weight distribution that can be determined with this tool have the potential to provide insight into the condition of the knee as a result of OA damage. The entire lower limb functions as a continuous system, and it is likely that variation in one part of this system can be measured and related to changes in another part of it.

1.2 Statement of Problem

There are many changes that can occur in the knee and in the entire lower limb due to OA. The complex, intertwined nature of these changes makes it challenging to understand the relationships between them. Also, there is a lack of a single, non-invasive and inexpensive test that can provide insight into a number of these changes with a single measurement. Further research is needed to improve the understanding of knee OA, specifically how the damaged condition of the knee might be related to the patient's plantar weight distribution.

1.3 Purpose of the Study

The purpose of this study is to measure the plantar force distribution in patients with knee OA and investigate if there is any relationship to certain changes seen in the knee, including joint alignment and the extent of soft tissue damage.

1.4 Significance of Study

This study could provide a means for clinicians and researchers to perform a single test on patients and obtain more information about the damage to the knee as a result of OA, as well as provide potential clues about the progression of any OA that might be undetectable in its current stage. This could allow physicians to implement corrective actions to prevent or delay the progression and/or incidence of OA.

1.5 Primary Research Questions

There are two primary questions that will be evaluated in this research:

- Is there a relationship between plantar weight distribution on the medial/lateral regions of the foot and the alignment of a knee with OA?
- Is there a relationship between plantar weight distribution on the medial/lateral regions of the foot and the condition of a knee with OA as evaluated during surgical intervention, including the condition of the menisci and anterior cruciate ligament (ACL), presence of osteophytes, and the degree of chondromalacia?

1.6 Hypotheses and Theoretical Framework

It is believed that the measured plantar weight distribution will relate in some way to the alignment of the knee. The mechanical axis carries the load in the lower limb from the hip, through the knee and ankle, and ultimately through the bottom of the foot. In a healthy individual, this axis travels through the center of the knee or possibly slightly to the inside[1]. If the alignment of the knee is abnormal, this should change the loading seen throughout the joint as well as the entire leg and foot.

It is also believed that there will be a relationship between the plantar force distribution and the extent of damage due to OA. The knee and rest of the lower limb, including the foot, act as a continuous system, and any change or damage to one part of this system should result in a change that can be detected in other portions of it. The joint is designed to carry load in a specified manner as discussed in the previous paragraph. If the tissues are damaged in the joint, this could be a result of a change in the loading conditions though the joint. Any difference in loading of the joint could possibly be detected by changes in plantar weight distribution.

1.7 Limitations

OA is a highly complex disease, with many interconnected symptoms. It is not entirely understood if certain symptoms, such as misalignment, are a result of the disease progression, or if they are more involved in the incidence of the disease. Also, a single, all-encompassing grading of each subject's OA was not available to use in this study. Therefore, all of the subjects that are included in this study as a result of their OA diagnosis, and desire to seek treatment, will have a very wide range of damage severity and disease progression.

In conjunction with the wide range of disease state and progression, a large subject pool is needed to ensure that a representative range of OA severity and progression is evaluated. This large subject pool could also help to understand the effects that other medical conditions could have on the results. In this study, patients with other medical conditions that could potentially influence the results were not excluded from participation in the study. Each patient's past surgical history was noted, however, as it was believed this could play a more direct role in changing the mechanical function of the joint and should be included in the study.

2. LITERATURE REVIEW

2.1 Introduction

The purpose of this section is to discuss the concepts that pertain to this work. These include the anatomy and soft tissues of the knee, various means of degeneration of the joint and its loss of proper function, methods to evaluate knee condition, and the use of a force-measuring mat to measure plantar weight distribution and the value of these measurements. Current literature and previous studies will also be examined in this section.

2.2 The Knee

The human knee is a joint that joins the thigh and the lower leg, allowing for flexion and extension of the leg, as well as slight internal and external rotation. It is made up of four bones; the femur, tibia, fibula, and patella (kneecap). The tibia and femur articulate with each other, as does the patella and femur. Finally, the joint can be divided into three compartments; the medial and lateral tibiofemoral (referred to hereafter as medial and lateral), and the patellofemoral, as shown in Figure 2. These compartments are important to remember when various disease diagnoses are discussed in section 2.3.

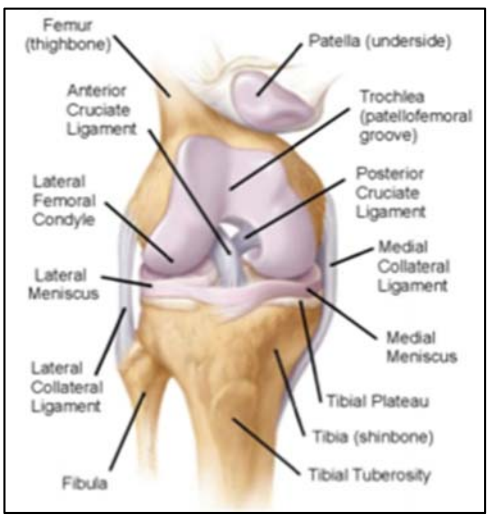

Figure 1. Anatomy of the Human Knee[9]

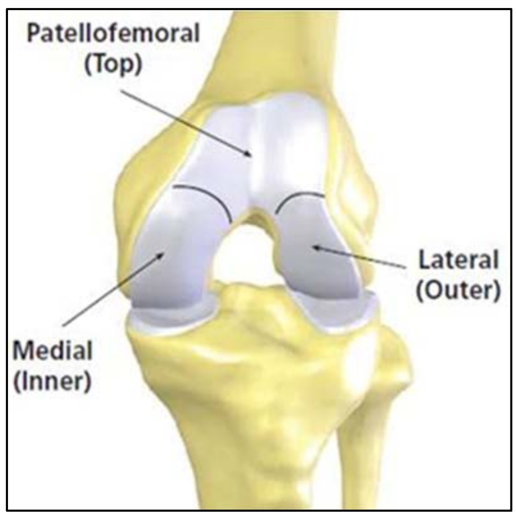

Figure 2. Knee Compartments[10]

Different connective tissue structures play important roles in the stability and function of the joint. There are four ligaments that span from the femur to the tibia. The first two are classified as intracapsular because they are contained inside the knee joint. The ACL runs from the lateral (outer) portion of the femur to the anterior (front) part of the tibia. Its purpose is to prevent the tibia from moving too far forward past the femur. The other intracapsular ligament is the posterior cruciate ligament (PCL) that runs from the medial (inner) portion of the femur to the posterior (rear) portion of the tibia. Opposite the ACL, the PCL prevents the tibia from moving away from the femur in a posterior (rear) direction. The other two ligaments in the knee are extracapsular, meaning they are located outside joint. These are the medial and lateral collateral ligaments (MCL, LCL), and they prevent movement of the joint when a bending force is applied to either side.

The knee also contains two menisci. These are collagen and cartilage based structures that provide spacing in the joint and aid in shock absorption. The medial and lateral menisci lie in the medial and lateral tibiofemoral compartments of the knee, respectively. As a result of injury, the menisci may become torn or cracked, resulting in pain and increased likelihood of the femur and tibia rubbing against each other. The healthy medial meniscus bears ~50% of the load transmitted through the medial portion of the knee, and the lateral bears ~80% of the lateral load. If the menisci are removed or damaged, they are unable to effectively distribute load across the tibia/femur. The area in which the load is distributed can decrease by 50-70% in the medial compartment and 45-50% in the lateral compartment, resulting in the same load being transmitted across a smaller area. This causes higher stress exceeding physiological design to affect the tibia and femur[11].

The ends of the bones in the knee joint are covered with articular cartilage that provides lubrication and protection against shock and impact. This cartilage is affected by osteoarthritis, which will be discussed in depth in section 2.3.1. If this cartilage gets degraded and the underlying bone is exposed, pain receptors in the surface of the bone can be triggered and cause the severe pain associated with OA.

Additional information about the anatomy of the knee and its structures can be found in Moore's Clinically Oriented Anatomy text[12].

2.2.1 Mechanoreceptors and Joint Proprioception

There are many aspects of joint movement involved in a well-functioning joint system. The joint needs to be able to detect its own position (proprioception) and motion, and be able to maintain balance[5]. Joints can do this with help from the central nervous system and various mechanoreceptors found in their tissues. These receptors detect stretch and tension, relaying this information back to the brain so that the body is aware of where it is in space and if anything must be done to maintain a proper position or move into one. Accurate information about alignment and position is needed to ensure proper forces are applied around a joint to maintain natural mechanical function. If these receptors become compromised due to disease, injury, or aging, the joint becomes less capable of detecting and relaying the information needed to function properly. More specifically, OA is one of the prominent means of damage that results in poorer than normal proprioception[13, 14], as does aging[15] and loss of the ACL[3].

Mechanoreceptors are known to be located in the knee within the capsule[2], menisci and ACL[6], collateral ligaments[4], PCL[5], and articular cartilage[3]. Therefore, it can be concluded that any absence of these tissues or damage to them could result in a lessened ability to detect joint position and maintain proper function and mechanics. For example, defects in the lateral cartilage have been shown to result in poor proprioception, as has joint laxity[3]. It is unclear, however, the specific role and to what extent each of the these tissues plays in maintaining proper joint function, as injury or damage to one typically results in impairment of others[3].

2.3 Mechanisms of Degeneration and Damage to the Knee

For this research study it is important to examine ways in which the knee can be damaged in order to have a better understanding of the extent to which different means of impairment can affect the function and mechanics of the joint. Trauma can lead to direct damage/loss of specific structures in the knee, such as an ACL or meniscus tear during a sporting event. Diseases such as osteoarthritis (OA) and chondromalacia can also damage the tissues in the knee and impair joint function.

2.3.1 Osteoarthritis

OA is the most common form of arthritis and leads to slow, progressive degeneration of joint structures. When the cartilage on the ends of the bones begins to wear away, the joint space decreases and bare bone is exposed, resulting in pain, loss of mobility and function, and possible deformity. OA can impact any of the joints in the body; however, it most commonly occurs in the knee and hip. In the United States, about 6% of adults over the age of 30 have OA of the knee[16].

The causes of OA have only recently become more understood. Previously, OA was thought to affect only the cartilage, but now it is clear that the disease affects the entire joint. There is even research suggesting that the cartilage wear is actually a result of a disease process occurring in the bone[16]. For the cartilage itself, inflammation and inflammatory cytokines, such as interleukin-1-beta (IL-1-beta) and tumor necrosis factor-beta (TNF-beta), are thought to be important players. These cytokines initiate a process that actively causes degradation. The cartilage is acting as a cushion between the two bones and allowing for smooth movement in the joint; when this support is lost, pain, muscle atrophy, and decreased function are just a few of the possible symptoms[16].

The primary symptom of knee OA and the determining factor for most patients seeking treatment is pain[17]. When the articular surfaces become worn and the joint space begins to narrow, the bones compress on each other more directly and elicit increased pain. People naturally do not want to experience pain, so any position or movement that causes pain will be avoided as best as possible. This presents the possibility that the mechanics and function of the knee may change as a result of pain[18]. If there is a particular standing position that causes more severe pain, the body will reflexively adjust to try and find relief.

2.3.2 Chondromalacia

Chondromalacia is a general term used to describe damage to any articular cartilage[19]. It is most commonly associated with the patellofemoral compartment, but can also be found in other compartments of the knee, notably the anterolateral portion of the femur[20]. Chondromalacia cannot be clinically diagnosed without use of advanced imaging since many instances are asymptomatic, making early detection difficult[19].

There are four grades of chondromalacia. Grade 1 indicates softening of the cartilage, grade 2 indicates softening along with abnormal surface characteristics, grade 3 indicates thinning of the cartilage with active deterioration of the tissue, and grade 4, the most severe, indicates exposure of bone with a significant portion of the cartilage deteriorated[21]. Aside from using magnetic resonance imaging (MRI) to grade the extent of damage, this grading can be made in the operating room when a patient is undergoing any type of knee repair and the articular surfaces are exposed. Any means of estimating the chondromalacia grade without advanced imaging or surgery would be very beneficial since the degree of cartilage damage is an important characteristic to know when a physician is treating a patient with knee complications or pain.

2.3.3 Osteophytes

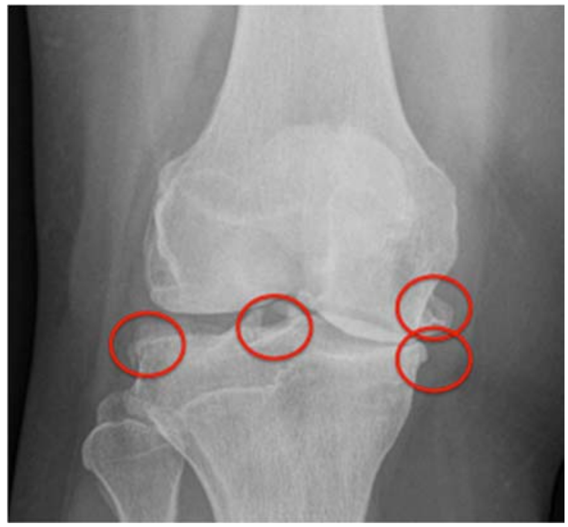

Figure 3. Knee Osteophytes Highlighted [22]

Osteophytes are bone spurs, or outgrowths, that commonly form in joints as a result of OA. OA causes repeated wear and tear on the joint, breaking down the cartilage and exposing bone. The body attempts to correct this loss by building up more bone and producing osteophytes. They often limit the joint's normal function and range of motion by interfering with movement of ligaments and other soft tissue. Most of the time osteophytes are asymptomatic and only visible on a radiograph. However, it is possible for them to break off and become loose bodies in the joint, further impeding normal joint function[23].

Along with joint space narrowing, OA is characterized by osteophyte formation[24]. It is important to understand the extent of osteophytes when working with patients who have been diagnosed with OA. Any additional insight about osteophyte formation in the knee can help provide a clearer picture of the patient's joint and the extent of OA damage.

2.4 Methods of Evaluating the Knee

There are numerous ways doctors can evaluate the condition of knees. Imaging techniques, such as radiographs, magnetic resonance imaging (MRI), and CT scans, are used to visualize the joint and its tissue. Scoring systems such as the Knee Society, WOMAC, and Ontario knee scores are also used to characterize a knee, and last of all, direct observation of the joint can be done when it is exposed in the operating room (OR) or arthroscopically. This study will specifically focus on using radiograph imaging (x-rays) to measure alignment of the joint in the frontal plane and the direct observation that can be done in the OR.

2.4.1 Knee Alignment in the Frontal Plane, Varus/Valgus Deformity

The load bearing axis of the leg extends from the center of the femoral head to the center of the ankle joint[25]. In a normal knee, this line passes directly through the center of the knee joint, or slightly medial[1]. When the knee is misaligned, the axis either lies medial or lateral to the center of the joint. If the axis lies medial, the deformity is characterized as varus, or bow-legged, and if the axis falls lateral, the joint is considered to be valgus, or knock-kneed (Figure 4). The angle formed by the two axes is commonly referred to as the hip-knee angle, or HKA. In general, negative HKA is classified as varus, and a positive one as valgus. More specifically, < -2° for varus and > +2° for valgus are accepted ranges for classification[25].

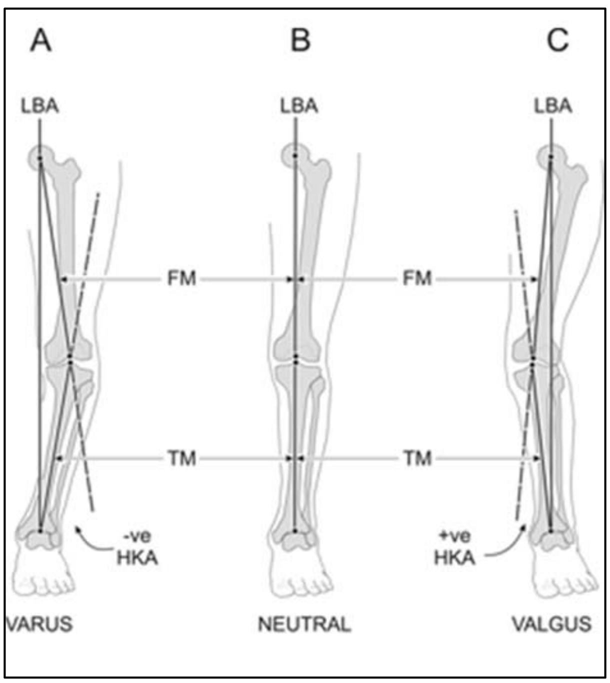

Figure 4. Common Frontal Plane Lower Limb Alignment Patterns. LBA: Load-Bearing Axis, HKA: Hip-Knee-Ankle Angle, FM: Femoral Mechanical Axis, TM: Tibial Mechanical Axis[26]

In the instance of varus or valgus misalignment, the knee experiences an abnormal load distribution across the joint[27]. It has been suggested that this misalignment-induced stress increase can play a crucial role early in the development of OA[28]. When the loading axis shifts further medial, a bending moment is developed in the knee that puts added stress on the medial compartment. This increased moment has been associated with the progression and possibly initiation of knee OA[29]. Overall, the role of misalignment in the incidence of OA only has limited study, yet the correlation between the progression of early OA and axial misalignment has been well established[1]. This suggests that the ability to detect misalignment in patients with early or even moderately progressed OA is valuable in treating the condition and working to prevent further damage.

The gold standard for measuring knee alignment is to use a full limb film. This allows the angle between the mechanical axes of the femur and tibia to be directly determined. However, full limb radiographs are rarely performed, and physicians and researchers will routinely measure the anatomical axis of the knee from a simple knee radiograph. Anatomical axes of the knee can be used in this instance to determine alignment. The anatomical axes of the femur and tibia run through the center of the shaft of each bone. As can be expected, the mechanical and anatomical alignment will not be equal since the mechanical axis runs through the femoral head. A gender-neutral offset of 5 degrees can be used for comparing mechanical and anatomical alignment, or 2 degrees in women and 4 in men, for gender specificity[30]. This offset is not particularly reliable in maintaining the varus/valgus/neutral classification between the anatomical and mechanical alignment values, yet it effectively predicts the risk of joint space loss, a distinguishing factor of OA progression. It is also just as reliable as the mechanical axes measurement when simply looking at changes in the knee alignment angle and not necessarily the specific classification of the angle[31].

2.5 Plantar Weight Distribution and the Relationship with the Knee

The anatomical structure of the foot has arches that maintain proper biomechanical function. Specifically, the medial longitudinal arch creates a space for soft tissue to act as a spring, storing energy of impact forces and using them to reduce the expenditure of ambulation[32]. In a clinical setting, the shape of a patient's arch can influence the type of injuries they are susceptible to. With a low arch, the feet will be in a pronated position while standing and will place more stress on the medial aspect of the foot (Figure 5). The foot will have a tendency to rotate outward in people with high arches, placing more stress on the lateral portion of the foot. Both of these conditions will alter the mechanical loading at the ankle and above.

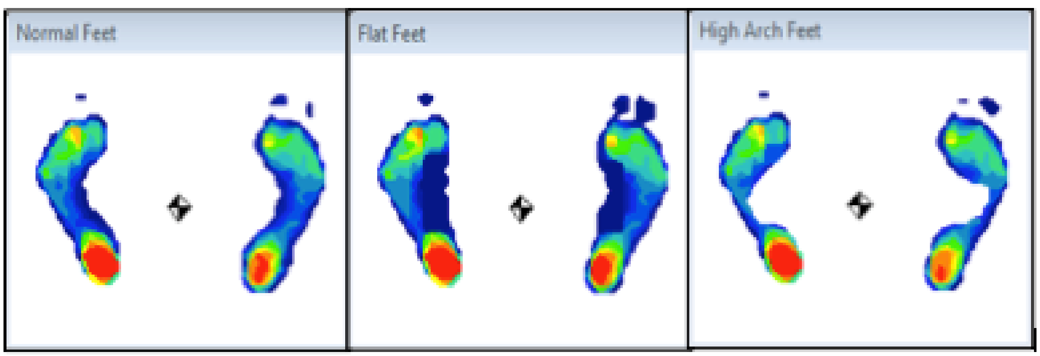

Figure 5. Example of Plantar Force Distributions, Taken from MatScan Software[33]

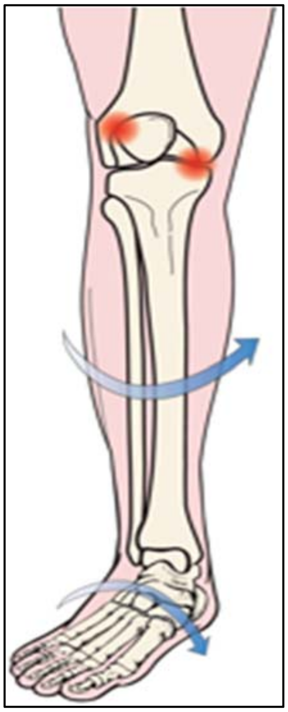

Figure 6. Theorized link between foot (arch alignment), knee, and hip mechanics[34]

The lower limb, from the hip joint all the way down to the ankle and foot, is a continuous system that works to maintain proper biomechanical function of the lower limb. The foot is immediately responsible for absorbing the mechanical load from ground contact and forming the pattern of mechanical and postural alignment in the knee and throughout the lower leg[34]. This structural relationship is based on an increased internal rotation of the tibia as the foot becomes more flat, as shown in Figure 6. This internal rotation of the tibia results in increased load in the medial tibiofemoral and lateral patellofemoral compartments of the knee, suggesting a contribution to the progression and severity of OA[7].

Improper foot structure has been linked to the development of pain and OA at the knee and hip[35]. A flat foot anatomical shape (planus) has been shown to contribute to both tibiofemoral and patellofemoral OA[34, 35]. Specifically, limbs with low arched feet had 1.3 times the odds of knee pain and 1.4 times the odds of medial tibiofemoral cartilage damage compared to those with a normal arch[34].

Differences in foot structure and arch shape/size are believed to have an influence on foot function during static and dynamic instances (Figure 6). As previously mentioned, planus feet will over-pronate and cause the ground reaction forces to move further medial, while cavus (high-arched) feet will have a tendency to display ground reaction forces more to the lateral portion of the foot. This idea was confirmed in a study by Hillstrom et al. in which there was significantly higher loading in the medial portion of the foot in patients with planus feet (Figure 7)[37].

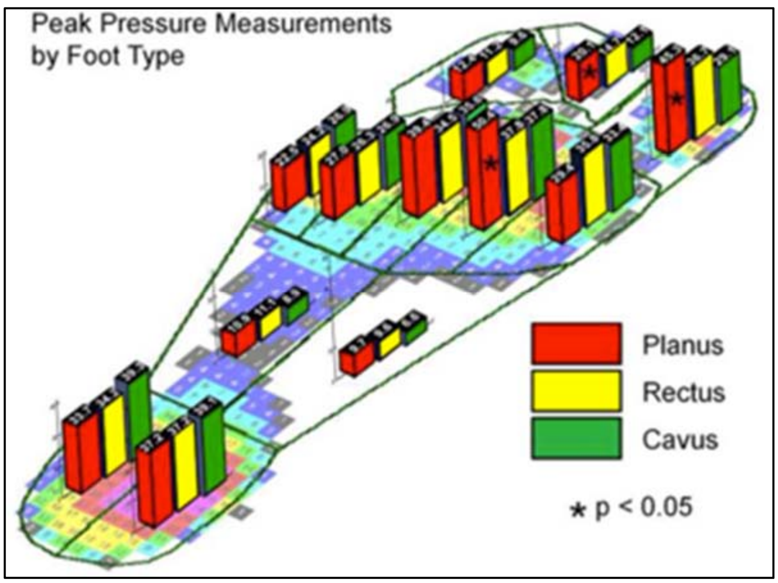

Figure 7. Peak Pressure Distribution Based on Foot Type. Planus: Flat Arch Rectus: Normal Arch, Cavus: High Arched[37]

2.6 MatScan System

The TekScan Matscan 3150 (TekScan Inc, South Boston, USA) system is a plantar pressure and force-mapping tool used to evaluate foot and gait biomechanics in a clinical and research setting. The mat features a resolution of 1.4 sensors/cm^2 and a sampling frequency of up to 40Hz[8]. The reliability of the tool has been evaluated in gait measurement[33] and static postural assessment[8].

The MatScan tool has been found to be highly reliable based on Intra-class Correlation Coefficient (ICC) values.

2.7 Conclusions

The following conclusions can be drawn based on the reviewed literature:

- The soft tissues of the knee contain many mechanoreceptors that are crucial in maintaining proper joint function and stability
- Loss or damage of certain soft tissues in the knee result in diminished proprioception
- Misalignment of the knee can promote the progression and possibly the incidence of OA of the knee based on altered stress and loading patterns
- Measurements of varus and valgus alignment can be made using either the mechanical or anatomical axis of the knee when predicting their effects on OA
- Anatomical variations in the foot and the arches of the feet result in different ground reaction force patterns
- Planus (flat) feet contribute to progression of knee OA

3. METHODS

3.1 Introduction

This section details the procedures and methods used to evaluate the questions of interest in this study. The statistical models that were used, what variables went in to these models, and how those variables were obtained will be presented. Recalling the specific questions of interest:

- Is there a relationship between plantar weight distribution on the medial/lateral regions of the foot and the alignment of a knee with OA?
- Is there a relationship between plantar weight distribution on the medial/lateral regions of the foot and the condition of a knee with OA as evaluated during surgical intervention, including the condition of the menisci and ACL, presence of osteophytes, and the degree of chondromalacia?

This study is only examining the relationship between variables and not the cause and effect of certain conditions. It is also not intended to serve as a predictive model.

Statistical models are often used to examine the relationship between variables. The model attempts to explain the outcomes of a response, or dependent variable, by using any number of independent variables that are believed to contribute to that outcome. There are many different types of models and statistical methods that can be employed, as well as various types of response variables and effects. The specific tools used in this study will be discussed in detail in the Statistical Methods section (Section 3.7). It is important to note that in order to end up with the most effective model for explaining the outcomes, the independent variables that are believed to play a role in explaining the response, as well as any specific effects of interest, must be measured and processed so that the final model can be constructed in a way that best allows for the relationship in question to be evaluated.

The two models that will be constructed to answer the questions of interest will subsequently be referred to as the “Alignment” and “Damage” Models. The specific variables that will be used for each of the models will be examined first, followed by the procedure used to obtain the more involved measurements. Lastly, the specific modeling and analysis used for the alignment and damage models will be discussed in detail.

3.2 Variables

The following tables describe the variables that were included in the models. Table 1 contains the variables for the Alignment Model and Table 2 contains those for the Damage Models. The dependent variable is the response, or outcome, and the independent variables are ones that are believed to either have an effect on the outcome or to be confounders.

Table 1. Variable List for the Alignment Model

Dependent Variable	Description	Measurement
Knee Alignment *(Alignment)*	Obtained as an angle and a categorical description, measurement of the angle between the mechanical axes of the femur and tibia.	Standing front knee radiographs
Independent Variables		
Medial Weight Distribution *(MedialWgt)*	The % of the total plantar force through the foot that is applied throughout the medial half of the foot.	TekScan MatScan system
Knee of Operation *(KneeOp)*	Side that is being operated on, either left/right/both	Electronic Health Record (EHR)
History of Lower Limb Surgical Intervention *(HxSurg)*	Yes/No, includes any history of lower limb arthroplasty, arthroscopy, cartilage repair, etc.	EHR
Sex	Male/Female	-
Age	Age at time of enrollment (years)	EHR
Body Mass Index *(BMI)*	Evaluated using patient's height and weight at the time of enrollment.	EHR, BMI calculator

The variable names used in the Analysis are included in *italics*.

Table 2. Variable List for the Damage Model

Dependent Variable	Description	Measurement
Knee Damage -Femoral Chondromalacia *(FemoralChond)* -Tibial Chondromalacia *(TibialChond)* -*Femoral Osteophytes* -*Tibial Osteophytes* -*Meniscus* -*ACL*	All recorded as ordinal data from 0-3, higher numbers indicating more severe damage. A separate model is built for each response.	Taken from surgery note, evaluated by Surgeon
Independent Variables		
Medial Weight Distribution *(MedialWgt)*	The % of the total plantar force through the foot that is applied throughout the medial half of the foot.	MatScan system
Compartment	Identifies the compartment in which damage is being recorded, medial/lateral	-
Side of Interest *(Leg)*	Identifier, as alignment was measured for both legs.	-
History of Lower Limb Surgical Intervention *(HxSurg)*	Yes/No, includes any history of lower limb arthroplasty, arthroscopy, cartilage repair, etc.	EHR
Sex	Male/Female	-
Age	Age at time of enrollment (years)	EHR
Body Mass Index *(BMI)*	Evaluated using patient’s height and weight at the time of enrollment	HER, BMI calculator
Presence of OA *(OAComp)*	A Yes/No question indicating if a diagnosis of OA has been given for the medial/lateral compartment	EHR

The variable names used in the Analysis are included in *italics*.

Knee Alignment:

Standing frontal knee radiographs were taken around the time of entrance in this study and were used to measure the knee alignment used in the Alignment Model (Table 1). A built-in measurement tool was used to record the angle between the femoral and tibial anatomical axes, as shown in Figure 8.

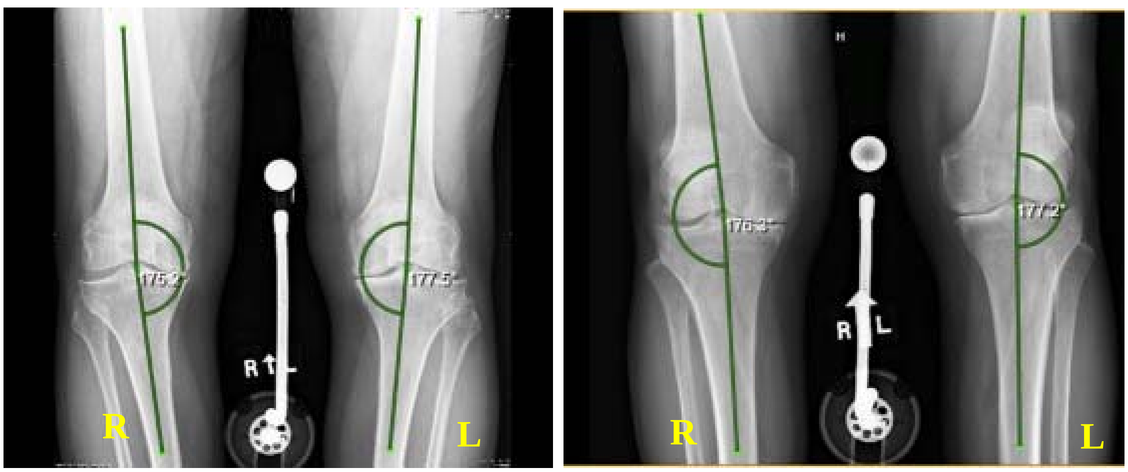

Figure 8. Alignment Measurement Examples: In the Image on the Left Both Knees Are at a Varus Alignment, and in the Image on the Right, Both Knees Are in Valgus Alignment.

If the measured angle was 175° and in a varus alignment, the recorded value would be either -5° and varus, or 175° and varus. On the other hand, if the knee were in valgus alignment, it could be recorded as either +5° and valgus, or 185° and valgus. Recall from the literature review that the alignment using anatomical axes is not equivalent to that when using the mechanical axes. For this study, the anatomical axes measurements, using 180° as "neutral", were converted to mechanical measurements using an equation developed by Kraus et al.[30]. These adjusted values were then used in the alignment model.

$$Angle_{mech} = 0.69Angle_{anat} + 53.69$$

Damage Variables:

The Damage Model dependent variables presented in Table 2 were all measured by direct observation in the operating room when the knee was exposed for surgical intervention. All of the patients in this study elected to undergo knee arthroplasty, independent of this study. The board-certified Orthopaedic Surgeon (MB) evaluated chondromalacia, osteophytes, meniscus quality, and ACL condition through direct observation. All of the conditions measured in the operating room were translated to a numerical grading from 0-3 for use in the model (Table 3). A value of 0 indicated everything was normal, and then each increase in value was equivalent to a worse condition, or more damage.

Table 3. Grading Values Used in the Damage Model

Numerical Grade for Damage Model	**Classification in Damage Model**	**Equivalent Classification From Surgery Note**			
		Chondromalacia	Osteophytes	Meniscus	ACL
0	None	0	None	Normal	Normal
1	Minimal	1	Small	Partial degeneration	Present but lax
1.5	Some	-	-	Degeneration	-
2	Substantial	2	Moderate	Mostly Degenerated	Non-functioning band
3	Extreme / Absent	3	Large	Absent	Absent

Classifications from surgery note were converted to the numerical grade for use in the Damage Model.

Plantar Weight Distribution:

The procedure for using the MatScan system to collect weight distribution data will be discussed later on, but a more detailed description of this variable and what it means is given here. Both the Alignment and Damage Models in this study deal with the relationship of plantar weight distribution to some characteristic of the knee. The weight distribution was considered to be the percentage of the total force applied through the foot that was on the medial half of the foot. In other words, the entire force measured on the medial region of the foot is compared to the total force measured over the entire foot. This gives a medial weight distribution as a percentage. Each foot was assessed separately, giving a left foot medial weight distribution and a right foot medial weight distribution for each patient. The lateral distribution can be easily found by subtracting the medial from 100. However, only one of the two measurements is needed in the model since having one directly gives the other.

3.3 Pilot Study

A pilot study was conducted in order to gain familiarity with the testing equipment, uncover potential challenges, and determine an estimate of how long data collection will take with each patient. 15 subjects were evaluated for their static standing balance with eyes open and then closed. Ideally, the data collection should be as quick as possible while still ensuring an adequate amount of data is collected for analysis. The average time in this pilot study was 8.5 minutes, with a total of 6 trials being completed during that time. This confirmed that two 20-second trials will be quick and adequate for the actual study. During the pilot study, some of the subjects took some time to get accustomed to what they were doing. Therefore, before the two trials are completed, a preliminary familiarization trial will be done for each patient, if they desire. This will be untimed and will allow the subject to become familiar with the equipment. Finally, the pilot study showed the importance of accurately and consistently naming data files.

3.4 Main Study Setting and Subject Pool

The study took place over one year beginning in May 2013 in Mooresville, Indiana at St. Francis Hospital. All of the subjects included in study had previously been diagnosed with either unilateral or bilateral OA. Subjects were eventually treated with either total or partial knee arthroplasty, independent of this study. The participants included both males and females. Dr. Michael Berend performed all assessments of the knee condition in the OR and was the primary investigator in this study.

A total of 37 subjects were enrolled in the study. All 37 patients were included in the analysis of weight distribution and knee alignment if there was no missing data. However, only 23 of the 37 were included in the analyses of knee condition since 14 of the subjects had not undergone surgery at the time of the analysis and therefore no data about the condition of the knee were available. A summary of patient demographics is shown below in Table 4.

Table 4. Subject Pool Demographics

Gender	**N**	**Age (yrs)**	**Weight (lbs)**	**BMI**	**Diagnosis**	
		Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Bilateral OA**	**Unilateral OA**
Male	19	64 (8)	230 (37)	33 (4)	7	12
Female	18	62 (9)	194 (43)	33 (7)	6	12
All	**37**	**63 (8)**	**212 (43)**	**33 (6)**	**13**	**24**

3.4.1 Exclusion Criteria

There was no exclusion criteria used to remove patients from the study. Rather, an additional variable, HxSurg, was added to the final statistical model to account for whether or not the subject had any history of surgical intervention on the lower limb. These possible events included hip replacement, prior knee replacement, knee/hip arthroscopy, toe replacement, and meniscectomy.

3.5 Instrumentation: Tekscan® MatScan®

The MatScan is a pressure-mapping device that is used to measure plantar weight distribution of the test subject during a variety of activities. The device is a low-profile mat roughly 2'x2' that sits 0.2" above the ground. It contains numerous pressure sensors that give the device a total measurement area of roughly 1.5'x1'. The mat contains roughly 2,300 sensors, with around 9 sensors per square inch, and the total pressure range is 0-125 psi. Table 5 shows the exact specifications of the pressure sensing capabilities of the mat.

Table 5. MatScan Specifications

Sensing Area (in)		**# Sensors**	**Sensor Density (per in²)**
Width	**Length**		
17.16	14.52	2,288	9.2

3.6 Procedure: Weight Distribution Data

A detailed, full procedure, including set up of the MatScan software and a more complete description of processing the data for weight distribution, can be found in Appendix A. The highlights and more crucial aspects of the procedure are included here.

Weight distribution data was collected for each patient independent of collection of the other variables presented at the beginning of this section. The MatScan software was set up for data collection as outlined in Appendix A and two 20-second trials were completed for each patient prior to surgery. The patient was instructed to remove their shoes, stand in the center of the mat in a normal comfortable stance, and look straight ahead with their eyes open, moving as little as possible. The software does not directly provide values for the medial weight distribution so additional steps were needed to process the raw MatScan data to obtain the medial weight distribution.

A template profile was placed around each foot and then adjusted by the user to best fit the areas of measured force (Figure 9). Next, the cyan colored line was adjusted to line up with the center of the heel and forefoot, as shown below and indicated by the two red lines. Next, objects defining the medial half of each foot and the total foot area were created (Figure 10). The absolute force values for these object areas were then exported into a .csv file for further evaluation.

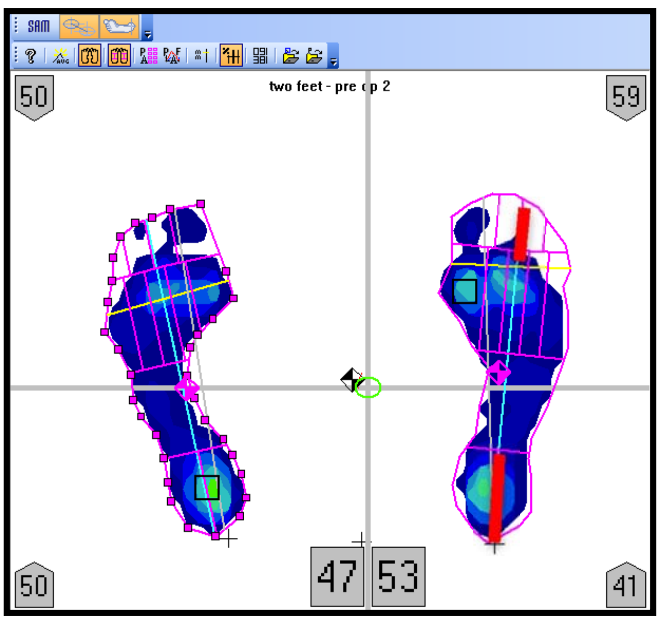

Figure 9. Foot Outline Profiles Fitted to the Boundaries of Force Distribution

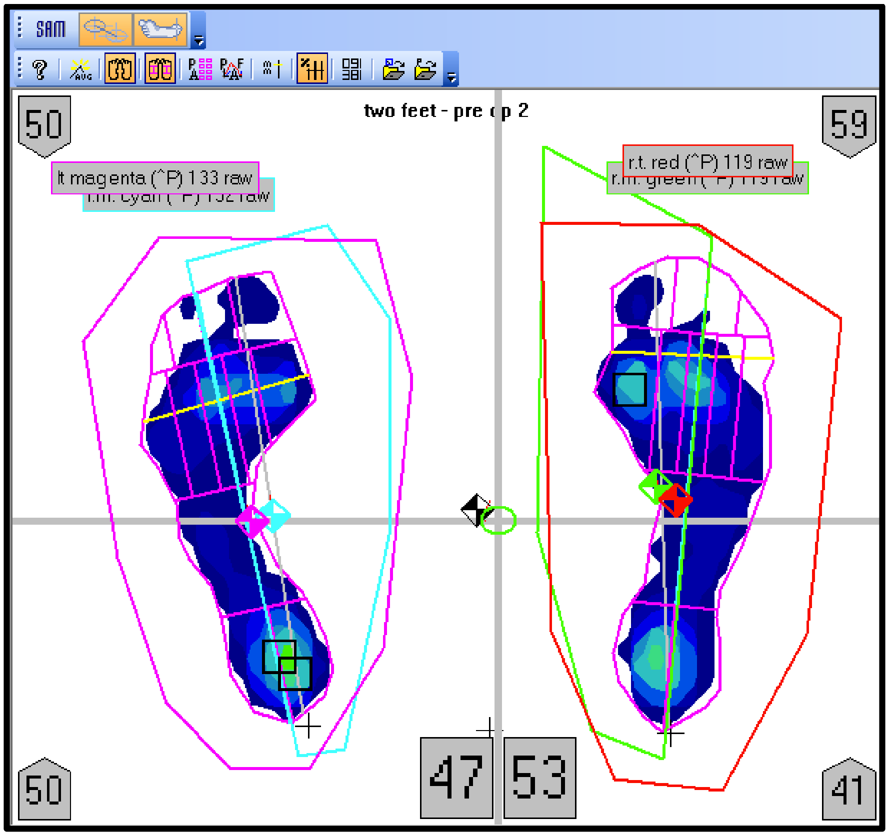

Figure 10. Object Regions Defining the Right Total (Red), Right Medial (Green), Left Total (Magenta), and Left Medial (Cyan) Areas of the Feet

Next, the exported data for total force for the left foot and the total force for the medial portion of the left foot as used to calculate what percentage of the total body weight is on the medial region. Finally, the % lateral force was found and this procedure was repeated for the right foot, as well as for both feet on the second trial.

3.7 Statistical Methods and Analysis

Once all of the variables were measured and the data was reduced to a form usable in analysis, the specific statistical methods that were to be used to answer the study's questions of interest could be employed. The alignment and damage models will be discussed separately, including a description of the model type, the rationale for choosing it, set-up of the model, and how to interpret the outcomes.

3.7.1 Alignment Statistical Model

The initial evaluation of the relationship between medial weight distribution and alignment was completed using only the data on knees that were operated on. A general linear model, assuming linearity, was constructed using generalized estimating equations (GEE) to examine the relationship between weight distribution and knee alignment on the population of surgery knees only. Repeated measures were used to account for the subjects that had surgery on both knees. The model accounted for age, gender, BMI, history of surgical intervention, and which leg (or both) was operated on. SAS statistical software (SAS, North Carolina, 2014) was used and a p-value of < 0.05 was used to denote statistical significance. All subsequent evaluations used the complete data set of knees with OA.

Following this initial evaluation, a generalized linear model was constructed using GEE. Repeated measures were used to account for some of the subjects having two knees with OA. The general linear model attempts to describe the mean outcome of a response, in this case knee alignment, by using a series of linear predictors that incorporate information about the independent variables into the model. The effect that each independent variable included in the model, as well any confounders or interactions, has on the expected mean of the response is explained by calculating a parameter, or coefficient, that gives the magnitude of the relationship and whether it is positive or negative. Also, confidence intervals on the range of this estimate are calculated, along with a p-value to determine statistical significance[38]. The equation below is the format of a general linear model. Y is the mean of the response, β_0 is the intercept, the X terms are for each independent variable, the remaining β terms are the parameter estimates for the effect that each variable has on the response, and ε captures the variability in the model.

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_p X_{ip} + \epsilon_i$$

The specific general linear model used in the analysis of knee alignment and weight distribution was calculated unadjusted and adjusted, the adjusted model accounting for age, gender, BMI, history of surgical intervention, and which knee (or both) the subject had operated on. Interactions between weight distribution and knee of operation, side of interest, and history of surgery were also evaluated. These interactions can be included in the model to determine if the effect of weight distribution on alignment varies depending on the value of the other interaction term. These interactions were found to be non-significant in the model; therefore they were taken out. For this model, a linear relationship between weight distribution and alignment was assumed and a p-value <0.05 was used to denote statistical significance.

3.7.2. Damage Statistical Model

The relationships between weight distribution and the various measures of knee damage were evaluated using ordinal logistic regression with repeated measures. The damage model needed to be different from the alignment model based on the type of response. For alignment, the response is continuous, theoretically being any value from negative to positive infinity. However, for the damage response, the outcomes can only be 0, 1, 1.5, 2, or 3, with each higher value representing an increased level of damage. This is known as an ordinal response. Ordinal logistic regression is simply an extension of logistic regression. Instead of modeling the probability of single event occurring, as is the case in a binary logistic regression model, ordinal logistic regression uses the cumulative logistic model to find the cumulative log odds of being in certain levels of the response or lower. This cumulative logistic model is explained further in Table 6 below, and more information about the cumulative logistic model and ordinal regression can be found in McCullagh and Nelder[39].

Table 6. Cumulative Log-Odds Model[39]

Ordered Level	Response	Cumulative Log Odds Model	Interpretation
1	D (Severe Damage)	$\log\left(\frac{p_D}{1-p_D}\right)$	Log odds of severe damage
2	C (Moderate Damage)	$\log\left(\frac{p_D+p_C}{1-(p_D+p_C)}\right)$	Log odds of moderate or severe damage
3	B (Mild Damage)	$\log\left(\frac{p_D+p_C+p_B}{1-(p_D+p_C+p_B)}\right)$	Log odds of mild, moderate, or severe damage
4	A (Normal)	$\log\left(\frac{p_D+p_C+p_B+p_A}{1-(p_D+p_C+p_B+p_A)}\right)$	Undefined, as the probability of any event happening is always 1

Each of the log odds are estimated using an intercept and a series of independent variables and their effect estimates, similar to a general linear model. Odds ratios for the effect that changing the value of an independent variable will have on the response are calculated by taking the exponential of the log odds estimate for each parameter included in the model. An odds ratio >1 indicates that increasing the value of the variable of interest will result in higher odds of moving into a lower cumulative response. In other words, an odds ratio >1 means increasing the variable of interest will result in higher odds of having an increased level of damage. This can be interpreted as saying that an odds ratio >1 is a damaging effect and an odds ratio < 1 indicates a protective effect for the damage model in this study. Since this study is evaluating the relationship between weight distribution, specifically medial weight distribution, and various types of knee damage, the following criteria will be used to interpret the results:

- Odds ratio > 1 indicates increasing medial plantar weight distribution increases the likelihood of having a more severe level of damage

- Odds ratio < 1 indicates increasing plantar medial weight distribution decreases the likelihood of having a more severe level of damage

A 95% confidence interval was calculated for each OR. If the interval includes 1, the effect is not statistically significant.

Any confounders and other variables that are believed to play a role in explaining the response were included in the model, along with any interactions of interest. Unadjusted and adjusted models were also examined for each response. The unadjusted models are important to get a baseline idea of any potential relationship and then use a means of comparison to see if the adjusted model actually does a better job of explaining the response. The models for chondromalacia, osteophytes, and meniscus damage were adjusted for age, sex, BMI, knee compartment (medial/lateral), history of surgical intervention, presence of OA in the compartment, and the leg/side of interest (if significant). The interaction between weight distribution and compartment was also included to get a better idea of how weight distribution can affect the odds of damage for each compartment, separately. The model for ACL condition accounted for age, sex, BMI, history of surgical intervention, and the side of interest. The compartment was not included because there is only one ACL and it is not located in either of the two compartments. The models were evaluated using the proportional odds assumption and statistical significance was denoted by p-value < 0.05. All statistical analyses for the alignment model with all OA knees and the damage models were completed using SAS statistical software. The exact code used for the complete analysis is included in Appendix C.

3.8 Ethical Considerations and Approval

This research has very limited risk to the participating subjects. The patients had both eyes open while the weight distribution was being measured and they were standing on two feet. There was very little, if any, added risk of injury as a result of participating in this study.

Informed consent was obtained from all patients at the time of enrollment. This contained a full description of the study and acknowledged all of the patients' rights while participating in the study, including their right to withdraw at any point. Each patient was provided with a copy of their signed form, if they desired, and all forms were stored, both the hard copy original and a scanned, electronic copy.

Patient anonymity was protected throughout the course of this study and in all results publications. No personal identifiers (date of birth, name, address, etc.) were made public throughout the course of this study. These identifiers were stored with the collected data, but this information was kept confidential to only the research team and was never made public.

Institutional Review Board (IRB) approval through Rose-Hulman Institute of Technology was obtained on 3/29/13. Also, Western Institutional Review Board (WIRB) approval was granted on 5/15/13, study number 1139155.

4. RESULTS

4.1 Alignment Model, Surgery Knees Only

The first model examined the relationship between plantar weight distribution and knee alignment using only data collected on knees that were undergoing surgery. The unadjusted model, in which the only independent variable was weight distribution, suggested a direct relationship between medial plantar weight distribution and knee alignment, although the result was not statistically significant. The results from the adjusted model (Table 7), which accounted for age, gender, BMI, and history of surgery, agreed with this direct relationship (0.14, p=0.347).

Table 7. Alignment Model Results, Surgery Knees Only

Parameter	Estimate [95% CL]	p-value
Intercept	-12.76 [-39.37, 13.85]	0.347
MedialWgt	0.14 [-0.22, 0.49]	0.449
Age	-0.08 [-0.25, 0.10]	0.382
Sex (Female)	0.62 [-1.07, 2.32]	0.479
BMI	0.25 [-0.36, 0.85]	0.429
HxSurg (Yes)	-1.66 [-4.69, 1.37]	0.284
KneeOp (Both)	-1.52 [-5.31, 2.27]	0.433
KneeOp (Left)	0.58 [-2.01, 3.16]	0.661

* denotes statistical significance

The model showed that the weight distribution does not have a significant effect on alignment. None of the other parameters are significant in the model, either. This result is understandable based on the small sample size in this specific model. There are only 25 observations in this model and that small number makes it difficult to model the response. The parameter estimate for medial weight distribution can still be used to determine a trend. The estimate is positive, indicating that the model is suggesting a direct relationship between medial weight distribution and alignment.

4.2 Alignment Model, Complete Data Set

This model examined the relationship between plantar weight distribution and alignment when considering all of the OA knees, not just the ones that underwent surgery. The unadjusted model showed a direct relationship between medial weight distribution and knee alignment, although it was not significant. This model was used to provide an initial assessment of the relationship in terms of whether or not it is positive or negative. After accounting for age, sex, BMI, which knee (or both) was operated on, and history of surgical intervention on the lower limb, medial plantar weight distribution was found to have a significant effect on alignment (0.19, $p=0.002$). The significance of medial weight distribution in this model directly answers the original question of interest. There is a statistically significant relationship between plantar weight distribution and knee alignment for knees with OA. Similar to the model involving surgery knees only, as the proportion of plantar weight transmitted through the medial side of the foot increases, the knee alignment angle increases and moves from in a varus-to-valgus direction. The complete results of the adjusted model can be seen in Table 8.

Table 8. Alignment Results, All OA Knees

Parameter	Estimate [95% CL]	p-value
Intercept	-19.92 [-33.43, -6.40]	**0.004***
MedialWgt	0.19 [0.07, 0.30]	**0.002***
Age	-0.06 [-0.18, 0.06]	0.328
Gender (Female)	-0.51 [-1.31, 0.28]	0.206
BMI	0.41 [0.21, 0.61]	**<0.001***
HxSurg (Yes)	-6.71 [-9.18, -4.23]	**<0.001***
KneeOp (Both)	0.24 [-1.05, 1.53]	0.714
KneeOp (Left)	0.88 [-0.26, 2.02]	0.130

* denotes statistical significance

Increasing BMI was also statistically significant (0.41, $p < 0.001$). This indicates that a higher BMI will result in moving from a varus-to-valgus direction. A positive history of lower limb surgery was significant in the model with an effect of decreasing the alignment angle and moving towards a varus alignment (-6.71 $p < 0.001$). This is the same effect seen in the previous model using only surgery knees.

4.3 Damage Models

The initial assessment of the damage models compared the unadjusted models to the adjusted ones. This was done in order to determine if the adjusted model was a "better" model using a goodness of fit estimate. The model with a lower value is considered the better-fit model. These fit estimates were compared between the adjusted and unadjusted models, and in all cases, the adjusted model had a lower fit estimate and was thus considered to be the better, or an improved model. There is no single statistic or p value that can tell if the overall adjusted model is significant, however.

In the alignment results previously discussed, the parameter estimates can explain the direct relationship between a change in the independent variable and the corresponding change in the dependent variable. However, in the ordinal logistic models used for the damage analyses, the parameter estimates are for the log odds of the response. This may seem more difficult to interpret, but they can simply be thought of as having either a positive or negative effect on the likelihood of having a higher level of damage. For example, a positive parameter estimate for BMI would mean that increasing BMI would result in a greater likelihood of having more severe damage. On the contrary, a negative estimate for BMI would indicate that increasing BMI lowers the likelihood of damage.

4.3.1 Parameter Estimates

The complete listing of parameter estimates from the Damage models is found in Table 9. Plantar medial weight distribution was significant in the model for ACL condition (-0.14, p=0.029). This means that an increase in medial plantar weight distribution will decrease the likelihood of having more severe levels of ACL damage. Older age is related to an increased likelihood of damage for all of the models evaluated, as would be expected. For all damage models in which it was considered, a diagnosis of OA was associated with increased likelihood of damage and is statistically significant. Finally, being female resulted in a significantly greater likelihood of having more severe levels of damage. The rest of the parameter estimates are not as consistent across the different models. Medial weight distribution, specifically, is protective against damage in some instances, and damaging in others. These results suggest that there is no clear relationship between plantar weight distribution and knee damage other than ACL quality. The odds ratio results will be discussed next to see if they can provide any additional insight to the original question of interest.

Table 9. Damage Models Results, Parameter Estimates

Parameter	Estimate (p value)					
	Meniscus	**Fem Chond**	**Tib Chond**	**Fem Osteo**	**Tib Osteo**	**ACL**
MedialWgt	-0.06 (0.391)	0.03 (0.738)	0.001 (0.993)	-0.17 (0.099)	-0.07 (0.274)	**-0.14* (0.029)**
Age	0.04 (0.305)	0.08 (0.280)	0.05 (0.336)	0.07 (0.196)	0.06 (0.165)	0.05 (0.367)
BMI	-0.02 (0.694)	0.09 (0.447)	0.07 (0.593)	-0.15 (0.251)	-0.004 (0.969)	0.06 (0.438)
Leg (Left)	-	**2.01* (0.044)**	-	**2.89* (0.045)**	**2.70* (0.001)**	**1.42* (0.007**
Sex (Female)	0.99 (0.125)	0.55 (0.593)	0.64 (0.525)	0.61 (0.429)	-0.01 (0.990)	**1.64* (0.045)**
HxSurg (Yes)	-0.13 (0.832)	-0.16 (0.892)	-0.392 (0.708)	**3.19* (0.024)**	1.29 (0.080)	1.25 (0.194)
Compartment (Medial)	1.29 (0.748)	13.58 (0.072)	-4.71 (0.167)	-6.70 (0.068)	2.73 (0.318)	-
OAComp (Yes)	**27.99* (<0.001)**	**6.05* (<0.001)**	**5.78* (<0.001)**	**7.41* (<0.001)**	**4.88* (<0.001)**	-
MedialWgt Comp (medial)*	0.001 (0.988)	-0.24 (0.152)	0.15 (0.081)	**0.23* (0.011)**	-0.05 (0.432)	-

* denotes statistical significance (p<0.05). Negative estimates indicate increasing the parameter will decrease odds of having damage, and positive estimates indicate increasing the parameter will increase odds of having damage
- denotes the parameter was not included in that model

4.3.2 Odds Ratio Results

Table 10 contains the odds ratios for all of the damage models, looking at both compartments (medial and lateral) of the knee. Each compartment is assessed separately because it is possible that the level of damage can be different between the two, and therefore the relationship of weight distribution to damage could be different in each compartment. Again, these odds ratios are based on increasing the percentage of plantar weight that is distributed on the medial region of the foot. An odds ratio> 1 indicates that this increase will result in a higher likelihood of greater damage, and an odds ratio < 1 indicates an increase in medial weight will result in lower likelihood of greater damage. Also, if the confidence interval contains 1, that denotes the odds ratio might actually be equivalent to 1, indicating no effect or change in the odds of more or less damage. Therefore, the odds ratio can only be considered statistically significant if the confidence limit does not contain 1.

Table 10. Damage Models Results, Odds Ratios for the Effect of Medial Weight Distribution.

Damage Model	**Odds Ratio Estimate [95% CL]**	
	Medial Compartment	**Lateral Compartment**
Meniscus	0.947 [0.834, 1.075]	0.946 [0.832, 1.074]
Femoral Chondromalacia	0.812 [0.598, 1.101]	1.029 [0.87, 1.218]
Tibial Chondromalacia	**1.168* [1.011, 1.349]**	1.001 [0.866, 1.157]
Femoral Osteophytes	1.062 [0.871, 1.296]	0.842 [0.686, 1.032]
Tibial Osteophytes	0.888 [0.757, 1.04]	0.933 [0.823, 1.057]
ACL Condition	**0.872* [0.772, 0.986]**	

* Denotes statistical significance

Only two of the odds ratios were significant: the relationship between weight distribution and tibial chondromalacia in the medial compartment and ACL condition. This result for tibial chondromalacia indicates that increasing medial weight distribution will give increased odds of having more severe damage in the medial compartment. For the ACL model it means that increasing medial weight distribution will decrease the odds of having more severe damage. The rest of the results don't provide any evidence of a relationship, however. The significant result for tibial chondromalacia even seems suspect since it does not follow any particular trend with the estimates for the compartments in the other damage models.

4.3.3 Probability Plots

So far, no clear relationship has been established between plantar weight distribution and knee damage other than for ACL condition. There is one more way the results can be examined to look for more information about a possible relationship. The results of the damage models are presented next as cumulative probabilities. The cumulative probabilities for each level of damage were calculated for each subject at a specified medial weight distribution and the average probabilities over the entire subject pool were plotted in Figures 11-16. Recall from Table 6 how the cumulative log-odds are the odds of being in one category of the response, or lower.

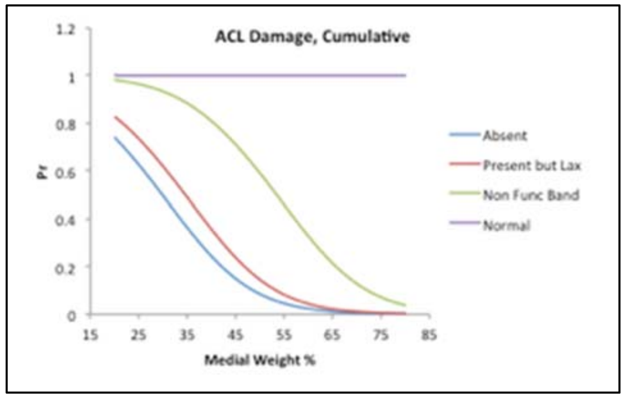

Figure 11. ACL Damage, Probability Plot

Looking at the ACL probability plot, for example, the line for "normal" indicates the probability of the ACL being normal, or anything lower (always 1) as the medial plantar weight distribution changes. Likewise, the line for "present but lax" indicates the probability that ACL condition is either "present but lax", "non-functioning band", or "absent". This pattern continues until reaching the probability of being "absent" only. In summary, all of the cumulative probabilities are for the specified level of damage, or higher/more severe.

One important note on these plots is to be aware of the applicable range based on the data collected in the study. The medial weight distribution data is primarily in the range of roughly 30-50%. The models in this analysis were constructed using that range, so making any claims using a portion of the plots other than this cannot be done as confidently as those made within the range.

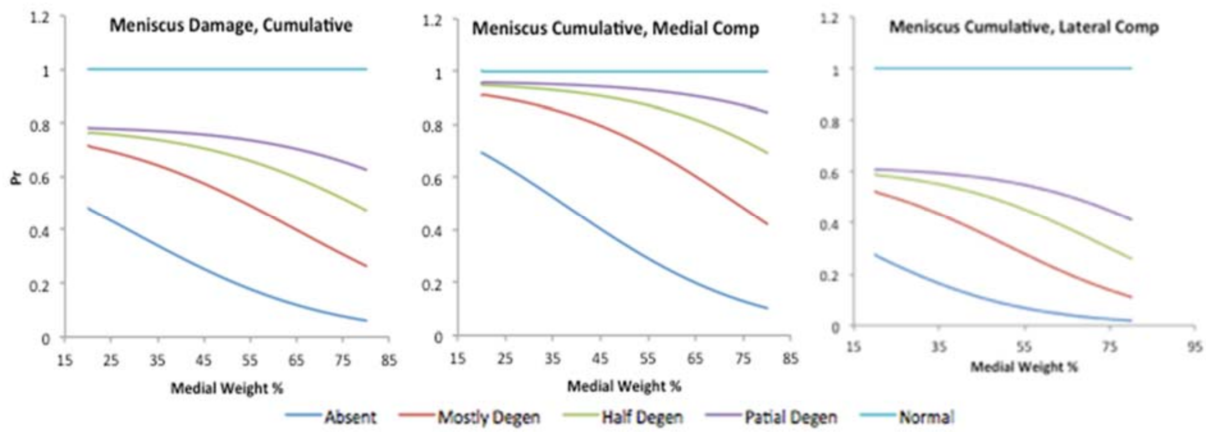

Figure 12. Meniscus Damage, Probability Plots

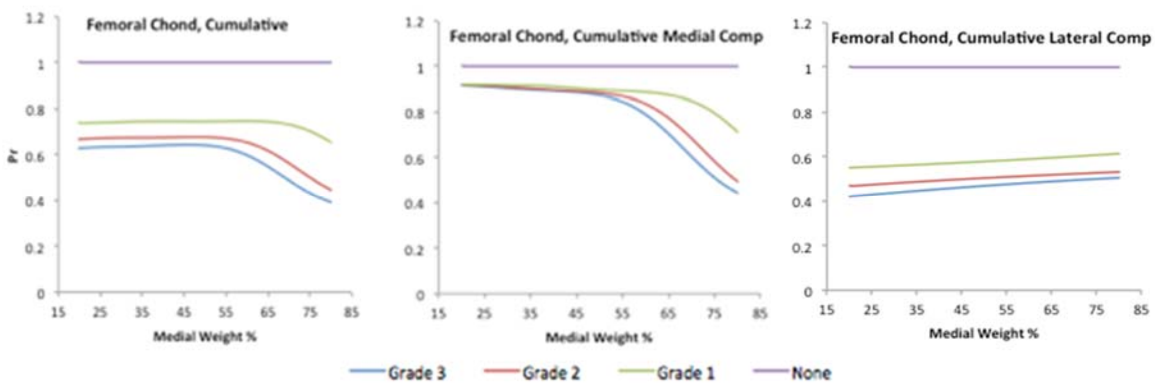

Figure 13. Femoral Chondromalacia, Probability Plots

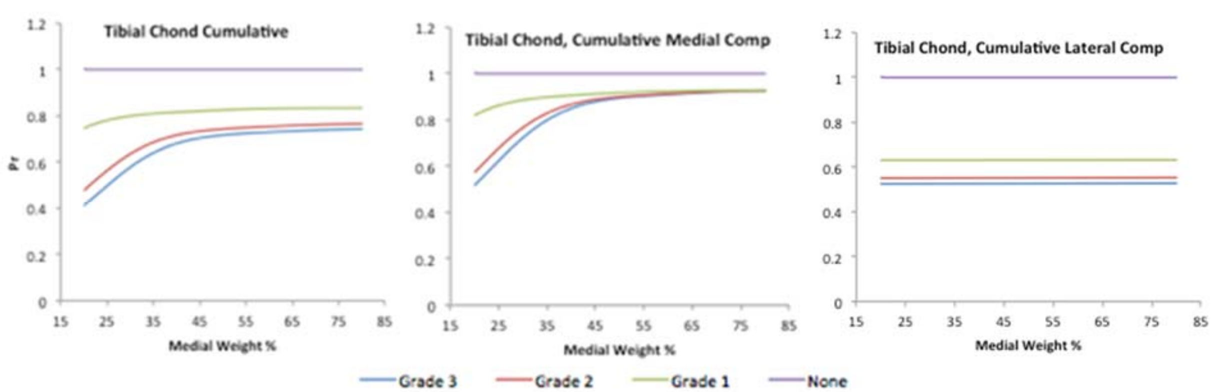

Figure 14. Tibial Chondromalacia, Probability Plots

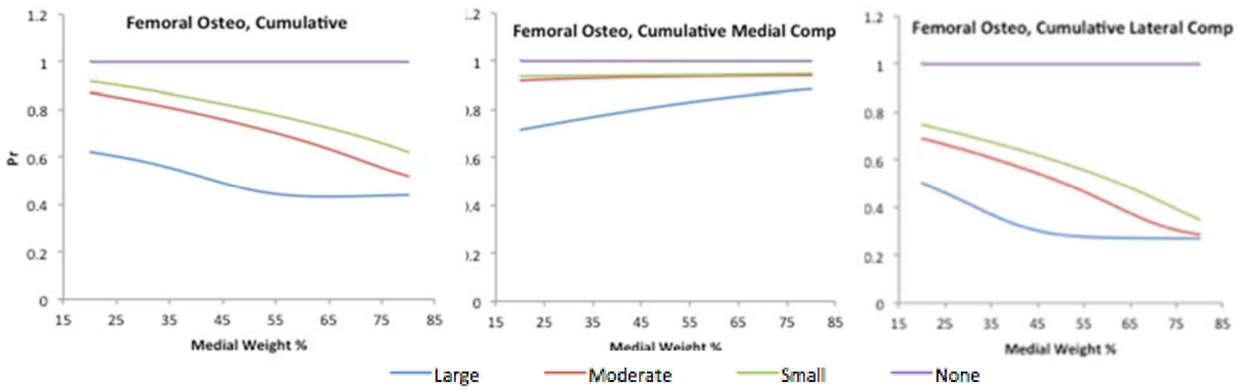

Figure 15. Femoral Osteophytes, Probability Plots

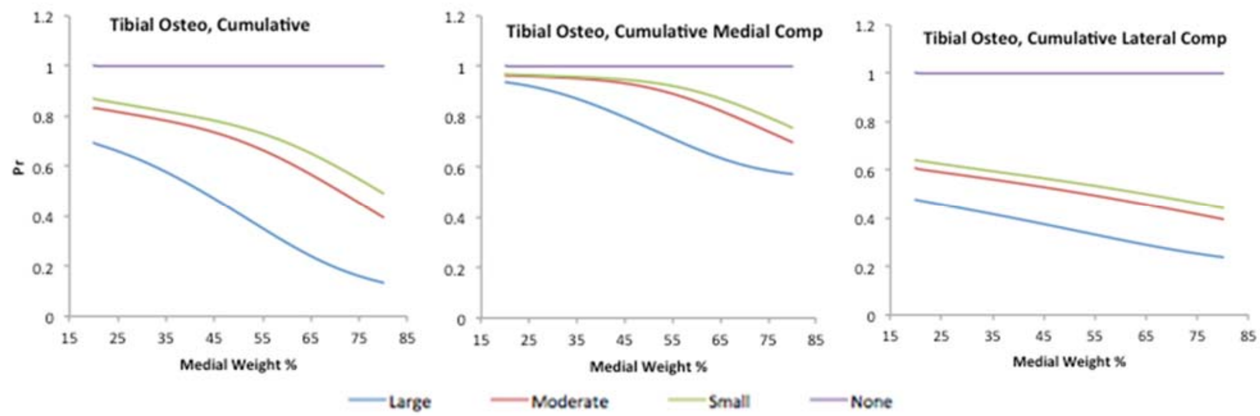

Figure 16. Tibial Osteophytes, Probability Plots

Aside from ACL damage (Figure 11), there is still no clear relationship for the remaining damage models. All of the overall cumulative probabilities, aside from tibial chondromalacia, show that increasing medial weight distribution lowers the probability of damage. This could indicate that moving towards a more even weight distribution lowers the likelihood of having more severe damage since the majority of data included in this model was below 50%. When the individual compartment probabilities are examined, however, a clear and consistent relationship cannot be observed.

The parameter estimates, odds ratios, and cumulative probabilities found as a result of this study show that there is a statistically significant relationship between plantar weight distribution and ACL condition. However, for the remaining damage models of meniscus, chondromalacia, and osteophytes, no clear and consistent relationship was determined with this study. There is reason to believe that a relationship might in fact exist, it just was not observed with the current data and models. The conclusions will address possible changes to the models and explore some reasons why a relationship might not have been observed, when one could actually exist.

5. CONCLUSIONS

5.1 Plantar Weight Distribution and Knee Alignment

This study showed a direct relationship between the percentage of weight on the medial portion of the foot and the alignment of osteoarthritic knees (0.19, p = 0.002). A positive knee angle corresponded with a valgus alignment in this study; therefore increasing medial weight is related to moving towards a valgus or more valgus alignment. Recall that a valgus alignment is when the knee bends inward. The relationship observed in this study can be easily experienced by simply standing on both feet and letting the knees fall inward. Naturally, more weight will shift to the medial portion of the feet.

The patient pool of OA knees for the alignment analysis consisted of 37 varus (negative angle), 3 valgus (positive angle), and 6 neutral knees. The vast majority of knees included in the alignment model were at a negative alignment angle. This means that the increase in angle related to increasing medial weight is more indicative of a movement away from varus and towards a less severe varus angle or closer to a neutral alignment. Figure 17 presents the medial weight distributions and knee alignments of the patients enrolled in the study.

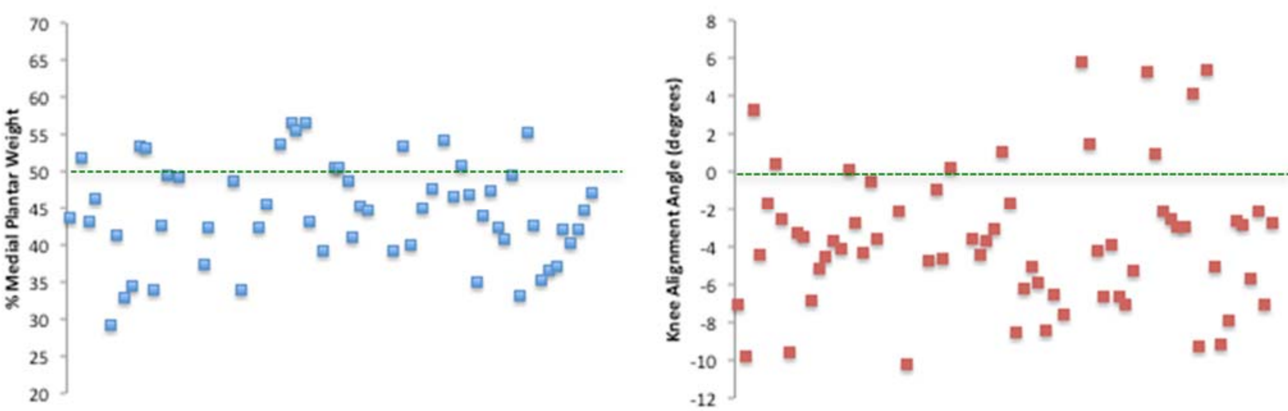

Figure 17. Measurements from Subjects in the Alignment Model. Left) Medial Plantar Weight Distributions and Right) The Alignments Measured in the Study

This tendency to move away from a varus alignment as medial weight increases is very beneficial when considering OA in the knee. As previously discussed, misalignment, and the corresponding bending moment produced in the knee, is associated with increased progression and possibly incidence of OA[29]. A neutral angle is optimal to lower the effects that knee alignment can have on OA. This study did not determine or attempt to find an optimal weight distribution that will result in neutral alignment, nor is the alignment model developed in this study a predictive tool that can be used to calculate a knee angle given some medial weight distribution. Rather, the relationship can be used to have a general idea about what a patient's knee alignment might be given their plantar weight distribution, as well as if any preventative measures could/should be put in place. For example, if a subject has a very low medial weight distribution, a clinician or researcher can have of general idea that the knee is most likely in an alignment that trends in the negative direction, or towards varus without the need for radiographs. With the known relationship between varus alignment and OA, the clinician might want to be more aware of possible OA or even suggest corrective measures that can provide for a more even plantar weight distribution, such as braces, orthotics, or even physical therapy.

The statistical significance of surgical history shows the need to expand this variable into multiple, more specific ones. As it currently stands, all of the surgical interventions are grouped together, so a knee arthroscopy is considered the same as a hip replacement. Future studies should make the surgical history more specific so that a better idea of how specific types of surgeries could have an effect on knee alignment. Increasing BMI also had a significant effect on increasing alignment. Although this result indicates that higher BMI is related to a varus-to-valgus alignment change, increasing BMI to move away from a varus alignment should not be considered a beneficial thing to do. It would be advisable for future studies to put weight and height in the model, separately, and then see what the effect of increasing weight is.

5.2 Plantar Weight Distribution and Knee Damage

An inverse relationship was found between medial plantar weight distribution and ACL damage (-0.14, p=0.029). As the percentage of plantar weight applied through the medial portion of the foot increases, the odds of observing more severe ACL condition decrease. This finding needs to be applied over the range of data observed in the study in order to ascertain its true meaning. Nearly all of the patients included in the damage model had uneven plantar weight distribution, with a lower portion of the total weight on the medial half of the foot. Therefore, the relationship observed can be thought of as the odds of increased ACL damage decreasing as the medial weight percentage increases and the weight becomes more evenly distributed on the bottom of the foot. This is a very reasonable and plausible finding. One possible factor at play is based on the prior discussion of foot arches. When the foot becomes flattened and more weight is naturally placed on the medial half, the tibia can internally rotate, and this rotation can be seen in the knee joint[34]. The majority of patients in this study had more weight on the outside of the foot, so it is plausible that this was in part producing some amount of external rotation of the tibia. If the tibia is internally/externally rotating, one of the attachment points for the ACL is moving, as well. There is undoubtedly a certain amount of forgiveness in the physiological movement of the ACL, but any twisting or load that is in excess of the normal amount could certainly increase the likelihood of damage. Moving towards a more even plantar weight distribution could be expected to place the knee joint, and as a result the ACL, in a more correct mechanical position and decrease the odds of experience higher levels of damage. Another interesting note from the ACL damage model is the effect of gender on the likelihood of damage. It is well established in the literature that women have an increased likelihood of ACL injuries compared to men, based on a variety of muscular and anatomical differences[40]. The fact that this relationship between ACL damage and women was also statistically significant in the present study adds more confidence to its results.

No consistent relationship was seen between plantar weight distribution and the other types of knee damage. The overall cumulative probability plots suggested that, in general, moving towards a more even plantar weight distribution lowers the likelihood of more severe damage, but when each compartment is examined individually, any consistent trend between the effects in the two compartments cannot be found. There is reason to believe, however, that a relationship does exist and just was not observed in this study for a myriad of possible reasons. The results from the alignment model suggested a significant relationship between plantar weight distribution and knee alignment. Previous research discussed in this paper recognized an established relationship between alignment and OA[1, 28, 29]. The current study attempted to establish a direct relationship between plantar weight distribution and OA. So essentially, as illustrated in Figure 18, relationships from A to B and B to C have been established, but what is still needed is evidence of the connection directly from A to C, if it exists.

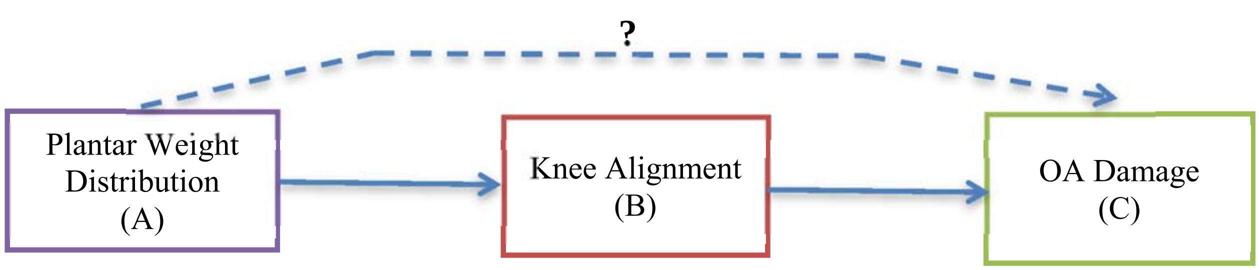

Figure 18. Relationships Examined Between Plantar Weight Distribution and OA Knees

There are many possible reasons why a relationship between weight distribution and OA damage could not be determined for all types of damage. The first is that a relationship simply might not exist, no matter how it is modeled or what data is collected. This seems unlikely, however, based on the connections described above. Also, the entire lower limb is a continuous system, so if one part of it is changed or damaged, the other parts should be affected in some way, as a result. The challenge is that damage is a very complex problem to describe and/or model. Everyone will compensate differently and there are many pieces of information that are needed to fully describe the effects. The other possible reasons why a relationship was not observed are a result of the model that was used and how/what data was collected. The next sections will examine the damage models more thoroughly and explore possible reasons for lack of an observed relationship and if there are any important adaptations that should be made to the data collection methods.

5.2.1 Methods and Variable Adjustments

Foot Placement and Arch Measurement:

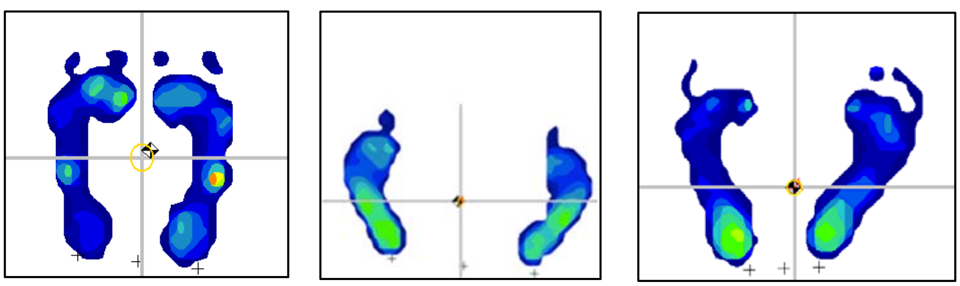

Figure 19. Example Plantar Weight Profiles from the Study

There were certain aspects of the data collection that could be adjusted to result in a better outcome. First of all, the exact foot position and alignment was not controlled during weight distribution testing. Each patient was instructed to stand in a "normal, comfortable stance" and remain as balanced as possible. This resulted in a wide array of foot positions, a few of which are shown in Figure 19.

It is very likely that adjusting the foot positioning will have a direct impact on both the plantar weight distribution and the mechanical loading environment seen at the knee. The MatScan mat actually does come with a printable template that has a specified foot placement region. Future work should use this template or some other means of controlling the foot placement and alignment between subjects. Along with controlling for foot placement, a measurement of each patient's arch type should be included as a potential confounder in the models. The prior research reviewed in this study showed a connection between foot arch height and both weight distribution and OA damage[35, 37].

Detailed Surgical History

A more detailed surgical history could help identify and model conditions where surgical intervention might have a strong impact on either weight distribution or OA damage. This current study grouped all lower-limb surgical interventions into a single yes/no variable. When these surgical events are broken down, they contained hip replacements, knee arthroscopy for cartilage and/or meniscus repair, foot surgeries, past knee arthroplasty, and even a toe replacement. Ideally, some of these patients, especially those with past knee arthroplasty, should either be removed from the study entirely or given a more specific variable to identify their past intervention. This could be adapted for each model, separately. For example, a variable identifying history of arthroscopic meniscus repair could be used only in the meniscus damage model. Also, another separate variable could be made for history of hip replacement, and yet another for history of knee replacement. These additional, more detailed pieces of information about each patient's history could help explain a significant part of the outcomes.

OA History and Duration

OA is a degenerative disease by nature. The longer a patient has OA, the greater the likelihood there is for damage, and more of it. It would make sense to include a variable in the model that specified how long each subject has had OA or what their diagnosis data was. This could help provide more information about how long the knee has been susceptible and possibly provide more connection between the different levels of damage that were recorded.

Subject Pool and Control Group

The subject pool size is always an important consideration during any research study. Unfortunately, this work was limited in terms of the number of patients that could be included in the study, but future work should make considerable effort to include as many subjects as possible. First of all, when some relationship or question is examined, the more data available to explain all of the possible variations, the better the model will be. A large subject pool increases the likelihood that all possible combinations of variables will be observed. Second, this allows the researcher to be more selective with the patients that are included in the study. The history of previous surgery was discussed earlier in terms of the importance of taking it into account. Ideally, there would be enough patients available to select from that none of the patients would have any history of possible confounders that could complicate the data.

Lastly, a control group would have been very beneficial to this study. There was no knowledge of what different plantar weight distributions are in a patient without OA, and so an optimal value for a healthy distribution could not be determined. The control group should be a population of individuals as similar to the OA patients as possible, minus the diagnosis of OA. This control group would also provide valuable information to the alignment model addressed in this study. The majority of patients had severe varus deformity, so ideally a control group would give an indication of what types of plantar weight distribution can be observed in a healthy individual.

Unfortunately these control patients would not have any damage on healthy knee tissues since they would not have had their knees surgically evaluated. They would, however, provide valuable information about plantar weight distribution and alignment.

5.2.2 Response Categories

The response of each damage model had up to 5 possible outcomes. If any of these possible outcomes did not have an adequate number of data points, the model will have a difficult time trying to explain any relationship. If a specific response, such as a male, no history of surgery, and with a level 3 damage response, was not observed in the study, the model acts as though that response is impossible. The truth is that it is possible; there just were not enough observations to see it. Another example of this challenge with low response counts considers a 10 sided-dice. If the dice is rolled 10 times and a 2, 3 or 4 is never rolled, the statistical model will treat this as if a 2, 3, or 4 are impossible outcomes. In reality, they are possible, the dice was just not rolled enough times to observe them. It is difficult to determine what constitutes "enough" data points for each response category, but when there are numerous categorical independent variables in the model, there are more possible combinations of variables and a large number of observations is needed to capture as many of these different combinations as possible.

One way to evaluate this effect is to model all of the damage responses as either "yes" or "no", in relation to the presence of damage. This could allow the number of data points in each response category to increase and possibly provide more consistent damage models across the two compartments. The original response counts and the modified "yes/no" counts are shown below in Table 11.

Table 11. Response Level Frequencies for the Original and Modified Outcomes of the Damage Models

Meniscus	
Level	**Total Frequency**
Extreme	9
Substantial	20
Some	9
Minimal	4
None	15
Modified	
Yes	42
No	15

Femoral Chondromalacia	
Level	**Total Frequency**
Extreme	29
Substantial	3
Minimal	5
None	12
Modified	
Yes	37
No	12

Tibial Chondromalacia	
Level	**Total Frequency**
Extreme	38
Substantial	2
Minimal	6
None	11
Modified	
Yes	46
No	11

Femoral Osteophytes	
Level	**Total Frequency**
Extreme	13
Substantial	19
Minimal	4
None	11
Modified	
Yes	36
No	11

Tibial Osteophytes	
Level	**Total Frequency**
Extreme	13
Substantial	19
Minimal	4
None	16
Modified	
Yes	36
No	16

ACL	
Level	**Total Frequency**
Extreme	8
Substantial	4
Minimal	22
None	23
Modified	
Yes	34
No	23

The response counts are not substantially different, but the response levels with counts <5 or even <10 have been removed. The ACL model has the most data points in both modified response categories. This could help explain why it was the only damage model that was significant and had a reasonable result. All of the above, modified models were evaluated and the odds ratio results are reported in Table 12.

Table 12. Odds Ratio Results for Damage Models with a Modified "Yes/No" Response

Damage Model	**Odds Ratio Estimate [95% CL]**	
	Medial Compartment	**Lateral Compartment**
Meniscus	0.827 [0.594, 1.152]	1.019 [0.823, 1.261]
Femoral Chondromalacia	0.996 [0.793, 1.250]	1.012 [0.826, 1.240]
Tibial Chondromalacia	1.014 [0.825, 1.247]	1.030 [0.814, 1.303]
Femoral Osteophytes	0.997 [0.790, 1.258]	1.017 [0.826, 1.252]
Tibial Osteophytes	0.989 [0.813, 1.203]	1.101 [0.879, 1.378]
ACL	0.992 [0.863, 1.140]	

These odds ratios using the modified response levels are not significant, but they are all consistent across the compartments. Increasing medial plantar weight distribution increases the odds of having damage in the lateral compartment but decreases the odds of having damage in the medial compartment. There is one result, tibial chondromalacia, that predicts a damaging relationship for both compartments, but the effect in the lateral compartment is still greater. The interpretation of these results can be explained with help from the Alignment model that was previously examined. The Alignment model showed increasing medial plantar weight distribution results in a tendency to move away from a varus alignment. Recall from the Section 2.4.1 that a varus alignment is when the knees are bowed outward. This misalignment results in a bending moment in the knee that places extra stress on the joint surfaces in the medial compartment[41]. The effect is also present in valgus alignment where the added stress is found in the lateral compartment. This added stress in the compartments is known to result in increased risk of cartilage loss, the primary characteristic of OA[41]. Figure 20 illustrates this effect in misalignment.

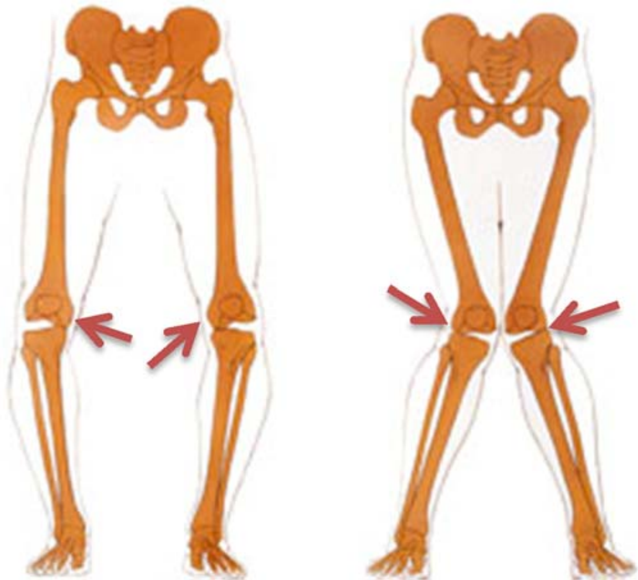

Figure 20. Locations of Increased Stress in Varus (Left) and Valgus (Right) Misaligned Knees[42]

The primary conclusion drawn from this post-hoc analysis is that there is value to having increased frequencies of each response. Also, although the odds ratios were not significant, this model begins to hint at the likelihood that a relationship that is consistent for all of the damage models between the two compartments does in fact exist. The modified response could be the next step to finding a consistent relationship that is statistically significant. Most likely, the significance is still limited by the number of data points. The modifications to the response helped and provide more insight into the question of interest in this study, but they were not quite enough to show significant results for all of the damage models.

5.3 Summary

This study observed a direct relationship between medial plantar weight distribution and the alignment of osteoarthritic knees in a varus to valgus direction (0.19, $p = 0.002$). As the percentage of the total weight on the foot that is applied through the medial half increases, knee alignment angle increases, as well. In this study, a positive alignment angle corresponds to a valgus deformity, and a negative angle corresponds to a varus deformity.

An indirect relationship was found between medial plantar weight distribution and ACL condition (-0.14, $p = 0.029$). Since the majority of weight distributions measured showed an uneven distribution with more weight on the outside of the foot, this result indicates that as the weight becomes more evenly distributed on the bottom of the foot, the odds of having more severe damage to the ACL decrease.

For the other damage models, no consistent relationship was observed between plantar weight distribution and knee damage. This was believed to be a result of the model setup and the methods used to collect data, more so than the lack of a relationship. This study established a relationship between weight distribution and knee alignment, and prior research has found the relationship between alignment and OA damage. There is good reason to believe that a relationship exists between weight distribution and damage, without the need to make the stop at alignment. One indication of this was seen when the response for the damage models was modified to a "yes/no" outcome to describe the presence of damage. The odds ratios from these adjusted models were not significant but showed a relationship between plantar weight distribution and damage in each compartment that was consistent with existing research and consistent across all of the damage models (Section 5.2.2). The relationship indicated that increasing medial plantar weight distribution increased the odds of damage in the lateral compartment and decreased the odds of damage in the medial compartment. There are also many improvements that can be made to the methods used in this study, additional variables can be collected, and the collection of variables already included can be improved.

OA is a damaging disease that most commonly affects the knee. The manifestations of this disease can affect the function of the entire lower limb. This study attempted to examine how the plantar weight distribution can be related to these various changes in OA knees. A direct relationship was found between the percentage of total weight that is applied through the medial region of the foot and an increase in knee alignment angle. Also, an indirect relationship was found between medial plantar weight distribution and ACL damage. However, no relationships were found between weight distribution and the other types of damage. It does seem reasonable to believe that the other relationships do in fact exist, however. There is a clear connection between weight distribution and alignment, and one between alignment and OA damage. This study and everything that that was learned from it can set the groundwork for future studies that will be more effective at examining a possible relationship and increasing the understanding of how changes observed in plantar weight distribution are related to the condition of osteoarthritic knees.

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APPENDICIES

APPENDIX A

A1. Detailed MatScan Setup and Procedure

The hardware/software will have been properly set up and ready to record data before each patient's arrival for their final pre-operative visit. First ensure that the USB connection is plugged in to the computer that is to be used for data acquisition. Start the MatScan Research software. If the mat has not been properly recognized, an error message will pop up when launching the software, noting the user that no hardware has been found. Once the software has loaded, the first screen you will see asks for you to choose the patient you would like to study, as shown below. To begin collecting data on a new patient, as will be done at the pre-operative visit, select 'new patient'. If time permits, it is optimal to have done this ahead of time in order to limit the duration of data collection for each patient.

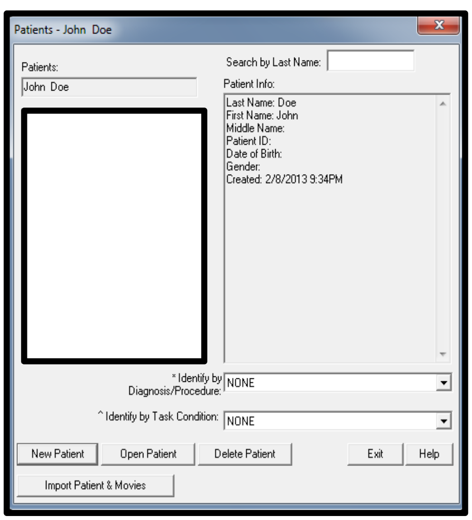

Figure A1. New Patient Setup

Be sure to enter data for each new patient in all of the fields shown in the figure below. The patient's middle initial will suffice, rather than the full middle name. This information will not be published, but it is necessary to ensure each patient's balance data is identifiable so it can be related to the same patient's knee score. Also, accurately identifying each patient's data helps in the instance where an anomaly might occur and a specific patient's data needs to be studied further.

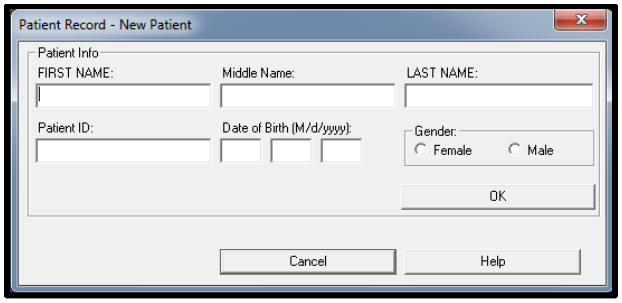

Figure A2. New Patient Record

After the patient's information has been added, it is time to set the proper settings for data collection. Select 'Options' > 'Data Acquisition Parameters' and adjust the time duration to 20 seconds and the frequency to 10Hz (The recommended frequency when using the USB connection, based on the software's own recommendation).

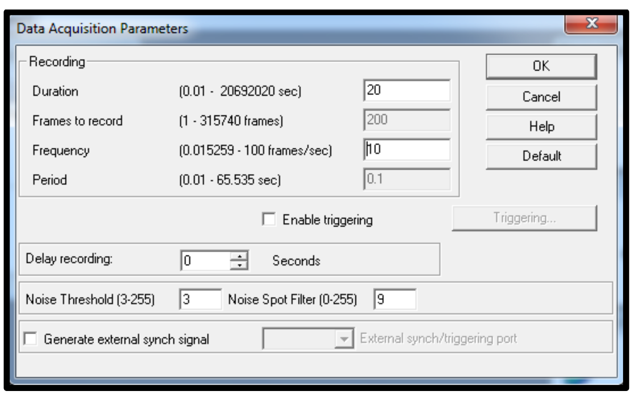

Figure A3. Data Acquisition Parameters

After the select the 'New' icon and you will see the data acquisition window appear. Select the 'SAM' button and you will be prompted to enter in more information about the trial.

Eventually, you arrive at a screen that asks you to select a predefined task. Since neither of the two tasks that are included by default (eyes open and eyes closed) match well with this experiment design, a new task should be entered in, either “Pre-Op 1” or “Pre-Op 2”, depending on the particular trial.

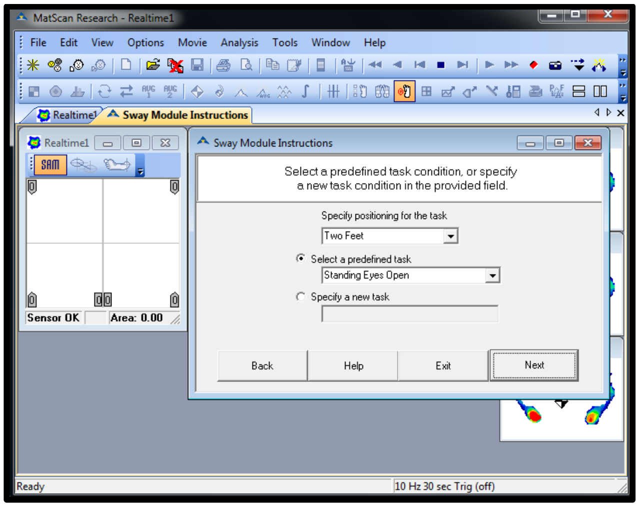

Figure A4. Task Designation

Once this information has been filled out, you will be prompted to start recording. At this point, have the patient stand barefoot (without shoes, but socks are OK) in their normal, comfortable standing position in the middle of the mat. Instruct the patient to look straight ahead and maintain their balance as best as possible. Once the patient is situated and notifies you that they are ready, press “record” and begin collecting data. After the trial has completed, instruct the patient to step off of the mat momentarily. Save the trial and prepare for the next one. Select a new recording one more time and repeat the previous steps to complete the second trial. The software will automatically save each trial with the patient’s name and the trial number.

Data Processing and Analysis:

After the trials have been completed, additional works needed to be done to collect the force distribution data from the MatScan files. With the movie file of interest opened, select the 'Templates/Regions-Toolbar' icon.

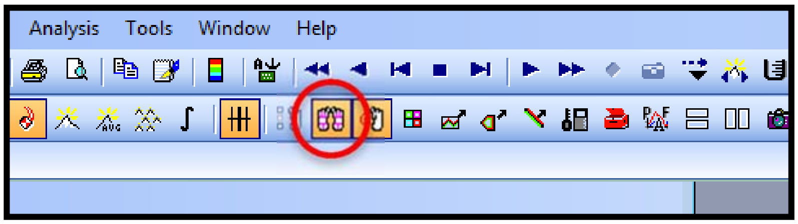

Figure A5. Selection for Force Distribution

This will bring up a new tool bar in the video display screen. Within this toolbar, select 'Templates' then choose 'Show Templates'. Next select 'Regions' and then 'show regions'. Ensure the 'Auto update regions' option is picked, as well.

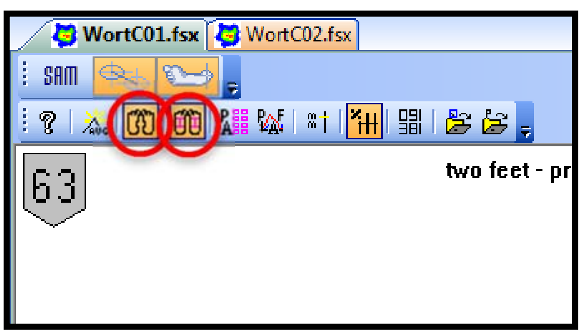

Figure A6. Foot Profile Selection Boxes

If the foot region templates are not displayed, advance the movie frame by frame until they appear. Once they appear, select the pink template boundary and adjust the profile to best fit the force distribution of each foot. This does not need to be a perfect fit, and it is best to leave a slight gap between the profile and foot contact regions to allow for some movement during the trial. Again, these do not need to be stressed over making perfect. Some of the auto-placements are very poor; therefore adjusting the profile is included as a step since it is necessary for some of the movie files. You will see a cyan colored line running the length of the foot profile, adjust this line so that it lies on top of the pink line bisecting the heel. Then adjust it so that the portion near the toes overlaps with the middle line dividing the toes. These two overlap locations are indicated with a dark red line in the image below. This adjusted cyan line will serve as the boundary for dividing the foot into medial and lateral portions.

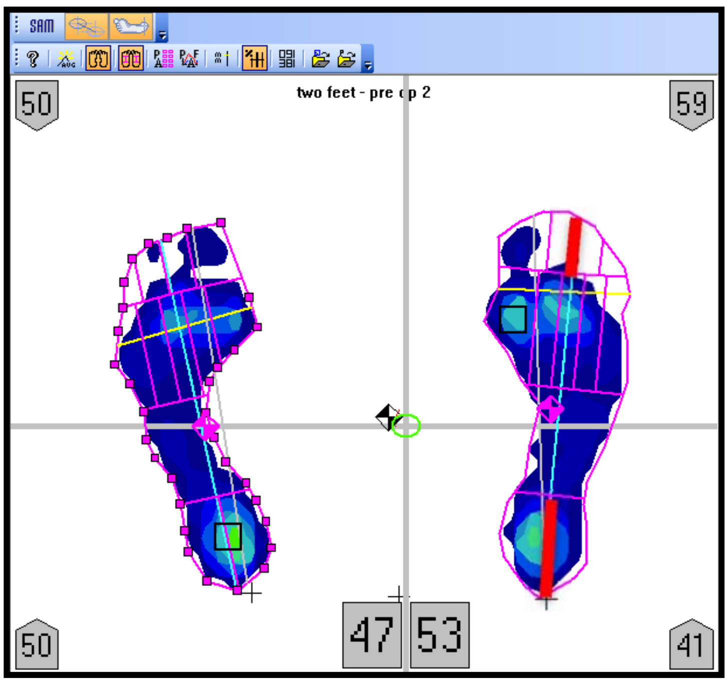

Figure A7. Foot Midline Alignment

Next, objects defining the medial half of each foot and the total foot area are created. This is done by first selecting the 'add polygon' button. Use the pointer to draw a region that encompasses the medial right, medial left, total right, and total left areas. These can be added to new or existing graphs, it does not make any difference. The boundaries of each area can be manually adjusted after they are created. Ensure the medial regions divide the foot along the cyan line that was previously adjusted.

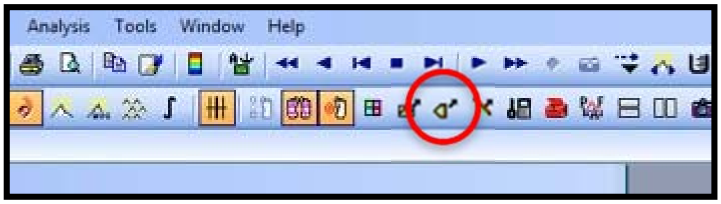

Figure A8. Create New Object

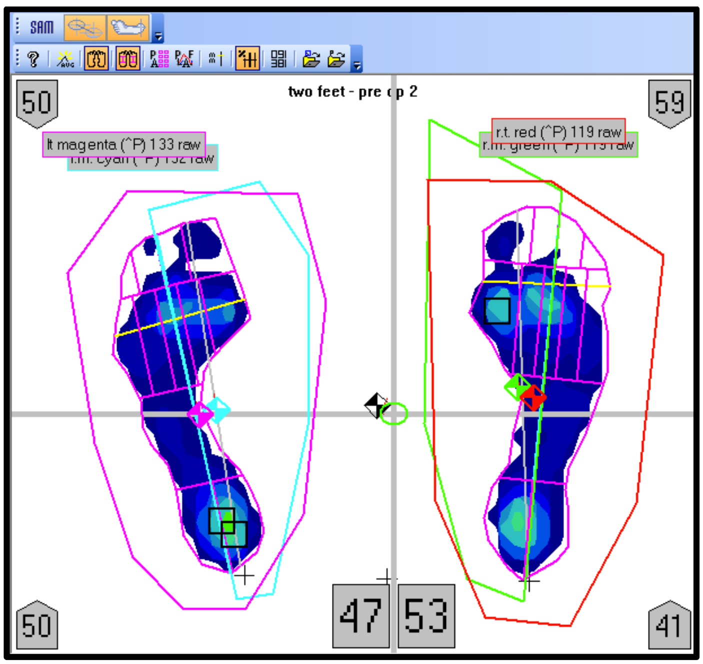

Figure A9. Defined Foot Objects

Once the objects for each area have been defined, select ‘Objects’ to bring up the objects display box.

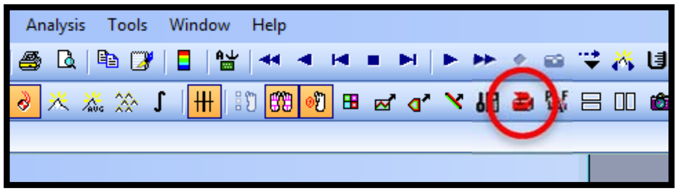

Figure A10. List Objects

The four objects that have just been created will be listed. Select one at a time and rename them to something that will be more identifiable when the data is exported. After this, save ASCII files for the absolute force values and the CoF values. This will create .csv files that can be opened and viewed for further data analysis.

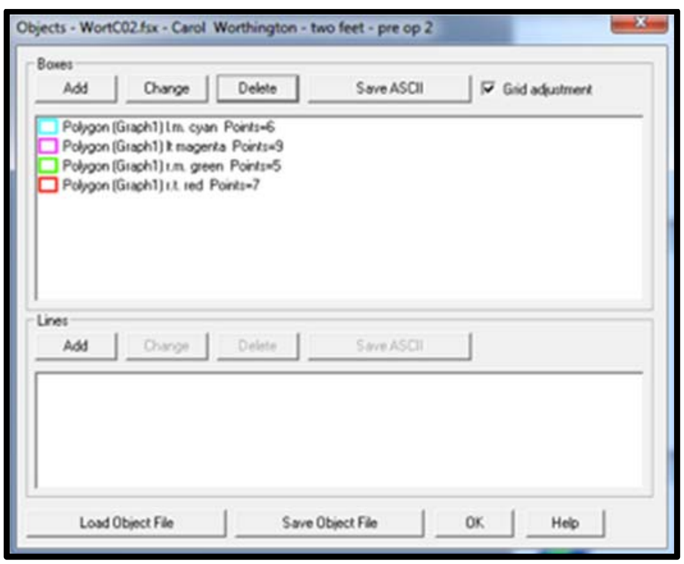

Figure A11. Listing of Objects

The data collected on absolute force was further reduced. Using the total force for the left foot and the total force for the medial portion of the left foot, calculate what % off the total is on the medial region. Next find the %lateral force and repeat this for the right foot, as well as for both feet on the second trial. Remember, the %medial/lateral are the % of that foot only. The

CoF data can be set aside for the time being. It is only collected now in order to save time if it becomes needed for future use.

APPENDIX B

B1. Raw Data

Table B1. Raw Data

Subject	***Age***	***Sex***	***BMI***	***Operated Knee***	***Hx of Lower Limb Surg.***	***Side of interest***	***Comp.***	***OA in Comp***	***Alignment (degrees)***	***MedWgt (%)***
1	72	M	27.09	L	N	R	medial	N	-7.1	51.62
1	72	M	27.09	L	N	R	lateral	N	-7.1	51.62
1	72	M	27.09	L	N	L	medial	Y	-9.8	43.64
1	72	M	27.09	L	N	L	lateral	Y	-9.8	43.64
2	83	M	36.03	L	Y	R	medial	N	3.3	51.79
2	83	M	36.03	L	Y	R	lateral	N	3.3	51.79
2	83	M	36.03	L	N	L	medial	Y	-4.4	43.11
2	83	M	36.03	L	N	L	lateral	Y	-4.4	43.11
3	63	M	34.96	R	N	R	medial	Y	-1.7	46.33
3	63	M	34.96	R	N	R	lateral	N	-1.7	46.33
3	63	M	34.96	R	N	L	medial	N	0.4	50.58
3	63	M	34.96	R	N	L	lateral	N	0.4	50.58
4	71	F	28.32	L	N	R	medial	Y	-2.5	29.29
4	71	F	28.32	L	N	R	lateral	Y	-2.5	29.29
4	71	F	28.32	L	N	L	medial	Y	-9.6	41.23
4	71	F	28.32	L	N	L	lateral	Y	-9.6	41.23
5	56	F	43.25	B	Y	R	medial	Y	-3.3	32.91
5	56	F	43.25	B	Y	R	lateral	Y	-3.3	32.91
5	56	F	43.25	B	N	L	medial	Y	-3.5	34.58
5	56	F	43.25	B	N	L	lateral	Y	-3.5	34.58
6	66	M	33.72	B	Y	R	medial	Y	-6.8	53.49
6	66	M	33.72	B	Y	R	lateral	N	-6.8	53.49
6	66	M	33.72	B	Y	L	medial	Y	-5.2	53.21
6	66	M	33.72	B	Y	L	lateral	N	-5.2	53.21
7	65	M	32.10	R	N	R	medial	Y	-4.5	33.82
7	65	M	32.10	R	N	R	lateral	N	-4.5	33.82
7	65	M	32.10	R	N	L	medial	Y	-3.7	42.62
7	65	M	32.10	R	N	L	lateral	N	-3.7	42.62
8	63	F	24.69	R	Y	R	medial	Y	-4.1	49.58
8	63	F	24.69	R	Y	R	lateral	N	-4.1	49.58
8	63	F	24.69	R	N	L	medial	N	0.1	43.59
8	63	F	24.69	R	N	L	lateral	N	0.1	43.59
9	75	F	32.45	R	N	R	medial	Y	-2.7	49.1

9	75	F	32.45	R	N	R	lateral	N	-2.7	49.1
9	75	F	32.45	R	Y	L	medial	N	-4.3	46.79
9	75	F	32.45	R	Y	L	lateral	N	-4.3	46.79
10	57	F	35.18	L	N	R	medial	N	.0.5	45.21
10	57	F	35.18	L	N	R	lateral	N	.0.5	45.21
10	57	F	35.18	L	N	L	medial	Y	-3.6	37.48
10	57	F	35.18	L	N	L	lateral	N	-3.6	37.48
11	56	M	31.66	R	N	R	medial	N	.	42.28
11	56	M	31.66	R	N	R	lateral	Y	.	42.28
11	56	M	31.66	R	N	L	medial	N	.	34.72
11	56	M	31.66	R	N	L	lateral	N	.	34.72
12	66	M	36.91	B	Y	R	medial	Y	-2.1	53.29
12	66	M	36.91	B	Y	R	lateral	Y	-2.1	53.29
12	66	M	36.91	B	N	L	medial	Y	-10.2	48.67
12	66	M	36.91	B	N	L	lateral	Y	-10.2	48.67
13	60	M	41.56	R	N	R	medial	Y	.	34.07
13	60	M	41.56	R	N	R	lateral	Y	.	34.07
13	60	M	41.56	R	N	L	medial	N	.	46.98
13	60	M	41.56	R	N	L	lateral	N	.	46.98
14	56	M	33.79	L	N	R	medial	N	-4.7	39.93
14	56	M	33.79	L	N	R	lateral	N	-4.7	39.93
14	56	M	33.79	L	Y	L	medial	Y	.0.9	42.44
14	56	M	33.79	L	Y	L	lateral	Y	.0.9	42.44
15	65	F	32.84	R	Y	R	medial	Y	-4.6	45.52
15	65	F	32.84	R	Y	R	lateral	N	-4.6	45.52
15	65	F	32.84	R	Y	L	medial	N	0.2	48.26
15	65	F	32.84	R	Y	L	lateral	N	0.2	48.26
16	69	F	24.69	L	N	R	medial	Y	.	53.62
16	69	F	24.69	L	N	R	lateral	Y	.	53.62
16	69	F	24.69	L	N	L	medial	Y	.	56.62
16	69	F	24.69	L	N	L	lateral	Y	.	56.62
17	72	F	36.03	B	Y	R	medial	Y	-3.6	55.65
17	72	F	36.03	B	Y	R	lateral	Y	-3.6	55.65
17	72	F	36.03	B	N	L	medial	Y	-4.4	56.59
17	72	F	36.03	B	N	L	lateral	Y	-4.4	56.59
18	70	F	32.61	R	N	R	medial	Y	-3.7	43.14
18	70	F	32.61	R	N	R	lateral	N	-3.7	43.14
18	70	F	32.61	R	N	L	medial	N	-3.1	41.7
18	70	F	32.61	R	N	L	lateral	N	-3.1	41.7
19	71	M	33.75	L	N	R	medial	Y	1.1	39.33
19	71	M	33.75	L	N	R	lateral	Y	1.1	39.33
19	71	M	33.75	L	N	L	medial	Y	-1.7	50.54
19	71	M	33.75	L	N	L	lateral	Y	-1.7	50.54
20	55	M	30.82	L	Y	R	medial	Y	-8.5	50.58
20	55	M	30.82	L	Y	R	lateral	N	-8.5	50.58

20	55	M	30.82	L	Y	L	medial	Y	-6.2	48.8
20	55	M	30.82	L	Y	L	lateral	N	-6.2	48.8
21	44	F	36.44	B	Y	R	medial	Y	-5.1	41.03
21	44	F	36.44	B	Y	R	lateral	Y	-5.1	41.03
21	44	F	36.44	B	Y	L	medial	Y	-5.9	45.22
21	44	F	36.44	B	Y	L	lateral	Y	-5.9	45.22
22	50	M	24.68	R	Y	R	medial	Y	-8.4	44.79
22	50	M	24.68	R	Y	R	lateral	N	-8.4	44.79
22	50	M	24.68	R	N	L	medial	N	-6.5	46.58
22	50	M	24.68	R	N	L	lateral	N	-6.5	46.58
23	65	M	34.21	L	N	R	medial	N	.	32.7
23	65	M	34.21	L	N	R	lateral	N	.	32.7
23	65	M	34.21	L	Y	L	medial	Y	-7.6	39.3
23	65	M	34.21	L	Y	L	lateral	Y	-7.6	39.3
24	62	F	26.62	L	N	R	medial	N	.	45.48
24	62	F	26.62	L	N	R	lateral	N	.	45.48
24	62	F	26.62	L	N	L	medial	Y	5.8	53.39
24	62	F	26.62	L	N	L	lateral	Y	5.8	53.39
25	54	F	34.44	R	N	R	medial	Y	1.5	40.09
25	54	F	34.44	R	N	R	lateral	Y	1.5	40.09
25	54	F	34.44	R	N	L	medial	Y	-4.2	44.94
25	54	F	34.44	R	N	L	lateral	Y	-4.2	44.94
26	52	F	36.31	L	N	R	medial	N	-6.6	51.98
26	52	F	36.31	L	N	R	lateral	N	-6.6	51.98
26	52	F	36.31	L	Y	L	medial	Y	-3.9	47.62
26	52	F	36.31	L	Y	L	lateral	N	-3.9	47.62
27	52	F	35.51	R	Y	R	medial	Y	-6.6	54.3
27	52	F	35.51	R	Y	R	lateral	Y	-6.6	54.3
27	52	F	35.51	R	N	L	medial	N	-7.1	37.3
27	52	F	35.51	R	N	L	lateral	N	-7.1	37.3
28	63	M	28.06	R	Y	R	medial	Y	-5.3	46.57
28	63	M	28.06	R	Y	R	lateral	N	-5.3	46.57
28	63	M	28.06	R	N	L	medial	N	.	50.85
28	63	M	28.06	R	N	L	lateral	N	.	50.85
29	59	M	34.74	L	N	R	medial	N	5.3	46.73
29	59	M	34.74	L	N	R	lateral	N	5.3	46.73
29	59	M	34.74	L	N	L	medial	Y	0.9	35.01
29	59	M	34.74	L	N	L	lateral	Y	0.9	35.01
30	67	F	32.22	R	N	R	medial	Y	-2.1	44.04
30	67	F	32.22	R	N	R	lateral	N	-2.1	44.04
30	67	F	32.22	R	Y	L	medial	N	-2.5	47.31
30	67	F	32.22	R	Y	L	lateral	N	-2.5	47.31
31	65	F	25.06	L	Y	R	medial	N	-2.9	42.35
31	65	F	25.06	L	Y	R	lateral	N	-2.9	42.35
31	65	F	25.06	L	N	L	medial	Y	-2.9	40.79

31	65	F	25.06	L	N	L	lateral	N	-2.9	40.79
32	63	M	28.89	L	N	R	medial	N	4.1	49.56
32	63	M	28.89	L	N	R	lateral	N	4.1	49.56
32	63	M	28.89	L	N	L	medial	Y	-9.3	33.03
32	63	M	28.89	L	N	L	lateral	Y	-9.3	33.03
33	69	M	36.91	L	N	R	medial	Y	5.4	55.21
33	69	M	36.91	L	N	R	lateral	Y	5.4	55.21
33	69	M	36.91	L	N	L	medial	Y	-5	42.69
33	69	M	36.91	L	N	L	lateral	Y	-5	42.69
34	72	M	34.85	R	Y	R	medial	Y	-9.2	35.17
34	72	M	34.85	R	Y	R	lateral	Y	-9.2	35.17
34	72	M	34.85	R	N	L	medial	Y	-7.9	36.62
34	72	M	34.85	R	N	L	lateral	Y	-7.9	36.62
35	54	F	53.04	R	N	R	medial	Y	-2.6	37.08
35	54	F	53.04	R	N	R	lateral	N	-2.6	37.08
35	54	F	53.04	R	Y	L	medial	N	-2.8	42.09
35	54	F	53.04	R	Y	L	lateral	N	-2.8	42.09
36	75	F	25.57	.	Y	R	medial	N	-5.7	40.28
36	75	F	25.57	.	Y	R	lateral	N	-5.7	40.28
36	75	F	25.57	.	Y	L	medial	Y	-2.1	42.08
36	75	F	25.57	.	Y	L	lateral	N	-2.1	42.08
37	71	M	26.54	R	Y	R	medial	Y	-7.1	44.8
37	71	M	26.54	R	Y	R	lateral	Y	-7.1	44.8
37	71	M	26.54	R	Y	L	medial	N	-2.7	47.06
37	71	M	26.54	R	Y	L	lateral	N	-2.7	47.06

Table B2. Raw Data, Continued

Subject	***Femoral Chond.***	***Tibial Chond.***	***Femoral Osteo.***	***Tibial Osteo.***	***Meniscus***	***ACL***
1	.	.	.	.	.	.
1	.	.	.	.	.	.
1	3	3	3	3	3	1
1	2	1	1	1	0	1
2	.	.	.	.	.	.
2	.	.	.	.	.	.
2	3	3	3	3	3	3
2	3	3	2	3	2	3
3	.	3	.	.	1.5	0
3	0	0	0	0	0	0
3	.	.	.	.	.	.
3	.	.	.	.	.	.
4	.	.	.	.	.	.
4	.	.	.	.	.	.
4	3	3	3	3	3	3
4	3	3	3	3	2	3
5	3	3	2	2	2	2
5	2	3	2	2	2	2
5	3	3	2	2	2	1
5	3	3	2	2	2	1
6	.	3	.	0	0	0
6	0	.	.	0	0	0
6	2	3	.	.	1.5	0
6	0	0	0	0	0	0
7	.	3	.	.	1.5	0
7	0	0	0	0	0	0
7	.	.	.	.	.	.
7	.	.	.	.	.	.
8	.	.	.	.	.	.
8	.	.	.	.	.	.
8	.	.	.	.	.	.
8	.	.	.	.	.	.
9	.	3	.	.	.	.
9	0	0	0	0	0	0
9	.	.	.	.	.	.
9	.	.	.	.	.	.
10	.	.	.	.	.	.
10	.	.	.	.	.	.
10	.	3	.	.	1.5	0
10	0	0	0	0	0	0

11	0	0	0	0	0	0
11	0	3	0	0	1.5	0
11	.	.	.	.	.	.
11	.	.	.	.	.	.
12	3	3	3	3	2	0
12	3	3	2	2	1	0
12	3	3	3	3	2	1
12	3	3	2	2	1	1
13	3	2	2	2	3	1
13	1	1	1	1	1	1
13	.	.	.	.	.	.
13	.	.	.	.	.	.
14	.	.	.	.	.	.
14	.	.	.	.	.	.
14	3	3	3	3	3	3
14	3	3	3	3	2	3
15	.	3	.	.	1.5	0
15	0	0	0	0	0	0
15	.	.	.	.	.	.
15	.	.	.	.	.	.
16	.	.	.	.	.	.
16	.	.	.	.	.	.
16	.	.	.	.	.	.
16	.	.	.	.	.	.
17	3	3	3	2	2	1
17	1	1	1	1	2	1
17	3	3	3	2	2	1
17	3	3	2	2	2	1
18	.	3	.	0	1.5	1
18	0	0	0	0	0	1
18	.	.	.	.	.	.
18	.	.	.	.	.	.
19	3	3	2	3	3	0
19	3	3	2	2	2	0
19	3	3	2	2	2	1
19	3	2	2	2	1	1
20	.	.	.	.	.	.
20	.	.	.	.	.	.
20	3	3	3	3	3	1
20	1	1	1	1	0	1
21	3	3	3	3	3	3
21	1	1	2	2	2	3
21	3	3	2	2	2	2
21	1	1	2	2	0	2
22	.	0	.	0	1.5	0

22	0	0	0	0	0	0
22	.	.	.	.	.	.
22	.	.	.	.	.	.
23	.	.	.	.	.	.
23	.	.	.	.	.	.
23	.	.	.	.	.	.
23	.	.	.	.	.	.
24	.	.	.	.	.	.
24	.	.	.	.	.	.
24	3	3	3	2	3	1
24	3	3	2	3	2	1
25	3	3	2	2	2	1
25	3	3	2	2	2	1
25	.	.	.	.	.	.
25	.	.	.	.	.	.
26	.	.	.	.	.	.
26	.	.	.	.	.	.
26	.	.	.	.	.	.
26	.	.	.	.	.	.
27	.	.	.	.	.	.
27	.	.	.	.	.	.
27	.	.	.	.	.	.
27	.	.	.	.	.	.
28	.	3	.	0	1.5	0
28	0	0	0	0	0	0
28	.	.	.	.	.	.
28	.	.	.	.	.	.
29	.	.	.	.	.	.
29	.	.	.	.	.	.
29	.	.	.	.	.	.
29	.	.	.	.	.	.
30	.	.	.	.	.	.
30	.	.	.	.	.	.
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APPENDIX C

C1. SAS Analysis Code

```
proc import datafile=fulldat
        out=FullDat
        dbms=csv
        replace;
   run;
* Clean up data;
proc format;
   value $ fsex "M" = "Male"
           "F" = "Female";
   value $ flr "L" = "Left Leg"
          "R" = "Right Leg";
   value $ fynl "Y" = "Yes"
           "N" = "No";
   value fynn 0 = "No"
          1 = "Yes";
   value foan 4 = "No OA"
                  5="tricompartmental"
                  6="medial compartment"
                  7="lateral compartment";
   value ford 0 = "None"
          1 = "Minimal"
          1.5 = "Some"
          2 = "Substantial"
          3 = "Extreme";
    run;
data FullDat;
   set FullDat;
   *MedialWgt50=MedialWgt*(MedialWgt>50)
   *give titles to variables;
   label Subject = "Subject"
       Age = "Age (yrs)"
       Sex = "Gender"
       Wgt = "Weight (lbs)"
       Hgt = "Height (in)"
       BMI = "Body Mass Index"
       KneeOp = "Operated Knee"
       HxKnee = "Indicator of Past Knee Replacement"
       HxSurg = "History of Lower Extremity Surgical Intervention"
       HxMedial = "Existing Medial Condition"
       Leg = "Side of Interest"
```

```
        Compartment = "Compartment"
        OAComp = "OA Diagnosed in Compartment"
        OverallOA = "Overall OA Diagnosis"
        FemoralChond = "Femoral Chond."
        TibialChond = "Tibial Chond."
        FemoralOsteophytes = "Femoral Osteophytes"
        TibialOsteophytes = "Tibial Osteophytes"
        Meniscus = "Condition of Meniscus"
        ACL = "ACL Condition"
        Alignment = "Alignment (degrees)"
        AlignDesc = "Alignment (description)"
        KneeScore = "Knee Score"
        FuncScore = "Function Score"
        Pain = "Pain Score"
        SwayArea = "Sway Area (sq-cm)"
        SwayPath = "Sway Path (cm)"
        MedialWgt = "Medial Weight Distribution (%)"
        LateralWgt = "Lateral Weight Distribution (%)"
        CoF = "Center of Force Movement";
   *change look of values;
   format Sex $fsex.
        KneeOp Leg $flr.
        HxKnee HxSurg HxMedial OAComp $fynl.
        OverallOA foan.
        FemoralChond TibialChond FemoralOsteophytes
        TibialOsteophytes Meniscus ACL ford.;
   run;
* Alignment Dataset;
*   This data is reduced to two records per patient, one for each leg. ;
* sort data;
proc sort data=FullDat
        out=FullDat;
   by Subject Leg;
   run;
data alignment;
   set FullDat;
   by Subject Leg;

   if first.leg;
   run;
Data alignment2;
         set alignment;
         if OAKnee="Y";
         run;
Data alignmentsurgonly;
         set alignment2;
```

```
        if HadSurg=1;
        run;
*****************************************************************************
**
* Alignment Analysis
*   Conduct an analysis to examine the relationship (unadjusted and adjusted)
*   between the weight distribution and the knee alignment. As alignment is
*   performed on both legs, we have repeated measures, and the correlation is
*   accounted for using generalized estimating equations (GEE).
*   We account for baseline variables as well as allow the effect to differ
*   depending on the knee and whether it was operated on.
* Unadjusted model;
proc genmod data=alignment2;
  class Subject;
   model Alignment = MedialWgt /
                 dist=normal link=identity lrci;
   repeated subject=Subject / corr=exch;
   title 'Alignment Model, Unadjusted';
   run;

* Adjusted model - interactions
  Results suggest interactions are not needed and can be removed. That is,
  the relationship between the weight distribution and alignment does not vary
  across the leg or depend on whether the knee is OA. ;
proc genmod data=alignment2;
   class Subject Sex KneeOp Leg HxSurg (ref="No" param=ref);
   model Alignment = MedialWgt Age Sex BMI KneeOp Leg HxSurg
                 MedialWgt*KneeOp MedialWgt*Leg /
                 dist=normal link=identity lrci;
   repeated subject=Subject / corr=exch;
   contrast "Interactions" MedialWgt*KneeOp 1 0 -1,
                      MedialWgt*KneeOp 1 -1 0,
                      MedialWgt*Leg 1 -1;
   contrast "Overall" MedialWgt 1,
                  MedialWgt*KneeOp 1 0 -1,
                  MedialWgt*KneeOp 1 -1 0,
                  MedialWgt*Leg 1 -1;
   title 'Alignment Model, Adjusted with Interactions';
   run;
* Adjusted model - no interactions;
*   Results suggest a nominal relationship between the weight distribution and
*   the alignment after accounting for other baseline characteristics. In
*   addition, there appears to be an effect of OA on the alignment if both
*   knees are OA. There is (as would be expected) a relationship between a
*   subject's BMI and alignment suggesting increasing BMI levels are related
*   to higher alignments.
```

```
*   Also, found that Leg is not significant, and I don't believe it to be a confounder in the general
population;
proc genmod data=alignment2;
   class Subject sex KneeOp HxSurg (ref="No" param=ref);
   model Alignment = MedialWgt KneeOp sex Age BMI HxSurg/
                 dist=normal link=identity lrci;
   repeated subject=Subject / corr=exch;
   title 'Alignment Model, Adjusted w/o Interactions';
   run;
************************
* Alignment model surgery knees only;
proc genmod data=alignmentsurgonly;
   class Subject sex KneeOp HxSurg (ref="No" param=ref);
   model Alignment = MedialWgt KneeOp sex Age BMI HxSurg/
                 dist=normal link=identity lrci;
   repeated subject=Subject / corr=exch;
   title 'Alignment Model surgery knees only, Adjusted w/o Interactions';
   run;
* Damage Analysis
*  Meniscus: Unadjusted model;
proc genmod data=FullDat descending rorder=internal;
   class Subject;
   model Meniscus = MedialWgt /
                dist=multinomial link=cumlogit;
   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   title 'Damage Analysis Model, Meniscus, Unadjusted';
  estimate "Medial" MedialWgt 1 / exp
   run;
* Meniscus: Adjusted model, without unneccessary interactions;
*Previous model showed that interaction of MedialWgt and HxSurg was not significant, so it
will be removed, as was Leg;
proc genmod data=FullDat descending rorder=internal;
   class Subject Sex (ref="Male" param=ref) OAComp (ref="No" param=ref)
Compartment(ref="lateral" param=ref) HxSurg (ref="No" param=ref);
   model Meniscus = MedialWgt Age BMI Sex compartment HxSurg OAComp
                                               MedialWgt*compartment/
                dist=multinomial link=cumlogit;
   output out=Meniscus predicted=meniscus_pred;
   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   estimate "Lateral Comp Effect" MedialWgt 1 / exp;
        estimate "Medial Comp Effect" MedialWgt 1 MedialWgt*Compartment 1 0 / exp;
   title 'Damage Analysis Model, Meniscus, no needed interactions, Adjusted';
* Femoral Chondromalacia: Unadjusted Model;
 proc genmod data=FullDat descending rorder=internal;
```

```
   class Subject;
   model FemoralChond = MedialWgt /
               dist=multinomial link=cumlogit;
  *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   title 'Damage Analysis Model, Femoral Chondromalacia, Unadjusted';
   estimate "Damage Effect" MedialWgt 1 / exp;
   run;
```

**** Feoral Chondromalacia, Adjusted model***

```
* Leg was significant so it was kept in;
proc genmod data=FullDat descending rorder=internal;
   class Subject Sex (ref="Male" param=ref) OAComp (ref="No" param=ref) Compartment
(ref="lateral" param=ref) HxSurg (ref="No" param=ref) Leg (ref="Right Leg" param=ref);
   model FemoralChond = MedialWgt Age BMI OAComp sex compartment HxSurg Leg
                                              MedialWgt*compartment/
               dist=multinomial link=cumlogit;
   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   estimate "Lateral Comp Effect" MedialWgt 1 / exp;
         estimate "Medial Comp Effect" MedialWgt 1 MedialWgt*Compartment 1 0 / exp;
   title 'Damage Analysis Model, Femoral Chondromalacia, Adjusted';
   run;
```

****Tibial Chondromalacia Unadjusted model;***

```
    proc genmod data=FullDat descending rorder=internal;
   class Subject;
   model TibialChond = MedialWgt /
               dist=multinomial link=cumlogit;
   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   title 'Damage Analysis Model, Tibial Chondromalacia, Unadjusted';
   estimate "Damage Effect" MedialWgt 1 / exp;
   run;
```

**** Tibial Chondromalacia, Adjusted model, "Leg" not significant, so taken out;***

```
proc genmod data=FullDat descending rorder=internal;
   class Subject Sex (ref="Male" param=ref) OAComp (ref="No" param=ref) Compartment
(ref="lateral" param=ref) HxSurg (ref="No" param=ref);
   model TibialChond = MedialWgt Age OAComp BMI sex compartment HxSurg
                                              MedialWgt*compartment/
               dist=multinomial link=cumlogit;
   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   estimate "Lateral Comp Effect" MedialWgt 1 / exp;
         estimate "Medial Comp Effect" MedialWgt 1 MedialWgt*Compartment 1 0 / exp;
   title 'Damage Analysis Model, Tibial Chondromalacia, Adjusted';
   run;
```

****Femoral Osteophytes, Unadjusted model;***

```
  proc genmod data=FullDat descending rorder=internal;
  class Subject;
  model FemoralOsteophytes = MedialWgt /
           dist=multinomial link=cumlogit;

  *only independent working correlation allowed for ordinal models;
  repeated subject=Subject / corr=ind;
  title 'Damage Analysis Model, Femoral Osteophytes, Unadjusted';
  estimate "Damage Effect" MedialWgt 1 / exp;
  run;
```

**** Femoral Osteophytes, Adjusted model;***

```
proc genmod data=FullDat descending rorder=internal;
  class Subject Sex (ref="Male" param=ref) OAComp (ref="No" param=ref) Compartment
(ref="lateral" param=ref) HxSurg (ref="No" param=ref) Leg (ref="Right Leg" param=ref);
  model FemoralOsteophytes = MedialWgt OAComp Age BMI sex compartment HxSurg Leg
                              MedialWgt*compartment/
           dist=multinomial link=cumlogit;
  *only independent working correlation allowed for ordinal models;
  repeated subject=Subject / corr=ind;
  estimate "Lateral Comp Effect" MedialWgt 1 / exp;
      estimate "Medial Comp Effect" MedialWgt 1 MedialWgt*Compartment 1 0 / exp;
  title 'Damage Analysis Model, Femoral Osteophytes, Adjusted';
  runn;
```

****Tibial Osteophytes, Unadjusted model;***

```
  proc genmod data=FullDat descending rorder=internal;
  class Subject;
  model TibialOsteophytes = MedialWgt /
           dist=multinomial link=cumlogit;
  *only independent working correlation allowed for ordinal models;
  repeated subject=Subject / corr=ind;
  title 'Damage Analysis Model, Tibial Osteophytes, Unadjusted';
  estimate "Damage Effect" MedialWgt 1 / exp;
  run;
```

**** Tibial Osteophytes, Adjusted model;***

```
proc genmod data=FullDat descending rorder=internal;
  class Subject Sex (ref="Male" param=ref) OAComp (ref="No" param=ref) Compartment
(ref="lateral" param=ref) HxSurg (ref="No" param=ref) Leg (ref="Right Leg" param=ref);
  model TibialOsteophytes = MedialWgt OAComp Age BMI sex compartment HxSurg Leg
                              MedialWgt*compartment/
           dist=multinomial link=cumlogit;

  *only independent working correlation allowed for ordinal models;
  repeated subject=Subject / corr=ind;
   estimate "Lateral Comp Effect" MedialWgt 1 / exp;
      estimate "Medial Comp Effect" MedialWgt 1 MedialWgt*Compartment 1 0 / exp;
  title 'Damage Analysis Model, Tibial Osteophytes, Adjusted';
```

```
   run;
*ACL, Unadjusted model;
   proc genmod data=FullDat descending rorder=internal;
   class Subject;
   model ACL = MedialWgt /
                dist=multinomial link=cumlogit;

   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
   title 'Damage Analysis Model, ACL, Unadjusted';
   estimate "Damage Effect" MedialWgt 1 / exp;
   run;
* ACL, Adjusted model;
proc genmod data=FullDat descending rorder=internal;
   class Subject Sex (ref="Male" param=ref) HxSurg (ref="No" param=ref) Leg;
   model ACL = MedialWgt Age BMI sex HxSurg Leg
                                           /
                dist=multinomial link=cumlogit;
   *only independent working correlation allowed for ordinal models;
   repeated subject=Subject / corr=ind;
     estimate "Damage Effect" MedialWgt 1 / exp;
   title 'Damage Analysis Model, ACL, Adjusted';
   run;
* Close ods connection;
*ods rtf close;
quit;
```