PILOT STUDY USING OXFORD RIG, CUSTOMIZED MATLAB PROGRAM, AND VICON SYSTEM TO STUDY THE STIFLE JOINT

by

Judith Navik

(Under the direction of Mark Haidekker)

Abstract

Knee joint kinematics and kinetics are studied by applying external forces and displacements using an Oxford Rig; a device which holds and moves human knee joints. In this study, a modified Oxford Rig was developed and tested that allowed the study of canine stifle (knee) joints and their artificial replacements. Chicken and turkey legs were used to develop the Rig.

Following these experiments, a new UGA/Oxford Rig was developed which allows for an intact leg system. This allowed for movement of the hip and hock (ankle) joints, which are no longer replicated by artificial means.

Customized software was developed that permitted output from a 3D motion analysis system to be transferred into joint angles for each frame of data collected. This involved moving from global to local coordinate systems for each leg bone, working with virtual (redundant) markers, and finding three different angles of movement that occur during stifle flexion.

INDEX WORDS: Kinematic, Broiler, Turkey, Layer, Chicken, Oxford Rig, Canine, Stifle, Knee, Motion, Flexion, Extension, Abduction, Adduction, Axial Rotation, Internal Rotation, External Rotation

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PILOT STUDY USING OXFORD RIG, CUSTOMIZED MATLAB PROGRAM, AND VICON SYSTEM TO STUDY THE STIFLE JOINT BROKEN ACROSS TWO LINES

by

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Chapter 1

Introduction

1.1 Overview

In 2003, 418,000 people had total knee replacements [3]. Veterinary medicine has often followed human medicine using similar surgical procedures and medication to treat diseases and syndromes. Total knee replacements for dogs have now become common enough to have commercialized parts rather than only custom made parts.

The total knee replacement is a common procedure for persons greater than 65 years of age [3,4]. The rate at which this procedure has been used has increased linearly, 40 females per 10,000 people in 1990 to 60 females per 10,000 in 2000. Similar statistics can be found for males with 25 males per 10,000 people in 1990 to 55 males per 10,000 in 2000 [3,4].

Veterinary medicine has often emulated human medicine using similar surgical procedures and medication to treat diseases and syndromes. Previously, arthroscopic surgery or pain medication was used to treat problems with canine knees. As people are taking better care of their pets they are demanding medical treatment equivalent to their own. As such, the advent of the total canine stifle replacement has reached commercialization at a company called Biomedtrix. Accurate kinematic analysis is important to understand the complexity of stifle (knee) joint mechanics for surgery so that ligament structures and implant components can be protected from high stresses and strains [5]. Understanding the knee is critical for the development of surgical strategies and the design of new implants which could improve patient satisfaction and lower the overall cost.

The long term objective of the lab is to study artificial canine stifle (knee) joints. The experiment described within this thesis was the pilot study of the initial technique used for the canine study; collecting kinematic data for a canine stifle and determining the measurements for a canine stifle with a total knee replacement. This data will be contrasted against comparable human data which the canine artificial knee has been based on.

The current commercial stifle replacements for canines have been modeled in part after human knee replacements. However, there is an angular relationship between the femur and the tibia that is present in canines that is not seen in humans. Unfortunately this relationship is not represented in the commercial stifle replacements resulting in abnormal wear and premature failure of the meniscus replacement. In order to create a better understanding of knee kinetics and total knee replacement design, researchers need to have a better understanding of the overall biomechanical behavior of the canine knee, particularly the femur-tibia angular relationship.

Liska et al. [6] developed a canine total knee replacement which successfully managed an irregular stifle joint and suggested that canine knee prostheses are commercially possible. Biomedtrix has made commercially available canine stifle joints. Schafer et al. [7] studied the impact of a total knee joint transplantation on a dog model. After replantation, dogs recovered fully, but after transplantation there was impaired movement. The histological results were normal for replant recipients, but using an infiltrative vasculopathy technique indicated chronic rejection in the transplanted joints.

"The purpose of determining the motions of a total knee replacement in vitro are to

characterize the stability and laxity characteristics and to predict the kinematic behavior of the total knee replacement when implanted" [1]. This study focused on preclinical testing to characterize total knee replacement motions allowing for better total knee replacement designs to be made.

1.2 Pilot Study

The experiment described in detail within this thesis is a pilot study for the laboratory's new equipment (an Oxford Rig) and a process for using it. For the pilot study it was decided to use domestic poultry. They are readily available and their stifle (knee) joints have not been extensively studied so it would allow for an additional set of knowledge to be discovered as well as pre-testing the system for future canine use. (The acceptance of poultry as a substitute for canines is discussed in section 2.4.)

There are several kinematic investigations that examine bird gait morphology and compare bird bipedal locomotion to human locomotion. Reilly et al. [8] and Higham [9] evaluated the leg kinematics of quail and wild turkeys, respectively, and related the birds' gait with stride speed and the leg joint angles to muscle displacement. Oviedo [10] examined the walking ability of commercial birds using digitalized video images and found that chicks have an asymmetric gait that generate ground reaction forces that could impact asymmetrical bone development. These studies, however, analyzed the avian leg in a two-dimensional framework that was not capable of providing the translational and rotational modes of joint movement that are needed to fully understand the forces/torques placed on the leg skeletal system. Rubenson et al. [11] investigated the three-dimensional kinematics of the ostrich leg during a running gait and assessed the varus/valgus, internal/external rotation and abduction/adduction displacements of the stifle. Goetz et al. [12] and Main and Biwiener [13] conducted similar investigations of the emu leg, but their major focus was investigating the forces that produced deflections in the femur and tibia during a full gait cycle and comparing these forces to those found in humans.

Many biomechanical studies examining leg problems in the poultry industry focus primarily on measuring the strength and stiffness of bone, parameters that describe bone structural integrity. From the mechanobiology perspective [14], these parameters are very important when comparing the effects of new practices and treatments for improved production of animal meat. However, knowing the strength and stiffness of the bone is not sufficient for understanding the entire biomechanical behavior of the skeletal structure and the mechanics of a bird's "walking ability." The kinematics of the bird's leg joints, specifically the stiffe and hock joints, and the sequence of these joints' movement are critical pieces of information if producers are going to provide a better understanding of the causes of leg problems in commercial birds.

The study herein investigated the three-dimensional anatomical movement of the femur relative to the tibia during a simulated leg extension of broilers, layers and turkeys. The two types of chicken, broiler and layer, were chosen for this study to compare the differences that have been genetically bred into them for their preferred function and then compared with another commercial avian species, the turkey.

Chapter 2

Stifle (Knee) Studies

2.1 What Needs to be Measured?

The laboratory's initial goal is to create a process to study canine knees and artificial replacements for canine knees. To further this human knee studies were used as guides as to what procedure and equipment might be needed. Avian species were used to test the procedure and apparatus within the UGA laboratory.

Regarding the canine knee, there are many different measurements that are important and at least one that differs in regards to human knee kinetics. The angular relationship between the femur and tibia is different in canines and humans. Dogs naturally stand with their knee at a 140 degree angle, while humans stand upright with their knee at approximately 180 degrees.



Figure 2.1: Joint angles are defined by rotations occurring about the three coordinate axes. Flexion and extension is about the femoral fixed axis. Internal and external tibial rotation is about the tibial fixed axis. Abduction and adduction is about the floating axis. This is true for all species that have six-degrees-of-freedom about the stifle (knee). [1]

Flexion and extension is the primary motion of the stifle (knee) joint (Figure 2.1), but during the motion the femoral condyles will roll and slide on the tibial table; in addition cranial and caudal displacement, compression and distraction, internal and external rotation, varus and valgus angulation, as well as lateral and medial translation will occur [15]. Analysis of this movement must also consider the ligaments of the stifle, since they are integral for joint stability. The human knee has four independent axes of movement: patella, posterior condylar, distal condylar and longitudinal axes, which create a complex helical motion of the joint [16]. Budsberg [17] indicated that cranio-caudal and medio-lateral translation of the femur and tibia, tibial rotation and caudal slope must be determined for success of stifle implants.



Figure 2.2: The Joint Coordinate System for the stifle joint is shown above for the femur (thigh bone) and tibia (shank bone). The X, Y, and Z axis are marked on each bone. The figure above is a left chicken leg. The femur (the thigh bone) of the chicken leg above has the following markers: GT:Greater trochanter, LEP:Lateral epicondyle, and MEP:Medial epicondyle. The tibia (the shank bone) of the chicken leg above has the following markers: PTC:Proximal tibial crest, DTC:Distal tibial crest, MMA:Medial malleolus, LMA:Lateral malleolus. The femur uses the GT and LEP to describe the Z-axis and the MEP and LEP to describe the Y axis, while the X-axis is the floating axis which points towards the front of the leg. The tibia uses the DTC and PTC to describe the Z-axis, the MMA and LMA to describe the Y-axis, and the X-axis is again the floating axis that points towards the front of the leg.

The 6-degrees-of-freedom kinematic analysis has had few studies using non-human subjects. There is a single study by Colborne et al. [18] consisting of five dogs using a spatial linkage anchored to bone planes. There were changes in joint degrees of freedom observed after anterior cruciate ligament transection and the measurements varied considerably from animal to animal. There have also been some studies done by Torres et al. [19] on canines, Goetz et al. [12] on the emu, Gatesy et al. [20] on the Guineafowl, and Rubenson et al. [11] on ostriches that have varying degrees of success at looking at kinematic motion of animal legs.

2.2 Measurement Techniques

In the area of knee research many tools have been used. To analyze the stifle (knee) Tashman et al. [21] used a biplane video-radiograph apparatus to determine the six degrees of freedom of the canine tibia relative to the femur. During early/mid stance the values prior to pawstrike as well as the maximum, minimum, and midpoint and range of motion were recorded. Knee kinetics have been measured using goniometers and reflective markers by attaching them to the skin; the movement of the bones versus the skin, especially on the thigh, has been found to vary; calling into question the usefulness of such a device [22–24].

Jaegger et al. [25] evaluated the reliability of goniometry in Labrador Retrievers and found that the results of the goniometer were not significantly different from radiographic measurement. The mean degree of flexion of the stifle joint was 42° , with a standard deviation of 2° and a median of 41° . The mean degree of extension was 162° , with a standard deviation of 3° and a median of 162° . In stark contrast Freeman et al. [26] state that "in living subjects conventional (non-instrumented) goniometers are only useful statically and even then they can be at least 10 degrees inaccurate with respect to flexion whilst longitudinal rotation and varus/valgus cannot be measured at all."

Ultrasonographic, magnetic resonance and computed tomographic images are other techniques used to compare experimental data that describes canine knee displacement [27]. Korvick et al. [28] has provided some three-dimensional kinematics of the intact knee using instrumental spatial linkage and radiophotogrammetry, and studied flexion/extension, internal/external rotation and abduction/adduction kinematics in the swing phase and flexion/extension in the stance phase. It was found that the intact stiffe had an increase in internal rotation with an increase in abduction.

An advanced measurement technique is using multiple cameras to view a point (or marker) and then triangulate its location based on the position of each camera and the position of the marker in the field of view of each camera to get a relative position in three dimensional space to a global coordinate system based on the calibrated field. The Vicon motion system collects data by taking still pictures, using several cameras, of a subject at a certain frame rate (hertz). The cameras read infrared reflections from markers placed on the subject. The Vicon software calculates where each marker is in three-dimensional space based on information it receives from at least 2 cameras. This is similar to animals detecting position and depth of an object in three-dimensional space by using two eyes. A user must label each marker in the computer system on a model that the software provides. The software then follows the markers through its movement over time.

Vicon motion systems are commonly used in human and animal motion studies. Michelson et al. [29] used a Vicon motion system to study the kinematics of ankle repair in human cadavers. MacWilliams et al. [30] did a three-dimensional kinematic and kinetic study of in-vivo, human, adolescent gait to determine the norms by using a Vicon motion system, a pressure plate and a force plate. Torres et al. [31] looked at the effect of changing the location of the reflective markers used in the Vicon motion system on noninvasive canine stifle kinematics. Squatting exercises in human adults were compared kinetically and kinematically by Flanagan et al. [32]. Even the leg movement of ostriches has been studied using the Vicon motion system by Rubenson et al. [11]. The use of the Vicon motion system is commonly used for three-dimensional motion tracking in scientific studies of humans and animals.

The system of motion tracking is not perfect. If there are large, quick movements the software "loses" the name of a marker and the user must redefine the marker in the system. Cameras may pick up random reflections, which may also show up as makers in the software and must be separated out from true makers by the user. The Vicon software is able to output an X, Y, and Z coordinate, with relation to a fixed global coordinate system based on the calibrated lab area, for each marker from each still frame picture. These coordinates

were used by the author to calculate the angles and rotations between the femur and tibia of the subjects as described in the computation portion of this thesis (Chapter 4).

2.3 History of the Knee Set-Up

Rather than studying legs of live animals it was chosen to use cadaver legs due to the invasive nature of the study. Obviously a cadaver leg will not produce motion without intervention and hence Knee Rigs, and various devices have been introduced that will allow cadaver leg motion. Cadaver legs from a variety of species have been used to study the stifle (knee) joint. Using six human cadaver knees, tested before and after implantation with a unicompartmental knee prosthesis and after implantation with a tricompartmental knee prosthesis it was found that the unicompartmental knee design, where the other compartments and knee ligaments are mostly left alone, "had the potential to restore or preserve normal kinematic function better than tricompartmental implants" [33]. Jojima et al. [34] used five human cadaver knees to evaluate the effects of partial posterior cruciate ligament release plus increasing posterior tibial slope "on the range of motion and stability characteristics of the knee after total knee arthroplasty done with correct femoral positioning and in a total knee arthroplasty done to make the knee excessively tight in flexion." It was found that "increasing posterior tibial slope is preferable for a knee that is tight in flexion during total knee arthroplasty." Jojima et al. [34]. Tapper et al. [35] characterized the three-dimensional joint motion of the intact ovine stifle joint and determined intra-subject variability in angular motion and joint flexion/extension was minor compared to the inter-subject variability. The authors suggested that future studies have multiple repetitions of a trial that allows variation due to the apparatus versus variation between subjects to be adequately acknowledged.

Many studies have used leg simulators, such as the Oxford Rig, for knee kinematic study where the simulator allows six degrees of motion at the joint, with the femur and tibia cut a specific distance above and below the joint, and removing various amounts of muscle and tissue; varying from preserving only the joint capsule and collateral ligaments to retaining the quadriceps and other major muscle groups [36–44]. The studies often maintain the quadriceps so that a force applied upon them will induce the joint to flex. The force used to induce stifle (knee) movement can thus be taken into account as one of the possible variables within the testing procedure.

2.4 Subjects for Experiments

2.4.1 Canine

Colborne et al. [18] found that there are large differences in kinematic patterns between Greyhounds and Labradors and concluded that analysis of joint kinetics should be breed specific. In a Labrador/Labrador mix breed study, Marsolais et al. [45] found a greater range of motion of the hip joint when healthy dogs swam compared to when they walked, but that in dogs with a cranial cruciate ligament rupture the hip joint range of motion did not vary between the two situations.

Colborne et al. [18] compared Labradors and Greyhounds and found the kinetics of each breed to be sufficiently different so that the authors recommended future studies use similar breed dogs for future research, rather than mixed-breed or various pure-breed canines. Chailleux et al. [46] used large breed dogs giving a better understanding of the 3D canine stifle kinematics of MRIT (modified retinacular imbrication technique) and TPLO-M (tibial plateau leveling osteotomy -Montavon), and the studies by Marsolais et al. [45] done on Labrador or Labrador-mix breed dogs found that aquatic rehabilitation of cranial cruciate ligament ruptures gives a better outcome then walking alone. Therefore, future experiments will focus on the hind legs of Labrador or Labrador mix breed dogs, which are considered the primary breed and size of dog that will need to have knee replacement.

2.4.2 Avian

Many papers have already shown that avian species have a stifle (knee) joint, similar to a canine, which allows six-degrees-of-freedom [11–13]. The two types of chicken (broiler and layer) were chosen for this study to compare the differences that have been genetically bred into them for their preferred function (similar to the idea of comparing Labrador and Greyhound canine breeds) with both compared with another commercial avian species, the turkey.

2.5 Why Are the Muscles Removed?

The articular surface of the stifle (knee) joint affects its kinematics. The study herein discusses the kinematics of the stifle joint, focusing on its articular surfaces and the ligaments within the joint capsule, with its excess tissue removed. Using a mathematical model and a cadaveric knee in a testing Rig, Wilson et al. [47] found that passive knee flexion is guided by articular contact and isometric fascicles of the anterior cruciate ligament, posterior cruciate ligament, and medial cruciate, which are all contained within the stifle's joint capsule. The bearing surface geometry of the knee has a major effect on kinematics [48]. Fitzpatrick et al. [49] made a statistical shape model of the knee because it was reported as a major determinant of patellar tracking, and the authors wanted to correlate the articular geometry and function (kinematics and contact mechanics) of the knee. Pandit et al. [50] did in-vivo analysis of four total knee replacement designs regarding their effect on the knee kinematics. It was found that kinematics primarily depends on the surface geometry of the femur, tibia, and shapes of the patella and trochlear groove. Amiri et al. [51] studied the tibial geometry to identify the roles that its features have in knee motion, and found that the medial meniscus promoted internal rotation and the lateral meniscus and medial aspect of the tibial eminence confined the tibia's internal rotation. Mesfar et al. [52] developed a finite element model based on the three-dimensional geometry of the stifle joint's bones, cartilage, menisci, and ligaments and found that increasing the force on the quadriceps increased forces on the anterior cruciate ligament, patellar tendon, contact forces per area, and the joint's resistant moment. The patellofemoral contact force per area increased during flexion, but all other factors decreased. This literature indicates that the muscle tissue is not the major contributor to the kinematics of the knee. The articular surface and items inside the joint capsule were studied in the manuscript herein as the literature has shown they have the greatest impact on the stifle movement.

Chapter 3

Materials and Methods

3.1 Apparatus Used

There is a history of using cadaver knees for in vitro studies of human and canine knees [33, 34, 46]. Using the Munich Knee Joint Simulator, Frey et al. [53] argued that individual or single knee data is needed since the non-linear elastic joint properties would be lost due to the large inter-individual variations when using averaged data of several knee joints. Chailleux et al. [46] looked at three-dimensional stifle kinematics by using the cadavers of large-breed dogs and electromagnetic movement sensors. The "range of motion was induced by applying 100 N of traction on the quadriceps tendon and recorded with electromagnetic movement sensors for the intact stifle (control)." The study took the stifles and looked at two techniques, modified retinacular imbrication technique (MRIT) and tibial plateau leveling osteotomy - Montavon (TPLO-M), and gave an objective look at their effects on canine stifle kinematics.

As described by Zavatsky [2], the Oxford Knee-Testing Rig has an ankle assembly that allows flexion/extension, abduction/adduction, and internal/external rotation about the knee joint, while the hip assembly allows flexion/extension, abduction/adduction, and allows vertical displacement relative to the ankle assembly. The vertical displacement allows the leg to stand or squat, thus allowing for the knee to flex and extend while in the Rig. While the Oxford Rig design does provide constraints at the hip and ankle joints that are not the physiological norm, its design has been accepted in the biomechanical research world and has been shown to capture the characteristics of stifle (knee) joint movement as well as other in-vitro systems [54].



Figure 3.1: The Oxford Rig design above was shown by Zavatsky [2]. It allows the stifle (knee) joint to flex based on the sliding of the hip joint, down the sliders. The ankle allows for a variety of rotations and the hip allows for translations.

The Oxford Rig was designed for biomechanical testing on human cadaver knees, which would allow six degrees of freedom of the joint during a flexed-knee movement. Zavatsky [2], proved mathematically that the "hip" and "ankle" of the Rig's assemblies combined to allow the appropriate six-degrees-of-freedom based on screw theory and the physiological norm range of motion during a knee-joint movement. The six independent parameters about a joint are normally taken to be three translations and three rotations, known as Euler or Cardan angles. One can also look at a "screw axis" which would be the general displacement about a line which is accomplished by translation along that line [55]. Zavatsky uses the screw axis, and screw theory, of the ankle, knee and hip to mathematically prove that the Oxford Rig allows the knee the requisite six-degrees-of-freedom.

Ramappa et al. [56] studied human cadavers using an Oxford Rig to review the patellofemoral mechanics and kinematics based on the Q-angle and other changes to the knee joint. Using an Oxford Rig, Browne et al. [57] studied the effects of knee arthroplasty on human cadaver knees. Patil et al. [33] studied kinematics of the human knee comparing a physiological normal knee to a knee with a uni-compartmental total knee replacement. D'Lima et al. [58] also looked at a human cadaver knee prosthesis using an Oxford Rig.

Based on human kinesiology, an Oxford Rig that tests the degrees-of-motion and angulation in-vitro was chosen as the mechanical device that would allow control of the stifle (knee) joint during dynamic flexion. The Rig used in the experimentation described herein, the UGA/Oxford Rig (Figure 5.5), had a universal joint as the ankle assembly and sliders in the X, Y, and Z directions at the hip joint. The knee joint was initially in a flexed position and then extended by pulling, parallel to the femur, on a clamp attached to the quadriceps muscles which were still attached to the patellar ligament. The use of a muscle clamp allows for the measurement of the force needed to move the leg from a flexed position to an extended position. The X and Y-axis sliders at the hip joint allow for the hip and hock (ankle) to line up naturally, rather then a specific position such as directly above one another.

3.2 Flowchart of Experiment

In figure 3.2 is a flowchart with a description of the overall process that was used for the experiment. A more detailed explanation of the steps may be found in the following chapters and sections.

For the data collection, each specimen's leg was disarticulated at the hip joint, allowing for just the leg to be frozen and later thawed. After thawing a leg for 12 hours the leg was prepared by removing most of the muscles, except the quadriceps, and the attachments within the joint capsule. K-wires (thin, stiff wire that has a sharpened point that may be used as a drill bit into bone) were drilled into the bony prominences of the femur and tibia, and markers applied to them, as required for later computation. Because some of the markers that were needed to correctly predict the angles (example: flexion) would be covered up when the leg is attached to the Oxford Rig, an anatomical picture was taken that allowed for finding the positions of markers that will be removed in relation to markers that will remain on the leg. Next the leg was potted (cement is used to attach the leg to pots that are then bolted into the Oxford Rig), and dynamic trials were run. The dynamic trials consisted of the leg starting at a flexed position and the quadriceps being pulled in an upward manner parallel to the femur. The X, Y, Z coordinates of each marker was computed by the Vicon Motion System and is the exported into excel files.

The stifle (knee) angles and rotations were computed from the excel files output by the Vicon Motion System. Programs were written in MATLAB (contained in Appendix A) that used data from an anatomical picture as well as five dynamic trials collected for each leg. The computations are described in the Calculations chapter (Chapter 4). The flexion/extension, internal/external rotation, and abduction/adduction information for each trial of each leg was output into excel.

Each of the trials that were analyzed was moved to a single excel tab for each leg. Thus,

there were five sets of data for each tab, and multiple tabs within a file with each representing a different leg for a specific type of bird; one file per bird type. The data was then graphed in excel to give an initial view of the relationship of flexion to axial rotation and flexion to abduction.

This data was loaded back into MATLAB where another customized program was written to analyze the data looking for linear or non-linear relationships of the data, in flexion versus axial rotation and flexion versus abduction. Only one trial was used for summation between specimens, and this was determined by the R^2 value of the data to its best fit line. The type of line that was used was determined by a Partial F-test of linear and 2^{nd} order polynomial approximations of the data. Finally mean rates of motion were modeled for each bird type.



Figure 3.2: The Flowchart shows the steps of the experiment and analysis.

3.3 Specimens and Tissue Handling

The poultry for the study, including the layers, broilers, turkeys, and Athens'-Canadians were obtained from previous, unrelated studies conducted at the University of Georgia Poultry Research Facility, Athens, GA, USA. These specimens were observed prior to death and were not obviously lame. The samples used were limited by availability as our lab obtained birds from other studies rather than procuring and raising them ourselves. The birds were sacrificed by cervical dislocation and the legs were disarticulated at the hip. Each leg was placed in a freezer at -43 degrees C within 30 minutes of death.

The 1996-Broilers were obtained from North Carolina State University, from Dr. Edgar Ovideo's lab. Similar to the Athens'-Canadian chickens who had their genetic breeding selection stopped in the 1950s, the 1996-Broilers' genetic breeding selection was halted in 1996. The birds, all female, were sacrificed, had their legs disarticulated at the hip and were frozen prior to their being picked-up by the University of Georgia. (As described in section 5.1 the data did not yield any conclusions for this type of bird.)

The canine samples that were used for testing the mechanics and procdure were obtained from previous, unrelated studies conducted at the University of Georgia Veterinary Research Facility, Athens, GA, USA. The canines were sacrificed by lethal injection and the legs were disarticulated at the hip. Each leg was placed in a freezer at -43 degrees C within 30 minutes of death.

Prior to testing, a leg was allowed to thaw to room temperature over 12 hours, the skin was removed and all muscles, except the quadriceps, were dissected away from the stifle joint capsule. Some muscle was left connected to the joint capsule to insure that the capsule was intact during testing. The quadriceps were retained in order to facilitate movement of the joint by putting a tensile load on the muscle. An anatomic picture was taken using the Vicon Motion System, which captured the legs with all the markers on it, prior to potting the leg. A potting procedure was used to attach the leg to the UGA/Oxford Rig that was used during the dynamic portion of the experiments. To attach the leg to the testing device, the proximal end of the femur and distal end of the tibia were each inserted into half-inch PVC caps where the bottom of each cap had been machined in order to hold a half-inch bolt. This bolt allowed the leg to be secured to the testing device, an Oxford Rig which is described in sections 3.1, 3.4, and 5.2.1. Quick setting cement was used to hold the leg in each PVC cap.

3.4 Instrumentation

An Oxford Rig, the UGA/Oxford Rig, was used to produce controlled joint movement of cadaver leg joints, and to simulate the active movement of the poultry stifle during a standing motion. This method is commonly used in human knee studies, as described in the Apparatus Used section (Section 3.1) and shown in figure 5.5. Using the bolt in the PVC cap, the ends of the leg were connected to the Oxford Rig's universal joint as well as sliders, and then customized clamps were connected to the quadriceps. The universal joint and sliders allow three-dimensional movements at the leg-Rig interface, allowing the stifle to move in three translation modes of motion and three rotational modes of motion. The UGA/Oxford Rig differs from the Oxford Rig shown in figure 3.1 in that the UGA rig had a universal joint at the lower, hock (ankle) joint, and sliders in the X, Y, and Z direction to allow for the translations at the upper, hip joint. To initiate joint movement, the quadriceps' clamps were pulled in a manner that moved the muscle parallel to the long-axis of the femur, thereby mimicking the natural muscle forces used to flex the stifle. The force used to pull the quadriceps was monitored using a S-type load cell (OMEGADYNE Inc., Sunbury, OH, 0-25 lb), and this force ranged from 7.6 to 21.4 N, depending on the joint geometry during loading.



Figure 3.3: The figure above of a left chicken leg shows the placement of the reflective markers used in the anatomic picture as described in the text. The femur (the thigh bone) of the chicken leg above has the following markers: GT:Greater trochanter, THI:Marker for the thigh, LEP:Lateral epicondyle, and MEP:Medial epicondyle. The tibia (the shank bone) of the chicken leg above has the following markers: PTC:Proximal tibial crest, DTC:Distal tibial crest, SHA:Marker for the shank, MMA:Medial malleolus, LMA:Lateral malleolus.

K-wires (IMEX Veterinary Inc., Longview Texas, 0.0045 in. x 6 in.) were drilled into the femur and tibia at the following bony landmarks: greater trochanter, femoral head, caudal femur (described as THI in the marking system), lateral epicondyle, medial epicondyle, proximal tibial crest, distal tibial crest, medial tibia (described as SHA in the marking system), lateral malleolus, and the medial malleolus. The caudal femur and medial tibia markers were placed one-half the distance of the length of the bone after the cartilage was removed. Reflective markers were placed over the K-wires next to each bony landmark; these markers were used to track the movement of these bony landmarks throughout the test.



(a) Anatomical Picture

(b) Dynamic Picture

Figure 3.4: In the anatomic picture the turkey leg has all of the markers on the k-wires as described in the text. In the dynamic picture the turkey leg has been secured into the rig, requiring the removal of several markers, as described in the text.

The three-dimensional movement of the femur and tibia about the stifle joint was measured using a digital video system [59, 60]. Briefly, the camera system (Vicon MX03, Centennial, CO: Vicon Motion Systems Inc.) monitored light reflection off each marker and the Motus software (Ver. 8.5. Centennial, CO: Vicon Motion Systems Inc.) calculated each marker position within a three-dimensional test space as defined by the calibration L-frame geometry; the accuracy of these positions by the Vicon Motion system was \pm one mm. Two local coordinate systems, an anatomic and a dynamic marker coordinate system, were established and used to translate the collected raw motion data into the Joint Coordinate System parameters of joint flexion/extension, internal/external rotation and abduction/adduction [61]. The UGA/Oxford Rig design required that some markers be removed during testing; thus, a virtual marker technique was used [62], which is explained in section 4.2. One potential problem of the reflective marker system is poor reflection of light off of any one marker during a single test. Therefore, five repetitions of each test were done before the leg was removed from the Oxford Rig. The first good data collection repetition, as defined by the R^2 value of its Pearson correlation determined best-fit trendline (discussed in 5.1.3)), was used to analyze the kinematics of the leg's stiffe.

3.5 Statistical Analysis

The relationship of the joint flexion to joint rotation was found using the Joint Coordinate System [61] (see Chapter 4 on Calculations). A curve fit (based on Pearson's correlation coefficient and described in section 5.1.3) of this relationship was found and the curve fit parameters were used to determine significant differences among the broiler, layer and turkey stifles. In a similar manner, the relationship of stifle flexion to abduction was found and the curve fit parameters compared. The R^2 value of each curve fit was used to determine which of the five repetitions would be used. Starting at the initial run of a set, if the R^2 value was over 0.90 it was accepted; if not, the next run was reviewed. If none of the runs were over the initial threshold the R^2 value went down by decreasing increments of 0.05 of the R^2 values (0.85,0.80 etc.), until 0.65. A partial F-test was used, where $F_{critical}$ was determined to be approximately 4, to distinguish if the curve fit was linear or a 2^{nd} order polynomial. Significant difference was defined as an alpha of 0.05. Further detail may be found in section 5.1.3.
Chapter 4

Calculations

4.1 Summary

The following section describes the computational procedure and its program which assembles the three dimensional data from the Vicon computer system and translates it into flexion/extension, abduction/adduction, and internal/external rotation data used to describe stifle joint movement.

Computation Summary (details follow)

- Define Translation Vectors (tibia and femur)
- Create Initial Coordinate System's Rotation Matrices (Global to Local Coordinate System) from Anatomical Data (single frame)
- Create Virtual Marker Rotation Matrices from Anatomical Data
- Relate the Two Rotation Matrices from Anatomical Data
 - Initial and Virtual Rotation Matrices for Femur, and Initial and Virtual Rotation Matrices for Tibia

- Create Rotational Matrices of Dynamic Data with Virtual Markers
- Build Back All Markers Using Relationship of the Initial and Virtual Rotation Matrices for Dynamic Data
- Find Rotation Matrix between Thigh and Shank for Dynamic Data
- Calculate Angles based on Initial Coordinate System's Rotation Matrix between Thigh and Shank for Dynamic Data
 - flexion/extension, internal/external rotation, and abduction/adduction

4.2 Explanation of Redundant and Virtual Markers

Markers are used to denote movement of specific objects in three-dimensional-space for camera systems. When a specific point is important for defining angles (ex. flexion), but will be difficult for a camera system to visualize for the entire movement of the experiment, excess markers were put into place. (These markers are referred to as virtual markers and redundant markers.)

The virtual markers are markers that are required for computation of the leg's angles and rotations, but while initially *real*, are removed prior to the actual movement and testing of the leg because of the potting (process of cementing end of bone and a bolt into a PVC cap which allows attachment of the leg into the Rig) required to hold the leg in the testing Rig. If bony prominences are not used for markers one cannot compare leg to leg or have any repeatability. The virtual markers are thus captured in the anatomic picture in relation to redundant makers and *core* markers (markers that are required for computation and are never removed).

The redundant markers are generally added onto each leg and whose location is used only for that particular leg's calculations of the virtual markers. In the calculation section 4.3, the redundant markers are RTHI, right thigh, and RSHA, right shank. The marker placements are shown in figure 3.3.

Using calculations and the process described below, the placement of the original marker that can no longer be tracked, the virtual marker, is found by triangulation of the redundant points with the original point. Wang et al. [63] used virtual markers to study the human knee's articular bearing surfaces.

Following is the procedure for redundant or virtual markers described in Rahmatalla et al. [62].

$$\vec{P}_G = \vec{R}_{LG} + \mathbf{A}_{LG} \cdot \vec{P}_L \tag{4.1}$$

 \vec{P}_G : Is the global position of point P

 \vec{R}_{LG} : Is the location of the local coordinate system(L) to the global coordinate system(G), established by a combination of three permanent markers/points, with respect to the global coordinate system(G)

 \mathbf{A}_{LG} : Is the transformation matrix between the local coordinate system and the global coordinate system

 \vec{P}_L : Is the position of point P within the local coordinate system

 \mathbf{A}_{LG} can be represented in the following fashion, between the local coordinate system (L) and the global coordinate system (G):

$$\mathbf{A}_{LG} = \begin{bmatrix} x_L X_G & y_L X_G & z_L X_G \\ x_L Y_G & y_L Y_G & z_L Y_G \\ x_L Z_G & y_L Z_G & z_L Z_G \end{bmatrix}$$
(4.2)



Figure 4.1: The diagram above has two coordinate systems; the Global Coordinate System is denoted with G on the axes names, and the Local Coordinate System is denoted with L on the axes names. The diagram shows point P in relation to the Global Coordinate System, \vec{P}_G , and the Local Coordinate System, \vec{P}_L . It also shows the vector \vec{R}_{LG} that relates the distance and direction between the Global and Local coordinate systems. The final piece, \mathbf{A}_{LG} , which relates the rotation between the two coordinate systems is not shown in the diagram.

The position of P, in figure 4.1, within the local coordinate system can be found by rearranging the above equation. The global position of P can be found by using the camera system.

$$\vec{P}_L = \mathbf{A}_{LG}^T \cdot (\vec{P}_G - \vec{R}_{LG}) \tag{4.3}$$

Point P is going to be removed, or occluded, due to the experimental set-up, but that specific position is required for future calculations. Three other points are necessary to allow for point

P to be recreated in three-dimensional space, in any given camera frame. These three points must not move independently of point P. In the case of this experiment the three points are all on the same bone as point P. Prior to the dynamic portion of the experiment an anatomic picture must be taken that shows all of the points, virtual and redundant, relative to each other. This allows the development of \mathbf{A}_{LG} and \vec{R}_{LG} between the three redundant points and point P.

4.3 Calculations of the Stifle Joint

The following calculations to set up a Local Coordinate System (LCS) for the thigh, a LCS for the tibia, a temporary thigh LCS, and a temporary shank LCS are all done on a single, anatomical, still frame of the leg.

As explained by Fu et al. [60] The LCS is set up based on the fixed markers on the femur and tibia. The markers have been placed on bony markers to increase their repeatability. The following calculations are based on the right leg. For the stifle joint, the femur and tibia are required to have the following markers applied:

On the femur:

RGT: Rt greater trochanter RLEP: Rt lateral epicondyle of femur RMEP: Rt medial epicondyle of femur RTHI: Rt thigh

On the tibia: RPTC: Rt proximal tibial crest RDTC: Rt distal tibial crest RMMA: Rt medial malleolus RLMA: Rt lateral malleolus RSHA: Rt shank

To define a LCS from the femur (thigh), the following process is used. Taking the Global Coordinate System (GCS) vector coordinates of the RLEP and RMEP, the LCS of Z-axis' unit vector is defined as follows [60]:

$$\vec{Z}t = \frac{(\vec{V}_{RLEP} - \vec{V}_{RMEP})}{|(\vec{V}_{RLEP} - \vec{V}_{RMEP})|}$$
(4.4)

The LCS of the X-axis unit vector is defined by taking the cross product of the GCS vector coordinates from RLEP to RGT and the LCS of the Z-axis' unit vector as described above [60].

$$\vec{Xt} = \frac{(\vec{V}_{RGT} - \vec{V}_{RLEP}) \times \vec{Zt})}{|(\vec{V}_{RGT} - \vec{V}_{RLEP}) \times \vec{Zt})|}$$
(4.5)

The final axis in the three-dimensional LCS, Y-axis, is defined by taking the cross product of the unit vectors from the Z and X-axis' as just defined [60].

$$\vec{Y}t = \vec{Z}t \times \vec{X}t \tag{4.6}$$

At this point a rotation matrix for the femur can be defined as the transpose of each of the X, Y, and Z-axis of its LCS as shown below. The term **rRg2t** stands for "right, rotation matrix, global to thigh."

$$\mathbf{rRg2t} = [\vec{X}t^T, \vec{Y}t^T, \vec{Z}t^T]$$
(4.7)

The translation vector for the femur is defined as the GCS' vector to the RLEP, where $rV\vec{g}2t$

stands for "right, translation vector, global to thigh."

$$r\vec{Vg2t} = \vec{V}_{RLEP} \tag{4.8}$$

The process to define the LCS' three axes for the tibia is similar to that of the femur. The global coordinate system (GCS) vector coordinates of the RLMA and RMMA are used to define the LCS of Z-axis' unit vector as follows [60]:

$$\vec{Zs} = \frac{(\vec{V}_{RLMA} - \vec{V}_{RMMA})}{|(\vec{V}_{RLMA} - \vec{V}_{RMMA})|})$$
(4.9)

The LCS of the X-axis unit vector is defined by [60]:

$$\vec{Xs} = \frac{(\vec{V}_{RPTC} - \vec{V}_{RDTC}) \times \vec{Zs})}{|(\vec{V}_{RPTC} - \vec{V}_{RDTC}) \times \vec{Zs})|}$$
(4.10)

The LCS of the Ys-axis' unit vector defined in the same manner as the femur, by the cross product of the LCS unit vectors of Zs and Xs axes.

The rotation matrix for the tibia can be defined as the transpose of each of the X, Y, and Z-axis of its LCS as shown below. The term **rRg2s** stands for "right, rotation matrix, global to shank."

$$\mathbf{rRg2s} = [\vec{X}s^T, \vec{Y}s^T, \vec{Z}s^T]$$
(4.11)

The translation vector for the tibia defined as the GCS' vector to the RLEP, where $rV\vec{g}2s$ stands for "right, translation vector, global to shank."

$$rV\vec{g}2s = \vec{V}_{RPTC} \tag{4.12}$$

Following a similar pattern the shank and thigh local coordinate systems and rotational matrixes are recalculated because of the constraints of the experimental set-up. To attach the leg to the Oxford Rig, the RGT from the femur as well as the RLMA and RMMA from the tibia are removed to allow the ends of the leg to be potted in a quick-drying cement apparatus that attaches to the Rig. Two additional makers are used on the leg to allow the recalculation of these lost points, RTHI and RSHA.

RTHI: Rt quadriceps marker (thigh marker)

RSHA: Rt gastrocnemius marker (shank marker)

For the femur, a new LCS, termed the "temporary thigh LCS" is computed. The "temporary thigh LCS" of the X-axis' unit vector is defined by taking the cross product of the GCS vector coordinates from RLEP to RTHI and the LCS of the Z-axis' unit vector as described above.

$$\vec{X}_{tTEMP} = \frac{(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}t)}{|(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}t)|}$$
(4.13)

Using the new X-axis (\vec{X}_{tTEMP}) , a new rotational matrix and translation vector are developed using the same equations as above. The original thigh LCS and "temporary thigh LCS" are related by the following equation:

$$\mathbf{Rt2t} = \mathbf{rRg2t}_{TEMP}^T \cdot \mathbf{rRg2t}$$
(4.14)

where $\mathbf{Rt2t}$ is the "rotational matrix of the thigh to the thigh," and $\mathbf{rRg2t}_{TEMP}$ is the rotational matrix of the "temporary thigh LCS." The translation vector is recomputed, where $rV\vec{g}2t_{TEMP}$ is the translation vector of the "temporary thigh LCS."

$$rV\vec{g}2t_{TEMP} = \vec{V}_{RLEP} \tag{4.15}$$

The original thigh LCS and "temporary thigh LCS" are related by the following equation:

$$V\vec{t}2t = rVg2t_{TEMP}^T \cdot rVg2t \tag{4.16}$$

where $V \vec{t} 2t$ is the "translation vector of the thigh to the thigh."

A similar process is followed by the tibia, where the new LCS, the "temporary shank LCS" is computed.

$$\vec{Z}s_{TEMP} = \frac{(\vec{V}_{RDTC} - \vec{V}_{RSHA})}{|(\vec{V}_{RDTC} - \vec{V}_{RSHA})|}$$
(4.17)

Using the new Z-axis $(\vec{Z}s_{TEMP})$, a new rotational matrix is developed using the same equations as above for the X and Y-axis. The original thigh LCS and "temporary thigh LCS" are related by the following equation:

$$\mathbf{Rs2s} = \mathbf{rRg2s}_{TEMP}^T \cdot \mathbf{rRg2s}$$
(4.18)

The translation vector is the same for both the tibia's original LCS and "temporary shank LCS."

The above calculations were necessary to allow for the original relationships between all of the markers to be determined and will later be used in identifying the angles and rotations of the stifle (knee) joint. This comprises all of the calculations required on a single, anatomical photograph. At this point, a dynamic data set is reviewed, where within each frame the following calculations are performed.

For the femur, the following calculations are done on the dynamic data:

$$\vec{Z}td = \frac{(\vec{V}_{RLEP} - \vec{V}_{RMEP})}{|(\vec{V}_{RLEP} - \vec{V}_{RMEP})|}$$
(4.19)

$$\vec{X}td = \frac{(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}td)}{|(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}td)|}$$
(4.20)

$$\vec{Y}td = \vec{Z}td \times \vec{X}td \tag{4.21}$$

$$\mathbf{rRg2t}_{TEMPd} = [\vec{X}td^T, \vec{Y}td^T, \vec{Z}td^T]$$
(4.22)

$$rV\vec{g}2t_{TEMPd} = \vec{V}_{RLEP} \tag{4.23}$$

To calculate back the points in the original thigh LCS, the following equations are done:

$$\mathbf{rRg2t} = \mathbf{rRg2t}_{TEMPd} \cdot \mathbf{Rt2t}$$
(4.24)

$$r\vec{Vg2t} = rVg2t_{TEMPd} \cdot Vt2t \tag{4.25}$$

For the tibia, the following calculations are done on the dynamic data:

$$\vec{Z}sd = \frac{(\vec{V}_{RDTC} - \vec{V}_{RSHA})}{|(\vec{V}_{RDTC} - \vec{V}_{RSHA})|}$$
(4.26)

$$\vec{X}sd = \frac{(\vec{V}_{RPTC} - \vec{V}_{RDTC}) \times \vec{Z}sd)}{|(\vec{V}_{RPTC} - \vec{V}_{RDTC}) \times \vec{Z}sd)|}$$
(4.27)

$$\vec{Y}sd = \vec{Z}sd \times \vec{X}sd \tag{4.28}$$

$$\mathbf{rRg2s}_{TEMPd} = [\vec{X}sd^T, \vec{Y}sd^T, \vec{Z}sd^T]$$
(4.29)

$$rV\vec{g}2sd = \vec{V}_{RPTC} \tag{4.30}$$

To calculate back the points in the original thigh LCS, the following equation was used:

$$\mathbf{rRg2s} = \mathbf{rRg2s}_{TEMPd} \cdot \mathbf{Rs2s}$$
(4.31)

Recall that the directional vector did not change for the shank's original LCS and temporary LCS, therefore it was not recalculated.

A rotational matrix was used to relate the thigh to the shank:

$$\mathbf{rRt2s} = \mathbf{rRg2t}^T \cdot \mathbf{rRg2s}$$
(4.32)

where **rRt2s**, stands for "right, rotational matrix, thigh to shank." From this matrix, the flexion/extension, abduction/adduction, and axial rotation angles can be computed using Euler Angles.

4.4 Euler Angles

Discussions of how to create rotation matrixes and solve for the angles within the rotational matrix are discussed by Woltring [64], Cappozzo et al. [59], Grood and Suntay [65], and can be found in many other journals and books. When looking at a standard two-dimensional graph with an X and Y axis, the rotational matrix is written below for a counter-clockwise rotation, i.e. from the X-axis to the Y-axis.

$$\mathbf{R}(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta\\ \sin\theta & \cos\theta \end{bmatrix}$$
(4.33)

What this is actually doing, is rotating column vectors using matrix multiplication as shown below:

$$\begin{bmatrix} X^{1} \\ Y^{1} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix}$$
(4.34)

By solving the above matrix equations, one can determine the new coordinates of X and Y, now X^1 and Y^1 , after the rotation has taken place.

$$X^1 = X\cos\theta - Y\sin\theta \tag{4.35}$$

$$Y^1 = X\sin\theta + Y\cos\theta \tag{4.36}$$

A clockwise rotation results in a negative vector rotation ($\theta = -90$ degrees), and positive ($\theta = +90$ degrees), if counter-clockwise. The following is a counter-clockwise rotational matrix:

$$\mathbf{R}(-\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$
(4.37)

Below are three rotation matrices that show three-dimensional rotation about the X, Y, or Z-axis. The vector rotations are counter-clockwise with regards to the axis.

$$\mathbf{R}_{X}(\psi) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{bmatrix}$$
(4.38)

$$\mathbf{R}_{Y}(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$
(4.39)
$$\mathbf{R}_{Z}(\phi) = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
(4.40)

The pattern for rotation has been established by several manuscripts for the stifle joint [19,31,60]. Using counter-clockwise/right-handed rotation, an orthogonal matrix with Euler angles ψ , θ , ϕ , (psi, theta, phi) with Z-Y-X convention, is given by

$$\mathbf{R} = \mathbf{R}_Z(\phi) \times \mathbf{R}_Y(\theta) \times \mathbf{R}_X(\psi) \tag{4.41}$$

$$\mathbf{R} = \begin{bmatrix} \cos\psi \cdot \cos\theta & \cos\psi \sin\theta \sin\phi - \sin\psi \cos\phi & \sin\psi \sin\phi + \cos\psi \sin\theta \cos\phi \\ \sin\psi \cdot \cos\theta & \sin\psi \sin\theta \sin\phi + \cos\phi \cos\psi & \sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi \\ -\sin\theta & \cos\theta \sin\phi & \cos\theta \cos\phi \end{bmatrix}$$
(4.42)

The stifle joint's rotation matrix was calculated as shown above, in equation 4.42 with the joint motion described as the distal segment relative to the proximal segment. The joint motions' axes were described by three non-orthogonal unit vectors. The flexion/extension axis was fixed on the proximal segment, the femur. The axial rotation (internal and external rotation) axis was defined around the distal segment, the tibia, with the final vector describing abduction/adduction about the floating axis which was perpendicular to the femur and tibia axes.

Based on the rotational matrix \mathbf{R} , described above, the following angles of the stifle joint may be determined:

$$\phi = \text{flexion/extension} = atan 2 \frac{\mathbf{R}(2,1)}{\mathbf{R}(1,1)} \cdot \frac{180}{\pi}$$
(4.43)

$$\theta = \text{axial rotation} = -asin(\mathbf{R}(3,1)) \cdot \frac{180}{\pi}$$
(4.44)

$$\psi = \text{abduction}/\text{adduction} = atan 2 \frac{\mathbf{R}(3,2)}{\mathbf{R}(3,3)} \cdot \frac{180}{\pi}$$
(4.45)

where asin describes the arcsine, and $atan2^{1}$ describes the arctangent with special properties that allow it to be defined in all four quadrants. The multiplication of "180/ π " is required to change the output of the above equations from radians to degrees.

¹atan2 is used within MATLAB and was originally FDLIBM that was developed by SunSoft, a Sun Microsystems business, by Kwok C. Ng, and others. For information about FDLIBM, see http://www.netlib.org.

Chapter 5

Findings of Experiment

5.1 Results

In total fifteen Layer (Highline W36s, 19 months old, 4.5-5 lb), thirteen 1996-Broiler, four Broiler (Cobb, six to eight weeks old, 5.5-8 lb), two Athen's-Canadian (6 lb), five Turkey (Nicholas, 12 weeks old, 14.25-15.5 lb), and twelve dog (Beagle, 17.4-22.4 lb) legs were tested in the apparatus to set-up the Oxford Rig to run poultry and canine legs. Three of the Turkey legs ended up with their joint capsules being broken into during the set-up process, as was one canine leg. Of the canine legs, three had problems with the set-up of the process. The study for the initial manuscript was to look at poultry, so no canine data was to be published at this point. Both of the Athen's-Canadian legs were found to be "bad," as were five of the 1996-Broilers', and five of the Layer's. Two of the Layers' legs were used for the initial practice set-ups, and one of the Layer's legs was actually broken. When looking at the data collected for the 1996-Broilers, two legs had set-up problems and most of the legs had such poor collection due to reflections of the markers being unstable; the remainder of the data was deemed unusable. In total, data was procured for four broilers, six layers, and one excessive marker fade-out or random reflections.



Figure 5.1: The flexion of the joint angle is described such that as the femur (thigh) moves towards the tibia (shank) in an anatomically correct fashion, the system moves from 0 degrees to -10,-20, etc. Therefore a turkey leg moves from a squat at -100 degrees to a standing position of -60 degrees. This forty degrees of movement could also be said to occur from a squat of 80 degrees, where the tibia is slightly less than a typical 90 degree sit, to a standing position of 120 degrees which is less than the human 180 degrees.

Figure 5.1 explains the numeric interpretation of the flexion angles. The kinematic data indicates that as the cadaver legs were moved from the bend position $(-100^{\circ} \text{ flexion})$ to a straighter position $(-60^{\circ} \text{ flexion})$ for turkeys (layers were -80° to -40° , broilers were -60° to -20°), two modes of rotational movement of the stifle occurred.

The first mode of movement involved the femur moving away from the central line of the body relative to the tibia; this is joint abduction (+ adduction, -abduction). The average rate of abduction for the four turkey legs was found to be a 2^{nd} order polynomial by a partial F-test (over a 1^{st} order polynomial) with $F_{critical}$ approximately equal to 4, but the value of the X^2 component of the polynomial was in the realm of 1/10,000 and over the forty degrees of flexion was considered null. (This is further explained in section 5.1.3) The layers' and broilers' value of the X^2 component of the polynomial was in the realm of 1/1,000 and over the forty degrees of flexion was also considered null. Therefore the abduction for all three bird groups was considered linear. The average rate abduction angle was 0.2 degrees per degree of flexion and the standard deviation of the slope was \pm 0.1 degrees for turkeys, 0.2 ± 0.1 for the broilers, and 0.4 ± 0.6 for the layers.

The second mode of rotation involved the femur rotating generally outwardly, resulting in external rotation of the stiffe (Figures 5.2, 5.3, 5.4)(+ internal rotation, - external rotation). The Partial F Statistic for the axial rotation of the layers stated that a 2^{nd} order polynomial was statistically significant over a 1^{st} order polynomial (linear model) with $F_{critical}$ approximately equal to 4. The femur showed internal rotation relative to the tibia at a rate of 0.3° per degree of flexion at the initial flexion (from a standing position) and an external rotation of 0.5° per degree of flexion at the end of leg flexion (in a squat position)for the layers (Figure 5.2). The data for the broilers gave a Partial F Statistic that again showed a need for a 2^{nd} order polynomial. The broilers showed internal rotation at a non-linear rate of 0.7° per degree of flexion at the end of leg flexion (from a standing position) and 0.6° per degree of flexion at the beginning of leg flexion (from a standing position) and 0.6° per degree of flexion at the end of leg flexion (in a squat position)(Figure 5.3). For the turkey legs, the Partial F Statistic showed the need for a non-linear model, where the rate of internal rotation began at 0.5° per degree of flexion and ended at an external rate of 1.1° per degree of flexion (Figure 5.4).



Figure 5.2: The non-linear relationship of flexion of the joint angle to its axial rotation for the Layer specimens is shown above. The Layer leg moves from a squat at -80 degrees to a standing position of -40 degrees.

Figure 5.3: The non-linear relationship of flexion of the joint angle to its axial rotation for the Broiler specimens is shown above. The Broiler leg moves from a squat at -60 degrees to a standing position of -20 degrees.

Figure 5.4: The non-linear relationship of flexion of the joint angle to its axial rotation for the Turkey specimens is shown above. The Turkey leg moves from a squat at -100 degrees to a standing position of -60 degrees.

5.1.1 Example of Calculations with Data

Following the process described in the Materials and Methods (Chapter 3) the following data was collected during the anatomic picture for a leg, and subsequently dynamic data was given as well. Below is a list of the markers used for computation where the X, Y, Z, coordinates are listed with regards to the Global Coordinate System in units of meters.

The sequence of equations in this subsection begins with equation 4.4. Below are the equations and the numerical calculations given the data for an anatomic and dynamic data trial. Only one frame of dynamic data is used to illustrate the computations. The data was taken of a right turkey leg and the computations have been written to show four decimals. The data presented was input into the MATLAB programs written in Appendix A, and output of the computations was derived from its execution. All steps can also be followed within the code presented in Appendix A. Below are data points taken from a single frame of an anatomic data picture and later a single frame of a dynamic data series. The coordinates are in meters and are referenced to a Global Coordinate System defined by an L-frame in which the space was calibrated. This data was exported out of the Vicon Motions Capture System.

Anatomic Data Calculations (listed below are the data points for the given markers, from an Anatomic frame of data in meters) On the femur: RGT: Rt greater trochanter (0.1788, 0.2225, 0.2755) RLEP: Rt lateral epicondyle of femur (0.2803, 0.2058, 0.2576) RMEP: Rt medial epicondyle of femur (0.2815, 0.2483, 0.2396) RTHI: Rt thigh (0.2304, 0.2301, 0.2511)

On the tibia:

RPTC: Rt proximal tibial crest (0.3201, 0.2189, 0.2534)

RDTC: Rt distal tibial crest (0.3203, 0.2359, 0.2247)

RMMA: Rt medial malleolus (0.3098, 0.241371, 0.0575)

RLMA: Rt lateral malleolus (0.3031, 0.2106, 0.0572)

RSHA: Rt shank (0.306164, 0.21064, 0.12766)

Calculations for Original Markers (Not Including Redundant Markers)

$$\vec{Z}t = \frac{(\vec{V}_{RLEP} - \vec{V}_{RMEP})}{|(\vec{V}_{RLEP} - \vec{V}_{RMEP})|}$$
(5.1)

$$\vec{Zt} = \frac{((0.2803, 0.2058, 0.2576) - (0.2815, 0.2483, 0.2396))}{|((0.2803, 0.2058, 0.2576) - (0.2815, 0.2483, 0.2396))|}$$
(5.2)

$$\vec{Zt} = (-0.0013, -0.0458, 0.0194)$$
 (5.3)

$$\vec{Xt} = \frac{(\vec{V}_{RGT} - \vec{V}_{RLEP}) \times \vec{Zt})}{|(\vec{V}_{RGT} - \vec{V}_{RLEP}) \times \vec{Zt})|}$$
(5.4)

$$\vec{Xt} = \frac{((0.1788, 0.2225, 0.2755) - (0.2803, 0.2058, 0.2576)) \times (-0.0013, -0.0458, 0.0194))}{|((0.1788, 0.2225, 0.2755) - (0.2803, 0.2058, 0.2576)) \times (-0.0013, -0.0458, 0.0194))|}$$
(5.5)

$$\vec{Xt} = (0.0116, 0.0198, 0.0475)$$
 (5.6)

$$\vec{Y}t = \vec{Z}t \times \vec{X}t \tag{5.7}$$

$$\vec{Y}t = (-0.0013, -0.0458, 0.0194)) \times (0.0116, 0.0198, 0.0475)$$
 (5.8)

$$\vec{Y}t = (-0.0512, 0.0058, 0.0102)$$
 (5.9)

$$\mathbf{rRg2t} = [\vec{X}t^T, \vec{Y}t^T, \vec{Z}t^T]$$
(5.10)

$$\mathbf{rRg2t} = \begin{bmatrix} 0.2207 & -0.9750 & -0.0262 \\ 0.3749 & 0.1096 & -0.9206 \\ 0.9004 & 0.1934 & 0.3897 \end{bmatrix}$$
(5.11)

$$r\vec{Vg2t} = \vec{V}_{RLEP} \tag{5.12}$$

$$r\vec{Vg2t} = (0.1788, 0.2225, 0.2755) \tag{5.13}$$

$$\vec{Zs} = \frac{(\vec{V}_{RLMA} - \vec{V}_{RMMA})}{|(\vec{V}_{RLMA} - \vec{V}_{RMMA})|})$$
(5.14)

$$\vec{Z}s = \frac{((0.3031, 0.2106, 0.0572) - (0.3098, 0.2413, 0.0575))}{|((0.3031, 0.2106, 0.0572) - (0.3098, 0.2413, 0.0575))|})$$
(5.15)

$$\vec{Zs} = (-0.0107, -0.0490, -0.0004)$$
 (5.16)

$$\vec{Xs} = \frac{(\vec{V_{RPTC}} - \vec{V_{RDTC}}) \times \vec{Zs})}{|(\vec{V_{RPTC}} - \vec{V_{RDTC}}) \times \vec{Zs})|}$$
(5.17)

 $\vec{Xs} = \frac{((0.3201, 0.2189, 0.2534) - (0.3203, 0.2359, 0.2247)) \times (-0.01076, -0.04906, -0.0004)}{|((0.3201, 0.2189, 0.2534) - (0.3203, 0.2359, 0.2247)) \times (-0.0107, -0.0490, -0.0004)|}$ (5.18)

$$\vec{Xs} = (0.04642, -0.00940, -0.0052) \tag{5.19}$$

$$\mathbf{rRg2s} = [\vec{X}s^T, \vec{Y}s^T, \vec{Z}s^T]$$
(5.20)

$$\mathbf{rRg2s} = \begin{bmatrix} 0.9702 & 0.1129 & -0.2142 \\ -0.2116 & -0.0349 & -0.9767 \\ -0.1178 & 0.9930 & -0.0099 \end{bmatrix}$$
(5.21)

$$r\vec{Vg2s} = \vec{V}_{RPTC} \tag{5.22}$$

$$rV\vec{g}2s = (0.3201, 0.2189, 0.2534)$$
 (5.23)

Equations Necessary for Virtual and Redundant Markers (in meters)

$$\vec{X}_{tTEMP} = \frac{(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}t)}{|(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}t)|}$$
(5.24)

$$\vec{X}_{tTEMP} = \frac{((0.2304, 0.2301, 0.2511) - (0.1788, 0.2225, 0.2755)) \times (-0.0013, -0.0458, 0.0194))}{|((0.2304, 0.2301, 0.2511) - (0.1788, 0.2225, 0.2755)) \times (-0.0013, -0.0458, 0.0194))|}$$
(5.25)

$$\vec{X}_{tTEMP} = (0.0034, 0.0192, 0.0456)$$
 (5.26)

$$\mathbf{Rt2t} = \mathbf{rRg2t}_{TEMP}^{T} \cdot \mathbf{rRg2t}$$
(5.27)

$$\mathbf{Rt2t} = \begin{bmatrix} 0.0689 & 0.3872 & 0.9194 \\ -0.9973 & 0.0509 & 0.0533 \\ -0.0262 & -0.9206 & 0.3897 \end{bmatrix} \cdot \begin{bmatrix} 0.2207 & -0.9750 & -0.0262 \\ 0.3749 & 0.1096 & -0.9206 \\ 0.9004 & 0.1934 & 0.3897 \end{bmatrix}$$
(5.28)

$$\mathbf{Rt2t} = \begin{bmatrix} 0.9982 & 0.1531 & 0 \\ -0.1531 & 0.9962 & 0.0000 \\ 0.0000 & 0 & 1 \end{bmatrix}$$
(5.29)

$$r\vec{Vg2}t_{TEMP} = \vec{V}_{RLEP} \tag{5.30}$$

$$r\vec{Vg2}t_{TEMP} = (0.1788, 0.2225, 0.2755)$$
(5.31)

$$\vec{Z}s_{TEMP} = \frac{(\vec{V}_{RDTC} - \vec{V}_{RSHA})}{|(\vec{V}_{RDTC} - \vec{V}_{RSHA})|}$$
(5.32)

$$\vec{Z}s_{TEMP} = \frac{((0.3201, 0.2189, 0.2534) - (0.3061, 0.2106, 0.1276))}{|((0.3201, 0.2189, 0.2534) - (0.3061, 0.2106, 0.1276))|}$$
(5.33)

$$\vec{Z}s_{TEMP} = (0.0070, 0.0125, 0.0478)$$
 (5.34)

$$\mathbf{Rs2s} = \mathbf{rRg2s}_{TEMP}^T \cdot \mathbf{rRg2s}$$
(5.35)

$$\mathbf{Rs2s} = \begin{bmatrix} -0.9794 & 0.1768 & 0.0973 \\ -0.1451 & -0.95206 & 0.2694 \\ 0.1403 & 0.2498 & 0.9581 \end{bmatrix} \cdot \begin{bmatrix} -0.9702 & 0.1129 & 0.2142 \\ 0.2116 & -0.0349 & 0.9767 \\ 0.1178 & 0.9930 & 0.0099 \end{bmatrix}$$
(5.36)
$$\mathbf{Rs2s} = \begin{bmatrix} 0.9991 & -0.020 & 0.0361 \\ 0.0289 & 0.2843 & 0.9583 \\ -0.0296 & 0.9585 & -0.2853 \end{bmatrix}$$
(5.37)

Dynamic Data Calculations (listed below are the data points for the given markers, for one frame of dynamic data in meters)

On the femur:

RLEP: Rt lateral epicondyle of femur (0.3426, 0.1188, -0.0019)
RMEP: Rt medial epicondyle of femur (0.2977, 0.1213, -0.0170)
RTHI: Rt thigh (0.3086, 0.1318, 0.0382)

On the tibia:

RPTC: Rt proximal tibial crest (0.3557, 0.1531, -0.0424)

RDTC: Rt distal tibial crest (0.3319, 0.1729, -0.04218)

RSHA: Rt shank (0.2308, 0.1681, -0.0466)

$$\vec{Z}td = \frac{(\vec{V}_{RLEP} - \vec{V}_{RMEP})}{|(\vec{V}_{RLEP} - \vec{V}_{RMEP})|}$$
(5.38)

$$\vec{Z}td = \frac{((0.3426, 0.1188, -0.0019) - (0.2977, 0.1213, -0.0170))}{|((0.3426, 0.1188, -0.0019) - (0.2977, 0.1213, -0.0170))|}$$
(5.39)

$$\vec{Z}td = (0.0177, -0.0009, 0.0060)$$
 (5.40)

$$\vec{X}td = \frac{(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}td)}{|(\vec{V}_{RTHI} - \vec{V}_{RLEP}) \times \vec{Z}td)|}$$
(5.41)

$$\vec{X}td = \frac{\left(\left((0.3086, 0.1318, 0.0382) - (0.3426, 0.1188, -0.0019)\right) \times (0.0177, -0.0009, 0.0060)\right)}{\left|\left(\left(0.3086, 0.1318, 0.0382\right) - (0.3426, 0.1188, -0.0019)\right) \times (0.0177, -0.0009, 0.0060)\right)\right|}$$
(5.42)

$$\vec{X}td = (0.0032, 0.0186, -0.0063)$$
 (5.43)

$$\vec{Y}td = \vec{Z}td \times \vec{X}td \tag{5.44}$$

$$\vec{Y}td = (0.0177, -0.0009, 0.0060), \times (0.0032, 0.0186, -0.0063)$$
 (5.45)

$$\vec{Y}td = (-0.0046, 0.0058, 0.0148)$$
 (5.46)

$$\mathbf{rRg2t}_{TEMPd} = [\vec{X}td^T, \vec{Y}td^T, \vec{Z}td^T]$$
(5.47)

$$\mathbf{rRg2t}_{TEMPd} = \begin{bmatrix} 0.1589 & -0.2808 & -0.9465 \\ 0.9532 & 0.3501 & -0.0531 \\ -0.3164 & 0.8936 & 0.3182 \end{bmatrix}$$
(5.48)

$$r\vec{Vg2}t_{TEMPd} = \vec{V}_{RLEP} \tag{5.49}$$

$$rV\vec{g}2t_{TEMPd} = (0.3426, 0.1188, -0.0019)$$
(5.50)

$$\mathbf{rRg2t} = \mathbf{rRg2t}_{TEMPd} \cdot \mathbf{Rt2t}$$
(5.51)

$$\mathbf{rRg2t} = \begin{bmatrix} 0.1589 & -0.2808 & -0.9465 \\ 0.9532 & 0.3501 & -0.0531 \\ -0.3164 & 0.8936 & 0.3182 \end{bmatrix} \cdot \begin{bmatrix} 0.9982 & 0.1531 & 0 \\ -0.1531 & 0.9962 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
(5.52)
$$\mathbf{rRg2t} = \begin{bmatrix} 0.2000 & -0.2532 & 0.9465 \\ 0.8706 & 0.4891 & -0.0531 \\ -0.4495 & 0.8347 & 0.3182 \end{bmatrix}$$
(5.53)

For the tibia, the following calculations are done on the dynamic data (in meters):

$$\vec{Z}sd = \frac{(\vec{V}_{RDTC} - \vec{V}_{RSHA})}{|(\vec{V}_{RDTC} - \vec{V}_{RSHA})|} /$$
(5.54)

$$\vec{Z}sd = \frac{((0.3319, 0.1729, -0.04218) - (0.2308, 0.1681, -0.0466))}{|((0.3319, 0.1729, -0.04218) - (0.2308, 0.1681, -0.0466))|}$$
(5.55)

$$\vec{Z}sd = (0.0187, 0.0008, 0.0008)$$
 (5.56)

$$\vec{X}sd = \frac{(\vec{V}_{RPTC} - \vec{V}_{RDTC}) \times \vec{Z}sd)}{|(\vec{V}_{RPTC} - \vec{V}_{RDTC}) \times \vec{Z}sd)|}$$
(5.57)

$$\vec{X}sd = \frac{((0.3557, 0.1531, -0.0424) - (0.3319, 0.1729, -0.04218)) \times \vec{Z}sd)}{|((0.3557, 0.1531, -0.0424) - (0.3319, 0.1729, -0.04218)) \times \vec{Z}sd)|}$$
(5.58)

$$\vec{X}sd = (-0.0006, -0.0025, 0.0170)$$
 (5.59)

$$\vec{Y}sd = \vec{Z}sd \times \vec{X}sd \tag{5.60}$$

$$\vec{Y}sd = (0.0187, 0.0008, 0.0008) \times (-0.0006, -0.0025, 0.0170)$$
 (5.61)

$$\vec{Y}sd = (0.0008, -0.0152, -0.0022)$$
 (5.62)

$$\mathbf{rRg2s}_{TEMPd} = [\vec{X}sd^T, \vec{Y}sd^T, \vec{Z}sd^T]$$
(5.63)

$$\mathbf{rRg2s}_{TEMPd} = \begin{bmatrix} 0.1589 & -0.2808 & 0.9465 \\ 0.9532 & 0.3501 & -0.0531 \\ -0.3164 & 0.8936 & 0.3182 \end{bmatrix}$$
(5.64)

$$rV\vec{g}2sd = \vec{V}_{RPTC} \tag{5.65}$$

$$rV\vec{g}2sd = (0.3557, 0.1531, -0.0424) \tag{5.66}$$

To calculate back the points in the original thigh LCS, the following equation is done (in meters):

$$\mathbf{rRg2s} = \mathbf{rRg2s}_{TEMPd} \cdot \mathbf{Rs2s} \tag{5.67}$$

$$\mathbf{rRg2s} = \begin{bmatrix} 0.1589 & -0.2808 & 0.9465 \\ 0.9532 & 0.3501 & -0.0531 \\ -0.3164 & 0.8936 & 0.3182 \end{bmatrix} \cdot \begin{bmatrix} 0.9991 & -0.020 & 0.0361 \\ 0.0289 & 0.2843 & 0.9583 \\ -0.0296 & 0.9585 & -0.2853 \end{bmatrix}$$
(5.68)
$$\mathbf{rRg2s} = \begin{bmatrix} 0.0083 & 0.9724 & -0.2333 \\ 0.1173 & -0.2327 & -0.9654 \\ -0.9931 & -0.0193 & -0.1160 \end{bmatrix}$$
(5.69)

$$\mathbf{rRt2s} = \mathbf{rRg2t}^T \cdot \mathbf{rRg2s}$$
(5.70)

$$\mathbf{rRt2s} = \begin{bmatrix} 0.2000 & 0.8706 & -0.4495 \\ -0.2532 & 0.4891 & 0.8347 \\ 0.9465 & -0.0531 & 0.3182 \end{bmatrix} \cdot \begin{bmatrix} 0.0083 & 0.9724 & -0.2333 \\ 0.1173 & -0.2327 & -0.9654 \\ -0.9931 & -0.0193 & -0.1160 \end{bmatrix}$$
(5.71)
$$\mathbf{rRt2s} = \begin{bmatrix} 0.5502 & 0.0005 & -0.8350 \\ -0.7736 & -0.3761 & -0.5100 \\ -0.3144 & 0.9266 & -0.2065 \end{bmatrix}$$
(5.72)

Finally, the angles are computed from the rotation matrix, rRt2s.

$$\phi = \text{flexion/extension} = atan2 \frac{\mathbf{rRt2s}(2,1)}{\mathbf{rRt2s}(1,1)} \cdot \frac{180}{\pi}$$
(5.73)

$$\phi = -54.58 \tag{5.74}$$

$$\theta = \text{axial rotation} = -asin(\mathbf{rRt2s}(3,1)) \cdot \frac{180}{\pi}$$
 (5.75)

$$\theta = 18.32\tag{5.76}$$

$$\psi = \text{abduction}/\text{adduction} = atan2 \frac{\mathbf{rRt2s}(3,2)}{\mathbf{rRt2s}(3,3)} \cdot \frac{180}{\pi}$$
(5.77)

$$\psi = 102.5$$
 (5.78)

The flexion/extension angle denotes that the thigh is -54 degrees from a vertical position (review the explanation and diagram shown in figure 5.1). The axial rotation states that the stifle joint was rotated 18.32 degrees internally. The value of 102.5 degrees for ψ , shows that the leg was excessively abducted. These values were obtained from a turkey with a broken joint capsule which is why the abduction is so extreme; a more normal value would be 20 degrees of abduction.

5.1.2 Calculation Advantages and Disadvantages

The advantage of using the virtual and redundant calculation scheme was that it is comparatively simple to using a least squares fit model, for each and every point. While not exceedingly complex, the least squares fit model does require a significant amount of programming. The markers are on k-wires that are permanently affixed to the bone; it is unnecessary to be concerned with skin-marker movement which is the primary reason to use a least squares fit model.

The disadvantage of the system is the possibility of lost markers and minor movements of the markers on the k-wires. One of the problems coding the angle analysis was simply ensuring that the correct points were being called in the correct order within the sub-functions, which caused a delay in completing the code.

Using the next generation of UGA/Oxford Rig (as described in Chapter 6) simplifies the coding requirements. When using this new device none of the markers were covered or removed during experimentation as the entire pelvis to foot remained intact and visible to the camera system at all times therefore, redundant markers were unnecessary and half the code described within the Calculations chapter, Chapter 4, was unnecessary including the need for an anatomic picture. Assuming the k-wires would attach the markers to the bony prominences, there would also be no need for a least squares fit computation to deal with skin marker movement.

5.1.3 Statistics

Using the same marker system as described in section 5.1.1, the following is a brief analysis of the magnitude of change caused by changing the location of a marker on the leg. The Greater Trochanter marker was chosen (GT) to have its X-axis component to be moved by a positive one millimetre. The GT was chosen because while it affects the axes of the thigh (femur) it is not measured during the dynamic trials because the GT marker is removed during potting (prior to collection of dynamic data). This allows for simple changes to be made to a single marker and enables the analysis of what effects those changes have, without recalculating its position during a dynamic trial. The original position of GT was (0.1788, 0.2225, 0.2755) and was changed to (0.1798, 0.2225, 0.2755). The customized MATLAB program was run and the flexion for the first frame of dynamic data output changed from -54.58 to -54.45 degrees. The abduction and axial rotation remained the same, at 18.32 and 102.5, respectively. When the RGT's X-axis position was moved by a positive five millimetres to 0.1838 and the computations were re-run, the flexion output was -53.94, and the abduction and axial rotation did not change. A one millimetre change caused a 0.13 degree change, or approximately a 0.24 percent change in flexion. A five millimetre change caused a 0.51degree change, or approximately a 0.93 percent change in flexion. Torres et al. [66] discuss the changes caused by the change in marker location. (The axis system references are the same as shown in figure 5.5.) The experiment had a walking canine subject with ten markers on bony prominences and multiple positions for the GT; moving along the Z-axis (dorsal and ventral), and X-axis (cranial and caudal) as well as including the proper location of the GT (14 total markers). The experimental data for a single repetition was collected for all of the markers simultaneously; the dog walked once with all the markers on so that no aberration in a single gait cycle would affect the error calculations due to the movement of the GT marker. The waveform of flexion angle over the percent of the gait cycle remained the same, it was simply shifted up or down the flexion axis; the initial angle of flexion may be higher or lower then the normal GT marker. The calculations of the stifle (knee) joint flexion angle were found to change the most when the markers were moved along the Z-axis, when each of the additional markers were moved ± 2 centimetres from the normal GT.

Regarding statistical errors, there are two that will be considered; the Type I (falsepositive or a test rejects a true null hypothesis (H_0)) and Type II (false-negative or a test fails to reject a false null hypothesis (H_0)) errors [67]. The level of significance, denoted with the Greek letter alpha (α), is used to define the amount of possible Type I error. A Type I error standard, often cited in business, is a level of six-sigma, or ±4.5 standard deviations of the mean of a normal distribution. Translating, that would mean out of every one million parts (1,000,000,000) only 3.4 parts could have a single defect. For many processes six-sigma is well beyond what quality level is required, but for a process such as the US Post Office delivering mail, it is actually not tight enough. In 2007, the US Post Office delivered an average of 703 million pieces of mail per day [68]. With a Type I error rate of six-sigma, the Post Office would incorrectly deliver an average slightly over 2,390 pieces of mail per day.

Regarding Type II errors, the false-negative rate, is denoted by the Greek letter beta (β) . The sensitivity or power of a test is determined by 1 minus β . If a Type II error occurs in research, a scientist would not find an effect that is actually present. One of the only ways to decrease both the Type I and Type II errors associated with a test, without actually improving the test itself, is to increase the amount of data or trials used in the analysis.

As described in section 3.5 and section 5.1, the experimental statistics within this thesis used an $\alpha = 0.05$, which is the probability of a Type I error. In calculating the Partial F Statistic (as shown in Appendix B), the following equation was used:

$$F = \frac{(RSS1 - RSS2)}{1} \div \frac{RSS2}{nr - 2}$$
(5.79)

where RSS1 was the root-mean-square of the linear equation squared and then multiplied by nr (the number of data points being looked at), and RSS2 was the root-mean-square of the 2^{nd} order polynomial equation squared and then multiplied by nr. The number 1, denotes the difference in the degrees of freedom between the two models and the number 2, denotes the total degrees of freedom of the second model. The value of the Partial F Statistic is significant if it is larger then $F_{critical}$. Using the number of the difference of the degrees of freedom between the two models, the number of data points, and the α level, statistical tables reveal that the $F_{critical}$ value is just under 4

For the flexion versus abduction/adduction relation, the Partial F Statistics were greater then $F_{critical}$, but the X^2 component value of the polynomial was so small, on the order of 1/10,000 (0.0001), that over a forty degree region (so X would vary from zero to forty degrees) the effect was so small as to be negligible. Therefore the flexion versus abduction/adduction relation was taken to be linear over the flexion region under consideration. When reviewing the flexion vs axial rotation relation the component of the polynomial related to X^2 was large enough to effect the relation over a forty degree flexion. As such, the flexion versus axial rotation relations were shown to be non-linear.

The determination of which trial (of the five repetitions done per leg) should be used in comparison with the other legs of the same poultry type was done by a comparison of R^2 values. The R^2 value is the square of the correlation coefficient between the original and modeled data. The correlation coefficient was computed using the Pearson's linear correlation coefficient formula. The original data was obtained during the experiments and the modeled data was derived from a linear model or 2^{nd} order polynomial model. The linear and polynomial models (as shown in Appendix B) were calculated by using a MATLAB builtin function called polyfit. The function gives a polynomial with the highest power N (N=1) for linear, N=2 for second order polynomial) that best fits the experimental data points in a least squares sense. Polyfit in MATLAB forms the Vandermonde matrix, V, and then solves the least squares problem $V_p \cong y$. The function will also output the triangular factor from a QR decomposition of the Vandermonde matrix of the X-variable, the degrees of freedom, and the norm of the residuals. As stated in section 3.5, the R^2 value of each curve fit was used to determine which of the five repetitions would be used. The Partial F Statistic evaluation determined if the linear or 2^{nd} order polynomial model would be used against the experimental data. Starting at the initial trial (or repetition) of a leg, if the R^2 value for that trial was over 0.90 it was accepted; if not, the next trial was reviewed. If none of the five trials were over the initial threshold the R^2 value went down by decreasing increments of 0.05 (0.85,0.80 etc.), until 0.65. The chosen trial then represented the leg in the averaging of the relationships of flexion versus abduction/adduction, or flexion versus axial rotation, for a poultry type. The mean of the slopes was taken at each point over the desired flexion range, as was the \pm standard deviation, which was then output for graphical representation (as seen in figures 5.2, 5.3, and 5.4).

5.2 Discussion

The peak magnitudes of rotation for the broiler, layer and turkey stifles were not consistent with the reported results for ostriches [11] or the abductions for emus [12]. This difference could be attributed to our comparison of cadaver leg data to those reported for live animals, the difference in the specimens' species, and also to the use of a mechanical device to simulate stances. While the Oxford Rig design does provide constraints at the hip and ankle joints that are not the physiological norm, its design has been accepted in the biomechanical research world and has been shown to capture the characteristics of stifle (knee) joint movement as well as other in-vitro systems [54].

The non-linear pattern of the joint rotation about the broiler, layer and turkey stifles (knees) is consistent with that seen in dogs [60] and in humans [69]. The joint rotation pattern as reported in Rubenson et al. [11] of the ostrich is difficult to determine from the graphs shown, but could be linear. The range of joint abduction for broiler, layer and turkey stifles (8-12 degrees) is similar for ostrich (10 degrees) [11], for that of the guinea fowl (10-15 degrees) [12], and for that of the emus (10 degrees) [20].

There is no explanation for the rotational differences of the broiler pattern of the stifles tested, but this could imply that the biomechanics of the broiler ligaments and joint capsule differ from the layer, turkey, ostrich [11] and dog [60]. Disruption of the function of ligaments can result in changes in the joint's kinematic pattern during gait. For example, the cruciate ligaments provide stifle (knee) stability by restraining anterior-posterior translations and limiting the range of internal/external rotation; loss of these ligament functions results in changing the magnitude of these modes of motion by as much as 35 percent [70]. Since the data presented herein indicate that the broiler stifle experiences internal/external rotation that is different from the layer and turkey stifles tested in these experiments, it could be suggested that the cruciate ligaments do not provide the same level of joint stability.

There is little information regarding production bird stifle ligaments although there is evidence that cruciate ligament problems exist in larger meat-type birds. Duff [71] investigated leg problems in 88 broiler breeder fowls and found that 35 birds had partial or complete rupture of a cruciate ligament with another 15 birds having disruption of the collateral ligaments. The cruciate ligament damage was a common problem with caudal cruciate ligament rupture occurring more frequently closest to the tibia and with the cranial cruciate ligament rupture on the femur side. In humans, disruption of the cruciate ligaments does not necessarily result in an inability to walk but will result in abnormal muscle firing pattern as the patient attempts to compensate for the loss of joint stability [72]. These findings suggest the need to examine the ligaments of the stifle in large meat production birds and to determine if damage to those ligaments corresponds to abnormal gait.

The modes of stifle (knee) movement have influence on the contact area forces between the articular surfaces of the tibia and femur and across the patella. For example, abnormal rotation of the human knee can produce cascading events that alter the Q angle, which is the angle between the quadriceps and the patella tendon. A change in the Q angle affects the direction and magnitude of the joint forces and this can result in knee instability [73]. MRI studies in dogs [74] indicate an increase in the Q angle correlated to a failure of ligaments that restrain tibia-femur rotation and thus joint instability occurred. Small rotations of less than 15° produce little changes in joint contact pressure but rotations larger than 20° , such those found with the turkey cadaver stifle, can alter the location as well as increase the contact pressure, leading to abnormalities in joint biomechanical function [73]. The magnitude of stifle rotation reported herein suggests that more attention needs to be given to the biomechanics of the production bird's patella, particularly the Q angle. Knowledge of this angle could provide a means to quantify characteristics that indicate better stifle joint stability that could lead to a reduction in bird lameness.

The articular surface geometry of the human knee has been shown to be linked to the magnitude of both knee abduction/adduction and internal/external rotation modes of motion. An increase in abduction/adduction motion is correlated to an increase in the medial/lateral cartilage thickness, which is an indication of higher mechanical stress on the joint's surfaces [75]. During the rotational mode of motion, the curve of the inner condyle helps to confine the movement as well as the gliding motion of the tibia across the surface. MRI and CT imaging has shown that the circular shape of the femoral surfaces and the flat shape of the lateral tibia surface help to minimize stifle (knee) valgus/varus motion during joint rotation [26]. Using a model to simulate passive motion of the knee, Amiri et al. [51] suggest that the shape of the tibial plateau contain the key features for promoting tibial rotation and restraining femoral posterior translation. Removing the medial meniscus from the model resulted in a decrease in rotation and an increase in translation. The study herein did not analyze only the stifle articular surfaces; however, medical studies investigating the tibial plateau angle [76–78] appear to be consistent with leg abnormalities found in the poultry industry when the tibial cartilage is abnormal [79]. Further investigation into the correlation of avian stifle modes of motion with joint cartilage geometry is needed since that geometry could be a breeding characteristic that leads toward reduced bird lameness.

5.2.1 General Idea

Figure 5.5: The UGA/Oxford Rig design above was used for the experiments described herein. It allows the stifle (knee) joint to flex based on the sliding of the hip joint, up the narrow Z-translation slider, which is caused by the force applied to the wire loop attached to the quadriceps clamp (with the s-load cell in between the top loop and the muscle clamp). The hock (ankle) apparatus is a universal joint which allows for rotations and abduction/adduction.

The UGA/Oxford Rig (Figure 5.5) is different from the Oxford Rig described by Zavatsky, and shown in figure 3.1. The differences are that the Rig used in the experimentation described herein had a universal joint as the ankle assembly and sliders in the X, Y, and Z directions at the hip joint. The knee joint was initially in a flexed position and then extended by pulling, parallel to the femur, on a clamp attached to the quadriceps muscles which were still attached to the patellar ligament, whereas the Oxford Rig Zavatsky described has the same Z-axis slider, but separate X and Y-axis rotation at the hock (ankle) joint, axial rotation also at the hock (ankle) joint, and X and Y axis rotation at the hip joint.

The UGA/Oxford Rig was designed with simplification and limited parts in mind. The universal joint at the bottom of the leg allowed for flexion/extension, axial rotation, and abduction/adduction, whereas Zavatsky's Rig had the flexion/extension, abduction/adduction and axial rotation controlled by individual mechanisms. This would allow Zavatsky to limit degrees of freedom with his apparatus. The UGA/Oxford Rig's Z-axis slider had the same purpose as Zavatsky's, although the UGA/Oxford Rig had a single slider as opposed to Zavatsky's two. This would make Zavatsky's system more resistant to torque on the X, and Y axes.

An advantage to the UGA/Oxford Rigs was that if the hock (ankle) and hip joints were not aligned on the zero degree of the X and Y axes, the Rig allowed for the leg to stand naturally, i.e. the hip could be an inch to the right of the hock and the Rig would not force the specimen to align unnaturally. This was also a disadvantage for gathering repeatable data if the experimenters did not mark the X and Y axes on the first run and reset the leg to those same points for each successive trial for that leg.

In an attempt to load the quadriceps muscle (which pulls on the patellar tendon and extends the leg from a flexed to extended position) in a natural motion, the muscle clamp and s-load cell (measuring the force of the load) were pulled parallel to a two-by-four piece of wood that extended from the X-axis sliders of the UGA/Oxford Rig. The double sliders for the X-axis were used to help support the weight of the wood and specimen (leg). The original design had called for a stepper motor to be attached to the wood which allow finite movement of the quadriceps and a more repeatable applied force on the quadriceps. It would be necessary to keep the motor on the wood to minimize the developments of moments caused by the motor's pull at an unusual or changing angle of force. The weight of the stepper motor was such that it caused a severe torque about the wood which twisted the stifle joint when a specimen was in the Rig. Therefore it was decided a human would apply a constant force to pull the quadriceps muscle and thereby extend the leg from its initial flexed state.

Upon completion of the experiments described herein, the lab redesigned the UGA/Oxford Rig. In the New UGA/Oxford Rig, described in Chapter 6, the quadriceps are not used to extend the leg, rather a human slides the hip assembly up the Z-axis slider at a constant rate. This allows for determination of the action caused by the quadriceps muscles with regards to the movement of the stifle joint, but does not allow for the force applied to the system to be measured.

5.2.2 Impact

The UGA/Oxford Rig used in the experimentation described within the thesis does not modify or advance engineering. It does allow veterinary medicine the opportunity to use experimentation to advance veterinary science and allow for the possibility for experiments to compare human and animal stifle (knee) joints so that animals may be used for human comparison or model studies.

The Purdue Knee Rig, and the subsequent Kansas Knee Rig, are very high tech, using hydraulic systems, but they will not fit smaller specimens such as dog or small bird (chicken) legs. These human knee simulators (Oxford Rigs) are used to study the impact of various artificial joints and help validate finite element models of the knee. The UGA/Oxford Rig allows that to be done for dogs, and other small animals. The Rig used in the experiments described herein allows for very small legs, with some specimens tested from chickens weighing less then five pounds. The upper limit of the Rig is approximately four feet from hip
to hock (ankle). While the UGA/Oxford Rig does requires significant human intervention (adding force to the quadriceps' clamp), it can accept a leg from a chicken, ostrich, human, or horse.

The UGA/Oxford Rig was built to allow the testing of cadaver legs in a manner acceptable to human, biomechanical medicine. The aim was to allow veterinary researchers to study the stifle (knee) joint in a manner similar to human studies that would increase the level of knowledge of how animal stifles moved. The data generated may be used to help determine genetic breeding guidelines, understand the level of control or limitation generated by certain ligaments and muscle groups, as well as allow for the testing and comparison of artificial animal joints.

5.2.3 Application of the UGA/Oxford Rig

There were several disadvantages to the UGA/Oxford Rig in practice. The time required to set-up the specimen (leg) was an additional 30-40 minutes due to the requirements to pot the ends of the leg (cementing the distal and proximal ends of the leg into PVC caps with bolts), necessary to attach the leg to the rig, and to take anatomical data of the leg prior to potting. Also, if any of the markers moved or were lost (came off) during testing, the leg data could not be used because the remaining markers would no longer be in the exact placement of the anatomical picture. This occurred at least once during the data collection. The virtual markers would not be computed to be in their actual/virtual place correctly. This would mean later calculations of the leg's angles and rotations would be incorrect. The design of the Rig had originally intended that the force on the quadriceps'clamp be applied by a stepper motor. The stepper motor caused significant torque on the apparatus and specimen due to the weight of the motor, and was never used. Using a human to apply the force to the quadriceps' muscle at a constant rate increased the variance of the experiment by an unknown amount, as it was eight seconds of movement at an unusual angle. Finally, the quadriceps' clamp originally would get hung up on the PVC cap that was holding the femur (part of the potting process) when the leg was being extended. To avoid this, extra care was taken in lining up the quadriceps' clamp and PVC cap.

An advantage of the Rig was that the leg could have its muscles removed and k-wires drilled into various points of the bone while maintaining the joint capsule's integrity and movement of the joint. The movement of a live animal would obviously change with these procedures done to its leg. The UGA/Oxford Rig allows for the study of the ligaments within the joint capsule, joint capsule, articular cartilage, and menisci of the stifle joint.

5.3 Summary

The results of this study indicate that stifle (knee) angles, as defined by the Joint Coordinate System technique, are non-linear for broilers, layers and turkeys when comparing flexion/extension and internal/external rotation. The layers and turkeys follow the non-linear pattern and external rotation as found in most other animals cited in literature and the broilers follow a non-linear, internal rotation. This data can be used as a standard for comparison when future researchers attempt to determine the effect of genetic and environmental variables on poultry production.

There are four areas of future study suggested by the literature cited and the findings herein. Further research needs to determine the effect of ligaments in the stifle have on avian gait. A study should determine an acceptable avian Q angle for stifle (knee) stability. The correlation between the cartilage geometry of the stifle (knee) to avian kinematics needs to be made. Finally, the effect of muscle groups on avian kinematics needs to be defined.

Chapter 6

Conclusion

From the experiments described, it was decided to attempt to modify the UGA/Oxford Rig to allow the hip and hock (ankle) joints to be retained and allow their normal range of motion as well as the ability to retain all the muscle groups of the leg. Using a hemi-pelvis canine specimen, the pelvis was attached to the Rig which allowed for vertical and horizontal movement as the leg was flexed. The foot was attached to a stationary platform. By not cutting any of the muscles or ligaments the procedure was to more approperately mimic the leg's natural movement.

The New UGA/Oxford Rig allows the stifle joint's stabilization and angles dependent upon muscles or ligaments to be studied individually. Thus the relative effect of the lateral gastrocnemius muscle, the medial collateral ligament, or any other part of the leg, on the motion of the stifle can be studied individually, or collectively.



Figure 6.1: The New UGA/Oxford Rig design above was redesigned from the UGA/Oxford Rig used on the experiments described within this thesis. It allows the stifle (knee) joint to flex based on the sliding of the hip joint, down the wider slider. The hock (ankle) and hip joints are retained from the specimen which allows for natural constraints of those joints to remain, rather then attempting to use artificial means to replicate the joints.

The original UGA/Oxford Rig was modified by having a wider Z-axis slider, to help with the torque in the X and Y axes. The Y-axis slider at the hip joint remained the same, but the X-axis slider was changed to a rail slider with a box hanging from the slider which was used to connect to the hemi-pelvis apparatus. A jig (hemi-pelvis apparatus) was made to attach to a hemi-pelvis. The universal joint at the hock (ankle) location was removed from the original UGA/Oxford Rig, and the paw or foot of the specimen was secured to the base of the experiential rig with tape or a sock and Velcro system which was glued to the base. As described above, the specimen (leg) would be flexed at initiation of the experiment and a human would slide the hip portion of the New UGA/Oxford Rig up the Z-axis slider.

Leaving the hip and hock (ankle) to foot intact meant that the testing system is no longer attempting to imitate those joints and should have given more realistic data. While the UGA/Oxford Rig allowed for axial rotation, abduction/adduction as well as translations during flexion of the stifle joint it did not take into account the restraints put on the joint due to the hip and hock. The hip and hock have a limited range of motion, and that was not necessarily being duplicated by the artificial apparatus of the UGA/Oxford Rig. The New UGA/Oxford Rig not only allows for all of the muscles on the leg and joint restrictions to be taken into account, but should most of the muscles be removed, the hip and hock joints would still be able to restrain the system in a manner more closely then that of the artificial means used by the UGA/Oxford Rig. A large assumption of the New UGA/Oxford Rig's study of the stifle joint is that the hip and hock of the specimen is healthy, or similar to the other specimens being tested; that those two joints are not causing the differences in the information gleaned from a stifle joint study.

Two sets of experiments were run on the New UGA/Oxford Rig. The first was to determine the input of various muscles and ligaments on the motion a canine leg in an attempt to quantify how much various muscles and ligaments supported the leg's movement [80]. It was found that the gastrocnemius muscle group is needed to allow any of the natural kinematics of the stifle, and the removal of other soft tissues can simplify the model [80]. The second was to characterize an intact canine stifle (cadaveric), following cranial cruciate ligament (CCL) rupture, after total knee replacement, and after the removal of two major hindlimb muscle groups [81]. It was found that rotations and translations of the stifle joint produced after the implantation of an artificial knee a very different then those produced by a natural stifle. [81]. One reason that the New Oxford/Rig simulator's approach is not often taken in human cadaver studies is that size of the human leg makes it difficult to work with and store. A second reason for human studies to only use a portion of the specimen's leg (that surrounding the knee) is that the specimen would have to have clinically normal hip, knee, and ankle joints, which may not happen often in older people who dedicate their bodies to science. As previously stated, an abnormal joint in the leg may cause the knee joint's data to also be abnormal even if the knee itself is not problematic.

Appendix A

MATLAB Programs to Calculate Angles

A.1 Main Program

```
1 close all;
                % clears out the exsisting stuff in Matlab
  fclose all;
3 clear all;
  clc;
5
  cd('e:\langle '); \% change to pull data in
7
  StaticMK = load ('New Lens 7-16-09 Test.3TD'); %loads the anatomic datafile
9
11 | m1 = [{ 'RGT' }; { 'RLEP' }; { 'RTHI' }; { 'RFH' }; { 'RLMA' }; { 'RSHA' }; { 'RMEP' }; { '
     RPTC'}; {'RDTC'}; {'RMMA'}; {'RFMH'}; ]; \% list of markers in order
  13 % Marker definition
  % RGT: Rt greater trochantor ( will vary between trials, as designed)
15 % RLEP: Rt Lateral epicondyle of femur
  % RTHI: Rt quadriceps marker (thigh marker)
17 % RFH: Rt fibula head
  % RLMA: Rt lateral malleolus
19 % RSHA: Rt gastrocnemius marker (shank marker)
  % RMEP: Rt medial epicondyle of femur
21 % RPTC: Rt proximal tibial crest
 % RDTC: Rt distal tibial crest
```

```
23 % RMMA: Rt medial malleolus
  % RFMH: Rt femoral head
cd('m:\matlab\yang cheih\'); % change to pick up sub-routines
27
  califrame = 1; % selects the calibration frame from the anatomic file
29 for i = 1 : length (m1)
      eval(strcat('[', char(m1(i)), '] = StaticMK(:, i*4-3:i*4-1)*1000;')); %
          convert into mm.
31 end
33 Sect-up the inital rotation GCS to LCS for virtual and normal marker systems
  [rRg2t, rVg2t, RGT_tlocal, RLEP_tlocal, RMEP_tlocal] = NaCoordThighChicken(0, NMEP_tlocal)
     RGT(califrame ,:), RLEP(califrame ,:), RMEP(califrame ,:));
35 [RFMH_tlocal, RTHI_tlocal] = coordg21(rRg2t, rVg2t, RFMH(califrame,:), RTHI(
      califrame ,:));
37 % to create plot of leg
  figure(1);
39 plot3(RGT_tlocal(1), RGT_tlocal(2), RGT_tlocal(3), 'b.');
  hold on;
41 plot3(RLEP_tlocal(1), RLEP_tlocal(2), RLEP_tlocal(3), 'go');
  plot3(RMEP_tlocal(1), RMEP_tlocal(2), RMEP_tlocal(3),
                                                        'rx ');
43 plot3 (RTHI_tlocal(1), RTHI_tlocal(2), RTHI_tlocal(3), 'kx');
  line ([RGT_tlocal(1), RLEP_tlocal(1)], [RGT_tlocal(2), RLEP_tlocal(2)], [
      RGT_tlocal(3), RLEP_tlocal(3)], 'color', 'k');
45 line ([RMEP_tlocal(1), RLEP_tlocal(1)], [RMEP_tlocal(2), RMEP_tlocal(2)], [
      RMEP_tlocal(3), RLEP_tlocal(3)], 'color', 'k');
  line ([RTHI_tlocal(1), RLEP_tlocal(1)], [RTHI_tlocal(2), RMEP_tlocal(2)], [
      RTHI_tlocal(3), RLEP_tlocal(3)], 'color', 'k');
47 %axis image
49 [rRg2tTEMP, rVg2tTEMP, RTHI_tlocal2, RLEP_tlocal2, RMEP_tlocal2] =
      NaCoordThighChicken(0, RTHI(califrame,:), RLEP(califrame,:), RMEP(califrame
      ,:));
  [RFMH_tlocal2, RGT_tlocal2] = coordg21(rRg2tTEMP, rVg2tTEMP, RFMH(califrame,:))
      , RGT(califrame ,:));
51 Rt2t = rRg2tTEMP' * rRg2t;% a fixed matrix that relates the other two matrices
       for the Thigh
  Vt2t = rVg2tTEMP' * rVg2t;\% a fixed matrix that relates the vector matrices
      for the Thigh
53
  [rRg2s, rVg2s, RPTC_slocal, RDTC_slocal, RLMA_slocal, RMMA_slocal] =
      FuCoordShankDog(0, RPTC(califrame,:), RDTC(califrame,:), RLMA(califrame,:)
      , RMMA(califrame ,:));
55 [RSHA_slocal] = coordg21(rRg2s, rVg2s, RSHA(califrame,:));
57 [rRg2sTEMP, rVg2sTEMP, RPTC_slocal2, RDTC_slocal2, RSHA_slocal2] =
      NaCoordShankChicken(0, RPTC(califrame,:), RDTC(califrame,:), RSHA(
      califrame ,:));
```

```
59 [RLMA_slocal2, RMMA_slocal2] = coordg21 (rRg2sTEMP, rVg2sTEMP, RLMA(califrame
      ,:) , RMMA(califrame ,:));
  Rs2s = rRg2sTEMP' * rRg2s;\% a fixed matrix that relates the other two matries
      for the Shank
61
  % Kinematics analysis
63 | \mathbf{cd}('e:\langle '); \% \ change \ to \ pull \ data \ in
  dynMK = load ('New Lens 7-16-09 Test0001.3TD');
65
67|\mathbf{cd}(\text{'m:} \mathbf{b} \mathbf{c} \mathbf{d}) ;%change to run sub-routines
  for i = 1 : length (m1)
       eval(strcat('[', char(m1(i)), '] = dynMK(:, i*4-3:i*4-1)*1000; ')); \%
69
           convert into mm.
  end
71
  n frames = length(RGT);
73
75 for frame=1:nframes
       %Thigh
       [rRg2tTEMPd, rVg2tTEMPd, RTHI_tlocalD, RLEP_tlocalD, RMEP_tlocalD] =
77
           NaCoordThighChicken(0, RTHI(frame,:), RLEP(frame,:), RMEP(frame,:));
       rRg2t = rRg2tTEMPd * Rt2t;
79
       rVg2t = rVg2tTEMPd * Vt2t;
81
       [RTHI_tlocal, RLEP_tlocal, RMEP_tlocal, RPTC_tlocal] = coordg2l(rRg2t,
          rVg2t, RTHI(frame,:), RLEP(frame,:), RMEP(frame,:), RPTC(frame,:));
       RPTC_{thighLocal} \{ frame \} = RPTC_{tlocal};
83
       RLEP_thighLocal \{ frame \} = RLEP_tlocal;
       %Shank
85
       [rRg2sTEMPd, rVg2sTEMPd, RPTC_slocalD, RDTC_slocalD, RSHA_slocalD] =
          NaCoordShankChicken(0, RPTC(frame,:), RDTC(frame,:), RSHA(frame,:));
       rRg2s = rRg2sTEMPd * Rs2s;
87
89
       rRt2s = rRg2t' * rRg2s;
       Out_rKA\{frame\} = rRt2s;
91
93
       rAngle_k(frame,:) = RotAngleZYX(Out_rKA{frame}); \% segment rotation, this
           gives the output in Flexion, Rotatoin, Abduction
95
  end
```

A.2 NaCoordThighChicken

```
[rRg2t, rVg2t, RGT_tlocal, RLEP_tlocal, RMEP_tlocal] =
   function
      NaCoordThighChicken(chk, RGT, RLEP, RMEP)
\mathbf{2}
  % Input:
4 %
            chk: 1 is for right and 0 is for left
  %
           RGT: Rt greater trochantor (Lt when 0)
6 %
           RLEP: Rt Lateral epicondyle of femur (Lt when 0)
           RMEP: Rt medial epicondyle of femur (Lt when 0)
  %
8 %
           RFMH: Rt femoral head (Lt when 0)
  %
10 \ \% \ Output:
  %
            rRg2t: Rotation matrics of global to THIGH coordinate system (Lt when
      0)
12 %
            rVq2t: Traslation vector of global to THIGH coordinate system (Lt when
       0)
  %
            RGT_{tlocal}: RGT marker in local frame. (Lt when 0)
14 %
            RLEP_tlocal: RLEP marker in local frame. (Lt when 0)
  %
            RMEP_tlocal: RMEP marker in local frame. (Lt when 0)
16 %
            RFMH_tlocal: RFMH marker in local frame. (Lt when 0)
  %
18
20 if chk = 1 \ \% chk: 1 is for right and 0 is for left
       rVg2t = RLEP; % define translation vector
22
       v1 = RGT - RLEP; %Rt greater trochantor minus Rt Lateral epicondyle of
           femur
       v2 = RLEP - RMEP; %Rt Lateral epicondyle of femur - RMEP: Rt medial
           epicondyle of femur
24
       z = v2/norm(v2); \% the unit vector of v2
26
       \mathbf{x} = \mathbf{cross}(\mathbf{v1}, \mathbf{z})/\mathbf{norm}(\mathbf{cross}(\mathbf{v1}, \mathbf{z})); \% the unit vector of v1 cross z
       y = cross(z, x)/norm(cross(z, x)); \% the unit vector of z cross x
28
30
       rRg2t = [x', y', z']; \% define rotation matrix (right, rotation, global
           to thigh)
        [RGT_tlocal, RLEP_tlocal, RMEP_tlocal] = coordg2l(rRg2t, rVg2t, RGT, RLEP_tlocal)
32
            , RMEP);
34
                     %chk: 1 is for right and 0 is for left
   elseif chk == 0
       rVg2t = RLEP; % define translation vector
36
       v1 = RGT - RLEP;
38
       v2 = RMEP - RLEP;
40
       z = v2/norm(v2);
       \mathbf{x} = \mathbf{cross}(\mathbf{v}1, \mathbf{z}) / \mathbf{norm}(\mathbf{cross}(\mathbf{v}1, \mathbf{z}));
```

```
42 y = cross(z, x)/norm(cross(z, x));
44 rRg2t = [x', y', z']; % define rotation matrix (right, rotation, global
46 [RGT_tlocal, RLEP_tlocal, RMEP_tlocal] = coordg21(rRg2t, rVg2t, RGT, RLEP
, RMEP);
48 end
end
```

A.3 FuCoordShankDog

```
[rRg2s, rVg2s, RPTC_slocal, RDTC_slocal, RLMA_slocal, RMMA_slocal] =
  function
       FuCoordShankDog(chk, RPTC, RDTC, RLMA, RMMA)
\mathbf{2}
  \% Syntex:
4 %
      [rRg2s, rVg2s, RPTC\_slocal, RDTC\_slocal, RLMA\_slocal, RMMA\_slocal] =
      FuCoordShankDog(RPTC, RDTC, RLMA, RMMA)
  %
6 % Input:
  %
           chk: 1 is for right and 0 is for left
8 %
          RPTC: Rt proximal tibial crest (Lt when 0)
  %
          RDTC: Rt distal tibial crest (Lt when 0)
10 \%
          RMMA: Rt medial malleolus (Lt when 0)
  %
          RLMA: Rt lateral malleolus (Lt when 0)
12 | \%
  % Output:
14 %
          rRg2s: Rotation matrics of global to shank coordinate system (Lt when
      0)
  %
           rVg2s: Traslation vector of global to shank coordinate system (Lt when
       0)
16 %
           RPTC\_slocal: RPTC marker in local frame. (Lt when 0)
           RDTC-slocal: RDTC marker in local frame. (Lt when 0)
  %
18 %
           RLMA_slocal: RLMA marker in local frame. (Lt when 0)
  %
           RMMA_slocal: RMMA marker in local frame. (Lt when 0)
20 %
  % Written by Yang-Chieh Fu, Biomechanics Lab UGA USA, Jan 2006.
22 % Revised by Yang-Chieh Fu, Biomechanics Lab UGA USA, Oct 2008.
  %
      Left side has been included.
24 % Version 2.0
26
  if chk = 1
28
      rVg2s = RPTC; % define translation vector
```

```
v1 = RPTC - RDTC;
30
        v2 = RLMA - RMMA;
        z = v2/norm(v2);
32
        \mathbf{x} = \mathbf{cross}(\mathbf{v}1, \mathbf{z}) / \mathbf{norm}(\mathbf{cross}(\mathbf{v}1, \mathbf{z}));
        y = cross(z, x) / norm(cross(z, x));
34
36
        rRg2s = [x', y', z']; \% define rotation matrix (right, rotation, global)
            to shank)
38
        [RPTC_slocal, RDTC_slocal, RLMA_slocal, RMMA_slocal] = coordg21(rRg2s,
            rVg2s, RPTC, RDTC, RLMA, RMMA);
40 elseif chk = 0
                         \% R becomes L
        rVg2s = RPTC; % define translation vector
42
        v1 = RPTC - RDTC;
        v2 = RMMA - RLMA;
44
        z = v2/norm(v2);
        \mathbf{x} = \mathbf{cross}(\mathbf{v}1, \mathbf{z})/\mathbf{norm}(\mathbf{cross}(\mathbf{v}1, \mathbf{z}));
46
        y = cross(z, x) / norm(cross(z, x));
48
50
        rRg2s = [x', y', z']; \% define rotation matrix (right, rotation, global to
             shank)
52
        [RPTC_slocal, RDTC_slocal, RLMA_slocal, RMMA_slocal] = coordg21(rRg2s,
            rVg2s, RPTC, RDTC, RLMA, RMMA);
   end
54 end
```

A.4 NaCoordShankChicken

```
function
             [rRg2s, rVg2s, RPTC_slocal, RDTC_slocal, RSHA_slocal] =
     NaCoordShankChicken(chk, RPTC, RDTC, RSHA)
2
4 % Input:
  %
          chk: 1 is for right and 0 is for left
          RPTC: Rt proximal tibial crest (Lt when 0)
6 %
  %
          RDTC: Rt distal tibial crest (Lt when 0)
8 %
          RMMA: Rt medial malleolus (Lt when 0)
  %
          RLMA: Rt lateral malleolus (Lt when 0)
10 %
          RSHA: Rt gastrocnemius marker (shank marker) (Lt when 0)
  %
```

```
12 % Output:
  %
            rRg2s: Rotation matrics of global to shank coordinate system (Lt when
       0)
14 %
            rVg2s: Traslation vector of global to shank coordinate system (Lt when
        0)
  %
            rSHAmatrix: right shank mantrix including RSHA
16 %
            RPTC_{slocal}: RPTC marker in local frame. (Lt when 0)
  %
            RDTC\_slocal: RDTC marker in local frame. (Lt when 0)
18 %
            RLMA_slocal: RLMA marker in local frame. (Lt when 0)
  %
            RMMA_slocal: RMMA marker in local frame. (Lt when 0)
20 | \%
22 if chk == 1
       rVg2s = RPTC; % define translation vector
24
       v1 = RPTC - RDTC;
       v2 = RDTC - RSHA;
26
       z = v2/norm(v2);
28
       \mathbf{x} = \mathbf{cross}(\mathbf{v}1, \mathbf{z})/\mathbf{norm}(\mathbf{cross}(\mathbf{v}1, \mathbf{z}));
       y = cross(z, x) / norm(cross(z, x));
30
       rRg2s = [x', y', z']; \% define rotation matrix
32
       [RPTC_slocal, RDTC_slocal, RSHA_slocal] = coordg2l(rRg2s, rVg2s, RPTC,
           RDTC, RSHA);
34
36 elseif chk = 0
                        \% R becomes L
       rVg2s = RPTC; % define translation vector
38
       v1 = RPTC - RDTC;
       v2 = RSHA - RDTC;
40
       z = v2/norm(v2);
42
       \mathbf{x} = \mathbf{cross}(\mathbf{v}1, \mathbf{z})/\mathbf{norm}(\mathbf{cross}(\mathbf{v}1, \mathbf{z}));
       y = cross(z, x) / norm(cross(z, x));
44
       rRg2s = [x', y', z']; \% define rotation matrix
46
        [RPTC_slocal, RDTC_slocal, RSHA_slocal] = coordg21(rRg2s, rVg2s, RPTC,
           RDTC, RSHA);
48 end
  end
```

A.5 RotAngleZYX

```
1 function Table=RotAngleZYX(R2b)
% calcualtion the rotation angles based on Z,Y,X rotation of the matrix
3
Abd = atan2(R2b(3,2),R2b(3,3))*180/pi; % calculate the abduction/adduction
angle
5 %(+) adduction, (-) abduction
Int = -asin(R2b(3,1)) * 180/pi; % calculate axial rotation
7 %(+) internal rotation, (-) external rotation
7 Flex = atan2(R2b(2,1),R2b(1,1)) * 180/pi; % calcualte the flexion angle
9 %(-)flexion, (+) extension
Table = [Flex Int Abd]; % output info in Flexion, Axial Rotatoin, Abductrion
order
11 end
```

Appendix B

MATLAB Program to Calculate Statistics

B.1 Main Program

1	% program to compute the F-statistic between Linear and Polynomial 2nd order
	%note, program is to be run in short parts to change the bird type, Flexion vs
	. Rotation or Abduction, where the data will be output to, leaner or non-
	linear, number of legs being reviewed, etc.
3	
	clc
5	clear
7	%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
	%input_file = 'Turkey Trends Calc.xlsx';
9	%output_file = 'Turkey Trends Calc results.xlsx';
	input_file = 'Layer trend calc_1.xlsx';
11	output_file = 'Layer trend calc_1 results.xlsx';
	$\% input_file = `Broiler trends calc.xlsx';$
13	%output_file = 'Broiler trends calc results.xlsx';
15	$output_sheet = 4; \ \%1=roation, \ 2=abduction \ 3=variations$
17	a = 1:4:17; % looking at Flexion
	$b = 2:4:18; \ \% vs. \ Rotation$
19	%b = 3:4:19; %vs. abduction
21	$\% no_legs = 4; \% number of legs (tabs)$

```
no_{legs} = 8; %number of legs (tabs) layers
23 no_runs = 5; %number of runs per leg (runs per tab)
  25 n1 = 1:no_runs:no_runs*no_legs; % start index for each leg
  n2 = 5: no_runs: no_runs* no_legs; % end intex for each leg
27
29 for j = 1 : no-legs; % j = number of Legs looked at (tabs on excel sheet)
       sprintf('working on sheet: %d',j)
       [data text] = xlsread(input_file, j); \% where the data is pulled from
31
       nr=size(data,1); % the number of data points being looked at
33
        for i = 1 : no_runs; \% i = number of runs per Leg
35
           % Calculations for polynomial, the RSS
           %Lp = polyfit(data(:, a(i)), data(:, b(i)), 1);
37
          Lpa = (round(data(:, a(i)) * 10) / 10);
           Lpb = (round(data(:, b(i))*10)/10);
           Lp=polyfit (Lpa,Lpb,1);
39
           Lcoeff(i, 1:2) = Lp; %only 2 columns for X & intercept of line
           Lyfit=polyval(Lp,round(data(:,a(i))*10)/10); \% rounding incoming data
41
           [Rsqd1 mae1 rmse1 nse1 d1] = performanceCoefficients(data(:, b(i))),
              Lyfit);
43
           RSS1 = rmse1^2 * nr;
           Lcoeff(i,3) = RSS1;
           Lcoeff(i, 4) = Rsqd1;
45
           % Calculations for linear, the RSS
47
           Pp=polyfit (round(data(:,a(i))*10)/10, round(data(:,b(i))*10)/10, 2);
49
           Pcoeff(i, 1:3) = Pp;
           Pyfit = polyval(Pp, round(data(:, a(i))*10)/10); \% rounding incoming data
           [Rsqd2 mae2 rmse2 nse2 d2] = performanceCoefficients(data(:, b(i))),
51
              Pyfit);
           RSS2 = rmse2^2 * nr;
53
           Pcoeff(i, 4) = RSS2;
           Pcoeff(i, 5) = Rsqd2;
55
          F(i, 1) = (RSS1 - RSS2) / ((RSS2 / (nr - 2))); \% calcualting the F-statstic
              between the polynomial 2nd order equation and the linear equation
57
       end
       Lleg(n1(j):n2(j),1:4) = Lcoeff; %Linear data for each leg
       Pleg(n1(j):n2(j), 1:5) = Pcoeff; % polynomial data for each leg
59
       Fleg(n1(j):n2(j),1)=F; % calcualting the F-statistic for each run/leg
61 clear data text;
63 end
65 %
  %examination of the "best" first run based on Rsquared values
67 \left| \% (leg(last column)) \right|
  %
69 \operatorname{linear} = 4;
```

```
83
```

```
polynomial=5;
information to be updated
   columns = polynomial; % chooise if the system should look at the Rsquared value
        of the polynomial or linear data
 73 leg = Pleg; % choose Pleg for polynomial data, and Lleg for linear
   %
 75 for ii = 1: no_legs % legs (just 4)
       N = leg(n1(ii):n2(ii), 1:columns);  %N = 5 runs for each leg
 77
        for jj = 1:no_runs \% runs (just 5)
 79
                if N(jj, columns) >= (0.9) %starts at 0.9
                    select (ii ,1: columns) = N(jj ,1: columns); %is Rsquared above
                        threshold?
81
                    break
                elseif N(jj, columns) >= (0.85)
                    select (ii ,1: columns) = N(jj ,1: columns); % is Requared above
83
                        threshold?
                    break
85
                elseif N(jj, columns) >= (0.80)
                    select (ii, 1: columns) = N(jj, 1: columns); % is Requared above
                        threshold?
87
                    break
                elseif N(jj, columns) >= (0.80)
89
                    select (ii, 1: columns) = N(jj, 1: columns); % is Requared above
                        threshold?
                    break
91
                elseif N(jj, columns) >= (0.75)
                    select (ii, 1: columns) = N(jj, 1: columns); % is Requared above
                        threshold?
93
                    break
                elseif N(jj, columns) >= (0.70)
                    select (ii ,1: columns) = N(jj ,1: columns); %is Requared above
95
                        threshold?
                    break
97
                elseif N(jj, columns) >= (0.65)
                    select (ii, 1: columns) = N(jj, 1: columns); % is Requared above
                        threshold?
99
                    break
                elseif jj == no_runs
101
                    select(ii, 1: columns) = 1: columns;
                else
103
                     select(ii, 1: columns) = 2: (columns+1);
                end \% if
105
       end \% jj
   end \%ii
107
109
   %
111 %trimming the data
   %
```

```
113 %clear L
                     \% trim = -100:0.5:-60; \% TURKEY
|115| trim = -80:0.5:-40; % LAYER
                     \% trim = -60:0.5:-20; \% BROILER
117 for qq=1:no_legs %based on the number of legs you start with
   L(qq,:) = polyval(select(qq,1:(columns-2)), trim); \%(1:2) reflects a 1st order
       polynomial
119 end
   L=L';
121
   %
123 % finding the mean, CI, and std of slope
   %
125 %only looking at certain legs "choice"
   %choice = [1 \ 2 \ 3 \ 4]; \% what tab leg from
127 choice = [1, 2, 3, 5, 6]; %LAYER 3&4 same leg, 7&8 same leg, and 7&8 messy
   meanROT = mean(L(:, choice), 2); \% get the mean for each leg
129 | stdROT = std(L(:, choice), [], 2); \quad \% get the std of each leg
   upper_CI = meanROT+(1.96*stdROT/size(L(:, choice), 2)); \% +95\% CI
131 lower_CI = meanROT – (1.96 * \text{stdROT} / \text{size} (L(:, \text{choice}), 2)); \% - 95\% CI
   figure (1)
133 | plot (trim, L(:,1), 'r'); hold on; % plot the legs over standard x range
   plot (trim , L(:, 2) , 'b');
135 plot (trim , L(:, 3), 'm');
   %plot(trim,L(:,4),'c');
137 plot (trim , L(:, 5), 'g');
   plot(trim,L(:,6),'k');
139 % plot(trim, L(:,7), 'y');
   \% p lot (trim, L(:, 8), 'c - - ');
141 hold on;
   plot(trim, upper_CI, 'r--'); % plot selected legs' mean & +/- CI
143 hold on;
   plot(trim, lower_CI, 'r--');
145 plot (trim, meanROT, 'b.-');
   hold off;
147
149 % find the slope of the left vs. right side, only for polynomials
   \%left = (-100:.5:-85)'; \% find slope of left side of graph: TURKEY
151 | left = (-80:.5:-70) ';
                              %:LAYER
   \% left = (-60:.5:-50)';
                               %broiler
153 | left_slope = polyfit ( left , meanROT (1: length ( left ) ) , 1 );
   % right = (-70:.5:-60)'; % find slope of right side of graph : TURKEY
155 | right = (-50:.5:-40) ';
                                  %:LAYER
   \% right = (-30:.5:-20)';
                                     %broiler
157 \mid \%aa = find (trim = -70); \%:TURKEY
                                %:LAYER
   aa = \mathbf{find}(\text{trim}=-50);
159 | \%aa = find (trim = -30);
                                 %:broiler
   right_slope = polyfit(right, meanROT(aa:end), 1);
161
```

%headings = ['C', 'B', 'A', 'RSS', 'Rsquared', 'C', 'B', 'A', 'RSS', 'Rsquared', 'left']slope ', 'left intercept ', 'right slope ', 'right intercept ']; 163 %xlswrite(output_file, headings, 1, 'B1'); xlswrite(output_file, leg, output_sheet, 'B2'); % all the line data (poly/linear), RSS, Rsquared 165 xlswrite(output_file, select, output_sheet, 'G2'); %the selected info for each legxlswrite(output_file, left_slope, output_sheet, 'L2'); %the left slope of the line & intercept 167 xlswrite(output_file, right_slope, output_sheet, 'N2'); %the right slope of the line & intercept xlswrite(output_file, Fleg, output_sheet, 'A2'); 169 % find the std & mean of the slope for selected legs if Linear is used %stdSLOPElinear = std(select(choice, 1), 0, 1); %evaluate for choosen(choice) legs 171 %meanSLOPElinear = mean(select(choice, 1), 1); %evaluate for %choosen(choice)legs 173 %xlswrite(output_file, stdSLOPElinear, output_sheet, 'L2'); %the standard devialtion of %the slope of a linear equation 175 %xlswrite(output_file, meanSLOPElinear, output_sheet, 'N2'); % the mean slope of a%linear equation

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