BIOMECHANICAL ANALYSIS OF THE EFFECTS OF A TOTAL KNEE REPLACEMENT ON A CANINE STIFLE

by

R. NICOLE HOWIE

(Under the Direction of TIMOTHY FOUTZ)

ABSTRACT

Several surgical procedures are used to repair CCL injuries successfully, but some animals have osteoarthritis that progresses despite surgery and these joints become painful and are dysfunctional. In this particular subset of cases, where all medical and surgical treatments have failed, TKR is used to restore the comfort and function of the stifle, but implant failure has been reported clinically. The studies herein used canine hemi-pelves hindlimbs collected from mixed breed dogs to test the three-dimensional kinematics of the stifle before and after TKR and soft tissue removal. This experimental procedure utilized an OKR apparatus that applied a dynamic force to each stifle, tested in 90 to 180 degrees of flexion, while preserving the natural coxofemoral and hock joints. The objective was to identify the specific positional changes of anatomical components within the stifle joint that could cause abnormal ranges of motion in canines leading to TKR implant failure.

INDEX WORDS: BIOMECHANICS, TOTAL KNEE REPLACEMENT, OXFORD KNEE RIG, CANINE STIFLE, CRANIAL CRUCATE LIGAMENT

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DEDICATION

I dedicate this work to my friends and family who have patiently listened to the sometimes gory details of my work and who have kept me laughing with running jokes about three legged dogs. I will always love you.

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I would like to express my deepest appreciation to my major professor and mentor, Dr. Tim Foutz, for his support and guidance. I have greatly enjoyed the humor and thought provoking questions of the past three years. I am thankful to my committee members, Dr. Sid Thompson for reviewing this manuscript, and Dr. Steve Budsberg for allowing me to observe the very interesting TKR procedure and for providing amusing commentary at the expense of Curtis.

I would also like to acknowledge Dr. Curtis Cathcart and Dr. Jeff Burmeister who were by my side through all of the extra long days filled with thousands of trials, malfunctioning computers, and super attractive goggles. I would not have survived the collection of my data without you. Finally, I would like to thank Amy Brooks for her help in collecting my data but most of all for showing an interest in my work. It was a pleasure to work with everyone mentioned. Thank you.

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CHAPTER 1

Introduction And Literature Review

1.1 Background And Importance

The 2010 dog ownership in the United States exceeded 72 million, with the majority of theses dogs being of mid to large size and the lifespan of domestic dogs continues to increase as veterinary medicine has improved. As a result, the bone and joint health of these older animals have deteriorated, causing lameness, the leading cause of which is a rupture of the Cranial Cruciate Ligament (CCL)[1]. In order to treat the most common orthopedic condition seen in dogs, a multitude of procedures have been created and implemented based on the severity of the rupture and the budget of the owner[2]. While all of these surgical procedures have had successes in treating ruptured CCL injuries, when severe osteoarthritis progresses to a stage where the joint becomes dysfunctional, Total Knee Replacement (TKR), a more intensive surgical procedure is needed to restore the function of the dogs' hindlimb. This procedure is often a last chance to restore the comfort and function of the stifle. Unfortunately, the TKR procedure has met with mediocre success. The exact cause of the failure is not well characterized which has lead to an inability to correct the design of the implant. It is the desire of this study to lay a foundation that will lead future researchers to the exact cause of the failure and ultimately a rectification of the implant that will save pet owners thousands and restore functionality to the dog.

1.2 Kinematics Of The Ccl-Deficient Stifle

It is well known that knee ligaments are the static stabilizers of the joint and that the CCL is the primary stabilizer for caudal translation and internal tibial rotation stability[3-5]. Research has determined that once the CCL has been transected there is an increase in internal tibial rotation and caudal femoral translation during normal flexion/extension angles that occur during a walking gait[1,5,6,8,9]. It was also determined that a cut or rupture of the CCL results in the normal adduction reversing to an abduction rotation[2,5] and a loss of the screw home movement[10]. The screw home motion is an external rotation followed by an internal rotation that occurs as the knee is flexed[6]. In contrast Fukubayashi[4] found that there was no significant difference in anterior/posterior displacement between knees with a cut cruciate ligament and normal knees. This difference could be explained through the experimental method that allowed the femur to rotate freely while in previous studies constraints had been placed on the femur limiting femoral rotation. While the most common injury is a CCL rupture, additional damage could have also occurred leading to a greater deviance from normal kinematics within the joint. Damage to the collateral ligaments causes a general laxity in the knee for internal/external rotation but the majority of the change is an increase in internal rotation[3]. Damage to the meniscus is also common and can lead to greater pain and deterioration within the joint.

1.3 Meniscus

There has been a strong correlation found between CCL rupture and damage of the medial meniscus[11-13]. One explanation to the question *why medial meniscus tears are commonly paired with reoccurring CCL tears*[12,14] is that the sharp rotation of the femur causes the medial femoral condyle into the posterior horn of the medial meniscus at an abnormal angle creating forces which cause lesions or tears on the medial meniscus[11]. Recognizing the relationship between the CCL and the medial meniscus is extremely important in determining where possible failures may occur in an artificial knee. Since the rupture of the CCL causes the caudal aspect of the medial epicondyle to shift into an unnatural position the prosthesis needs to be able to compensate for the increased instability and find a way to constrain the abnormal motion.

Over 40 years ago, Frankel et al.[15] found that as the femur rotated it had localized pressure points on which all of the pressures are focused onto the tibial plateau. If the primary stabilizers are damaged then the femoral epicondyles and tibial plateaus are brought together on abnormal pressure points, producing localized high pressures under these new locations. The location that is now supporting the increased localized pressure is often not suited for that function and damage to the meniscus or implant is common. As described by Frankel[15], the new location of the localized point of pressure could cause a different path for load transference to be created. As a damaged knee transmits 2.5 times the stress as a normal knee[7], the abnormal paths of stress exacerbate the damage within the knee by causing the implant to shield the surrounding bone ultimately leading to the body removing the unused bone, weakening the structure.

1.4 Current Solutions

There are a number of surgical procedures that are used to repair CCL damage, each with specific strengths and weaknesses that make determining the best course of action for a CCL rupture dependent on factors unique to each clinical case. Extra Capsular

Imbrication (ECI) is a method used for minor tears that uses a figure eight suture design that attaches the tibia to the femur. It has been found that ECI decreases the total flexion and increases external rotation and abduction of the normal range of motion[2]. Other procedures to repair a CCL tear include tibial tuberosity advancement (TTA) and tibial plateau leveling osteotomy (TPLO). TTA shifts the tibia tuberosity within a canine knee forward a predetermined distance to remove any shear force that occurs in the stifle joint of the dog while reducing the likelihood that the CCL will have to carry a load. TPLO shaves the tibia until it is parallel to the ground, so that the femur rests on the flat surface, decreasing the load the CCL has to produce in order to stabilize the joint, but it was found to also increase caudal translation[2,5].

1.5 Total Knee Replacement

While many procedures are used to repair CCL injuries successfully, there are animals in which, despite surgery, the osteoarthritis progresses and these joints become painful and dysfunctional. In this particular subset of cases, where all medical and surgical treatments have failed, Total Knee Replacement (TKR) is indicated to restore the comfort and function of the stifle. TKR for canines, first performed in 2007[17], is very similar to human knee replacements. The implant consists of two components, a colbolt chrome element that attaches to the femur and a UHMWPE component which is inserted into the leveled tibia. Despite some successes with the TKR procedure, even small variations associated with component placement and orientation during the procedure has been found to adversely impact *in vivo* joint mechanics in humans[18], usually by preventing the natural femoral rollback motion[19].

To better characterize the joint kinematic changes that alter joint function due to physiological conditions and treatment options such as TKR, three-dimensional analysis is commonly utilized. Kinematic motion of a human knee after a TKR is well documented[20-23], however, fewer studies for canines have been conducted. While implant failures have been reported in canines, the exact causes behind the failures remain well contained, although it has been documented that changes in joint kinematics greatly influence the long-term performance of TKR because of the relative motions contributing to wear and fatigue damage within the implant[18] and a reduction in the post-operative flexion/extension range of motion[24]. These changes alter loading within the joint and contribute to a negative mechanical environment of the stifle prosthesis, leading to the progression of disease and ultimately failure[25]. Therefore it is important to accurately characterize the kinematic motions that occur in the stifle after the implantation of TKR prosthesis in order to optimize the current implant designs and prevent further failures.

1.6 Oxford Knee Rig

The three-dimensional kinematic characterization of the canine stifle under different physiological loading mechanisms is important for both the clinical and research model arenas[1]. Experimental testing with knee simulators is often used to quantitatively evaluate the performance of specific treatments on the kinematics of the joint[26]. The most commonly used simulator for kinematic testing is the Oxford Knee Rig (OKR) which has controlled loading and allows for six-degrees-of-freedom articulation of the stifle joint during a deep flexion stance[27]. The six-degrees-of-freedom are characterized in clinical terms as three rotations (flexion/extension, abduction/adduction, internal/external tibial rotation) and three translations (cranial/caudal, medial/lateral, and proximal/distal)[28]. *In vitro* (cadaveric) models have been utilized during a variety of kinematic studies using the OKR because of the apparatuses unique ability to simulate physiological circumstances and preserve the natural motions of the stifle joint without the activation of muscle forces.

Many OKR studies use a simplified model where a significant number of the muscles around the cadaver joint are removed. Using this type of simplified model, Chailleux et al.[2] investigated two surgical techniques for the repair of a CCL deficient stifle and compared the results to a clinical setting. In this particular *in vitro* canine stifle kinematic study, the quadriceps were left intact and were pulled by the mechanism, allowing flexion and rotation of the stifle to occur. In a study to analyze techniques to correct CCL-deficient stifles, Hagemeister et al.[29] analyzed the kinematics of cadaver legs with intact stifles by allowing the OKR mechanism to displace the femur and tibia without use of muscle tension. Bergfeld et al.[8] and Gei et al.[30] used similar techniques to study the kinematics of human cadaver knees after surgery or implants. In many of these studies that use the OKR to drive the motion of the cadaveric specimen, only the quadriceps are retained. This can cause a distortion in the joints natural kinematics, because the removal of the other muscle groups result in a loss of the muscle tensions and constraints placed across the joint. It has been suggested that the inclusion of more physiologic constraints can have important implications with regards to the ability of OKR type setups to simulate physiologic knee motion[9]. From this perspective, it is important to determine which muscles can be removed for simplicity of such models and if the coxofemoral and hock joints of a hindlimb need to be preserved in order to maintain the natural stifle kinematics.

1.7 Purpose Of Study

The primary objective of this study was to characterize the six degrees-of-freedom kinematic motion of a cadaveric canine stifle when utilizing an OKR before and after TKR implantation in a CCL deficient stifle, with the goal of identifying the specific positional changes of anatomical components within the stifle joint that could cause abnormal motion in canines.

Two other objectives were to provide insight into differences that could occur if other soft tissues are left intact or removed, leading to the use of a simplified model for stifle kinematic analysis. First, a study was performed to determine if a hindlimb stripped of most of its soft tissue could serve as an accurate and simplified model for testing procedures. A second study was performed to characterize the effects of a CCL-deficient stifle on the TKR function as well as how the removal of the hindlimb's soft tissues effect the kinematics of the TKR motion. These two objectives will shed insight into the use of a simplified model for stifle kinematic analysis and what soft tissues must be preserved to obtain an accurate but simplified model.

A final objective was to determine if the preservation of natural joint rotation, as provided by the OKR design, influences the three-dimensional kinematics of the stifle. An analysis of the kinematics found within the joint was chosen because of the unique ability of engineering principles to find relationships between positional changes and resulting injuries or failure.

Understanding how the stifle kinematics change given a manipulation of the limbs anatomical constraints, including joint fixation and muscle and ligament removal, will provide important information on how TKR alters the mechanical properties of the stifle joint postoperatively, which can then be corrected. This would provide an important basis for optimization of the current TKR prosthesis design, leading to a decrease in failures and better quality of life for the thousands of canines that will require this procedure in the future.

1.8 Preview

The following two chapters present the experimental procedure implemented to test the objectives of this thesis, and the results of those tests. The first paper gives an overview of the preliminary data collected to determine the best OKR setup for our testing protocol and the kinematic significance of the CCL and major muscle groups on the stifle joint. The information gleaned from the preliminary data provided OKR constraint requirements that would preserve the most physiologically normal kinematics for the stifle, as well as, giving a foundation for the kinematic motions that can be expected for a stifle given the use of the OKR and the removal of certain anatomical structures. Once the contributions of the CCL and muscle groups to the motions of the joint were characterized then further experimentation was conducted to determine the adverse affects of the TKR on the tibiofemoral joint. The second paper used the same OKR procedure to test the response of the stifle given CCL transection, a TKR surgical procedure, and muscle removal. The different stifle kinematic motions given each of the experimental treatments were characterized and compared to the normal to determine what changes occurred and where potential abnormalities could result in failure.

CHAPTER 2

In Vitro Three-Dimensional Kinematic Characterizations Of The Canine Stifle Following Cranial Cruciate Ligament Transection And Sequential Muscle Removal.[1]

[1] Howie, RN, TL Foutz, JS Burmeister, C Cathcart, and SC Budsberg. To be submitted to American Journal of Veterinary Research

2.1 Abstract

Objective – To describe the three-dimensional kinematic characterization of the intact cadaveric canine stifle joint following cranial cruciate ligament (CCL) rupture as well as the sequential removal of three major hindlimb muscle groups.

Sample – Four hemi-pelves collected from mixed breed dogs (1 intact female, 1 spayed female, and 2 intact males with weights of 20.0 kg, 24.9 kg, 25.4 kg, and 25.9 respectively)

Procedures –The stifles were tested in 90 to 180 degrees of flexion using a modified Oxford Knee Rig. This apparatus applied a dynamic force to each stifle while preserving the natural hip and hocks and the resulting kinematic changes at the stifle were measured. The motions at the stifle for the physiologically natural, ruptured CCL, and removed muscle groups were collected, as well as, a constrained and unconstrained coxofemoral joint and center of gravity. The changes in internal/external and abduction/adduction rotations, cranial/caudal, proximal/distal and lateral/medial translations were collected and characterized.

Results – The fixation of the coxofemoral joint greatly restricted the natural motion of the stifle while the fixation of the center of gravity of the hindlimb had no effect. A variety of kinematic changes of the stifle were found given the removal of the muscle groups and the CCL, the most significant of which being the removal of the gastrocnemius muscle group.

Conclusions and Clinical Relevance – The retention of the gastrocnemius muscle group is required if any semblance of the natural kinematics of the stifle is to be preserved, while the removal of the other soft tissues can be utilized to simplify the model.

2.2 Introduction

The three-dimensional kinematic characterization of the canine stifle under different physiological loading mechanisms is important for both the clinical and research model arenas[1]. Oftentimes these types of studies use an *in vitro* procedure where a cadaver leg is placed in an apparatus known as the Oxford Knee Rig (OKR), which is capable of placing the stifle joint through a series of simulated flexed-knee (flexed-stifle) motions[2-4]. The OKR simulates physiological circumstances and preserves the natural six degrees-of-freedom of movement of the knee. In clinical terms these motions are characterized as three rotations (flexion/extension, abduction/adduction, internal/external tibial rotation) and three translations (cranial/caudal, medial/lateral, and proximal/distal)[5].

Many OKR (or similar mechanisms) studies use a simplified model where a significant number of the muscles around the cadaver joint are removed. Using this type of simplified model, Chailleux[6] investigated two surgical techniques for the repair of a CCL deficient stifle and compared the results to a clinical setting. In this particular *in vitro* canine stifle kinematic study, the quadriceps were left intact and were pulled by the mechanism, allowing flexion and rotation of the stifle to occur. Having only the quadriceps retained can cause a distortion in the joints natural kinematics, because the removal of the other muscle groups result in a loss of the muscle tensions and constraints placed across the joint. It has been suggested that the inclusion of more physiologic constraints may have important implications with regards to the ability of OKR type setups to simulate physiologic knee motion [4].

The objective of the study presented here was to characterize the six degrees-of-freedom kinematic motion of a cadaveric canine stifle when utilizing an OKR, as well as, determine the affects a transected CCL and the sequential removal of major muscle groups have on the three-dimensional kinematics of the dog stifle. The removal of the CCL is known to affect the motion of the stifle but this study also tested its affect after the removal of all muscle groups to determine if differences are apparent in comparison to a rupture with all other soft tissues intact. Finally, the affect of coxofemoral joint fixation was studied with the purpose of discovering if the preservation of the natural joint rotation influences the three-dimensional kinematics of the stifle.

2.3 Methods And Materials

2.3.1 Simulated Stance

An OKR was used to simulate the motion of intact cadaver stifles during stance and placed each stifle specimen through a range of motion by displacing the femur and tibia of the specimen[7]. A hemi-pelvis specimen (described below) was attached to the OKR using angle iron and was allowed to slide along each of the three axes (vertically, lateral/medial, and craniocaudal) as the flexed-stifle motion was simulated. The hock was preserved by implementing the use of a dog boot, which secured the foot to a stationary platform while still allowing any natural rotations and translations of the joint to occur (Figure 2.1). This scheme of connecting the leg to the OKR does not require the cutting of muscles or ligaments, allowing the stifle joint to rotate and translate in a normal manner.

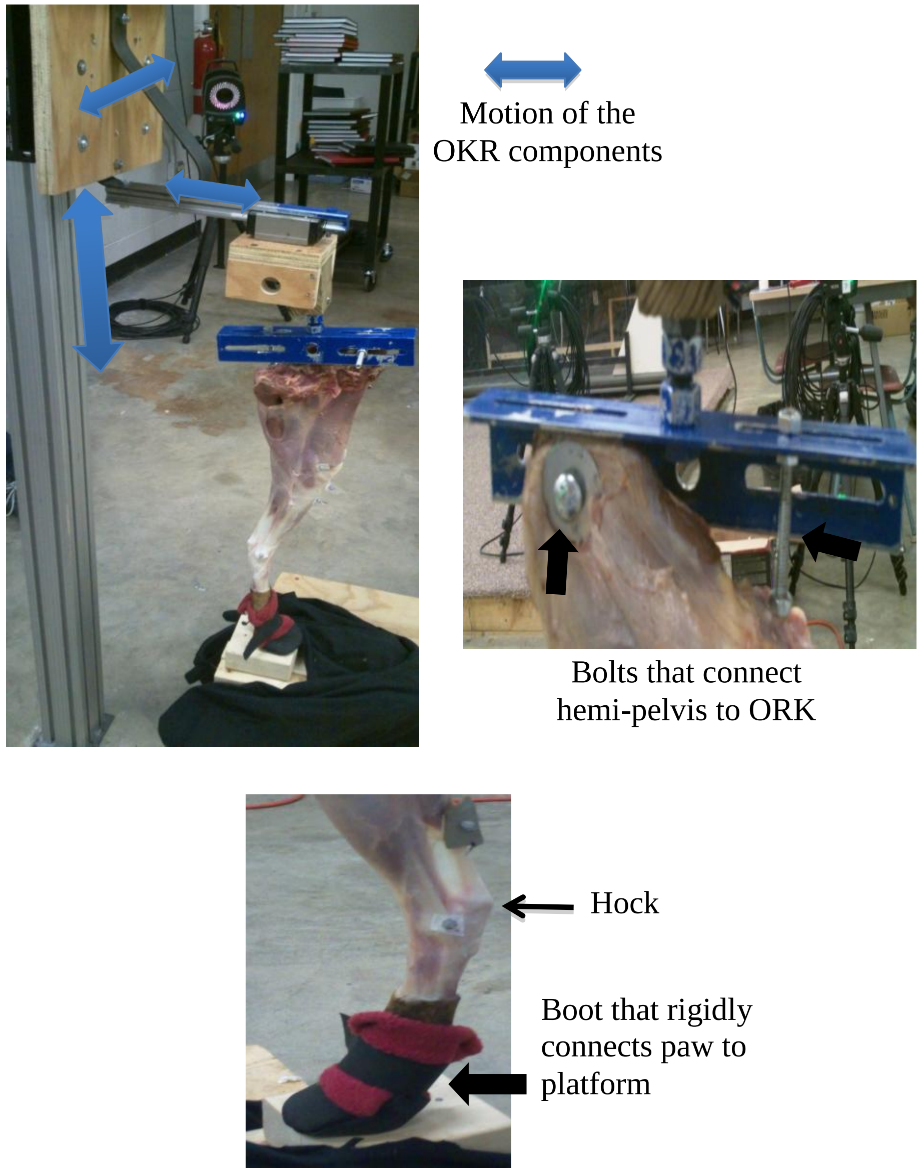

Figure 2.1: Pictures of the modified Oxford Knee Rig that characterize its motion, how the vertical bolt running through the ischial tuberosity and a horizontal bolt through the sacroiliac joint of the ilium were used to attach the hemi-pelvis to the OKR while preserving the coxofemoral joint, and the dog boot that preserved the hock.

2.3.2 Cadaver collection and preparation

Four hemi-pelves were collected from four mixed breed dogs (1 intact female, 1 spayed female, and 2 intact males with weights of 20.0 kg, 24.9 kg, 25.4 kg, and 25.9, respectively) which were euthanized for reasons unrelated to this study. The specimens were stored in a freezer at 20º C until just prior to testing to preserve the sample. One day prior to testing, a hemi-pelvis was removed from the freezer and allowed to thaw at room temperature. On the day of testing, the skin was carefully removed from the hindlimb as to not damage any underlying tissues. A custom made apparatus consisting primarily of angle iron was bolted to the pelvis with a vertical bolt running through the ischial tuberosity and a horizontal bolt running through the sacroiliac joint of the ilium. This allowed the pelvis to be attached to the OKR. Positional nuts were secured so that the angle iron was horizontal when pelvis was in a simulated natural standing position. The hemi-pelvis was also aligned so that the bolt used to attach the hemi-pelvis to the OKR was directly above the coxofemoral joint.

2.3.3 Kinematic markers

Reflective markers were used to define the stifle motion during testing. A series of 10 markers were used to define both the femoral and tibial segments of the hind leg. The markers were placed at muscle surface level on 1.6 mm Kirschner wires that were drilled into the bone at specific anatomical bony locations, except for two markers that were sutured to soft tissue locations[8]. Prior to testing the coxofemoral, stifle, and hock joints were put through a full range of motion to ensure normal movement with no impingements from the wires as well as no palpable orthopedic abnormalities.

The angular and translational motion of the stifle joint during the simulated stance was determined using techniques described by Fu[8]. The reflective markers were used to create two separate coordinate systems on the hindlimb; one on the tibia and the second on the femur. Using a Vicon Motus system that employed six 200 Hz infrared cameras arranged around the OKR's platform, the angular and translational motion of the stifle joint was determined by capturing the movement of the reflective markers and calculating the motions of the axes relative to each other. Changes in the 6 degrees of freedom (flexion/extension, abduction/adduction, internal/external rotations, distal/proximal, cranial/caudal, and medial/lateral translations) were calculated as described previously[8].

2.3.4 Experimental procedure

To test the affect of different constraints on stifle kinematics a series of modifications to the hindlimb were applied and then the changes in motion that occurred were captured (Table 2.1). The modifications chosen to test were:

- A constrained and unconstrained hip, which would allow either full or no motion at the coxofemoral joint
- A locked and free plate, which would allow the center of gravity of the hindlimb to either remain stationary or to shift as the leg was extended
- CCL removal
- Finally the removal of three major muscle groups (flexors, extensors, and gastrocnemius)

To determine the affect of hip and plate fixation, an experimental procedure was applied that would fix or open the hip and plate in every combination possible to determine if any changes occurred. The hip and plate changes were implemented after each modification of the hindlimb, such as CCL or a muscle group removal.

Table 2.1: Procedural outline for the CCL deficient stifle data collection. Free plate indicates that the plate on the Oxford Knee Rig was not clamped. Unconstrained hip indicates that the coxofemoral joint of the canine was not pined. Data collection for the second sequence follows the same procedure with the CCL transection becoming the last treatment.

Treatment	Number or Trials	Hip	Plate
Natural	5	Unconstrained	Free
Natural	5	Unconstrained	Locked
Natural	5	Constrained	Free
Natural	5	Constrained	Locked
CCL Transection	5	Constrained	Free
CCL Transection	5	Constrained	Locked
CCL Transection	5	Unconstrained	Free
CCL Transection	5	Unconstrained	Locked
Flexor Dissection	5	Unconstrained	Free
Flexor Dissection	5	Unconstrained	Locked
Flexor Dissection	5	Constrained	Free
Flexor Dissection	5	Constrained	Locked
Extender Dissection	5	Constrained	Free
Extender Dissection	5	Constrained	Locked
Extender Dissection	5	Unconstrained	Free
Extender Dissection	5	Unconstrained	Locked
Gastrocnemius Dissection	5	Unconstrained	Free
Gastrocnemius Dissection	5	Unconstrained	Locked
Gastrocnemius Dissection	5	Constrained	Free
Gastrocnemius Dissection	5	Constrained	Locked
	Total Trials = 100/leg		

The effects of the coxofemoral joint on the kinematics of the stifle motion during this simulated stance was examined by fixing the coxofemoral joint. Fixation was achieved by transarticular placement of two 1.58 mm Kirschner wires, through the joint. To change the setup between hip fixation and a free moving hip, the first pin that was positioned through the femoral head and across the acetabulum, was retracted from the pelvis and then advanced again as necessary, while the second pin coursing from ischium to the femur was retracted from, and advanced into the femur as necessary to ensure that the coxofemoral joint was fixed and no rotational motion occurred.

The OKR design employs a sliding plate that simulates a shifting of the center of gravity of the hindlimb. Because the hindlimb is in motion the natural constraints of the muscles and the ligaments cause specific motions which could cause the center of gravity of the hindlimb to shift affecting the position of the plate along a horizontal bar. With the plate locked in place, the shifting of the center of gravity of the leg is blocked, which in turn affects the stifle kinematics. The influence of this plate on the OKR simulation was studied by first constraining the plate's motion during the simulated stance and then removing the constraint and repeating the simulated stance.

2.3.5 Ligament dissection for kinematic trial

The affect of the CCL transection was tested by transecting it either as the first alteration or after all the muscular dissections occurred. To transect the cranial cruciate ligament a 1.5 cm incision was made in the joint capsule just lateral of the patellar tendon through which a scalpel was used to sharply incise the ligament at its insertion on the tibia. A positive drawer test was used to confirm complete transection of the cranial cruciate ligament.

2.3.6 Muscle group dissection for kinematic trials

To determine the effects of the intact muscles, a set of muscle dissections were made to isolate muscle groups and then determine the effects the muscle groups had on the cadaver three-dimensional kinematics. Preliminary data indicated that once the gastrocnemius muscles were severed the motion at the stifle changed so drastically that the affect of the extensor muscles could not be characterized. Therefore the sequence of muscle cuts of flexors, extensors, and finally the gastrocnemius removal sequence was implemented.

The first dissection consisted of removal of muscles from the caudomedial aspect of the thigh that primarily functioned as stifle flexors or hip extension and adduction. The muscles removed were the semitendinosus, semimembranosus, gracilis, adductor, and pectineus, and for the purpose of simplicity will be called flexors for the remainder of the paper. They were removed by sharp dissection of their origins at the ischium and pubic symphysis, with blunt digital dissection removing them from adjoining muscles. The adductor was sharply dissected from its caudal femoral attachments, and the entire group of muscles was freed by incising along the aponeurosis near their insertion at the tibia.

The second dissection consisted of removal of the muscles from the craniolateral aspect of the thigh that primarily functioned as stifle extensors. Minor secondary function included hip extension (Biceps femoris) and hip flexion (Sartorius). The muscles removed were the Sartorius, Biceps femoris and Quadriceps femoris, consisting of the Rectus femoris, Vastus lateralis, Vastus intermedius, and Vastus medialis. For simplicity this group with subsequently be referred to as extensors. The muscles were removed by sharp dissection of their origins at the proximal femur and ilium. The muscles were freed from the femur with sharp dissection, and their distal attachments freed by incising the Biceps aponeurosis as well as transecting the common quadriceps tendon proximal to its transition into the patellar tendon.

The third dissection consisted of removal of the caudal muscles of the crus, which primarily function as flexors of the stifle as well as extensors or for fixation of the tarsus. The muscles removed included the medial and lateral heads of the gastrocnemius and the superficial digital flexor. The muscles were removed by transecting the common calcanean tendon at its insertion on the calcaneus; then lifted and sharply dissected at the origins of these muscles at the caudal aspect of the femoral condyles. Again care was taken to leave the stifle joint capsule intact. In addition to removal of these muscles, the long digital extensor, being the last remaining muscle spanning the stifle, was transected just distal of the tibial plateau.

2.3.7 Kinematic Characterizations

The kinematic affect of each treatment was determined by placing the loaded hindlimb through a range of motion, in stance, that began at 90° and was extended to a full extension (approximately 180°). A baseline measurement was collected at the initial 90° of flexion and then changes for each of the two rotations and three translations from the initial baseline where collected. Data was collected only when changes from the baseline occurred. As the change in rotational degree or translational displacement began the exact degree of extension was also recorded giving the degree within the extension stance that the changes began to occur and the extension degree where the changes in each motion stopped. As anatomical structures were removed it was expected that the degree of extension where changes occur would deviate due to the removal of the natural constraints of the stifle.

All translational (cranial/caudal, proximal/distal, and lateral/medial) changes began at 0 because the changes recorded were as the femoral epicondyle moved in relationship to a mathematically fixed tibial crest. Therefore at the collection of the baseline, the femoral epicondyle location in relationship to the tibial crest was initialized. The rotational (interior/exterior and abduction/adduction) changes were slightly different in that the femoral axis system was compared to that of the tibial axis system, both of which where aligned along the central axis of their respective bone. This allowed a non-zero starting degree if at the 90° baseline the femoral axis was not aligned with the tibial axis system.

2.4 Results

The resulting natural kinematic motion of the canine stifle using an OKR setup was characterized in this study, the resulting motions are illistrated in Figure 2.2. This study found the natural cadaver stifle as having a 25 ± 10 mm, 18 ± 5 mm, and 8 ± 3mm displacement of the lateral femoral epicondyle from the tibial crest for caudal, proximal, and medial translations (Figure 2.2) respectively as the hindlimb extends from 90° flexion to full extension of 180°. It should be noted that the proximal translation was caused by the vertical motion of the OKR as the mechanism was used to pull the hindlimb to full extension, while in a clinical setting the leg will most likely move distally due to the weight of the animal loading the joint. The degree of the change in the rotations found at the stifle during the same extension duration were 25°± 1° and 10°± 1°

degrees of internal and adduction rotation respectively (Figure 2.2). All kinematic changes that occurred due to the experimental procedure were compared to the natural kinematic results as described above.

It was determined that fixation of the hip caused a decrease in both the translations and rotation (Figures 2.3 through 2.7) that occur during the extension of the hindlimb. The caudal translation was also shortened by an average of 10 mm (Figure 2.3), while the internal and abduction rotation angles (Figures 2.6 and 2.7) were generally restricted by an average of 11°±4° and 7°±3° degrees, respectively. There were no observed changes in proximal translations (Figure 2.4) and medial translations (Figure 2.5) between the constrained and unconstrained hip. The results also indicated no changes were observed in any of the rotations or translation measure for trials where the plate was locked as compared to the free plate trials. These results indicate that fixation of the coxofemoral joint limits the kinematic motion at the stifle and that there is no significant shifting of the center of gravity of the hindlimb, as proven through the comparison between the open and locked plate trials. The unconstrained hip and free plate trials were used to determine the affects of muscle and CCL removal on the cadaveric stifle.

During these tests two sequences of cuts took place, one that applied the removal of the CCL before any muscle removal (Figures 2.3-2.7); the second that applied the CCL removal after all the muscles were transected (Figures 2.8-2.12). For the CCL deficient stifle motion, the initial starting points of all translations and rotations were shifted further into the extension angles using this experimental sequence, the changes due to the sequence of dissections varied drastically except for the shifting of the initial starting point. One leg showed a pronounced reduction in the duration of all rotations and the medial translation. The other leg retained the angles and lengths traveled but did show the shifting trend (Figure 2.3-2.7). When studying the affect of the CCL on the kinematic characterization of the stifle, it was found that the removal of the CCL before any other treatment did cause deviations from the norm in internal rotation by reducing the extent of the rotation by 15º ± 2º (Figure 2.6), but otherwise it generally did not affect the stifle motion. The removal of the CCL after the removal of the gastrocnemius muscle caused no substantial difference except for a consistent shifting of the initial extender position further into the extension of the hindlimb (Figures 2.8-2.12).

The most common result that occurred in the CCL intact stifle motion was a shifting of the initial starting points of the rotations and translations after the gastrocnemius was severed. The most significant rotational variance was a more positive shift in the initial internal rotation angle, 17°±5° (Figure 2.12). There was little variance of the natural adduction rotation as the anatomical structures were removed. For all three translations, the initial starting points of the degree of flexion angles tended to shift toward the right side of the axis, which is further into the extension of the hindlimb, after the gastrocnemius muscle was removed. The shifts along the axis were 10°±5°, 5°±5°, 15°±2° degrees for the caudal, proximal, and medial translations respectively (Figures 2.8- 2.10). The most significant was the reversal of medial to lateral translation after the gastrocnemius transection. The most significant observation from both experimental procedures was that large deviations from the natural kinematics of the stifle joint for every angle and translation occurred after the removal of the gastrocnemius muscle group.

2.5 Discussion

The three-dimensional kinematic characterization of the canine stifle under the influence of different muscle connections is an extremely useful tool in modeling the reactions of stifle. Simplified models are generally used but it is important to know which muscle groups can be removed without causing a significant deviation from natural kinematics and which structures need to be preserved to have a simplified but realistic model. The unique technique and instrumentation used in this study yielded the most natural reactions of the stifle given the preformed alterations. Based on the results found during this experiment, it was determined that fixing the coxofemoral joint of the limb limits the natural rotations and translations of the stifle and prohibits the natural motion. For the most natural results, even in a simplified model, it is best if the hip is left open so that the natural constraints caused by the hip and hocks can be felt by the stifle. It was determined that there was no significant shifting in the center of gravity of the hindlimb as the leg was fully extended; therefore clamping the plate had no effect on the resulting kinematic data.

Based on the results, it was determined that the flexor muscles can be removed with little to no affect on the kinematics of the stifle. The removal of extensor muscles had a greater affect on the kinematics of the stifle especially when measuring the abduction rotation and the medial translation. It was also found in both normal and CCL deficient stifles that the removal of the gastrocnemius muscle was extremely detrimental to the natural kinematics of the joint. The lack of major influence of the CCL on the stifle could be indicative of the fact that ligaments are static stabilizers while muscles are the dynamic stabilizers of the stifle, and this experiment tested dynamic motion[9-11].

It should be noted that within each of the four specimens, the gastrocnemius muscle created the largest deviance from the previous cut indicating that the gastrocnemius is extremely important for preserving the natural kinematics of a stifle. Based on these results the extensors were determined to be the second most important structure to preserve when the maintenance of natural kinematics is paramount. It should be noted that this study only contained four subjects and that differences were also found between the legs tested under each procedure. With this number of specimen, changes from the norm were found with the removal of each muscle group, but with the limited number of specimens tested it is impossible to accurately predict what changes will occur. A larger test population is needed in order to describe any overall trends that might occur given this experimental procedure.

In order to have a simplified model that still accurately mimics the natural motion of a stifle, it is recommended that only the CCL and flexors be removed. If only slight variation from the norm can be tolerated then the extensor muscles can be removed. In conclusion, in accurately modeling the canine stifle the gastrocnemius muscles cannot be removed from a cadaveric specimen if any comparison to an anatomical normal stifle is to be made.

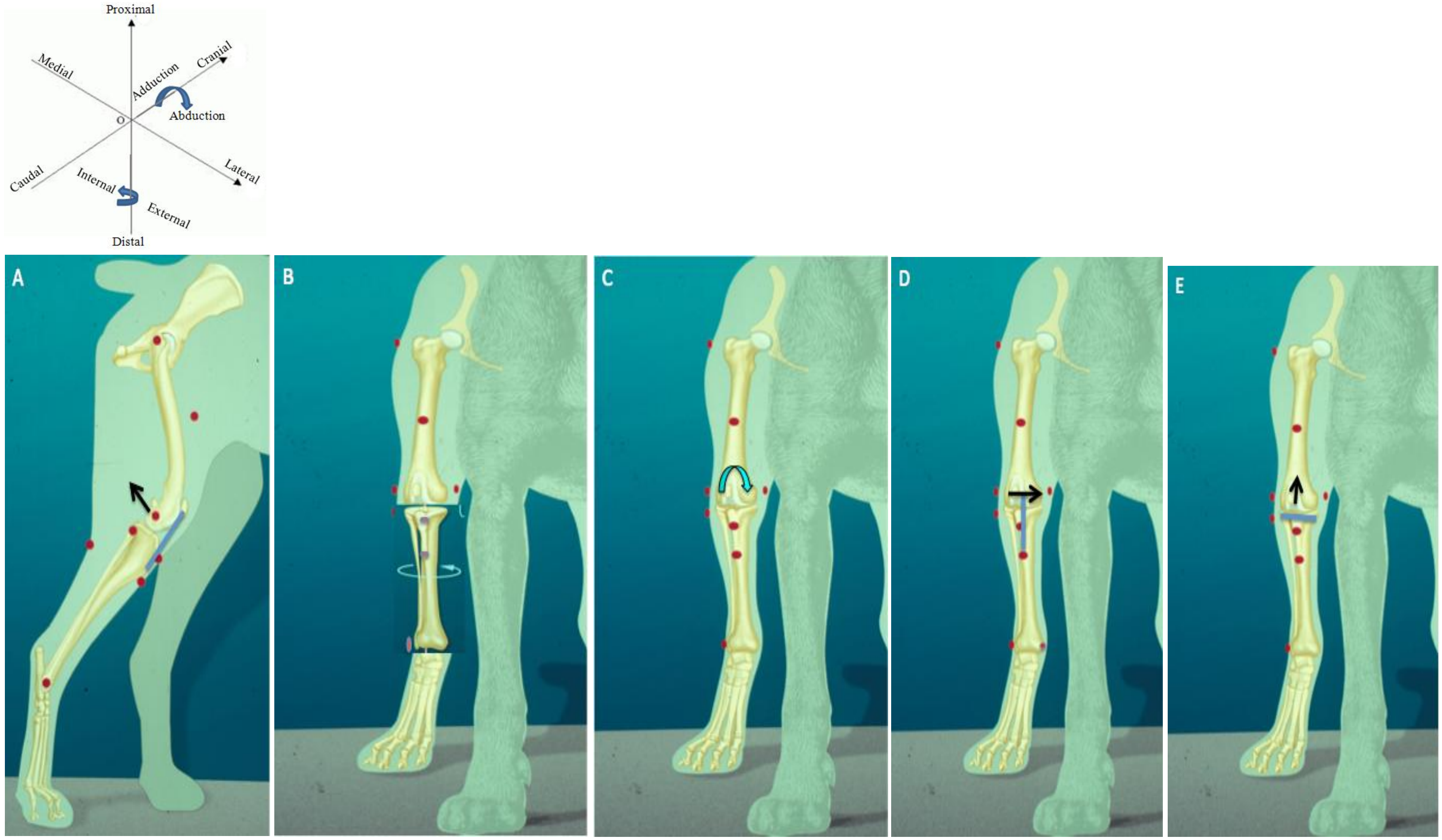

Figure 2.2: Characteristic motion of a normal stifle as it extends from 90° flexion to a full extension of 180°. Black arrows indicate translational direction of travel from an initial position in relation to the tibial crest as indicated by the blue line, while green arrows indicate rotational direction of the femoral and tibial axis system in relation to each other. A) The femoral epicondyle travels 25 ± 10 mm caudally B) the femoral and tibial axis systems rotate 25°± 1° internally C) the femoral and tibial axis systems rotate 10°± 1° in adduction D) the femoral epicondyle travels 8 ± 3 mm medially and finally, E) the femoral epicondyle travels 18 ± 5 mm in the proximal direction.

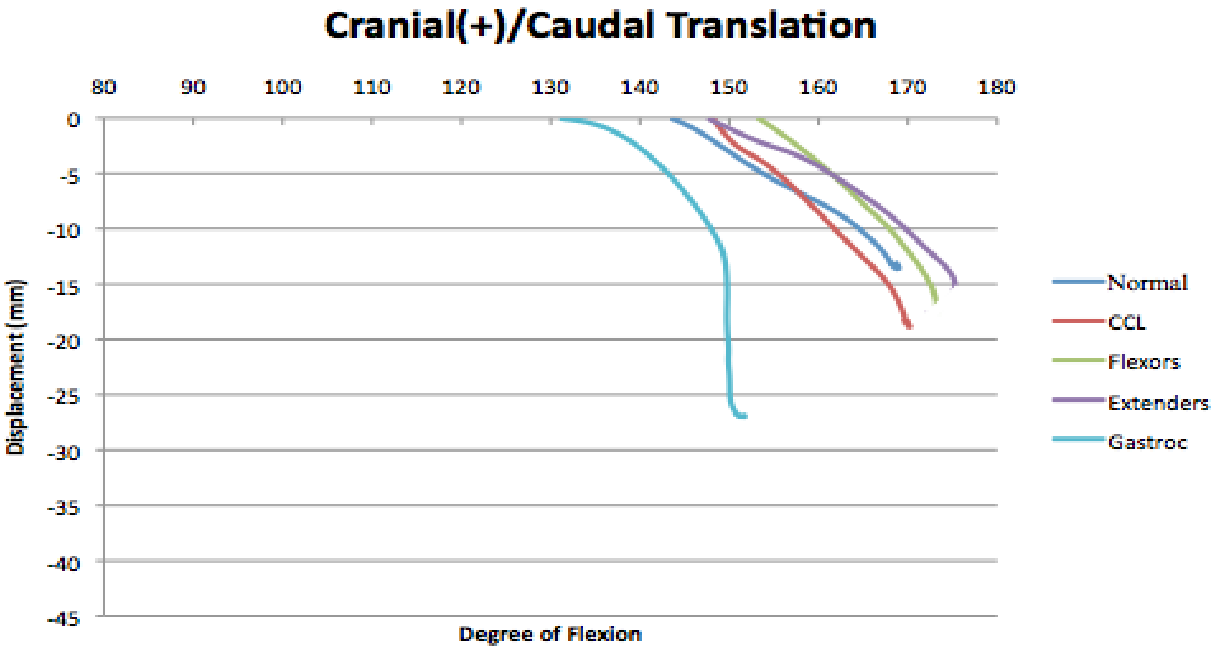

Figure 2.3: The change in caudal displacement of the lateral femoral epicondyle from the tibial crest as the hindlimb extends from 90° flexion to full extension (180°) for each of the sequential treatments given in the procedural order of Normal, then the removal of the CCL, Flexors, Extenders, and Gastrocnemius.

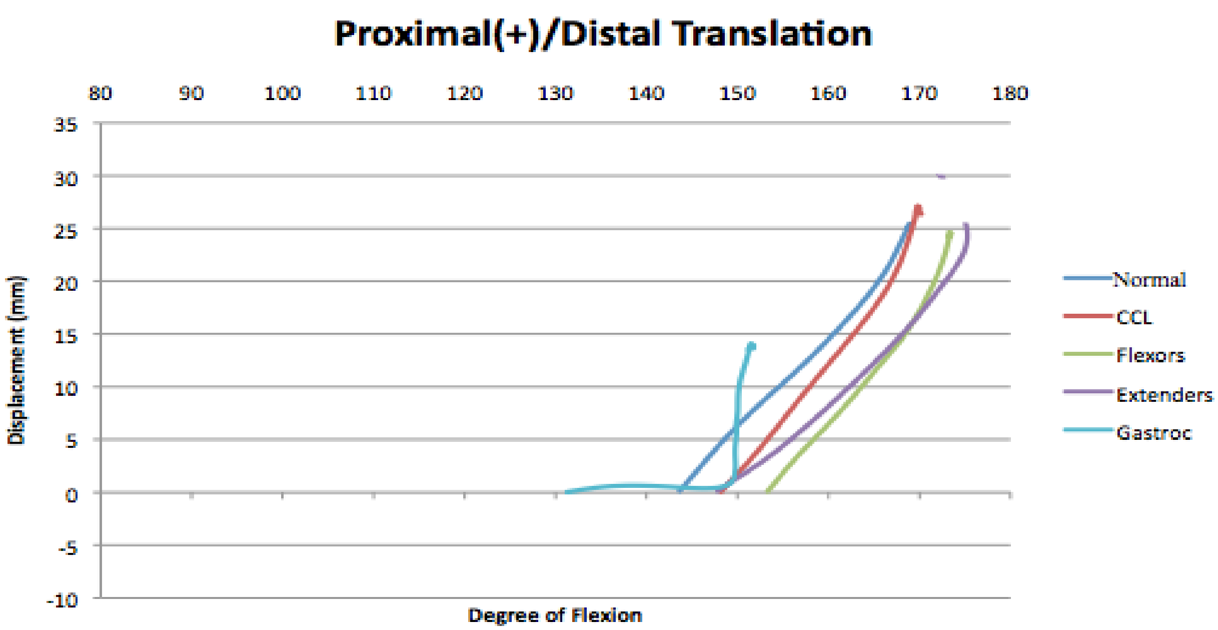

Figure 2.4: The change in proximal displacement of the lateral femoral epicondyle from the tibial crest as the hindlimb extends from 90° flexion to full extension (180°) for each of the sequential treatments given in the procedural order of Normal, then the removal of the CCL, Flexors, Extenders, and Gastrocnemius.

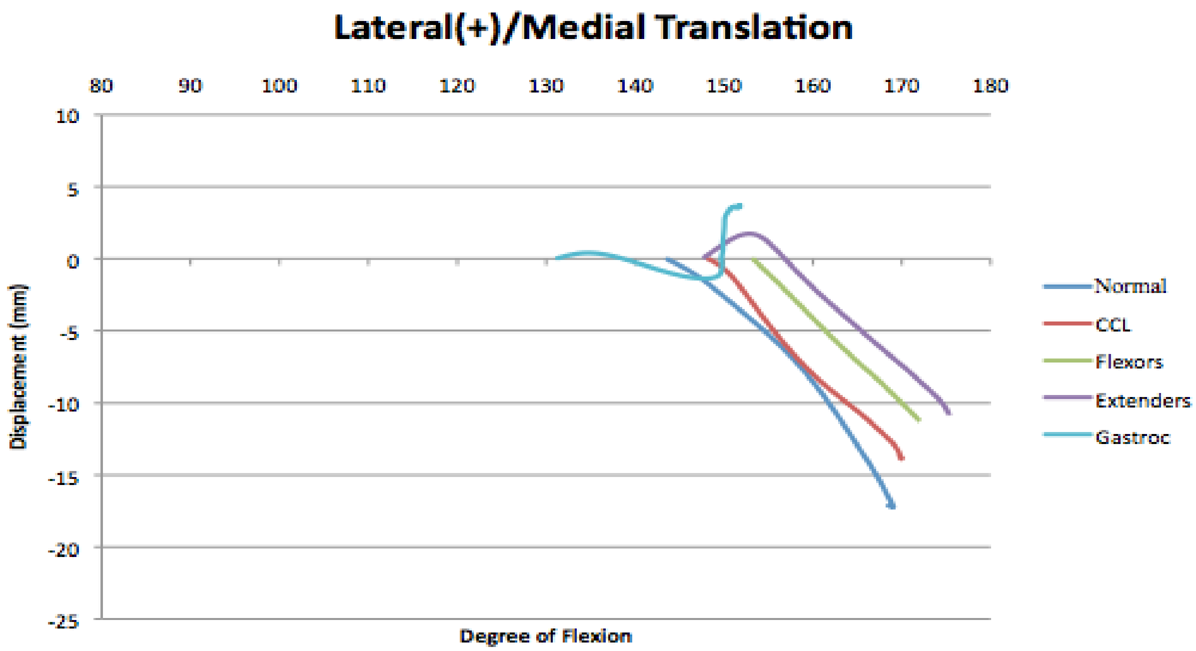

Figure 2.5: The change in medial displacement of the lateral femoral epicondyle from the tibial crest as the hindlimb extends from 90° flexion to full extension (180°) for each of the sequential treatments given in the procedural order of Normal, then the removal of the CCL, Flexors, Extenders, and Gastrocnemius.

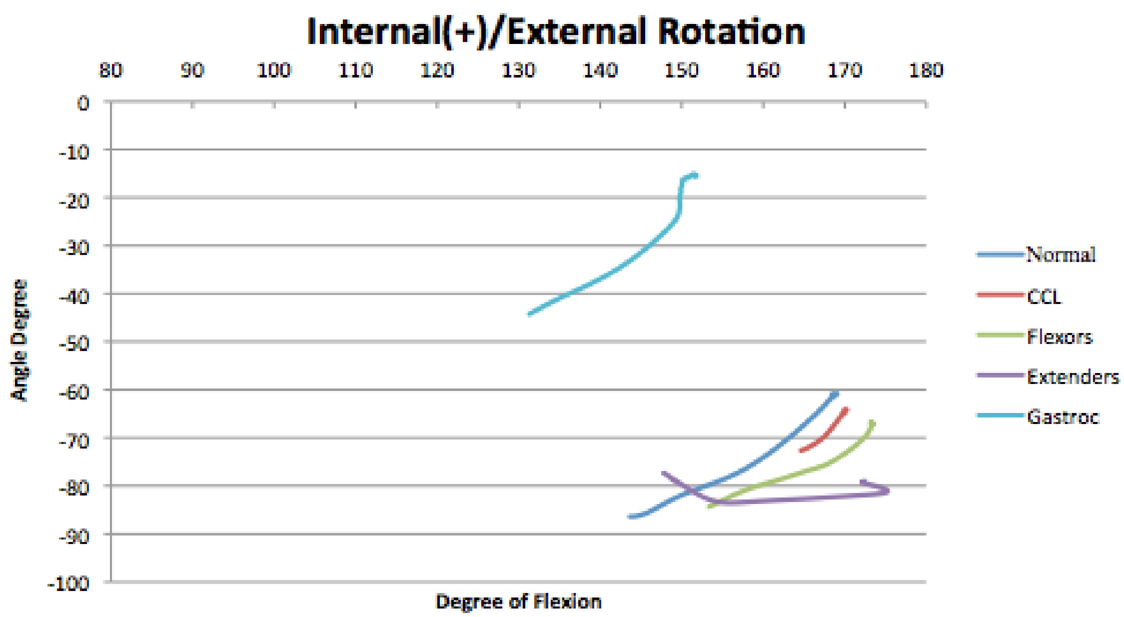

Figure 2.6: The change in internal rotation of the femoral axis system in comparison to the tibial axis system as the hindlimb extends from 90° flexion to full extension (180°) for each of the sequential treatments given in the procedural order of Normal, then the removal of the CCL, Flexors, Extenders, and Gastrocnemius.

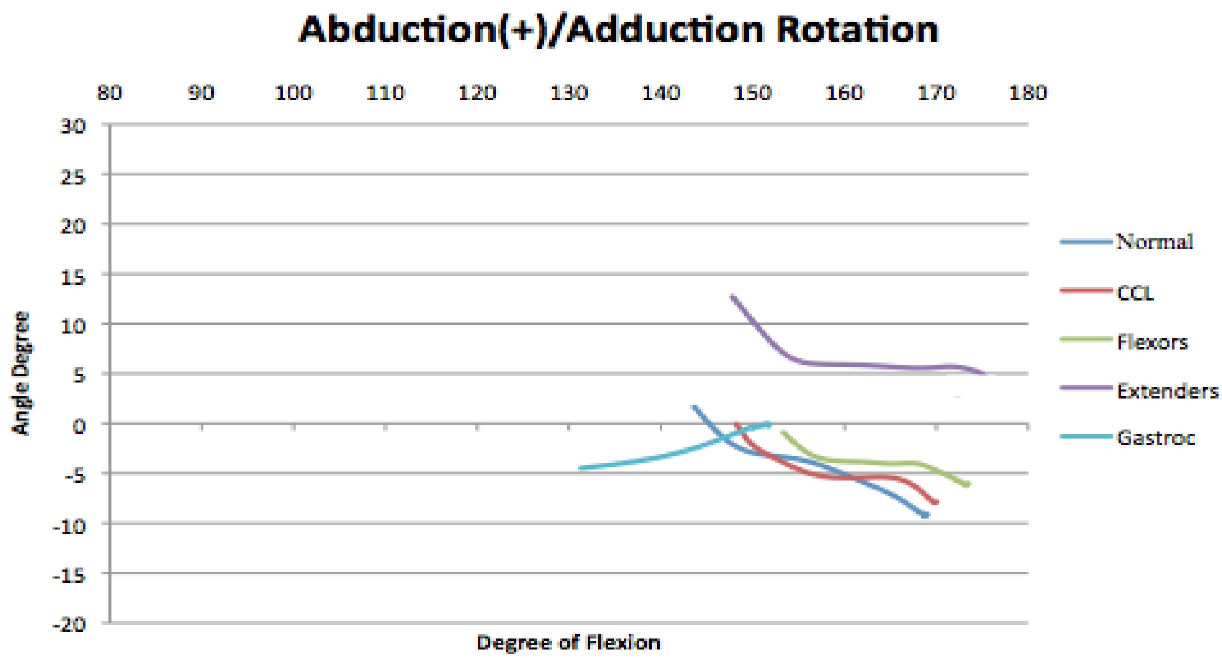

Figure 2.7: The change in adduction rotation of the femoral axis system in comparison to the tibial axis system as the hindlimb extends from 90° flexion to full extension (180°) for each of the sequential treatments given in the procedural order of Normal, then the removal of the CCL, Flexors, Extenders, and Gastrocnemius.

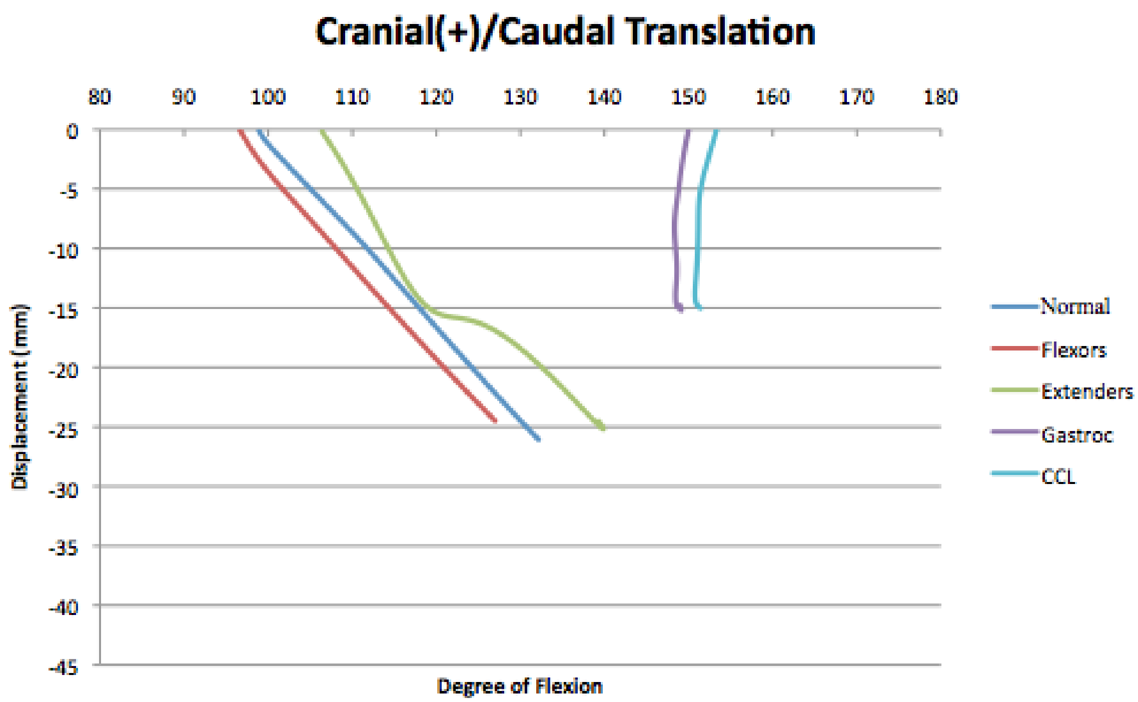

Figure 2.8: The change in caudal displacement for each treatment, given in the procedural order of Normal, then the removal of the Flexors, Extenders, Gastrocnemius, and finally the CCL. Follows the characterization given in Figure 2.2-2.7. Normal extension from 90° to 180°.

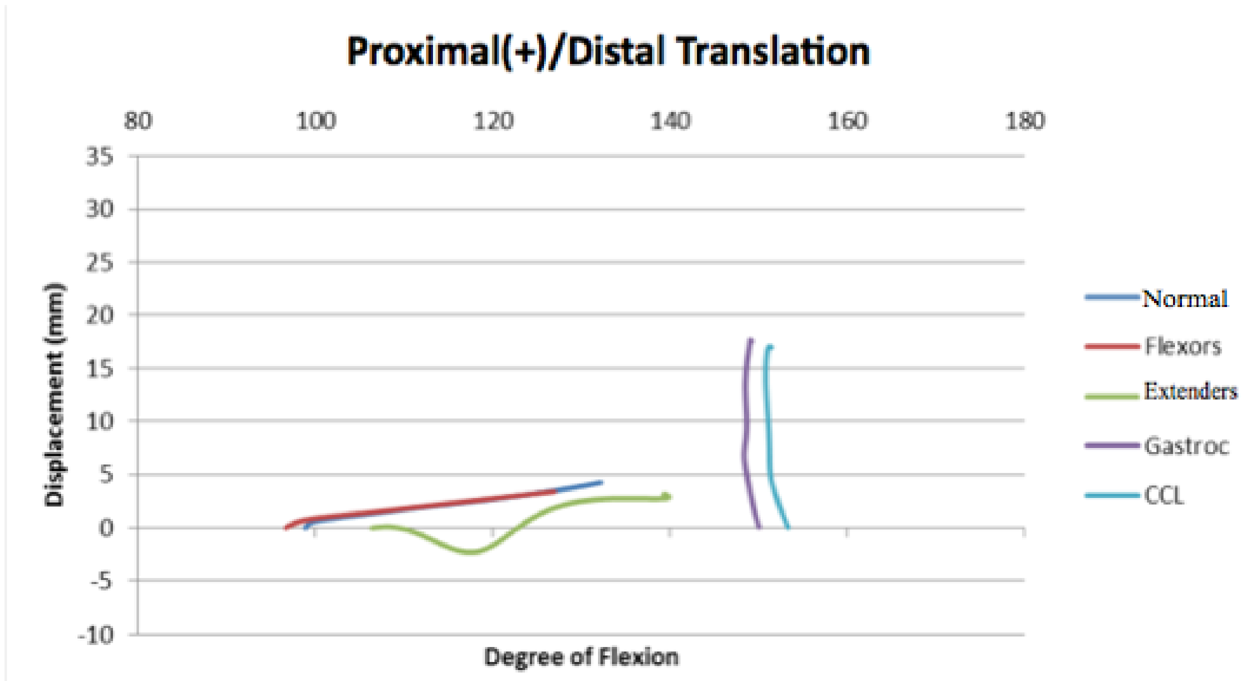

Figure 2.9: The change in proximal displacement for each treatment, given in the procedural order of Normal, then the removal of the Flexors, Extenders, Gastrocnemius, and finally the CCL. Normal extension from 90° to 180°.

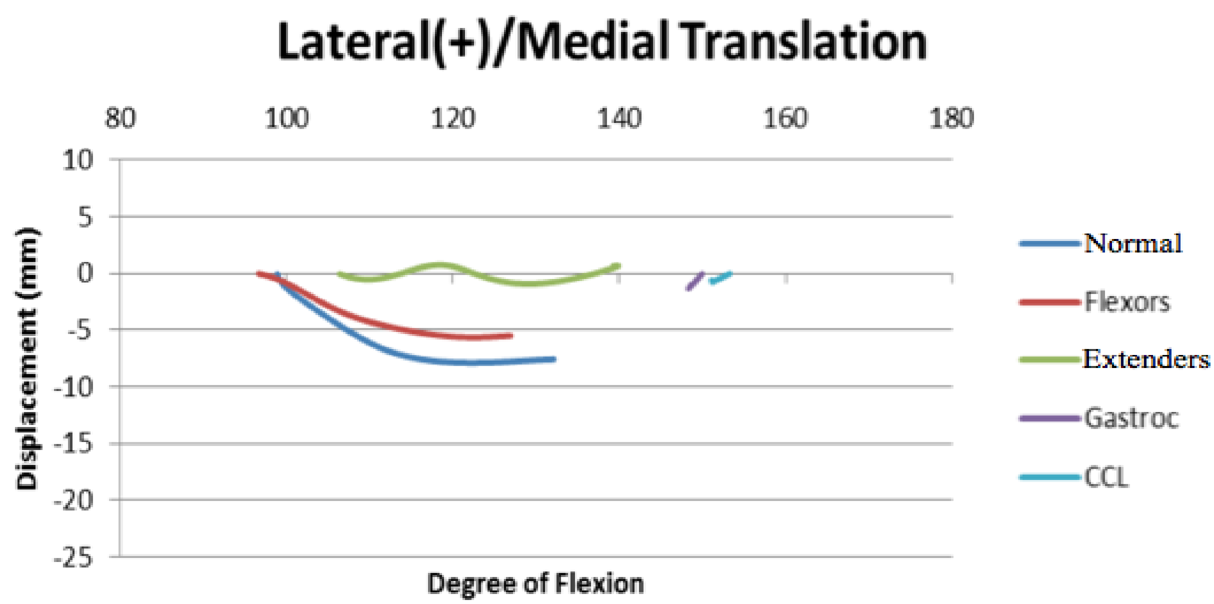

Figure 2.10: The change in medial displacement for each treatment, given in the procedural order of Normal, then the removal of the Flexors, Extenders, Gastrocnemius, and finally the CCL. Normal extension from 90° to 180°.

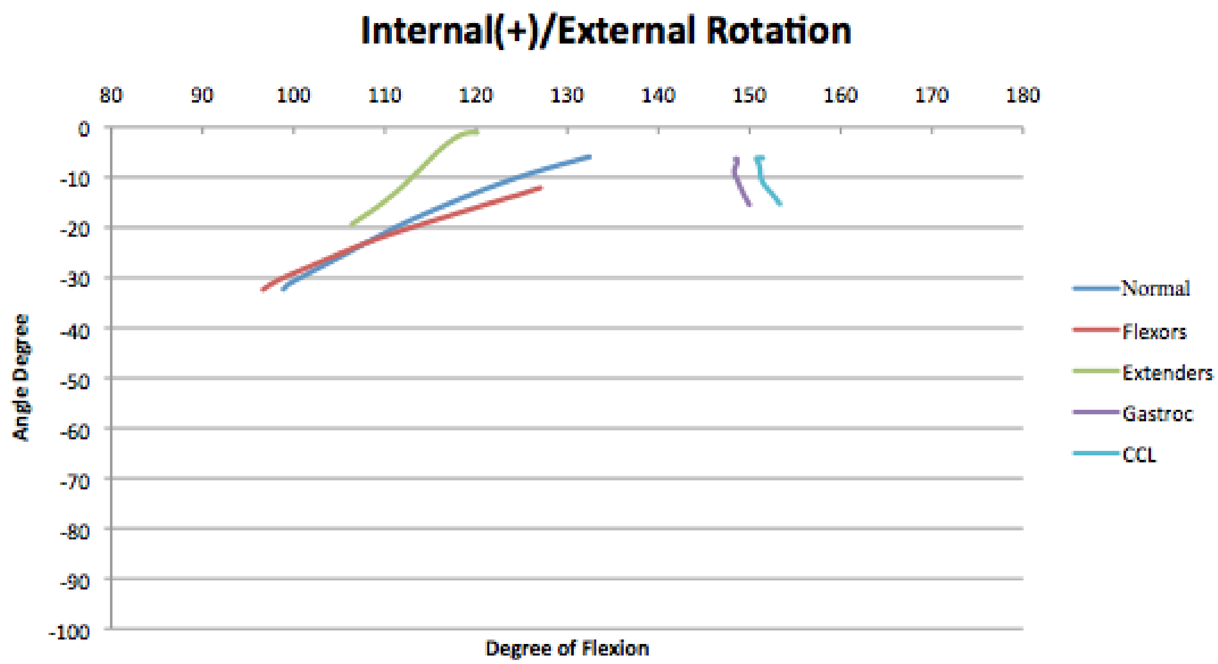

Figure 2.11: The change in internal rotation for each treatment, given in the procedural order of Normal, then the removal of the Flexors, Extenders, Gastrocnemius, and finally the CCL. Normal extension from 90° to 180°.

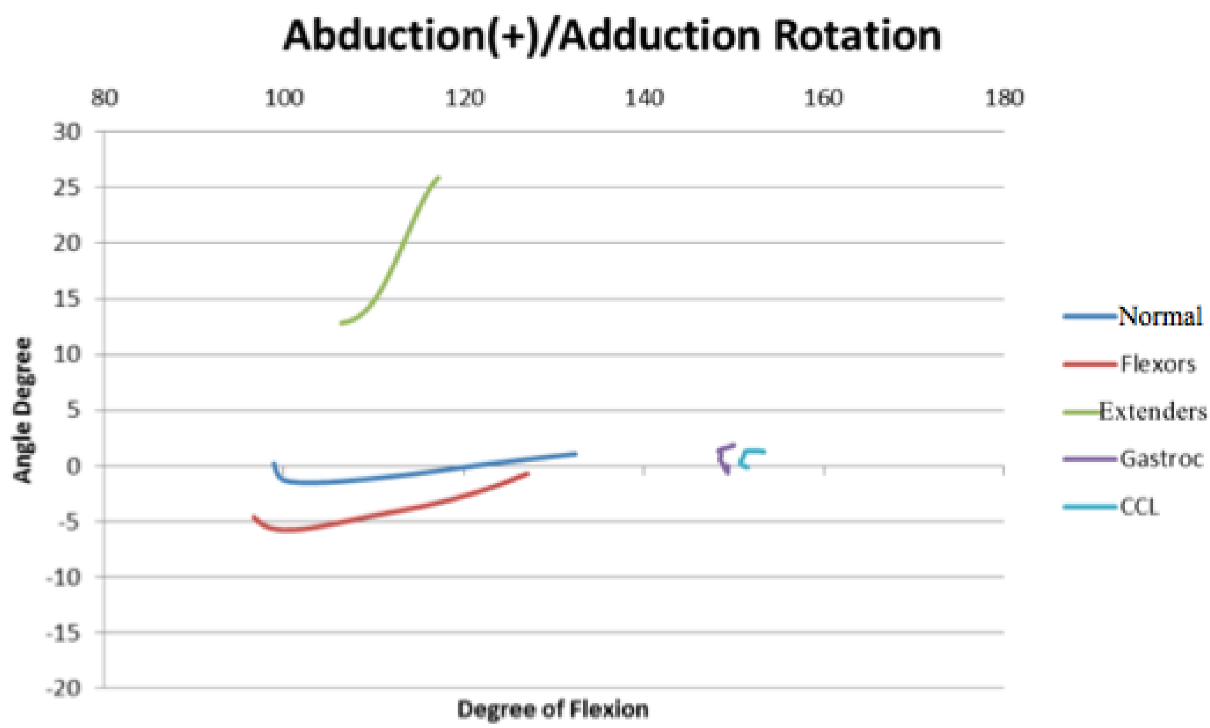

Figure 2.12: The change in abduction rotation for each treatment, given in the procedural order of Normal, then the removal of the Flexors, Extenders, Gastrocnemius, and finally the CCL. Normal extension from 90° to 180°.

2.6 References

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CHAPTER 3

Biomechanical Analysis Of The Effects Of A Total Knee Replacement On Canine Stifles[2]

[2] Howie, RN, TL Foutz, JS Burmeister, C Cathcart, SC Budsberg, and H Hu. To be submitted to American Journal of Veterinary Research

3.1 Abstract

Objective: To describe the three-dimensional kinematic characterization of the intact cadaveric canine stifle joint following cranial cruciate ligament (CCL) rupture, total knee replacement (TKR), and the removal of two major hindlimb muscle groups.

Sample**-** Eight hemi-pelves collected from six, mixed breed dogs between the ages of 1 to 5 years (1 intact female, 1 neutered male, and 4 intact males with weights of 20.9 kg, 24.9 kg, 20.0 kg, 23.4 kg, 25.4 kg, and 24.9 respectively)

Procedures**-** The stifles were tested in 90 to 180 degrees of flexion using a modified Oxford Knee Rig. This apparatus applied a dynamic force to each stifle while preserving the natural hip and hocks and the resulting kinematic changes at the stifle were measured. The rotational and translational motions at the stifle were collected for the physiologically natural, ruptured CCL, TKR, and removed muscle groups. The changes in internal/external and abduction/adduction rotations, cranial/caudal, proximal/distal and lateral/medial translations were collected and characterized.

Results**-** The TKR procedure caused significant changes for all rotations and translations, including a reduction of extension from the normal to a reduced range of 85º ± 10º to 105º ± 10º. A resulting increase of 7.3 ± 3.4 mm caudal, 4 ± 1 mm proximal, and 5 ± 8.8 mm medial translation, as well as, 10º ± 5.5º and 4º ± 2.7 º reductions in internal and abduction, respectively. A CCL deficient stifle has an increased caudal translation by 4.75 ± 5 mm, while the removal of the muscle groups significantly reduced all motion except for an increased proximal translation by 3.5 ± 3 mm.

Conclusions and Clinical Relevance**- S**tifle kinematics patterns established by the TKR procedure cause detrimental alterations to the normal motions found within a stifle, and

the changes in rotations and translation could lead to the failures that have been reported clinically.

3.2 Introduction

Total Knee Replacement (TKR) for canines, first performed in 2007[1], is very similar to human knee replacements. The implant consists of two components, a cobalt chrome element that attaches to the femur and a UHMWPE component, which is inserted into the leveled tibia. Despite some successes with the TKR procedure, even small variations associated with component placement and orientation during the procedure has been found to adversely impact *in vivo* joint mechanics in humans[2]. To better characterize the joint kinematic changes that alter joint function due to physiological conditions and treatment options such as TKR, three-dimensional analysis is commonly utilized. The most commonly used simulator for kinematic testing is the Oxford Knee Rig (OKR) which is used to produce a controlled simulated loading of the stifle while allowing for six-degree-of-freedom articulation of the stifle joint during a deep flexion stance[3]. The six-degrees-of-freedom are characterized in clinical terms as three rotations (flexion/extension, abduction/adduction, internal/external tibial rotation) and three translations (cranial/caudal, medial/lateral, and proximal/distal)[4].

The focus of this study was to test the relationship between tibiofemoral kinematics before and after TKR implantation in a CCL deficient stifle, with the goal of identifying the specific positional changes of anatomical components within the stifle joint that could cause abnormal ranges of motion in canines. A secondary focus was to determine if a hindlimb stripped of most of its soft tissue could serve as an accurate and simplified model for testing the TKR procedure. An analysis of the kinematics found within the joint was chosen because of the unique ability of engineering principles to find relationships between positional changes and resulting injuries or failure. Understanding how the stifle kinematics change provides important information on how TKR alters the mechanical properties of the stifle joint postoperatively, which can then be corrected, providing a basis for optimization of the current TKR prosthesis design.

3.3 Materials And Methods

3.3.1 Simulated Stance

An OKR was used to simulate the motion of intact cadaver stifles during stance and placed each stifle specimen through a range of motion by displacing the femur and tibia of the specimen [5]. A hemi-pelvis specimen (described below) was attached to the OKR using angle iron and was allowed to along each of the three axes (vertically, lateral/medial, and craniocaudal) as the flexed-stifle motion was simulated. The hock was preserved by implementing the use of a dog boot, which secured the foot to a stationary platform while still allowing any natural rotations and translations of the joint to occur. This scheme of connecting the leg to the OKR does not require the cutting of muscles or ligaments, allowing the stifle joint to rotate and translate in a normal manner.

3.3.2 Cadaver collection and preparation

Eight hemi-pelves were collected from six, mixed breed dogs between the ages of 1 to 5 years (1 intact female, 1 neutered male, and 4 intact males with weights of 20.9 kg, 24.9 kg, 20.0 kg, 23.4 kg, 25.4 kg, and 24.9 respectively) euthanized for reasons unrelated to this study. The day prior to testing, a hemi-pelvis was removed from the -20°

freezer and allowed to thaw at room temperature. On the day of testing, the skin was removed from the hemi-pelvis with care taken as to not damage any underlying tissues. A custom made apparatus consisting primarily of angle iron was bolted to the pelvis with vertical bolt running through the ischial tuberosity and a horizontal bolt through the sacroiliac joint of the ilium and thus allowing the attachment of the pelvis to the OKR. Positional nuts were secured so that the angle iron would be horizontal to the ground when the pelvis was in a simulated natural standing position. The hemi-pelvis was also aligned so that the center bolt used to attach the hemi-pelvis to the Oxford Rig was directly above the coxofemoral joint.

3.3.3 Kinematic Markers

A 10 marker system of reflective markers was used to define both the femoral and tibial segments of the hind leg which were used to monitor the stifles motion during testing. The markers were placed at muscle surface level on 0.062” diameter (1.6mm) Kirschner wires that were drilled into the bone at specific anatomical bony locations, except for two markers that were sutured to soft tissue locations[5]. The coxofemoral, stifle, and hock joints were put through a full range of motion to ensure normal movement with no impingements from the wires as well as no palpable orthopedic abnormalities.

The angular and translation motion of the stifle joint during the simulated stance was determined using techniques described in Fu[5]. The reflective markers were used to create two separate coordinate systems one on the tibia and the second on the femur of the hindlimb. Using a Vicon Motus system that employed six 200 Hz infrared cameras arranged around the OKR’s platform, the angular and translational motion of the stifle joint was determined by capturing the movement of the reflective markers and calculating the motions of the axes relative to each other. Changes in the 6 degrees of freedom (flexion/extension, abduction/adduction, internal/external rotations, distal/proximal, cranial/caudal, and medial/lateral translations) were calculated Fu[5].

3.3.4 Kinematic Characterization

To test the affect of different constraints on stifle kinematics a series of modifications to the hindlimb were applied and the changes in motion that occurred were captured. The kinematic affect of each treatment was determined by placing the loaded hindlimb through a range of motion, in a stance that began at 90° and was extended to an extension of approximately 145°. A baseline measurement was collected at the initial 90° of flexion and then changes for each of the two rotations and three translations from the initial baseline where collected. Data was collected only when changes from the baseline occurred. As the change in rotational degree or translational displacement began the degree of extension was also recorded giving the degree within the extension stance that the changes began to occur and the extension degree where the changes in each motion stopped. As anatomical structures were removed it was expected that the degree of extension where changes occur would deviate due to the removal of the natural constraints of the stifle.

All translational (cranial/caudal, proximal/distal, and lateral/medial) changes began at 0 because the changes were based on the femoral epicondyle position relative to a mathematically fixed tibial crest. Therefore at the collection of the baseline, the femoral epicondyle location in relationship to the tibial crest was initialized. The rotational (interior/exterior and abduction/adduction) changes were slightly different in that the femoral axis system was compared to that of the tibial axis system, both of which where aligned along the central axis of their respective bone. This allowed a non-zero starting degree if at the 90° baseline the femoral axis was not aligned with the tibial axis system.

3.3.5 Experimental Procedure

Kinematic trials of the physiologically normal stifle were collected to determine the innate motion of each specimen before experimental changes were applied. Following the collection of the control trials the cranial cruciate ligament was transected using a 1.5 cm incision into the joint capsule just lateral of the patellar tendon through which a scalpel was used to sharply incise the ligament at its insertion on the tibia. A positive drawer test was used to confirm complete transection of the cranial cruciate ligament. Next, the TKR procedure as found in Allen et al.[6] was performed on the cadaveric hindlimb and the resulting kinematic motion captured [a-c]. After the procedure the joint capsule was sutured together to restore its physiological effects on the stifle. The utmost effort was made to correctly align and position the femoral and tibial elements of the TKR with the anatomical components of the hindlimb, in order to reduce the likelihood of kinematic differences resulting from surgical error (Figure 3.1).

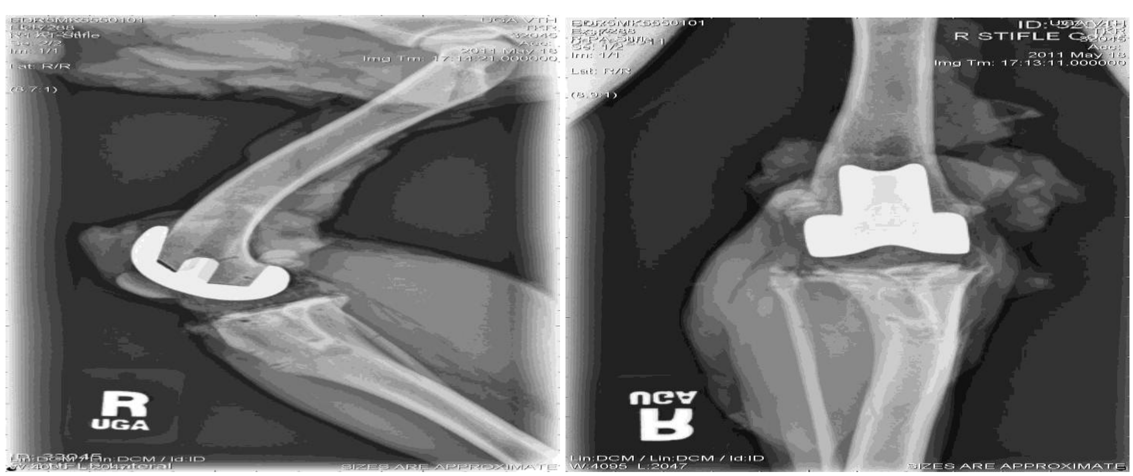

Figure 3.1: Lateral and cranial radiographs of the hindlimb of a canine cadaver with a TKR prosthesis implanted.

Finally, muscle dissections were made to determine the importance of certain muscle groups to the cadaver three-dimensional kinematics after a TKR procedure, in order to determine if a simplified model is appropriate when trying to draw conclusions for physiological normal situations. The dissections consisted of the removal of the muscles from the caudomedial aspect of the thigh that primarily functioned as stifle flexors or hip extension and adduction. The muscles removed were the semitendinosus, semimembranosus, gracilis, adductor, and pectineus, and for the purpose of simplicity will be called flexors for the remainder of the paper. They were removed by sharp dissection of their origins at the ischium and pubic symphysis, with blunt digital dissection removing them from adjoining muscles. The adductor was sharply dissected from its caudal femoral attachments, and the entire group of muscles was freed by incising along the aponeurosis near their insertion at the tibia.

The muscles from the craniolateral aspect of the thigh that primarily functioned as stifle extensors were removed at the same time as the stifle flexors. Minor secondary function included hip extension (Biceps femoris) and hip flexion (Sartorius). The muscles removed were the Sartorius, Biceps femoris and Quadriceps femoris, consisting of the Rectus femoris, Vastus lateralis, Vastus intermedius, and Vastus medialis. For simplicity this group of muscles will subsequently be refferred to as extensors. The muscles were removed by sharp dissection of their origins at the proximal femur and ilium. The muscles were freed from the femur with sharp dissection, and their distal attachments freed by incising the Biceps aponeurosis as well as transecting the common quadriceps tendon proximal to transition into the patellar tendon. Care was taken to leave the stifle joint capsule intact. In addition to removal of these muscles, the long digital extensor, being the last remaining muscle spanning the stifle, was transected just distal the tibial plateau.

3.3.6 Statistical Analysis

The raw data for all 5 runs of a trial were used to determine the statistical significance of a treatment. The angles or displacements traveled for a specific motion were averaged and the standard deviation calculated so that every motion was expressed as mean ± standard deviation. ANOVA's Tukey method was used for comparisons between treatments and specimen. Data for each specimen was plotted and analyzed for stability based on the scatter plot and statistical analysis of outliers. Variables with a significant correlation ($P < .01$) were included in the analysis. While specimen-to-specimen differences were significant, since the same effects were significant with or without the effect of specimen differences, the final models were built without including dummy variables to account for specimen effects [d].

3.4 Results

The resulting natural kinematic motion of the canine stifle using an OKR setup was characterized in this study; the resulting motions are illustrated in Figure 3.2. This study found the natural cadaver stifle as having a 31.6 ± 4 mm, 4.2 ± 3 mm, and 12.4 ± 4 mm displacement of the lateral femoral epicondyle from the tibial crest for caudal, distal, and medial translations (Figure 3.2a, d, and f), respectively as the hindlimb extends from 85° ± 10º flexion to full extension of 145°± 15º. The degree of the change in the rotations found at the stifle during the same extension duration were 21.5°± 3° and 8°± 2° degrees of internal and abduction rotation respectively (Figure 3.2b and c).

Post-severance of the CCL, the laxity of the stifle joint increased from that of the normal, most notably through the increased caudal translation of the femur by 4.75 ± 5 mm (Figure 3.3). The CCL deficient stifle also deviated from the normal kinematics through a reduction of internal rotation by 2º ± 3º (Figure 3.7), and an increase of 3º ± 1.6º, 2.3 ± 1.7 mm, and 2.3 ± 1.3 mm in abduction and distal and medial translation, respectively (Figures 3.4-3.6).

After the TKR procedure there was statistically significant changes for all rotations and translations when compared to the motions resulting from a CCL-deficient stifle. A resulting increase of 7.3± 3.4 mm caudal and 5 ± 8.8 mm medial translation was seen (Figures 3.3 and 3.5), while a reduction in the overall rotations was felt by the stifle. 4º ± 2.7 º and 10º ± 5.5º reductions in abduction and internal, respectively, rotation resulted from the implantation of the TKR components (Figure 3.6 and 3.7). There was also a complete reversal of the distal translation to a proximal translation of 4 ± 1 mm from the center of the stifle joint, an overall change of 3.5 ± 3 mm from the distal translations seen in a CCL deficient joint (Figure 3.4). While changes in all rotations and translations occurred, the most noteworthy was the overall reduction in the extension angle that the hind leg could achieve. There was a reduction of extension from the normal to a reduced range of 85º ± 10º to 105º ± 10º. The resistance of the TKR to allow full extension was so great that there was a notable increase in the difficulty to lift the leg on the OKR apparatus, for three out of the eight specimens tested, in order to achieve the reduced extensions.

When compared to the normal stifle kinematics, a TRK stifle had a resulting overall increase of 12.1± 4.2 mm caudal and 7.3± 7.8 mm medial translation, while a reduction in the overall rotations were felt by the stifle. 6º ± 3 º and 7º ± 2.8º reductions in internal and abduction, respectively, rotation from the normal resulted from the implantation of the TKR components. There was also reversal of the distal translation seen in the natural cadaveric leg, to a proximal translation a change of 5.8 ± 5 mm.

Finally, the kinematic response of a TKR under a simplified model that removed all soft tissue except for the gastrocnemius muscle was tested. Again there was a significant change in every motion. There was no reversal in the directionality of the motions created by the TKR procedure but there was an overall increase in the laxity of the joint. The reduction in all but one kinematic motion resulted after the removal of the soft tissues. A reduction of 14.5 ± 10 mm caudal and 3.6 ± 3.5 mm medial translations (Figures 3.3 and 3.5) as well as 9º ± 5º and 8º ± 7º in abduction and internal rotations (Figures 3.6, and 3.7) respectively. The only increased duration of motion was found in the proximal translation, which increased by 3.5 ± 3 mm (Figure 3.5). The removal of the soft tissue constraints from the hindlimb did not cause a change in the flexion/extension range.

3.5 Discussion

The three-dimensional kinematic characterization of the canine stifle after a TKR procedure is extremely useful in determining if the normal physiological motions of the stifle are being preserved after the implantation of prosthesis. If deviations occur, such as those found in this study, then the differences in the motions of the postoperative stifle from that of the normal can be identified and measures can be taken to correct the abnormalities that result. If the exact cause of failures in knee implants can be determined, then optimization of the implant could take place, reducing the number of failures and save the pet owner thousands of dollars. An optimized prosthesis would increase the quality of life for dogs with damaged knees, reducing the pain and suffering the animal contends with after such an invasive surgery.

In this study, a general decrease in the stability of the stifle occurred as the CCL was severed as evident by the increase in the amount of rotational and translational motion at the joint. The most significantly affected motion was the caudal translation that increased by 4.75 ± 5 mm from the normal (Figure 3.3). The altered constraint of removing the CCL does not allow natural femorotibial kinematics and can ultimately result in gait adaptation [7], which could cause abnormal contact with the TKR components leading to failure [8]. While the CCL did cause significant deviations from the norm, the most significant finding in this study was the reduction in the range of the full extension angle after the TKR procedure was performed from 145°± 15º to 105º ± 10º. This reduction in the extension angle could be the cause the multitude of changes in the physiological motions at the stifle that were observed in this study. These resulting abnormal rotations and translations could also alter the joint loading and contribute to a negative mechanical environment that can have a harmful effect on the implant itself as well as the general environment of the joint[2]. When paired with a significant reduction of any rotational motion, the increasing of the caudal and medial translations and the reversal of the distal translation to proximal translation due to the TKR procedure would cause a concentration of the dynamic load within the stifle joint, possibly leading to shifting of the load to unconditioned areas of cartilage, accelerating degradation[9,10]. A direct correlation between changes in the kinematic motions of the knee and contact pressure on the wear of an implant have been[11,12], which lead to TKR failure.

The resulting kinematic data from the removal of the soft tissues illustrate that the motion at the stifle was not only changed but that the general laxity of the joint was increased, indicated by the increased standard deviation for each of the rotations and translations measured. Without the resultant forces created by soft tissues, the joint had a large decrease in the movement within the joint. Similarly, a previous study that determined the affects of soft tissue removal on CCL-deficient stifles, found that the removal of soft tissues caused a reduction in all rotations and in the medial translation[13]. Due to such a decrease in the motion found at the stifle, a simplified model of a TKR should include all soft tissues in order to preserve a more natural motion. This conclusion would apply to kinematic and wear type experiments since the implant would not be worn in a fashion that could be compared to a clinical setting due to the deviation from the normal path of the femoral epicondyles on the tibial insert[14]. The results from this study suggest that the stifle kinematics patterns established by the TKR procedure causes detrimental alterations to the normal motions found within a stifle, and that these changes in the rotations and translation might be factors associated with failures that have been reported clinically. The results herein may serve as the foundation for better quantifying the abnormal kinematics found within a TKR stifle and lead to an optimization of the current TKR implant.

[a.] Simplex Bone Cement, Stryker Howmedica Osteonics, Mahwah, New Jersey.
[b.] Canine Total Knee Femoral Component, BioMedtrix, LLC, Boonton, New Jersey.
[c.] Canine Total Knee Tibial Component, BioMedtrix, LLC, Boonton, New Jersey.
[d.] SAS System for Windows, version 9.2, Service Pack 4, SAS Institute Inc, Cary, NC.

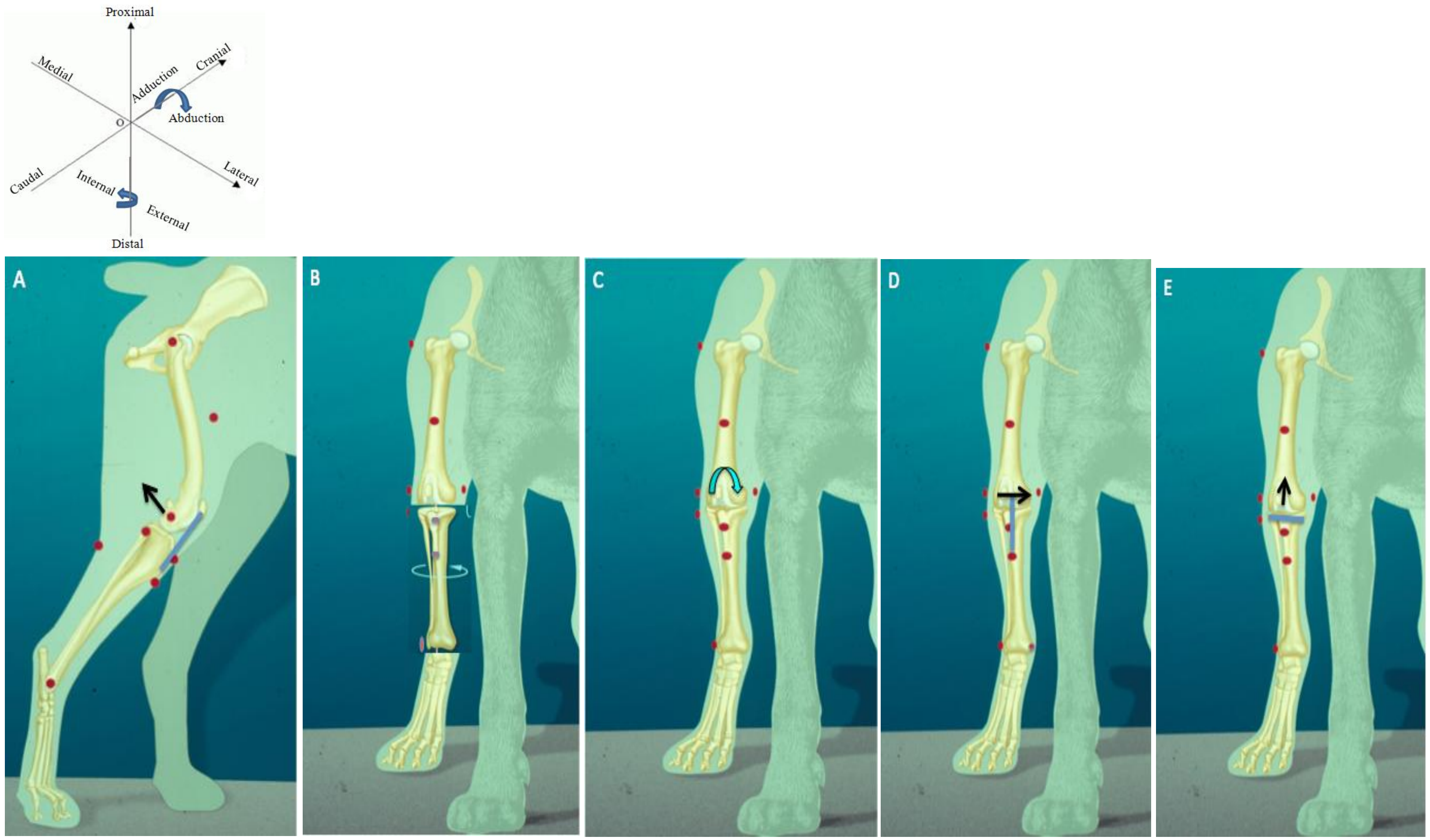

Figure 3.2: Characteristic motion of a normal stifle as it extends from 85° flexion to an extension of 145°. Black arrows indicate translational direction of travel from an initial position in relation to the tibial crest as indicated by the blue line, while green arrows indicate rotational direction of the femoral and tibial axis system in relation to each other. A) The femoral epicondyle travels 31.6 ± 4 mm caudally B) the femoral and tibial axis systems rotate 21.5°± 3° internally C) the femoral and tibial axis systems rotate 8°± 2° in abduction D) the femoral epicondyle travels 4.2 ± 3 mm medially and finally, E) the femoral epicondyle travels 12.4 ± 4 mm in the distal direction.

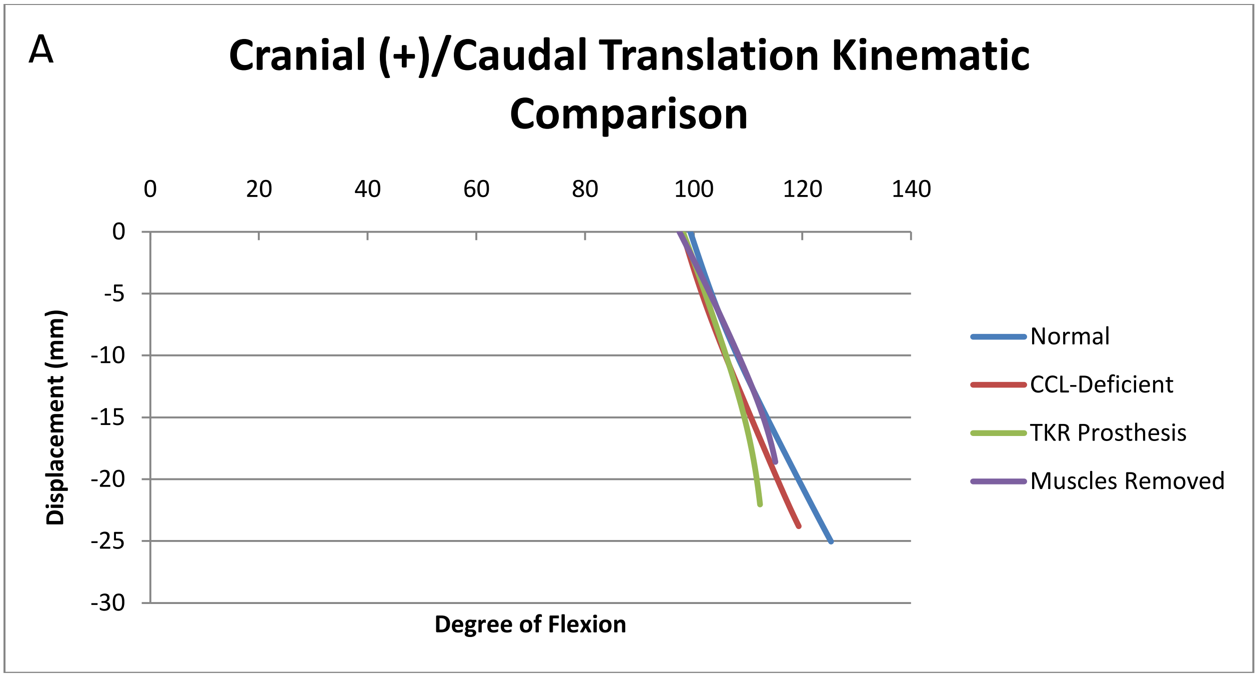

Figure 3.3: Characteristic kinematic motion of a stifle as it progresses through the experimental treatments shown in order as indicated by the legend. Follows the flexion/extension range and data collection protocol as explained in Figure 3.2. The change in caudal displacement of the lateral femoral epicondyle from the tibial crest as the hindlimb extends from 90° flexion to 145°.

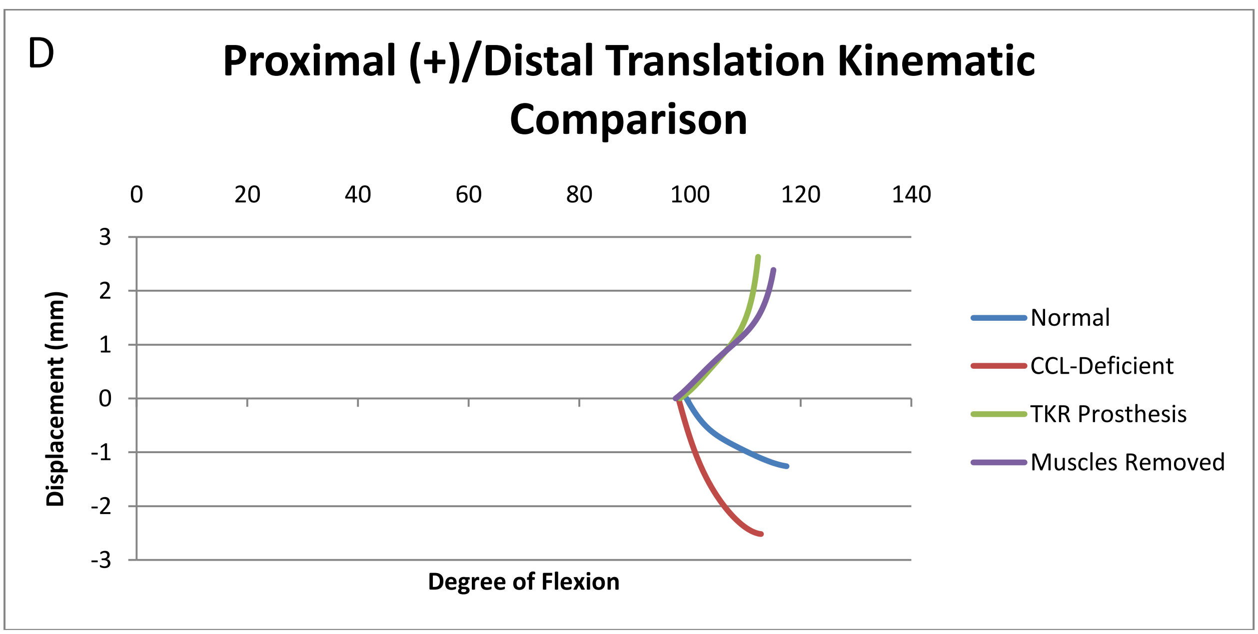

Figure 3.6: The change in distal (Normal and CCL-deficient) and proximal (TKR and Muscles removed) displacement of the lateral femoral epicondyle from the tibial crest as the hindlimb extends from 90° flexion to 145°.

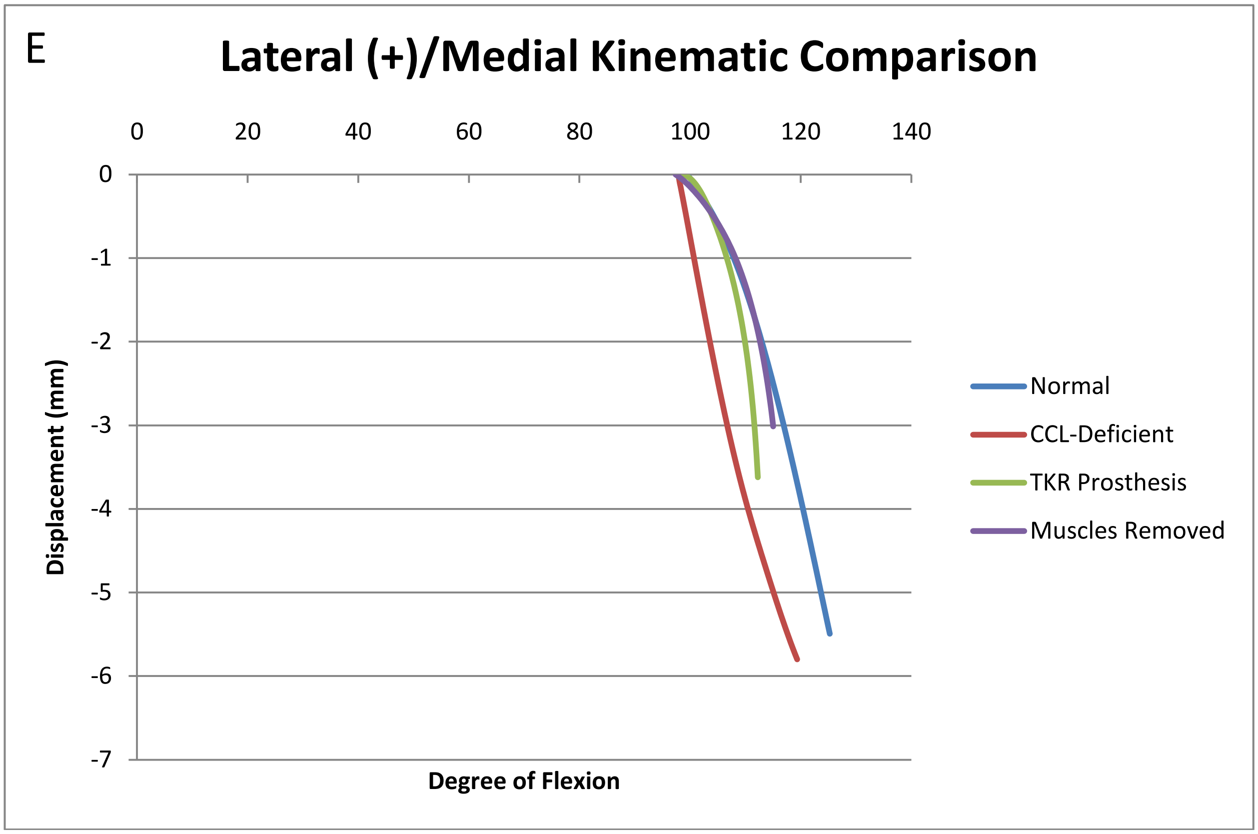

Figure 3.7: The change in medial displacement of the lateral femoral epicondyle from the tibial crest as the hindlimb extends from 90° flexion to 145°.

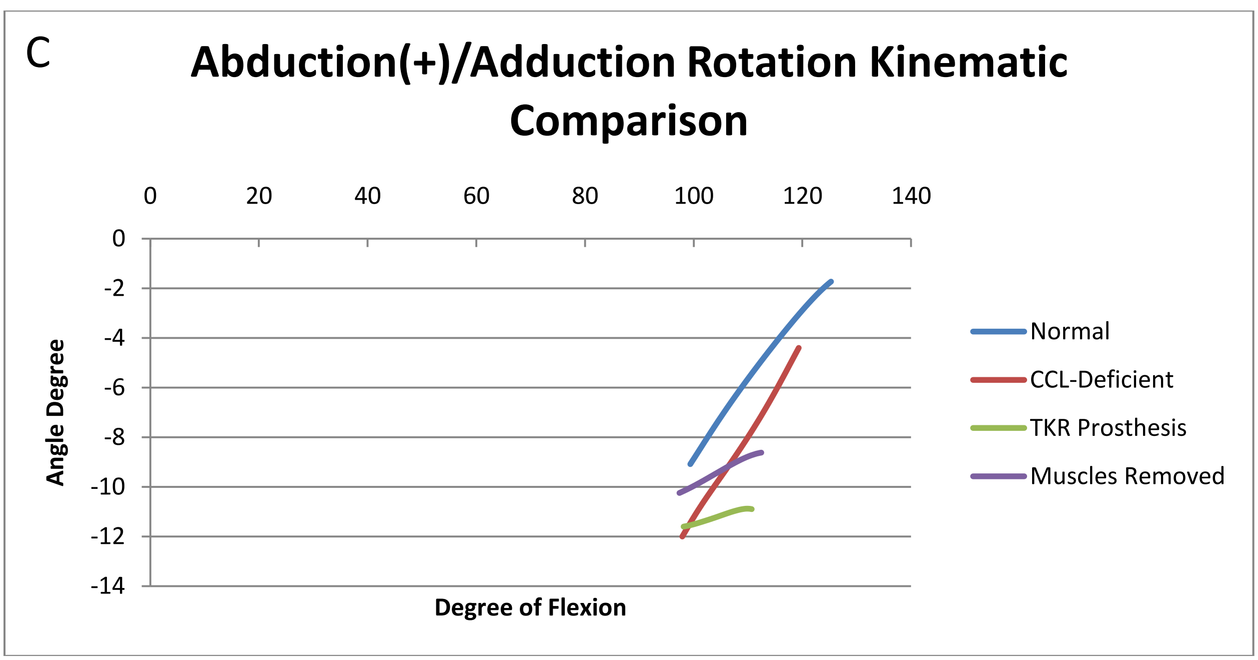

Figure 3.5: The change in abduction rotation of the femoral axis system in comparison to the tibial axis system as the hindlimb extends from 90° flexion to 145°.

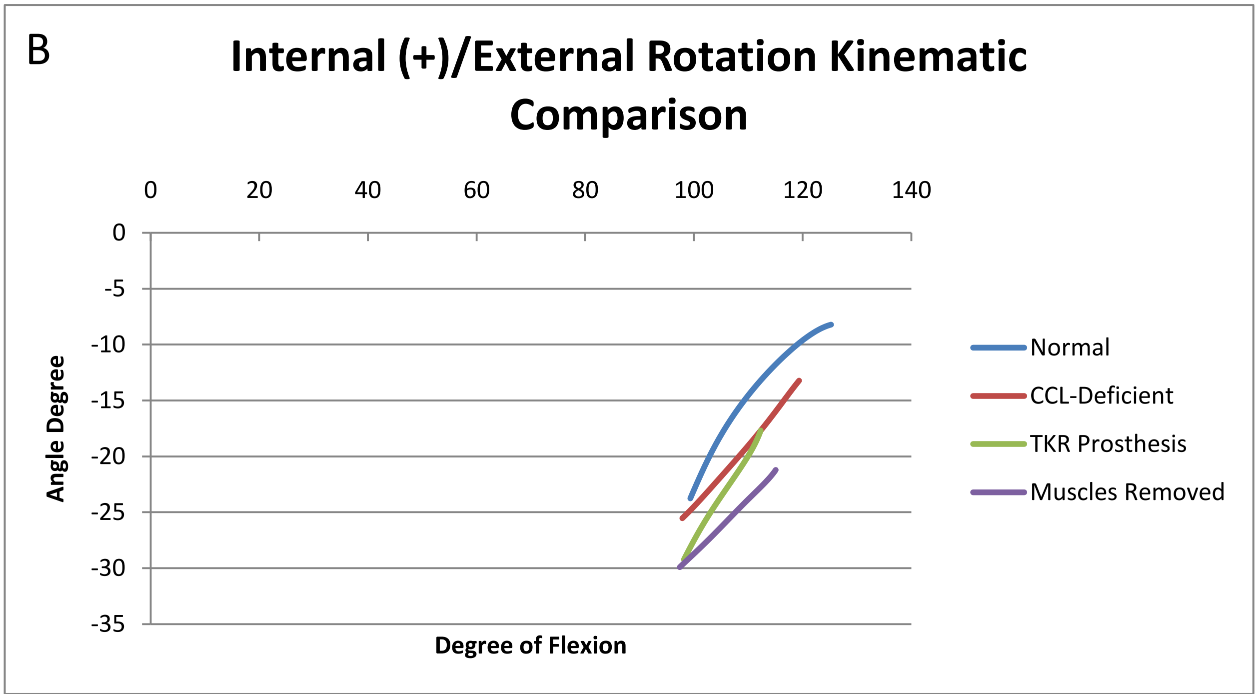

Figure 3.4: The change in internal rotation of the femoral axis system in comparison to the tibial axis system as the hindlimb extends from 90° flexion to 145°.

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CHAPTER 4

Conclusion

4.1 Summary

The previous two chapters both described the three-dimensional kinematics of a normal canine stifle and stifles with different treatments applied. The purpose of both studies was to understand how different treatments, CCL and muscle removal as well as a TKR, affected the kinematics of the joint, as could be characterized by an OKR setup. The first paper determined the best OKR setup for our testing protocol and the kinematic significance of the CCL and major muscle groups on the stifle joint. It was found that the OKR constraint requirements that would preserve the most physiologically normal kinematics for the stifle were a retained coxofemoral and hock joint with no constraints placed on the joints, allowing freedom of motion. The first study also provided an initial understanding of the kinematic motions to be expected for a stifle given the use of the OKR and the removal of anatomical structures. The second paper built on the foundation acquired and further characterized the motion of the stifle given a TKR.

These two studies both indicated that while the transection of the CCL did causes abnormal motion, the resulting differences were not as drastic as the affects of removing the gastrocnemius muscle or the implantation of the TKR. Both studies also proved that a larger sample size is necessary to correctly describe the affects that occur given the application of certain treatments. Due to the importance of the gastrocnemius muscle as described in the first study, the second study preserved that anatomical structure in order to collect data that would still retain some of its natural motion. Both of the studies also pursued the proposal of a simplified design to test future OKR experiments that utilized a cadaveric specimen. It was found that the CCL and flexor muscles could be removed while still preserving reasonably normal motions but that if any other changes occurred, including a TKR, that the deviations were too drastic to accurately simulate normal kinematics; therefore, eliminating the idea of using a simplified design when testing the affects of specific treatments on the stifle. The lack of major influence of the CCL on the stifle could be indicative of the fact that ligaments are static stabilizers while muscles are the dynamic stabilizers of the stifle[31-33], and this experiment tested dynamic motion.

The second study suggests that a general decrease in the stability of the stifle occurred as the CCL was severed as evident by the increase in the amount of rotational and translational motion at the joint. The removal the CCL does not allow natural femorotibial kinematics and can ultimately result in gait adaptation[34], which could cause abnormal contact with the TKR components leading to failure[24]. While the CCL did cause deviations from the norm, the most significant finding in this study was the reduction in the range of the full extension angle after the TKR procedure was performed from 145°± 15º to 105º ± 10º. This reduction in the extension angle could be the cause the multitude of changes in the physiological motions at the stifle that were observed. The resulting abnormal rotations and translations could also alter the joint loading and contribute to a negative mechanical environment that can have a harmful effect on the implant itself as well as the general environment of the joint[18, 34-36].

The resulting increasing of the caudal, medial, and the reversal of the distal to proximal translation resulting from the TKR procedure, paired with a significant reduction of any rotational motion would cause a concentration of the dynamic load within the stifle joint, could lead to shifting of the load to unconditioned areas of cartilage, accelerating degradation[7,25]. A direct correlation between changes in the kinematic motions of the knee and contact pressure on the wear of an implant have been documented[25,26], which lead to TKR failure.

The results from the studies suggest that the stifle kinematics patterns established by the TKR procedure and gastrocnemius removal caused the most significant detrimental alterations to the normal motions found within a stifle. The importance of the retention of the gastrocnemius muscle is essential because of the common practice for OKR type studies to remove all soft tissue except for the quadriceps. The studies herein have found that the removal of the gastrocnemius changes the stifle kinematics so drastically that if it is removed the resulting kinematic data cannot be comparable to that of the normal. It is concluded that further studies implementing an OKR protocol should preserve the gastrocnemius muscle. The resulting reduction of the extension angle after a TKR was significant in the fact that it could be the cause the multitude of changes observed in the physiological motions at the stifle. These changes in the rotations and translation might be factors associated with failures that have been reported clinically, and warrant further study. The results herein should serve as the foundation for better quantifying the abnormal kinematics found within a TKR stifle and lead to an optimization of the current TKR implant.

4.2 Recommendations For Future Study

The results presented within this thesis are only meant to provide a foundation for future studies that are needed to accurately characterize the abnormal motions found within the stifle after an artificial stifle is implanted. The results herein were to focus future research in the direction leading to optimization of the TKR components. To properly address the deficiencies within the implant the following approaches could be helpful.

- A three-dimensional kinematic characterization of TKR stifles through entire naturally occurring gaits, using both cadaveric and live animals.
- Description of the exact path the femoral epicondyles forge along the tibial plateau and what changes occur once the TKR components are implanted
- Characterization of loads and moments (kinetic analysis) within the stifle before and after TKR
- Finite Element Analysis to determine if abnormal stresses or stains are occurring post TKR operation.

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