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A Description of the Movement of the Canine Pelvic Limb in Three Dimensions Using an Inverse Dynamics Method, and a Comparison of Two Techniques to Surgically Repair a Cranial Cruciate Ligament Deficient Stifle

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To the Graduate Council:

I am submitting herewith a dissertation written by Jason Headrick entitled "A Description of the Movement of the Canine Pelvic Limb in Three Dimensions Using an Inverse Dynamics Method, and a Comparison of Two Techniques to Surgically Repair a Cranial Cruciate Ligament Deficient Stifle." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Comparative and Experimental Medicine.

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A Description of the Movement of the Canine Pelvic Limb in Three Dimensions Using an Inverse Dynamics Method, and a Comparison of Two Techniques to Surgically Repair a Cranial Cruciate Ligament Deficient Stifle

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Abstract

The purposes of the dissertation were: 1) to describe three-dimensional (3D) motion of the canine pelvic limb using an inverse dynamics method, and 2) to compare these motion patterns between normal, healthy dogs and those that have had their stifles stabilized by one of two surgical methods approximately five years earlier.

Twenty-five dogs were allocated to three groups; healthy control dogs, dogs that had received the tibial plateau leveling osteotomy (TPLO), and dogs that had received the lateral fabellar suture (LFS) stabilization technique. Both surgical techniques were performed approximately five years prior on stifles with surgically induced cranial cruciate ligament (CCL) rupture. A kinematic model was created so that virtual markers could be used to describe the pelvic limb motion in 3D. Kinetic, kinematic, and morphometric data were integrated so that an inverse dynamics method could be used to describe angular displacement, joint moment and power across the hock, stifle, and hip joints in the sagittal, frontal, and transverse planes. Discrete points and shapes of waveforms were analyzed for any differences among groups.

Motion and energy patterns were successfully determined in 3D for all three joints of the canine pelvic limb. There was similarity between all three groups for all variables studied in the three planes with the exception of two variables. In the sagittal plane, the TPLO group had a more extended hip at the beginning of stance phase compared to the control group. Also, in the frontal plane, the LFS group had a significantly larger maximum power across the stifle when compared to the normal group. Despite the differences between these two variables, there were no differences in gait patterns between these groups that would suggest that one surgical procedure is superior to the other. Both surgical groups moved similarly to the healthy control group. The method of collecting kinematic data in this study allowed for the description of motion of the canine pelvic limb in 3D using inverse dynamics. Comparison between normal controls and dogs that had two different methods of repair for stifle instability showed similar gait patterns for all three groups.

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LIST OF ABBREVIATIONS

ACL – Anterior cruciate ligament
AUC – Area under the curve
CCL – Cranial cruciate ligament
HTO – High tibial osteotomy
LFS – Lateral fabellar suture
Nm – Newton·meter
OA – Osteoarthritis
ROM – Range of motion
TPLO – Tibial plateau leveling osteotomy
W – Watts
3D – Three-dimensional

CHAPTER 1

INTRODUCTION

Inverse dynamics research has provided vast information on how gait is adapted to compensate for injury, pathology or anatomical differences in the knee joint. By learning more about these adaptations, more appropriate therapy may be applied for pathology of the knee. When the muscle activity surrounding both healthy and pathologic joints is understood, more appropriate therapy may be applied to try and avoid injury to the healthy joint, or reduce the progression of further pathology in one that is affected by injury. Veterinary medicine is beginning to benefit from advances in human inverse dynamics research through the application of this science to its patients.

Human research

The quadriceps avoidance gait was described by Berchuck et al.[1] when they studied an altered flexor moment in anterior cruciate ligament (ACL) deficient subjects. A reduced flexor moment led them to speculate that these subjects also had reduced antagonist activity of the quadriceps muscles. They reasoned that this quadriceps avoidance gait was an adaptation to avoid applying tension to the anterior portion of the tibia, an action that would cause subluxation of the knee joint in the absence of the ACL. Other groups have verified the presence of the quadriceps avoidance gait[2–6]; however, many groups have been unable to replicate similar findings[7–9]. Similar gait adaptations have been found in subjects with osteoarthritis (OA) of the knee joint[10–12].

Further research suggests a multitude of possible adaptations to help stabilize the ACL deficient knee. Some groups believe that the apparent reduced extensor moment is actually due to an increased flexor moment, caused by increased activity of the hamstring muscles to stabilize the tibia by decreasing anterior translation[13–18]. Also, an increased flexed angle of the knee during activity causes the hamstrings to actively stabilize the tibia[9,14,19,20]. One group observed a mixed response with some ACL deficient subjects displaying a quadriceps avoidance gait and others with an increased flexion of the knee[4]. The hamstring muscles are biarticulate, spanning both the hip and knee joints. With shortening, they not only flex the knee but also extend the hip. Some groups found subjects with injured ACLs had increased hip extensor moments along with increased hamstring activity[21,22].

Veterinary research

The use of inverse dynamics to better describe canine gait is relatively new to veterinary medicine and earlier research relied on ground reaction force and kinematic data to describe and understand pathologic gait. Studies focused on kinetic changes, specifically ground reaction forces, provided a clearer definition of the pathologic gait of dogs with OA in the hip and stifle[23,24]. Others used kinematic descriptions to better define these conditions[25,26]. Kinematic research has also provided specific information on changes in CCL deficient dogs as well as those with stabilized stifles after transection of the CCL to help understand how these patients' gaits are changed with injury and what some factors may be that can be monitored for indications of return to normal function[27–29].

There are very few studies describing the movement of the canine pelvic limb in 3D[30–34], and only one that describes 3D motion of the hip, stifle, and hock joints[31]. Other literature describes motion of the stifle joint alone. It is difficult to compare current 3D results to many of these as they were either cadaveric in nature[30] or used invasive methods to collect data making a clinical application difficult[32,33]. Only two of these studies use contemporary, clinically applicable methods to define 3D motion of the canine pelvic limb joints using joint centers to obtain the data[31,34].

Inverse dynamics has been used rarely to help describe motion of the canine pelvic limb[35–40]. Only one of these studies described differences between stifles of normal dogs and those with arthritis[40]. One group provided the only morphometric data available for the canine pelvic limb while comparing the power distribution across the pelvic limb in two different breeds[37]. The inverse dynamics method has helped provide a better understanding of the asymmetry or "handedness" of canines[35] and of the recovery after corrective surgery[39]. There is no inverse dynamics research that describes the kinetics of the canine pelvic limb in 3D.

To our knowledge, there are only four studies that compared the two procedures of TPLO and LFS[30,41–43]. None of these have used the inverse dynamics method for description of the kinetics of these limbs. Veterinary medicine is advancing in the use of technology so that the collection of data for inverse dynamics research is becoming more clinically relevant. One group has used noninvasive methods to collect morphometric data in the Labrador Retriever[44]. In the future, this may be applied to a clinically applicable method of building a database of morphometric measurements for other breeds.

Diagnostic tests such as force plate and kinematic analysis alone do not fully describe canine motion. Also, they do not describe the changes that occur around a particular joint or a specific muscle group. Inverse dynamics takes information from both kinetic and kinematic data and combines it to give a more comprehensive description of movement and the forces that create it. There are very few veterinary studies that use the comprehensive method of inverse dynamics to describe canine motion, and fewer still that study this motion in three dimensions. Furthermore, there is a paucity of research comparing the common surgical techniques of tibial plateau leveling osteotomy (TPLO) and lateral fabellar-tibial suture (LFS), both commonly used to stabilize the CCL deficient stifle.

Problem Statement

It was our intention to develop a means to study the motion of the normal canine pelvic limb in three dimensions while at the same time to apply an inverse dynamics solution to further characterize that motion. Our goal was to produce a model that allowed the study of pelvic limb gait of healthy dogs in three dimensions, as well as dogs that had their cranial cruciate ligament-deficient stifles stabilized by one of two surgical techniques several years prior to evaluation. In addition to study of stifle stabilization techniques, the dogs also had OA. There is reason to postulate that although the dogs' stifles were surgically stabilized, OA or the loss of the CCL may interfere with normal gait[13,18]. Given all of the information in humans regarding the many possible gait adaptations that may occur with arthritic or ACL deficient/repaired knees, we were interested to more accurately determine how normal dogs move their pelvic limbs and how this differs in an arthritic/surgical model.

Hypothesis

The following hypothesis was tested:

There would be no difference in gait biomechanical characteristics between the TPLO and LFS groups when analyzed by the inverse dynamics method.

CHAPTER 2

LITERATURE REVIEW

Introduction

Inverse dynamics is the branch of biomechanics that combines kinetic and kinematic data along with morphometric measurements to produce a comprehensive description of motion by computing the joint forces and joint moments responsible for creating that motion. By combining the measureable information of ground reaction force, joint kinematics (angular position and velocity), and inertial properties of the segments of a limb (mass, mass moment of inertia, and location of center of mass), causes of motion are described more fully through the indirect discovery of the forces that cause the motion, namely moment (torque) and power (rate of work). The net moment of a joint is the net torque produced by the muscles acting on the center of rotation of the joint. Moment is the tendency of a force to cause rotation about an axis and is measured in Newton·meters (Nm). The moment obtained from inverse dynamics designates which muscle group, flexor or extensor, is responsible for causing the net moment about a joint. This is not to say that both are not active during an activity, but rather which is causing the net moment. The moment about a joint is calculated by the following equation:

Moment = Moment of inertia multiplied by angular acceleration ($M = I \cdot \alpha$)

The moment of inertia is the angular equivalent to mass and indicates and object's resistance to change in angular motion. An object's moment of inertia is dependent on both the object's mass and distribution of mass with respect to the axis of rotation. The moment of inertia of a segment is calculated from the segment's radius of gyration, which is the distance from the axis of rotation to a point at which the mass can be assumed to be concentrated without changing the inertial characteristics of the segment. The moment of inertia can be calculated by:

$$I = m(\rho l)^2$$

where m is the mass of the segment, ρ is the radius of gyration, and l is the length of the segment.

The power across a joint is the rate of work (Work/time) being performed by the muscles, and it is determined by the moment multiplied by the joint velocity:

$$P = M \cdot \omega$$

When the moment and velocity occur in the same direction, power will be positive, indicating concentric activity of the muscle and that energy is being released. When the moment and velocity occur in opposite directions, power will be negative, indicating eccentric muscle activity and energy absorption. Power is measured in Watts (W).

Each segment of a limb acts independent of the others and is under the influence of muscle moments and reaction forces acting on either end, in addition to the forces due to gravity. Given known reaction forces, kinematics, and anthropometric measurements of a distal segment, proximal reaction forces and muscle moments can be calculated. Given a free-body diagram (Figure 1) where R_{yd} and R_{xd} are distal reaction forces, M_d is the net muscle moment acting on the distal joint, m is the mass of the segment and a_y and a_x acceleration of the center of mass, mg is the gravitational force, R_{yp} and R_{xp} are proximal reaction forces, M_p is the proximal net muscle moment, Θ is the angle of the segment in the plane of movement and α is the angular acceleration, M_p can be computed by combining the following equations:

$$\Sigma F_x = ma_x$$

where the sum of the forces in the x direction are equal to the mass of the segment multiplied by the acceleration in the same direction. This is extended to:

$$R_{xp} - R_{xd} = ma_x$$

The forces in the y direction are considered similarly with:

$$\Sigma F_y = ma_y$$

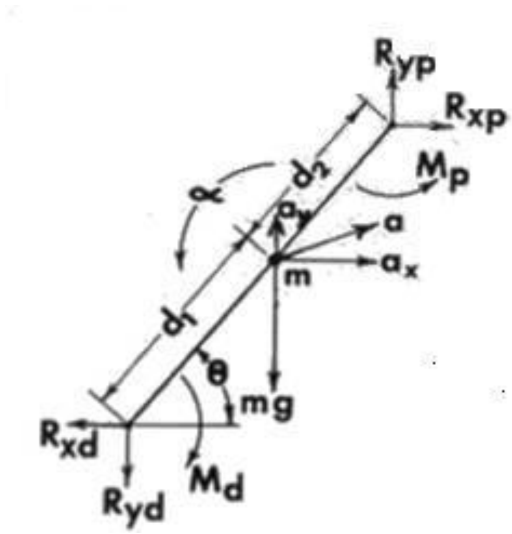

Figure 1. A free-body diagram of a single segment, indicating reaction and gravitational forces, net moments, and linear and angular accelerations. (From Winter [auth], Biomechanics and Motor Control of Human Movement (2nd Edition), John Wiley & Sons, 1990)

where the sum of the forces in the y direction are equal to the mass of the segment multiplied by the acceleration in the same direction. This equation is extended to:

$$R_{yp} - R_{yd} = ma_y$$

Finally, the moment about the center of mass is computed considering:

$$\Sigma M = I\alpha$$

Inverse dynamics has allowed a deeper understanding of pathologic gait in humans and has subsequently been used to help develop strategies for recovery from and even avoid injury. Evaluation, prognosis, and treatment options for rehabilitation and orthopedic patients have been impacted by the application of moment and power data in human patients.

Kinetic and kinematic studies in human medicine have given a broad, although often contradictory, understanding of the mechanics behind pathologic knee gait and the factors that may lead to greater pathology as well as some information that may benefit the diseased knee in recovery. These studies have taken into account musculoskeletal differences in muscle contraction patterns, strength, and anatomy. Other variables studied include osteoarthritis (OA) status, gender, and repair status. A review of the literature reveals how complex the interaction of these factors is and how difficult it is to precisely define the adaptations that exist in a pathologic joint. Kinetic and kinematic information is often not sensitive enough to appreciate these differences, yet inverse dynamics may be able to define significant alterations in how affected subjects move compared to normal patients [21,45].

Quadriceps Avoidance Gait

Human studies of anterior cruciate ligament (ACL) deficient subjects suggest the presence of some form of gait retraining or learned gait dynamics called quadriceps avoidance gait. The quadriceps avoidance gait was first described by Berchuck et al.[1] when they discovered that 75 percent of their ACL deficient subjects had a reduced flexor moment across the knee compared to normal subjects. They proposed that a reduced flexor moment would be paired with a reduced co-contraction of the quadriceps muscle group at the same time. They theorized that this occurred in response to increased laxity in the joint, and that this was a means to reduce anterior translation of the proximal tibia in relation to the femur. The quadriceps insertion point is the anterior aspect of the tibia, and with reduced quadriceps contraction, there would be less tension on the tibia and therefore less anterior translation with flexion of the knee. Since Berchuck's discovery, numerous other groups have noted the presence of this gait adaptation [2,4–6,46]. The presence of the quadriceps avoidance gait is disputed, and other studies have been unable to identify this gait adaptation in similar groups of subjects [7,8,47].

The terms "copers", "noncopers" and "adapters" came into use to describe the level of activity an athlete could return to after conservative management of a torn ACL[9]. Copers are those athletes that can return to a high activity level in sports, while noncopers cannot compensate for the ACL deficiency, and adapters return to activity at reduced level than prior to the injury. Additional research has shown that alterations in the ACL deficient gait and adaptations made by those recovering from this injury may be more complex than simply avoiding contraction of the quadriceps group. Studies have shown noncopers to have normal quadriceps activity with increased activity of the hamstrings and gastrocnemius[14,17]. The counterargument to the quadriceps avoidance gait is that the lower than normal knee extension moment is caused not by reduced quadriceps activity but rather increased cocontraction of the hamstrings. Hamstring coactivation has been suggested to be a significant factor in maintaining knee joint stability[13,15,16,18]. It is possible that a lower resultant joint moment is misinterpreted as reduced muscle activity across a joint, when in fact it may be due to an increase in antagonist muscle activity. Furthermore, noncopers may alter the position of their knees when moving, allowing for a more flexed position to help stabilize the knee[9,14,19,48]. An increased flexion angle to the knee may allow the hamstrings more opportunity to contribute to knee stability[8,49]. One study showed a mixed response to ACL deficiency with some subjects showing the quadriceps avoidance gait and others a "knee flexed gait"[4].

Additional research has indicated that there may be numerous strategies, such as alterations in hip and knee flexion and extension strategies and variations in muscle group contraction patterns, to help compensate for the ACL deficient knee[8,50–52]. Other research reveals quadriceps muscle atrophy as a difference between copers and noncopers. Williams[53] used MRI and EMG activity to show that noncopers displayed significantly greater quadriceps atrophy than copers with a more dramatic difference noted in the vastus lateralis. They also saw decreased muscle control of the vastus lateralis and lateral gastrocnemius muscles in the noncoper group. A study that looked at ACL deficient soccer players found noncopers to have not only weak quadriceps, but also weaker hamstring muscles when compared to players with the same injury[54]. This weakness of the quadriceps muscle has also been shown in ACL repaired groups [55–58]. One of these groups[55] showed that recovery of thigh muscle activity and function to be closely linked. Those subjects with poor function had reduced strength in both hamstring and quadriceps muscle groups. Patients with good function had good strength in both muscle groups. Those subjects with fair function had reduced extensor strength and normal flexor strength when compared to the nonsurgical leg.[55] Another of these studies was unable to find a significant relationship between objective instability and functional activity score; however, for subjects with an intraarticular repair, as hamstring and quadriceps strength increased toward that of the normal leg, functional activities also increased.[56] Kvist looked at and compared the gaits of functional and nonfunctional ACL deficient subjects[59] (copers and noncopers, respectively). The motion of the injured leg was compared to that of the contralateral leg. The functional group had more anterior tibial translation than the contralateral tibia when compared to the nonfunctional group. Both groups had similar instability when tested by hand. It was speculated that the functional group was able to provide a functional stabilization to the knee joint by moving the tibia to the extent of soft tissue restraint and that the nonfunctional group, through mechanisms not explored, could not stabilize the joint in the same manner.

Studies of Patients With ACL Deficient and Repaired ACL Knees

Studies have looked at the mechanical differences between ACL deficient patients, those that have their ACL reconstructed, and those that have uninjured knees. Isaac et al.[60] evaluated these three groups prior to and 4 months after surgery and found the ACL deficient subjects were able to maintain anterior tibial translation to an amount similar to the intact ACL group prior to surgery. The repaired subjects, however, had a significant amount of anterior translation of the tibia after surgery in which a hamstring tendon graft was used for stabilization of the joint. This difference was attributed to an increase in hamstring activity in the ACL deficient group that the repaired group did not have. It was suggested that this increased hamstring activity helped to stabilize the knee joint, and despite no changes in EMG patterns in the pre- and post-surgical groups, that the grafted patients had reduced strength in their hamstring muscles. When Bryant et al. [61] compared muscle activity around the knee of ACL deficient and ACL repaired subjects using EMG, they found that the ACL deficient subjects had increased hamstring antagonist torque. The ACL repaired subjects did not have this increased hamstring activity and it was speculated that this increased activity allowed the ACL deficient subjects to have some stability to the joint and thus more normal activity on the affected limb. Other groups [62,63] recognize the importance the hamstrings play in stabilizing the knee joint, especially in specified angles of flexion, and the role they play in counteracting anterior directed ACL shear[63–65]. One study examined the 3D gait kinetics of subjects with ACL deficiency, varus malalignment of the knee, and knee medial compartment OA[5]. Although they did not measure muscle activity, the authors believed that their findings were consistent with increased hamstring activity and decreased quadriceps activity due to measurements of higher knee abduction and flexor moments when compared to normal subjects.

A few studies have looked specifically at other aspects of gait in ACL deficient patients that have had a repair technique performed on their knee. Osternig et al. found that post-ACL surgical subjects appear to accommodate to ACL substitution by using hip extensors to a significantly greater extent than uninjured controls[22]. Similarly, Devita's group found that subjects that were 6 months out from surgical stabilization of an ACL deficient knee used a larger hip extensor moment than did healthy controls during the support phase of gait[21]. Also, Andriacchi and Birac discovered that a similar group of subjects showed a higher net hamstring muscle moment during the early support phase of various running activities[2]. Hurwitz[3] proposed that this increased hamstring force could dynamically substitute for the ACL during stressful activities.

Inverse Dynamics and Knee Osteoarthritis

Quadriceps avoidance has also been noted in patients with knee OA[10,12]; however, these findings have been disputed in other research[66,67]. Some researchers have found that increased quadriceps and hamstring cocontraction is used to stabilize arthritic [68,69] and ACL deficient [20,70] knees. This same population may also show altered muscle contraction patterns when compared to healthy controls [17,66,68]. Kaufman et al. found patients with OA of the knee compensate with reduced extensor moment and interpreted that to be a means to reduce knee joint loading[11]. Females in this study showed increased knee flexion as well as a greater knee extensor moment, leading the authors to comment that this gender difference may help explain the increased incidence of OA in females. Although not strictly a quadriceps avoidance gait, other groups' research has determined the quadriceps muscles of knee OA subjects to be weaker than normal controls [12,71–74]. One group saw a reduction in pain associated with knee OA through quadriceps strengthening; however, this depended on the amount of varus malalignment present and it did not result in a reduction of the increased abduction moment across the knee [75].

Numerous studies illustrate the importance of studying the entire kinematic chain in order to better understand knee pathology. Astephen et al. looked at not only the kinetic and kinematic changes of the arthritic knee, but also the compensatory changes that occur at the hip and ankle in patients suffering from moderate to severe knee OA[76]. They found that both moderate and severe arthritic groups had increased mid-stance knee abduction moments, decreased peak knee extension moments, and decreased peak hip abduction and flexion moments. They also discovered that some changes were significant between groups as knee OA progressed. These gait differences included decreased stance phase knee flexion angles, decreased early stance knee flexion moments, decreased peak stance phase hip external rotation moments, and decreased peak ankle ventroflexion moments. When compared to the contralateral limb as a control, Briem et al. found a decreased hip and knee extension moment in patients affected with medial knee OA and a lateral sway of the trunk over the affected limb, a strategy thought to offload the medial compartment and that would be reflected as a lower abduction moment at the hip[77]. McGibbon et al. looked at the mechanics of the hip, knee and ankle joints in the sagittal plane of subjects with unilateral knee OA[78]. They found that this group had a reduced knee extension concentric power and an increased hip extension eccentric power and proposed that these alterations would reduce articular load by reducing contraction of the quadriceps muscles. Another study attributed a reduction of medial knee OA progression over time to an increased hip abduction moment[79]. A similar study found that exercise could help increase this abduction moment, although changes during gait were not as significant as those during the specified exercise[80].

Medial knee OA is a common sequella in ACL deficient patients. One procedure used to attempt to reduce the onset of OA is the high tibial osteotomy (HTO). The purpose of a high tibial osteotomy is to offload the medial compartment of the knee in hopes of redistributing the knee forces to a more axial or even lateral position. Ramsey et al. found that there was a tendency after HTO for decreased medial quadriceps and gastrocnemius coactivation in patients with a varus gonarthrosis[81]. Another study looking at post-operative HTO patients found patients to have reduced abduction moments about the knee[82]. These patients did not show either a stiff legged or quadriceps avoidance gait after recovering from surgery.

Inverse Dynamics and Gender

Females have a 2-8 times higher rate of non-contact ACL injury than their male counterparts [83–86]. The increased rate of injury is attributed to various etiologies, including anatomical, hormonal, and motor control factors. Differences in tibial and thigh lengths and height have been studied [87,88]. Studies have shown that Q angles are larger in women than in men[89] and are larger in athletes who sustained a knee injury than in noninjured athletes [90]. It is possible that the different shape of the pelvis in women, which is often wider than that found in men, may lead to this increased Q angle, and thus an increased valgus formation to the knee, leading to an increased injury rate [91,92]. Nagano speculates that the increased rate of noncontact ACL injuries may be due to increased internal tibial rotation along with greater quadriceps activity in female athletes.[93].

Studies have reported the effects various hormones and the fluctuations of these hormones have on the ACL in women. Although equivocal and controversial, an increase in estrogen levels is cited to be the cause of increased rates of ACL injury in females[92,94]. Conversely, one study found an increased injury rate in female soccer players during the luteal phase [95], a period in the estrous cycle low in estrogen and high in progesterone. This finding is in accordance with a study by Slauterbeck[96]. There is debate regarding the possibility that hormone cycling in women causes knee joint laxity and subsequent ACL injury [91,92,97–99].

Some research notes gender differences in the timing of hamstring muscle contraction during activity which may lead to inadequate stability and joint protection[100–103]. One group found greater rectus femoris activity in females compared to males during the early stance phase of high activity maneuvers[101]. Numerous studies have evaluated the motor control aspect of ACL injury and discussed how motor control training and injury prevention methods may help reduce these injuries [101,104–108].

Veterinary Medicine

Although veterinary medicine's use of inverse dynamics lags behind that of human research, numerous studies have emerged in recent years to help better understand animal gait mechanics[35–37,39,40,44,109–114]. Furthermore, not only have these studies given a better understanding of possible factors behind the pathogenesis of musculoskeletal disease and injury, more information has been gained regarding normal movement of veterinary patients. Prior to this research, studies focused on ground reaction forces and/or kinematic variables alone to describe the gaits of dogs affected by hip or stifle conditions.

Kinetics and Kinematics of Pathologic Gait

Kinetic and kinematic research has played an important role in describing gait characteristics of dogs with abnormal pelvic limbs and has provided the foundation for more recent inverse dynamics research. The technology for this research is becoming more available and the methods have been adapted for veterinary research. This allows for a broader application and thus a clearer understanding of normal and pathologic gait in dogs. Recent kinematic research has resulted in a more concise description of spinal motion [115,116], stair ascent [117], stair and slope descent [118], swimming [119], treadmill locomotion [120], and sit to stand exercises [121]. Agostinho et al. were able to describe kinematic differences between the elbow and stifle joints of healthy Rottweilers and Labrador Retrievers[122]. This research introduces how important it is to understand breed differences in movement, given the variability in size and morphology of dogs, in order to provide the most accurate inverse dynamics solution for dogs.

A common cause of pelvic limb lameness in the dog is OA secondary to hip dysplasia. The lameness has been described by research focused on kinetic and kinematic changes in the gait of dogs with hip dysplasia. Recent kinematic studies have allowed for a better description of movement in dogs with hip dysplasia [25,26]. Poy et al. was able to use kinematic methods to add variables of interest such as limb abduction/adduction, limb circumduction, side-to-side gait, joint angular acceleration, and vertical foot motion to better describe pelvic limb movement in affected dogs[26]. Bockstahler et al. were able to differentiate between healthy dogs and those with nonclinical hip OA through kinematic assessments when dogs had no differences in kinetic variables[25]. Other groups described only changes in ground reaction forces in dogs with either hip or stifle OA[23,24].

DeCamp et al. looked at the kinematics of the canine pelvic limb one, three, and six months after having their CCL experimentally transected and were able to describe changes in the activity of hip, stifle, and hock joints [28]. Affected dogs walked with more stifle flexion and hip and hock extension. They also showed more significant changes in their stride length and frequency. Dogs had a shorter stride 1 and 6 months post CCL transaction and increased stride frequency at 3 and 6 months when compared to the same pre-injury variables. Sanchez-Bustinduy et al. were able to use kinematic analysis of CCL deficient dogs and compare their movements to normal dogs to find that several variables, especially paw velocity, and stride length, could be used consistently to define the lameness of the CCL deficient dog[29]. Every dog with CCL rupture had a shortened stride and reduced paw velocity on affected limbs compared to healthy control dogs. Using this information, de Medeiros et al. monitored dogs over 12 weeks during recovery from TPLO surgery. They were able to use a kinematic model to correlate increased stance time and paw velocity with return to normal function[27].

The first 3D study of the canine stifle was performed by Korvick et al. [32]. This group documented 3D kinematics of the normal stifle as well as kinematics of the CCL deficient stifle 7 weeks after transection of the ligament. They showed the canine stifle to be CCL-dependent during stance phase, with CCL deficient stifles exhibiting both cranial displacement of the tibia and negative distraction (compression) between the femur and tibia. The dogs compensated for

CCL deficiency by placing the limb in a more flexed position and reducing the load placed on the limb during weight bearing. A similar study was performed by Tashman et al. where they performed serial 3D kinematic studies over a period of two years on dogs with experimentally induced CCL transection[33]. They found a significant increase in cranial tibial translation in CCL transected subjects compared to normal controls as well as increased mean stifle adduction throughout the stance phase in the same subjects.

There have been very few additional canine studies that have looked at 3D movement of the canine pelvic limb [30,31,34]. Chailleux et al. performed a 3D kinematic evaluation of cadaveric limbs prior to and after CCL transection and subsequent stabilization by placement of a lateral suture and then a TPLO surgery[30]. They found that the lateral suture subjects had a reduced range of motion (ROM) of the stifle. Both surgeries reduced cranial translation of the tibia during simulated weightbearing and the TPLO surgery resulted in a caudal translation of the tibia. There was increased tibial adduction throughout ROM in the TPLO limbs and increased abduction in the lateral suture limbs. Both procedures resulted in a significant increase in tibial external rotation.

Torres et al. developed and tested a Joint Coordinate System (JCS) on the stifle of healthy dogs and compared their findings to linear and segmental models[34]. A JCS describes the 3D orientation of the body segments comprising a joint with respect to each other so that the JCS moves dynamically with the subject. It makes the study of extension/flexion, abduction/adduction, and internal/external rotation at every joint possible. The motion of two body segments relative to each other is defined by the JCS and described by axes that are fixed to the segments and a mutually orthogonal floating axis. This group was able to produce kinematic data for sagittal plane motion of the stifle that was consistent with the other two methods while at the same time describe stifle motion in the other two planes. Fu et al. then used the same system to describe 3D motion of the hip, stifle, and hock joints of normal dogs[31].

Veterinary Inverse Dynamics

The earliest notable inverse dynamics study in veterinary patients was performed on dogs to analyze the joint forces and joint moments in the pelvic limb before and after total hip arthroplasty [39]. This study showed that although kinematic variables returned to normal shortly after surgery, kinetic parameters were more sensitive in analyzing an antalgic gait. It allowed new understanding of the forces and muscle activity in the pelvic limb of dogs. In this case, although kinematic changes were not significant one month post-operatively, joint forces as well as moments across the joints were reduced in dogs.

Equine studies have been at the forefront of veterinary medicine inverse dynamics research with descriptions of horse forelimb and hindlimb joint motion, moment, and power in both the swing and stance phases [110–112,123,124]. These early studies described how energy is transferred between joints and used to propel the horse. By establishing a database of energy profiles, these researchers built a foundation to apply their findings to the study of equine lameness. In addition, the differences in these profiles may be applied to the description of compensatory motions for different forms of lameness in horses.

Inverse dynamics research has resulted in a better understanding of forelimb motion and joint disease [109,114,125], and pelvic limb motion, symmetry, breed differences, and joint disease in dogs [35–40]. Nielsen et al. were the first to describe canine forelimb motion using an inverse dynamics method[114]. They described kinetic and kinematic features of healthy canine forelimbs as well as morphometric data of the forelimb for a medium sized mixed-breed dog. With this research, there is an understanding of how energy is transferred between the metacarpophalangeal, antebrachiocarpal and elbow joints during the stance phase of the dog at a walk. The morphologic data can also be used on similarly sized dogs in future research. This research provided the groundwork for helping to understand the compensatory changes in dogs with fragmented coronoid processes [109] as well as further information on treatment options for affected dogs [125]. Canine pelvic limb mechanics have been studied more recently with descriptions of differences between breeds. With an understanding of how energy is transferred between joints, a better understanding may be obtained of how specific breeds may be prone to certain injuries because of their conformation and motion patterns [37]. Other studies have described an asymmetric gait or "handedness" in otherwise normal dogs – an asymmetry not appreciated without the aid of inverse dynamics [35,36]. Only one other study has looked at the full inverse dynamics profile of the canine pelvic limb (hip, stifle, hock), and this study compared differences between normal and CCL deficient dogs [40]. This group found that CCL deficient dogs had reduced net moment, power, and vertical and braking joint reaction forces for all joints studied. It is important to realize, however, that the CCL deficient dogs had no repair performed to stabilize the stifle joint.

Related Research

3D gait observation and inverse dynamics research have allowed veterinarians to better understand the complexity of the normal canine gait and to apply this knowledge to pathologic gait. In developing the ability to collect patient specific morphometric data noninvasively, one group discovered anatomic differences that may help explain part of the complex pathogenesis behind CCL rupture, comparing their findings to the quadriceps avoidance gait in humans [113]. In this study, those dogs that were CCL deficient had atrophy of the quadriceps group, and these CCL deficient limbs, as well as the contralateral limb, had a dominance of the gastrocnemius muscle. Advances in canine kinesiology are allowing for true 3D evaluation of healthy and pathologic canine limbs [30–34] which in turn is allowing for an understanding of breed specific anatomic differences and how they may relate to disease processes with breed predilections. Inverse dynamics research and 3D kinematic evaluation also allow an understanding of how various treatment options for stifle joint instability may benefit or deter patients' recovery from stifle surgery.

Numerous studies have attempted to compare post-operative function after surgery for a ruptured CCL using various kinetic and kinematic objective measures. Although these studies record improvement from the injured state, none have shown one procedure to be more superior to the other in long term function [126]. To our knowledge, only four studies have directly compared the TPLO and the lateral suture procedures [30,41–43], and none are able to suggest that one procedure is better for the CCL deficient stifle than the other. One study performed 3D kinematics research on cadaver stifles immediately after each procedure was done, and compared these results with those of an intact stifle [30]. Although they were able to describe differences between the kinematics of these procedures, neither one was superior to the other. One group looked at radiographic scores more than 12 months post-operatively and were unable to find any significant differences in these scores between the TPLO and lateral suture groups [43]. Forceplate analysis of these two groups were performed at six [42] and twenty-four [41] months post-operatively and neither were able to determine any significant differences.

Much research has been reviewed to support the purpose of this study. Human research shows the broad application of inverse dynamics research. It also presents many different etiologies of and adaptations for altered gait due to knee pathology. It is apparent how deficient veterinary medicine is in inverse dynamics research and how much information may be gained from it. There are inadequate longterm studies comparing the two common methods to repair an unstable stifle of TPLO and LFS. Also, there is not enough research focusing on 3D motion of the canine pelvic limb to fully understand and discuss its motion in normal and pathologic gaits.

CHAPTER 3

MATERIALS AND METHODS

Subjects:

25 hound type dogs were evaluated in this study. Three dogs were male and 22 were female. The mean (+/- SD) weight was 22.08 kilograms (+/- 1.88) with a range of 17.9 to 26.1 kilograms. These dogs were used as part of an ongoing study that grouped the dogs into three categories. Group 1 (n=6) included dogs free of any orthopedic or neurologic abnormalities. Physical examination of these dogs revealed no gait deficiencies or orthopedic or neurologic problems, and radiographic study revealed no osteoarthritic changes in the caudal spine, pelvis or pelvic limbs. The two treatment groups consisted of dogs that had received either a TPLO (Group 2, n=13) or LFS (Group 3, n=6) surgery previously. Surgery was performed on average 70 months prior to the start of this study with a standard deviation of 18 months. For both surgical groups of dogs, the CCL was surgically transected immediately prior to the stabilization procedure. The TPLO surgery was performed as previously described [127]. Briefly, an osteotomy of the proximal tibia was created using a circular saw blade. The proximal tibial component was rotated caudally so that the tibial plateau angle was approximately 5 degrees to the long axis of the tibia. The two tibial components were held in place with a 6 holed TPLO plate (Figures 2 and 3). The LFS group was stabilized with two nylon sutures passed around the lateral femoral fabella and through a hole created in the proximal tibial tuberosity (Figure 4). Once recovered from surgery, all surgical dogs were allowed the same amount of leash restricted activity and were kept in the same controlled kennel-type environment. The control group was similarly housed. The only abnormal orthopedic and radiographic findings in the two surgical groups were evidenced in the stifle joint of that surgery. These dogs had various degrees of radiographic evidence of osteoarthritis in the stifle having received surgery, but no other sources of possible lameness were appreciated on physical and radiographic examination. Ventro-dorsal

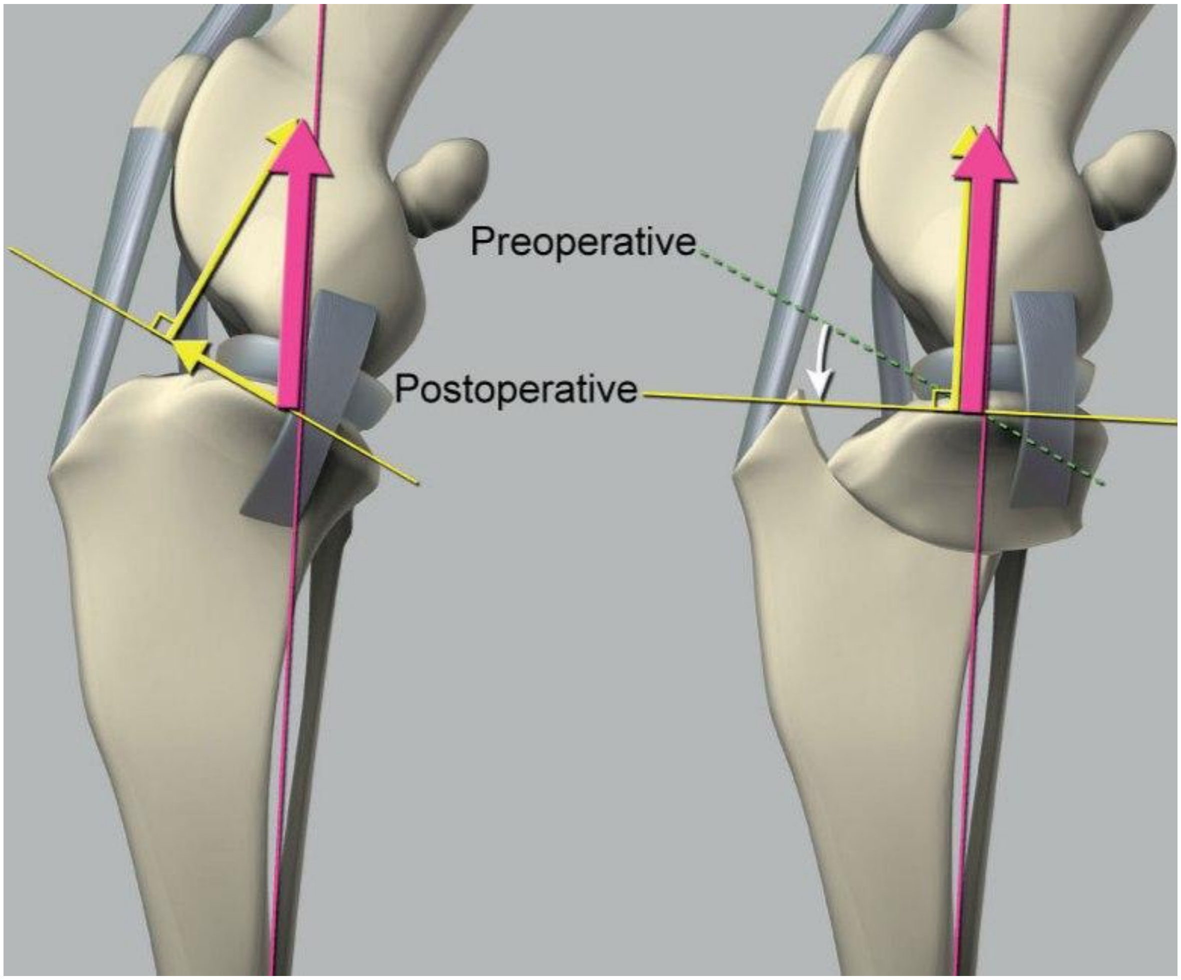

Figure 2. A representation of a tibia before and after the proximal tibial osteotomy for the tibial plateau leveling osteotomy. (From Kowaleski MP, Boudrieau RJ, Pozzi A: Stifle Joint. In Tobias KM, Johnston SA, editors: Veterinary Surgery Small Animal, ed 1, 2012, Saunders/Elsevier)

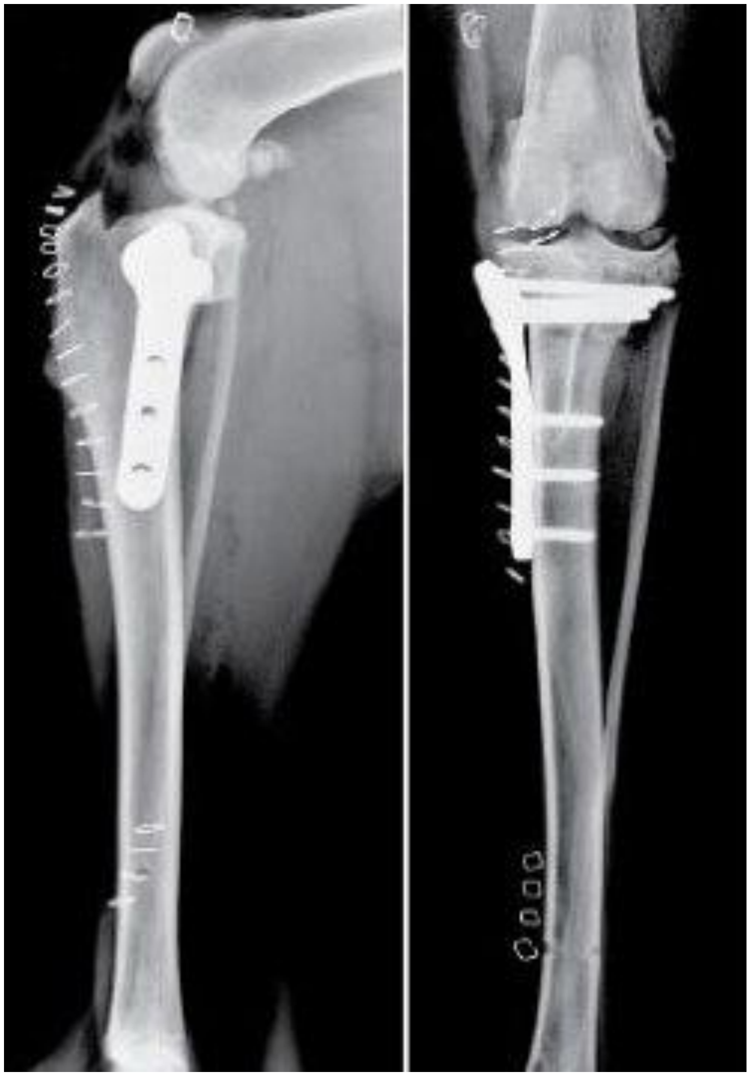

Figure 3. Post-operative radiographic images of a TPLO procedure. (From Kowaleski MP, Boudrieau RJ, Pozzi A: Stifle Joint. In Tobias KM, Johnston SA, editors: Veterinary Surgery Small Animal, ed 1, 2012, Saunders/Elsevier)

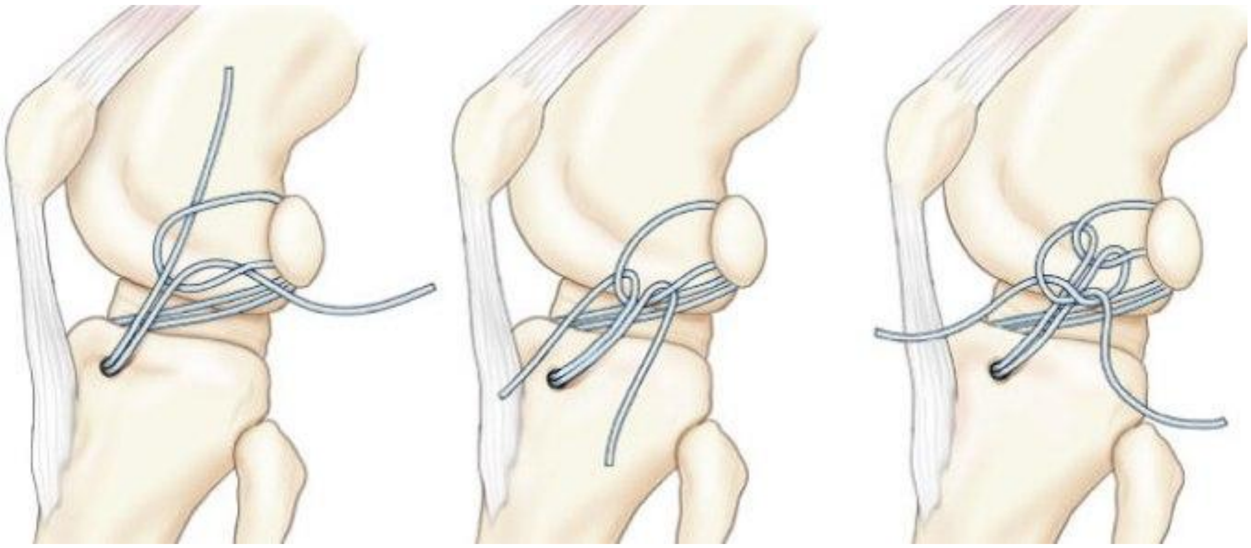

Figure 4: Representation of lateral fabellar suture procedure. (From Kowaleski MP, Boudrieau RJ, Pozzi A: Stifle Joint. In Tobias KM, Johnston SA, editors: Veterinary Surgery Small Animal, ed 1, 2012, Saunders/Elsevier)

and lateral views of the caudal spine, pelvis, and pelvic limbs were available from the start of this study as well as from previously, at the start of the initial ongoing study. The study protocol was approved by the University of Tennessee Institutional Animal Care and Use Committee.

Computer skeletal model:

A canine skeleton model file was purchased (Exchange3D LLC, New Orleans, LA, USA) and each bone file was resized and configured (Autodesk 3D Max 9, San Rafael, CA, USA and Excel, Microsoft Office 2007, Redmund, WA, USA) to make it compatible for study of our subjects' movements in 3D biomechanics software suite (Visual 3D, C-Motion, Inc., Germantown, MD, USA). The 3D skeleton allowed for visualization of the 3D model and a more precise study of each segment's motion through the kinematic space (Figure 5).

Experimental protocol:

Kinetic and kinematic data were simultaneously collected during dynamic movement trials. Kinetic data were collected from a force platform (1000 Hz, American Mechanical Technology Inc., Watertown, MA, USA) mounted flush in the middle of a 10.68 meter runway. The force platform signal was processed and stored by use of a specialized computer software program (Acquire 7.3, Sharon Software, Inc., Dewitt, MI). Kinematic data were collected using a 4-camera 3D motion capture system (60 Hz, Vicon Motion Systems Inc., Centennial, CO). Prior to any data collection, the 3D space was calibrated with a calibration frame along with dynamic calibration with a wand.

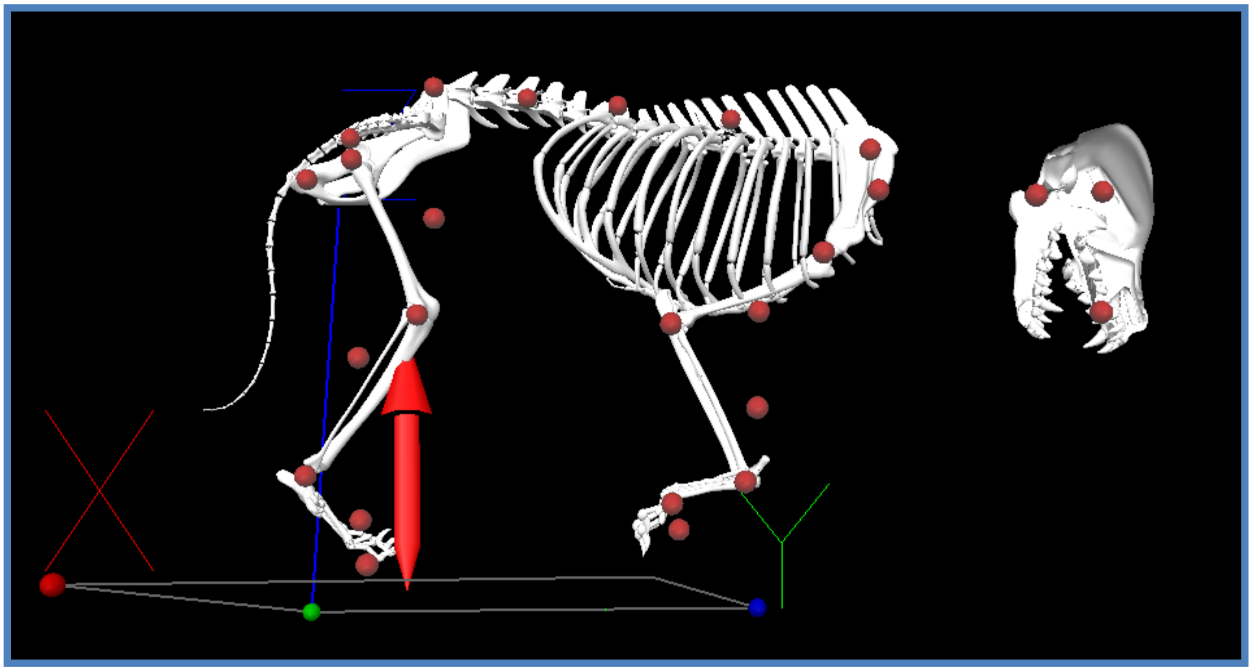

Figure 5: Screenshot of computer full-body skeletal model depicting placement of full-body markers (current study did not use spinal, forelimb, or skull markers), ground reaction force, and forceplate

The dogs were outfitted with spherical reflective anatomical and tracking markers 14 mm in diameter. Anatomical markers defined the approximate proximal and distal joint centers of segments and were removed after static calibration of the subject. Tracking markers were used to monitor movement of the subject and remained in place during the dynamic trials. Hair was shaved and the reflective markers were fastened to the subjects with cyanoacrylate adhesive over various anatomic sites of the pelvic limb. Markers were placed on one pelvic limb at a time. The markers were placed over distal aspect of the 2^{nd} and 5^{th} metatarsal bones, medial and lateral malleoli of the hock, medial and lateral aspects of the stifle between the condyles of the femur and tibia, over the left and right greater trochanters, left and right ischial tuberosities, and cranial most aspect of the left and right ilial bodies. In order to name a segment (pelvis, femur, tibia, foot) a third sphere was required per segment, and had to be placed so as not to be collinear with the marker on either side of it. These were placed on the dorsum of the foot, craniolateral aspect of the crus and thigh, and over the lumbosacral junction. A static calibration was performed with the dogs standing still in the testing area. All 16 markers were visible by at least two of the four video cameras and a three second video of the standing dog was performed (Figure 6). The anatomic markers on the contralateral ischium, ilium, and trochanter, as well as those on the medial aspect of the foot, hock and stifle were removed after the static trial.

After removal of the anatomic markers, dogs were trotted through the testing space and over the forceplate at an average velocity between 1.70 and 2.1 m/s and acceleration of $-0.5 m/s^2$ and $0.5 m/s^2$. Velocity and acceleration were monitored by 5 infrared photoelectric cells placed 50 centimeters apart from each other (Sharon Software, Inc., Dewitt, MI). Trials were collected until 5 successful passes were successfully recorded. A trial was valid when there was no aberrant movement of the subject's head or body during the trial in the calibrated space, the

Figure 6: Images depicting a static calibration over the forceplate along with placement of all pelvic limb markers

velocity and acceleration were within the appropriate range, the ipsilateral fore and hind paw struck the forceplate, and all markers were in view of at least two cameras at all times. Stance time was defined as toe down to toe off and measured by the end point and starting point of movement of the metatarsal marker respectively. Mediolateral, craniocaudal, and vertical components of the ground reaction force were assigned the values of x, y, and z respectively. These forces were normalized by the subject's body weight and reported as a percentage of the body weight. The same investigator (JH) placed all markers during all testing sessions and the same handler (RM) trotted the dogs in all trials. A Cardan sequence (XYZ) was used to compute the 3D angular kinematics. The conventions of 3D angular kinematic variables were determined by using a right-hand rule.

Data Processing:

Three-dimensional coordinates of marker trajectories were smoothed by a Butterworth 4^{th}-order low-pass filter at a cut off frequency of 6 Hz. Kinetic data were processed by custom software (Acquire 7.3, Sharon Software, Inc., Dewitt, MI) and kinematic data analysis performed using a commercially available motion analysis system (Peak Performance Technologies, Inc., Centennial, CO). Synchronization of these data occurred in a different custom software program (Combine, Sharon Software, Inc., Dewitt, MI). These files of synchronized data were processed, computer models created and analyzed, and reports produced in commercially available software (Visual 3D, C-Motion, Inc., Germantown, MD, USA). Critical events and values of the computed variables from outputs of Visual3D were determined by the use of customized computer programs (VB_V3D and VB_Tables, version 1.50, University of Tennessee, Knoxville, TN, USA). Morphometric data from a previous study[37], including segments' percent of body weight and centers of gravity were input into Visual 3D for use in the inverse dynamics calculations. This study compared differences in the distribution of power across the joints of the pelvic limb in Labrador Retrievers and Greyhounds. Given the lack of breed specific data available in the literature, we used the Labrador Retriever data from this study for our research hounds as the hound's form more closely resembles the retriever than the Greyhound. The resultant variables of interest were obtained through the combination of the kinetic, kinematic, and morphometric data through an inverse dynamics solution.

Virtual points representing the center of the hip, stifle, hock and metatarsal-phalangeal joints were mathematically reconstructed by the software (Visual 3D, C-Motion, Inc., Germantown, MD, USA) in relation to the anatomic markers from the static calibration. The center of rotation of the hip, stifle, and hock joints was assigned a virtual point configured by two distinct means. The hip joint virtual point was designated to be on a line connecting both greater trochanter markers and was programmed to be placed at a point medial to the greater trochanter marker on the side being studied. This point was specific for each dog and was based on measurements taken on a ventro-dorsal pelvic radiograph of the dog. A line was drawn on the digital radiograph from the greater trochanter on one side to that of the other, coinciding to the placement of the reflective spheres. Another line was drawn from the same origin as the first line and ended at a point approximating coxofemoral articulation (Figure 7). A ratio of these two measurements was used to program a virtual point medial to the greater trochanter marker being studied. The stifle, hock, and metatarsal-phalangeal center of rotations were mathematically determined from the static calibration as the points midway between the lateral and medial markers of these joints.

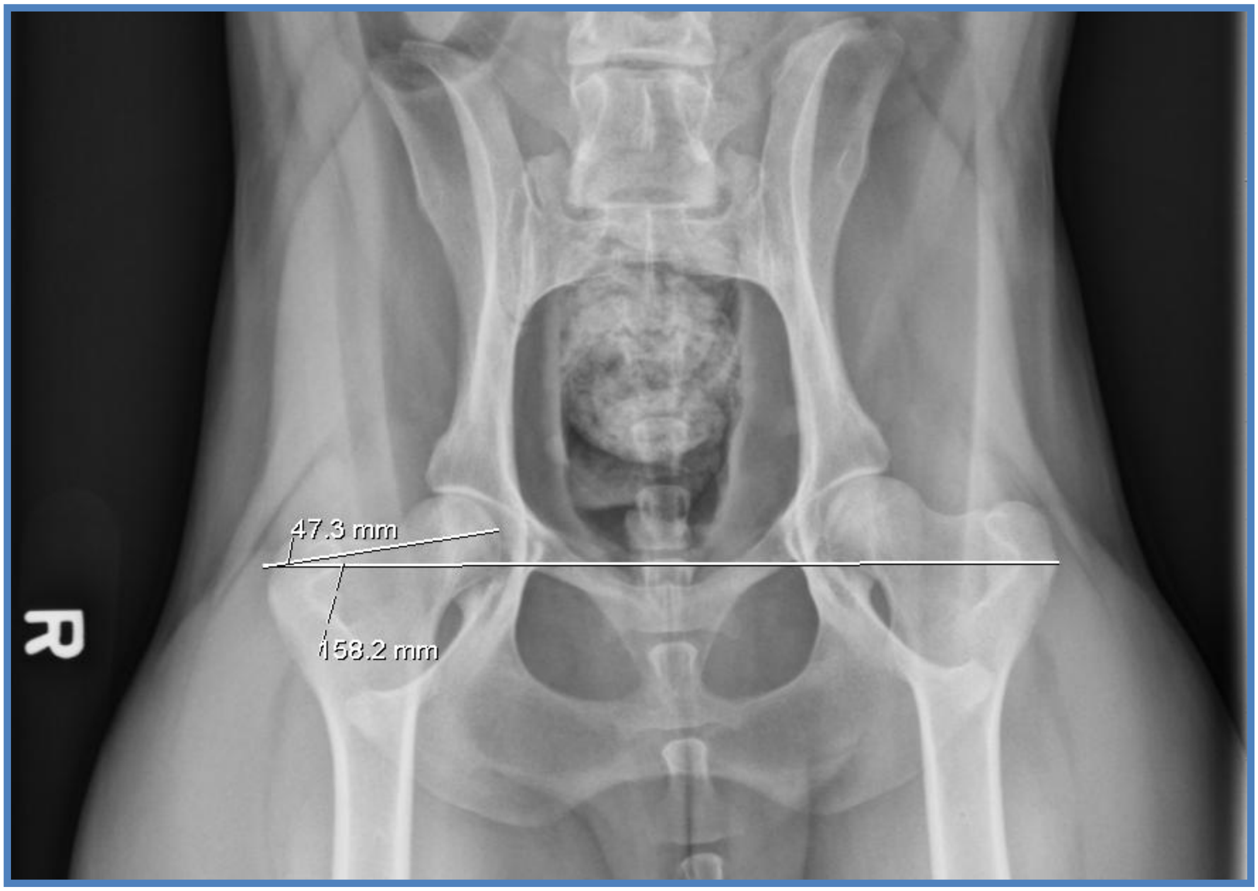

Figure 7: Method used for determining the hip joint center. A line was drawn from one trochanter to the other. Another was drawn from the origin of the first line to the joint center of interest. A ratio of these measurements was used to create a virtual point at the hip joint center in relation to the trochanteric marker being studied.

Joint angles, moments and powers in the sagittal, frontal, and transverse planes during the stance phase of the gait cycle were examined. The moments and powers were normalized by the mass of each dog resulting in units of Nm/kg and W/kg, respectively. Joint angle was named after the direction that the distal segment moved in relation to the proximal segment, and each angle determined by the virtual points mathematically created and designated to the joint centers. 180 degrees would designate a straight line between segments in the sagittal plane and an angle measured higher than this in would be overextension. In the frontal plane a measurement of 0 degrees was equivalent to a straight line between segments with a positive angle equaling a greater adduction angle and a higher negative measurement representing a greater abduction angle. In the transverse plane a measurement of 0 degrees was noted when the cranial aspect of both segments aligned with each other. A higher positive measurement equaled greater internal rotation of the distal segment and a more negative measurement as associated with a greater external rotation. ROM is defined as the angular displacement of a joint throughout the stance phase, from toe on to toe off. Joint excursion is defined as the difference between the maximum and minimum joint angles during this same period. A positive moment was assigned to those moments across the cranial aspect of the pelvic limb (hip flexors, stifle extensors, and hock flexors) and a negative moment assigned to those moments across the caudal aspect of the limb (hip extensors, stifle flexors, and hock extensors). A positive power represents power generated by the soft tissues across the joint. This is seen with concentric muscular contraction or shortening of the muscle fibers as they generate tension. Eccentric contraction, or lengthening of the muscle fiber during tension generation, is labeled as negative power and indicates energy absorption at the joint. The moments recorded are net moments across a joint and the associated power indicates activity of the muscle group assigned to the net moment.

Mean joint angular excursions, net joint moments, and net joint powers were determined for all dogs. Graphs for all three groups were plotted on the same time and amplitude scales in order to make comparisons between the groups. Graphs were created for inverse dynamics study of the hock, stifle, and hip joints in the sagittal, frontal, and transverse planes. Critical points such as maximum and minimum points and areas under the curve on each graph were chosen for statistical comparison. These points of interest were chosen subjectively based on appearances of possible variations between any of the groups. Maximums and minimums of some waveforms were easily determined. In other areas that did not have an obvious maximum or minimum, or a starting point or ending point, the area under the curve between the neutral axis and the positive or negative inflection was used for comparison.

Statistics

A randomly selected hind limb from each control dog (n=6, Group 1) was chosen for comparison with the surgically corrected limbs from groups 2 (n= 13, TPLO surgery) and 3 (n=6, LFS surgery). An ANOVA model (PROC GLIMMIX) was used to test the association of each of the measurements in the X, Y and Z planes with group (SAS version 9.2, SAS Institute, Cary, NC). Dog and group were included as class variables, group was included as the independent variable and measurement as the dependent variable in the model. The method of Tukey was used to adjust the P-values to compensate for the effect of multiple levels of group. The fit of the model to the data was assessed by comparing the residuals to a normal distribution. Where necessary, the dependent variable was transformed by using the log, square root or rank (PROC RANK) procedure in order to normalize the residuals from the model. Results for transformed data are reported as medians along with ranges, instead of least mean squares and standard error of the mean. The test statistic of Shapiro-Wilk was used to assess normality of the residuals. A P-value of < 0.05 was used to determine statistical significance in all tests.

CHAPTER 4

RESULTS

Sagittal plane (Figure 8)**:**

Movement patterns were consistent between all three groups in all three joints with only small variations appreciated.

Hock Joint: The hock joint began stance phase in flexion and continues to flex until approximately 40% into the stance phase, at which time it moved toward extension through the remainder of stance phase. There was a net extensor moment throughout motion with an increase in torque across the joint for the first 40% of the time and decrease through the remainder of the stance phase. The power curve revealed energy absorption during the first 40% of stance suggesting muscles lengthening and eccentric contractions of the extensor muscles. This muscle action stores elastic energy in the muscles and helps increase concentric contraction of the muscles across the joint to propel the hind limb for the second 60% of the stance phase, shown as energy generation in the second part of the power curve. The normal group began the stance phase slightly more flexed (p=0.19) and attained a more maximally flexed angle (p=0.17) when compared to the other two groups; however, there were no significant differences among groups regarding ROM (Table 1).

Stifle joint: The stifle joint began the stance phase in flexion and continued to flex for approximately the first 60% of the stance and then extended until toe-off. Although for a majority of this time there was a net extensor moment, the first 10 to 20% of stifle flexion was controlled by a net flexor moment. During this net flexor moment, the hamstrings muscles contract concentrically. The remainder of the stance phase revealed the quadriceps muscles contracting eccentrically for the first half of the time and concentrically for the remainder of the time. Although not significant (p=0.57), the LFS group had more stifle extension throughout stance (Table 1). Both TPLO and suture groups have a slightly increased and prolonged flexor moment at the beginning of stance phase compared to the control group.

Hip joint: All groups had continuous extension of the hip throughout stance phase. Both surgical groups remain more extended throughout the stance phase when compared to the normal population. The angle of the hip at toe down is significantly different between the TPLO and normal groups ($p=0.03$) (Table 1). This is the only variable studied in the sagittal plane to show a significant difference between any groups. All three groups have a nearly identical moment and power curve throughout hip excursion. For the first 50% of stance phase the extensors cause the net moment and contract concentrically, propelling the dog forward. For the second 50% of stance phase the flexors caused the net moment and were absorbing energy while contracting eccentrically, slowing the limb down and preparing it for the swing phase.

Variables of interest in the sagittal plane were chosen from graphs in Figure 8 and are recorded in Table 1.

Ensemble Mean Curves for Sagittal Plane Angles, Moments, and Powers for Hock, Stifle, and Hip Joints

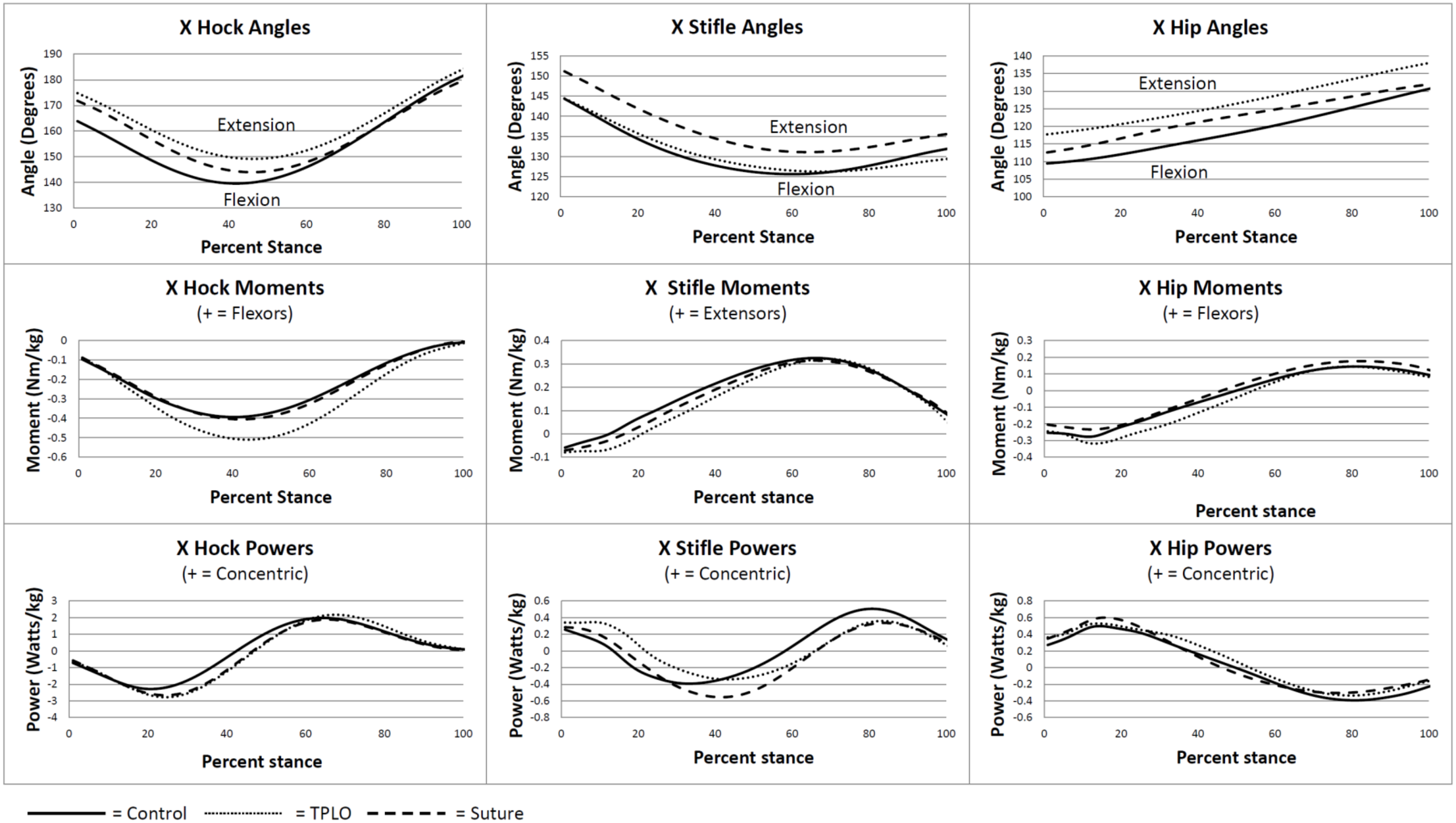

Figure 8: Ensemble mean curves of sagittal plane angles, moments and power for the hock, stifle and hip joints

Table 1. Mean/median values of sagital plane variables of interest

	Sagittal Plane Variables		
	Normal	TPLO	LFS
Hock Contact Angle (Degrees)	167.05 (3.38)*	174.74 (2.30)	171.66 (3.38)
Hock Toe Off Angle (Degrees)	182.94 (2.91)	184.56 (1.98)	180.06 (2.91)
Hock Minimum Angle (Degrees)	141.72 (3.17)	148.62 (2.16)	143.72 (3.17)
Hock Excursion (Degrees)	35.5 (4.19)	30.86 (2.85)	32.25 (4.19)
Hock Max Extensor Moment (Nm/kg)	-0.41 (0.06)	-0.52 (0.04)	-0.41 (0.06)
Hock First Max Eccentric Power (W/kg)	-2.51 (0.41)	-3.03 (0.28)	-2.75 (0.41)
Hock Negative Work (J/kg)	0.12 (0.02)	0.15 (0.015)	0.14 (0.02)
Hock Max Concentric Power (W/kg)	2.11 (0.28)	2.24 (0.19)	1.94 (0.28)
Hock Positive Work (J/kg)	0.11 (0.02)	0.12 (0.01)	0.09 (0.02)
Stifle Contact Angle (Degrees)	145.96 (3.44)	144.4 (2.34)	151.09 (3.44)
Stifle Toe Off Angle (Degrees)	133.55 (3.55)	129.52 (2.41)	135.64 (3.55)
Stifle Minimum Angle (Degrees)	127.49 (3.57)	125.49 (2.43)	130.07 (3.57)
Stifle Excursion (Degrees)	18.47 (1.54)	18.91 (1.04)	21.02 (1.54)
Stifle Max Extensor Moment (Nm/kg)	0.31 (0.05)	0.33 (0.04)	0.32 (0.05)
Stifle Negative Impulse (Ns/kg)	0.002 (0-0.005)**	0.002 (0-0.013)	0.001 (0.0005-0.002)
First Max Eccentric Power (W/kg)	0.48 (0.10)	0.48 (0.07)	0.60 (0.10)
Stifle First Max Concentric Power (W/kg)	0.40 (0.11)	0.53 (0.07)	0.37 (0.11)
Stifle Second Max Concentric Power (W/kg)	0.43 (0.10)	0.39 (0.07)	0.37 (0.10)
Stifle Positive Work (J/kg)	0.03 (0.01)	0.03 (0.004)	0.02 (0.01)
Stifle Negative Work (J/kg)	0.02 (0.01)	0.02 (0.003)	0.03 (0.01)
Hip Contact Angle (Degrees)†	109.25 (2.60)	117.73 (1.77)	112.63 (2.60)
Hip Toe Off Angle(Degrees)	130.58 (2.75)	138.18 (1.87)	132.03 (2.75)
Hip Excursion (Degrees)	21.34 (1.11)	20.44 (0.76)	19.40 (1.11)
Hip Max Extensor Moment (Nm/kg)	0.32 (0.04)	0.36 (0.03)	0.26 (0.04)
Hip Max Flexor Moment (Nm/kg)	0.15 (0.03)	0.15 (0.02)	.19 (0.03)
Hip First Max Concentric Power (W/kg)	0.61 (0.12)	0.68 (0.08)	0.67 (0.12)
Hip Positive Work (J/kg)	0.030 (0.01)	0.04 (0.004)	0.03 (0.01)
Hip First Max Eccentric Power (W/kg)	-0.39 (0.06)	-0.38 (0.04)	-0.35 (0.06)
Hip Negative Work (J/kg)	0.02 (0.01)	0.02 (0.003)	0.02 (0.01)

*Least Square Mean (1 standard error of the mean)

**Median (Range)

† indicates significant difference between Control and TPLO groups

Frontal plane (Figure 9):

Joint excursions were much smaller in this plane, and joint moments and powers were approximately 5 to 10 times less than those seen in the sagittal plane. Any appreciable visual differences on the graphs are actually very small in comparison to sagittal plane differences.

Hock joint: The hock joint began stance phase in slight abduction and adducted throughout the ROM. The normal joint adducted to approximately zero degrees and the two surgical groups adducted a few more degrees on average to the end of stance phase. For the majority of the stance phase, the abductors are contracting eccentrically causing a net abductor moment and absorbing energy for most of this time period. There was no statistical difference found in any joint angle variable between groups in frontal plane motion of the hock.

Stifle joint: The normal stifle also began the stance phase slightly abducted. All groups showed a slight adduction for the first 50% of stance phase and slight abduction for the second half of the phase. The surgical groups, although not significantly different from each other or the controls, began the stance phase in a more adducted position (p=0.64) and reached a higher angle of adduction (p=0.49) during weight bearing (Table 2). A net abductor moment existed for the suture and control groups for the first 60 to 70% of stance phase, and a very slight adductor moment toward the end of the phase for both of these groups. The TPLO group had a net abductor moment throughout the stance phase. The moments for all groups were predominately concentric in nature throughout. The only significant variable studied in the frontal plane was between the suture group and the control group and was the maximum power across the stifle. The suture group had a significantly larger concentric power burst when compared to the control group's power across the stifle (p=0.01) (Table 2).

Hip joint: The hip abducted throughout the stance phase for all groups. The normal controls began with a slightly more abducted hip joint and had nearly twice the degrees of excursion (approximately 10 degrees compared to approximately 5 degrees) as the surgical groups, although these differences were not statistically significant (p=0.90 and p=0.91 respectively) (Table 2). For all groups, the abductors caused a net abduction moment and contract concentrically throughout most of stance phase.

Variables of interest in the frontal plane were chosen from graphs in Figure 9 and are recorded in Table 2.

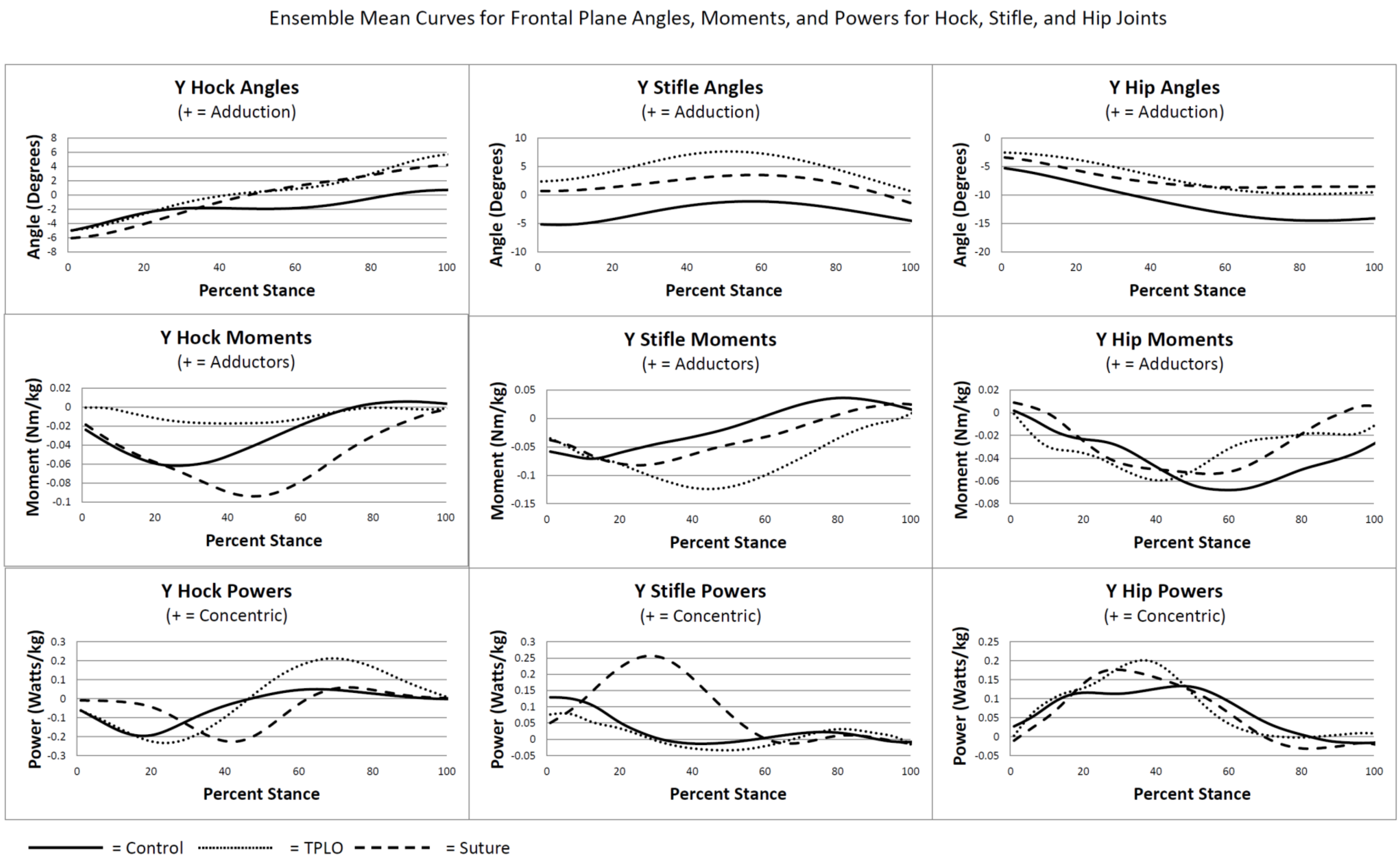

Figure 9: Ensemble mean curves for frontal plane angles, moments and power for the hock, stifle and hip joints

Table 2. Mean/median values of frontal plane variables of interest

	Frontal Plane Variables		
	Normal	TPLO	LFS
Hock Contact Angle (Degrees)	-4.32 (1.90)*	-4.95 (1.29)	-6.01 (1.90)
Hock Toe Off Angle(Degrees)	3.07 (2.43)	5.73 (1.65)	4.23 (2.43)
Hock Excursion (Degrees)	7.38 (2.00)	10.68 (1.36)	10.24 (2.00)
Hock Positive Impulse (Ns/kg)	0.0008 (0.0002-0.02)**	0.005 (0.001-0.04)	0.003 (0.0 - 0.02)
Hock Negative Impulse (Ns/kg)	0.01 (0.006)	0.02 (0.004)	0.02 (0.006)
Hock Max Eccentric Power (W/kg)	-0.19 (-0.29 - 0.04)	-0.09 (-1.15-0.03)	-0.15 (-0.61 - -0.07)
Hock Max Concentric Power (W/kg)	0.07 (0.10)	0.21 (0.07)	0.06 (0.10)
Stifle Contact Angle(Degrees)	-2.46 (4.16)	2.37 (2.82)	0.70 (4.16)
Stifle Toe Off Angle(Degrees)	-3.66 (5.31)	0.48 (3.6)	-1.37 (5.31)
Stifle Maximum Angle (Degrees)	-0.60 (5.70)	7.62 (.87)	3.52 (5.70)
Stifle Excursion (Degrees)	3.67 (1.53)	7.41 (1.04)	3.17 (1.53)
Stifle Max Abductor Moment (Nm/kg)	-0.06 (-0.079 - -0.021)	-0.14 (-0.41-0.18)	-0.12 (-0.29-0.02)
Stifle Max Adductor Moment (Nm/kg)	0.001 (-0.03-0.19)	0.01 (0.04)	0.001 (-0.03-0.19)
Stifle Max Concentric Power (W/kg)†	0.03 (0.08)	0.03 (0.05)	0.26 (0.08)
Stifle Positive Work (J/kg)	0.003 (0.0004-0.0133)	0.008 (0.00-0.04)	0.01 (0.0007-0.04)
Hip Contact Angle(Degrees)	-4.04 (2.91)	-2.53 (1.98)	-3.45 (2.91)
Hip Toe Off Angle(Degrees)	-12.69 (2.91)	-9.48 (1.98)	-8.51 (2.91)
Hip Excursion (Degrees)	8.65 (2.53)	7.67 (1.72)	7.15 (2.53)
Hip Max Abductor Moment (Nm/kg)	-0.05 (0.02)	-0.06 (0.01)	-0.05 (0.02)
Hip Max Concentric Power (W/kg)	0.08 (0.011-0.147)	0.105 (-0.009-0.920)	0.15 (0.026-0.55)
Hip Positive Work (J/kg)	0.0039 (0.0001-0.0138)	0.005 (0.00-0.065)	0.008 (0.0002-0.039)

*Least Mean Square (1 standard error of the mean)

**Median (Range)

† indicates significant difference between Control and LFS groups

Transverse plane (Figure 10):

Similar to the other planes, there was consistency in angular excursions, moments, and powers among groups for all three joints in the transverse planes. Also, as for the frontal plane, excursions, moments, and powers were a small fraction of those seen in the sagittal plane.

Hock joint: For most dogs, the hock joint began stance phase in a slightly internally rotated position and then rotated externally for most of stance phase. Aside from a small deviation of the power curve of the lateral suture group (p=0.19) showing a period of eccentric activity, there was a net external rotation moment for the first 60 to 80% of stance phase caused by concentric activity of the external rotators (Table 3).

Stifle joint: Although not statistically different, the internal/external rotation curve for the surgical groups was slightly different compared to the control group. The normal group began stance phase at a nearly neutral angle and externally rotated for the first 50% of the phase. It then remained in that position for the remainder of the period. The surgical groups began at a more internally rotated position, externally rotated for the first 50 to 60% of the phase, and then internally rotated instead of remaining in position for the remainder of the stance phase. This period of time revealed eccentric activity of the internal rotators as they caused a net internal rotation moment. They lengthened and absorbed energy during the external rotation of the tibia.

Hip joint: All groups began stance phase externally rotated and internally rotated for approximately the first 60% of the phase. From this point to the end of stance phase the hip remained in position with very little change in the transverse plane. Although not statistically significant, the surgical groups were more internally rotated, as they were in the stifle, throughout joint excursion. The majority of stance phase had predominately eccentric activity of the external rotators throughout joint excursion. There were small changes in the control group's eccentric/concentric activity of the external rotators through stance phase.

Variables of interest in the transverse plane were chosen from graphs in Figure 10 and are recorded in Table 3.

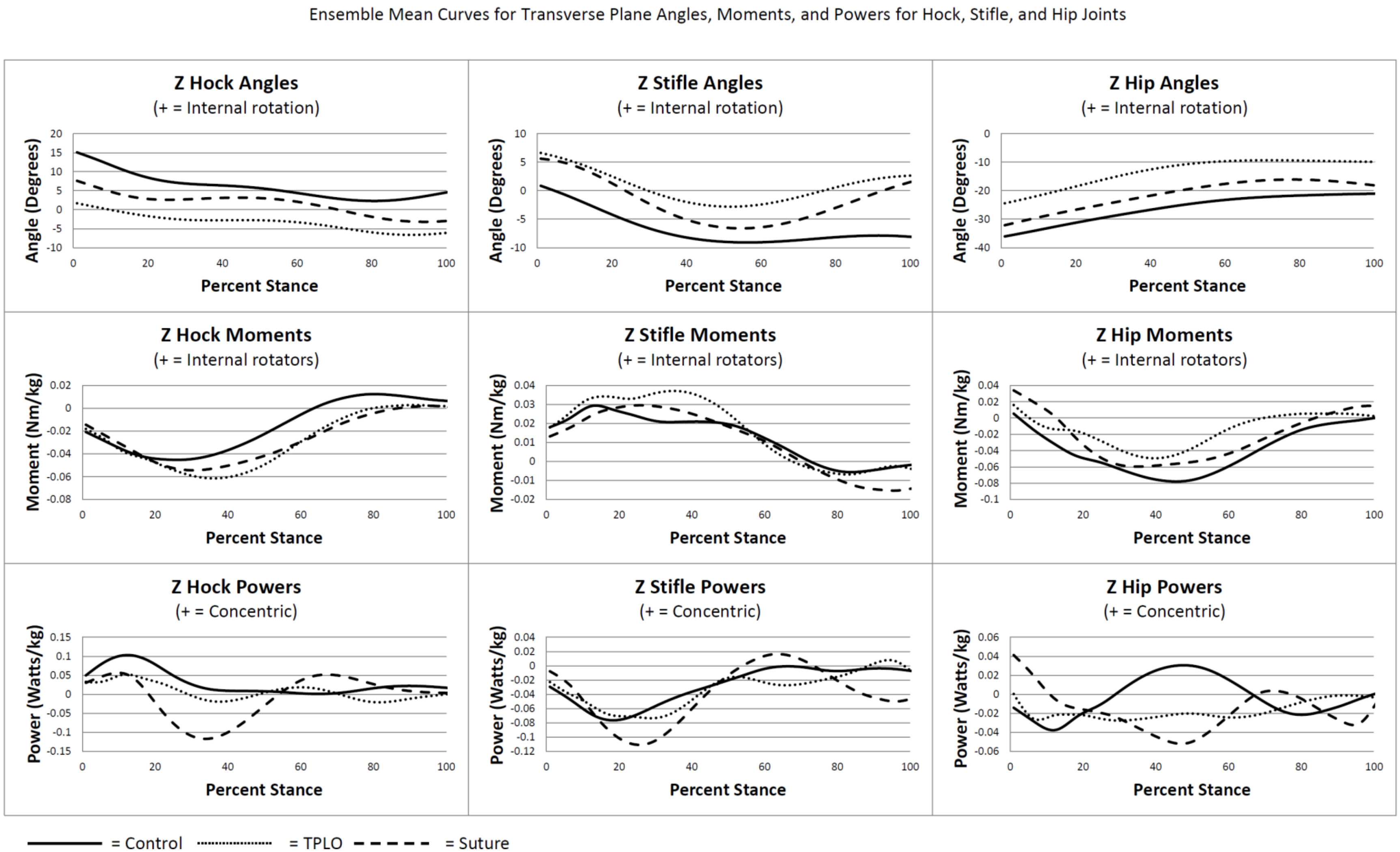

Figure10. Ensemble mean curves for transverse plane angles, moments and powers for the hock, stifle and hip joints

Table 3. Mean/median values of transverse plane variables of interest.

Transverse Plane Variables	Normal	TPLO	LFS
Hock Contact Angle (Degrees)	22.48 (11.47)*	1.69 (7.80)	7.55 (11.47)
Hock Toe Off Angle (Degrees)	10.93 (10.32)	-6.01 (.008)	-2.93 (10.32)
Hock Excursion (Degrees)	15.50 (2.65)	11.40 (1.80)	15.06 (2.65)
Hock Max External Rotation Moment (Nm/kg)	-0.04 (0.01)	-0.08 (0.009)	-0.06 (0.01)
Hock Max Internal Rotation Moment (Nm/kg)	0.027 (0.01)	0.03 (0.007)	0.007 (0.01)
Hock Max External Rotation Power (W/kg)	-0.05 (-0.23 - 0.04)**	0.09 (-0.41-0.009)	-0.124 (-0.787-0.012)
Hock Max Internal Rotation Power (W/kg)	0.10 (0.01-0.74)	0.09 (0.00- 0.46)	0.11 (-0.018-0.257)
Stifle Contact Angle (Degrees)	-2.99 (5.03)	6.64 (3.42)	11.61 (5.03)
Stifle Toe Off Angle (Degrees)	-7.80 (4.09)	2.68 (2.78)	3.63 (4.09)
Stifle Excursion (Degrees)	10.13 (2.91)	10.04 (1.98)	17.39 (2.91)
Stifle Max Eccentric Power (W/kg)	-0.02 (0.03)	-0.10 (0.02)	-0.11 (0.03)
Stifle Max Internal Rotation Moment (Nm/kg)	0.03 (0.009)	0.05 (0.006)	0.04 (0.009)
Stifle Negative Work (J/kg)	0.001 (0.002)	0.005 (0.001)	0.006 (0.002)
Hip Contact Angle (Degrees)	-31.19 (8.21)	-24.41 (5.58)	-34.92 (8.21)
Hip Toe Off Angle (Degrees)	-20.45 (8.31)	-9.92 (5.65)	-16.34 (8.31)
Hip Excursion (Degrees)	10.74 (2.77)	14.50 (1.88)	18.57 (2.77)
Hip Max External Rotation Moment (Nm/kg)	-0.07 (0.01)	-0.06 (0.009)	-0.08 (0.01)
Hip Max Eccentric Power (W/kg)	-0.09 (0.03)	-0.11 (0.02)	-0.15 (0.03)
Hip Max Concentric Power (W/kg)	0.07 (0.03)	0.09 (0.02)	0.06 (0.03)

*Least Mean Square (1 standard error of the mean)

**Median (Range)

Ground reaction forces:

Vertical and breaking/propulsion ground reaction forces and impulses were compared between groups. There were no significant differences between groups for any of the ground reaction forces variables studied (Table 4).

Table 4. Mean values of vertical and breaking/propulsion ground reaction forces

	Ground Reaction Forces		
	Normal	TPLO	LFS
Vertical Ground Reaction Force Max (N/kg)	0.63 (0.03)*	0.64 (0.02)	0.65 (0.03)
Vertical Ground Reaction Force Rate (N/s)	7.75 (0.61)	7.51 (0.41)	7.88 (0.61)
Vertical Ground Reaction Impulse (Ns/kg)	0.08 (0.004)	0.08 (0.003)	0.08 (0.004)
Breaking Ground Reaction Force (N/kg)	-0.04 (0.007)	-0.04 (0.005)	-0.05 (0.007)
Propulsion Ground Reaction Force (N/kg)	0.086 (0.007)	0.084 (0.005)	0.076 (0.007)
Breaking Impulse (Ns/kg)	-0.003 (0.001)	-0.004 (0.0007)	-0.004 (0.001)
Propulsion Impulse (Ns/kg)	0.0045 (0.001)	0.004 (0.0008)	0.003 (0.001)

*Least Mean Square (1 standard error of the mean)

CHAPTER 5

DISCUSSION

We describe pelvic limb inverse dynamics results in three dimensions of the normal and surgically repaired cranial cruciate deficient dog. Kinetic, kinematic, and morphometric data were combined in order to describe motion of the hock, stifle, and hip joints in the sagittal, frontal, and transverse planes. We were unable to find many significant differences between the kinetic, kinematic, or inverse dynamics patterns of normal dogs and those that had their CCL repaired with one of two techniques approximately 5 years prior to the study reported here. There was no evidence of orthopedic conditions in the pelvic limb joints of the normal control dogs on physical or radiologic examination that would lead one to consider their gait abnormal. Despite evidence of radiographic OA in the stifles of the surgical groups, and despite stifle arthrotomy and corrective surgery after transection of the cranial cruicate ligament, these two groups had similar gait characteristics to normal age matched dogs an average of 5 years after surgery.

There are a few veterinary studies that have described the kinematics of the canine stifle in three planes [30–34] and only one of these has described 3D kinematics of the hip, stifle, and hock joints [31]. Those studies that have described the motion of the canine pelvic limb using inverse dynamics [35,37,38,40] have been limited to the sagittal plane. To our knowledge this is the first study to describe the inverse dynamics of the canine hip, stifle, and hock joints in three dimensions. We also compare our results with those other studies that have followed and compared the two common procedures of TPLO and lateral suture for a length of time post-operatively [27,41–43]. We are unaware of any other study that has followed these two surgical groups out 5 years or more and compared them with a normal control using inverse dynamics.

The three groups studied here showed a surprising similarity with each other in saggital plane joint angles, moments, and powers. Although not significant, the surgical groups had a slightly more extended hock and hip joint throughout stance phase when compared to the controls (the hip angle at toe down was significantly higher statistically in the TPLO group compared to the normal group). This is similar to DeCamp's findings of dogs that were one, three, and six months out from having their CCLs experimentally transected [28]. The dogs from that study walked with a more flexed stifle and extended hip and hock joints when compared to healthy dogs. Although our dogs did not show a difference in stifle angles, and no significant differences were apparent in sagittal plane moments or powers, extended hips and hocks may help compensate for an altered stifle.

It is interesting to see the changes among groups when looking at the first 20% of stance phase in the sagittal plane, specifically examining the flexor moment across the stifle. Although not statistically significant, there was an increased flexor moment impulse for both surgical groups during this flexor moment. This slight change in the flexor moment may be an indication that the hamstrings were attempting to stabilize an unstable joint at the point of impact. It would be interesting to study this area of the stifle moment curve at various points in the recovery of a CCL deficient stifle. Interestingly, Ragetly et al. found this flexor moment to be reduced in Labrador Retrievers with a recently ruptured CCL [40]. Compared to this group's findings, our dogs had a more extended hock and hip along with a smaller hock excursion. Patterns are similar for joint angles, moments and power; however, amplitudes in hock moment and power along with the hip moment are different between the studies. Our subjects had a nearly two-fold increase in flexor moment and the concentric power during the second half of stance phase was nearly twice the magnitude compared to Ragetly's findings. Any differences found between our joint angle and kinetic measurements and those of other studies may be due to the fact that our variables were derived from the "true" joint center of each joint. Other inverse dynamics studies of the canine pelvic limb were in the sagittal plane only and relied on lateral markers without concern of the joint center[37,39,40]. Prior 3D studies of the canine limb were cadaveric in nature[30] or used invasive bone implants to collect kinematic data[32,33]. Others have used joint centers for the study of the pelvic limb of dogs but did not attempt to approximate the hip joint center[31,34], so it is difficult to know how this changes the resultant measurements. To our knowledge this is the first time a virtual hip joint center has been described, and use of this in measuring kinematic data should be more accurate and encouraged in future 3D canine biomechanical studies. Although collecting sagittal plane joint angle information in 2D has been shown to be accurate when compared to that collected in 3D [128], further studies are needed to compare these results with information collected from approximated joint centers. Other differences between our and other groups' joint angle results may be due to marker placement. Differences between moment and power results may be due to the differences noted above in kinematic data collection (joint centers, marker placement) but also due to the fact that we used historical morphometric data from dogs in a different study [37]. Our study did not use subject specific inertial information, but rather used software that estimated inertia based on geometric form (Visual 3D, C-Motion, Inc., Germantown, MD, USA), and this may serve as a source of difference between our and other reported inverse dynamics results.

In comparing our sagittal plane hock and stifle inverse dynamics results to that study which used the same morphometric data as we did [37], the hock joint acted in a very similar manner in both studies, but there were differences in the stifle. Although the total joint angle excursion was similar for the stifle joint between both groups, our dogs' stifles were approximately 10 to 15 degrees more flexed throughout stance phase. They reported a concentric flexor moment at the beginning of stance phase, which is similar in our dogs; however theirs had a longer duration. Their subjects had no eccentric extensor activity and a very small, if any, concentric extensor activity. Later studies by this same group showed a moment and power pattern that more resembles those of our study [35,36,38]. The morphometric data we used in our study are the same that were used in their studies. Given the differences this group studied between the Greyhound and Labrador Retriever, it is possible that breed differences between the Labrador Retrievers and our hound type dogs are variable enough to cause different results. However, we believe that our power curve results are consistent even though we used data from Labrador Retrievers because our dogs had similar body type and the results should be relatively proportional. It seems logical, however, that the extensors have a period of eccentric activity in stance phase prior to the concentric activity that propels the body forward. Further studies are required to build breed specific databases for further comparison of breed differences in motion patterns.

The only other statistically significant variable studied, aside from the sagittal hip angle at onset of stance phase, was found in stifle power in the frontal plane. It is important to note once again that the motions and energy absorption/generation patterns in both the frontal and transverse planes were a fraction of those seen in the sagittal plane. Taking that into consideration, these motions may still play a significant part of the pathologic gait after CCL rupture and need to be studied [30,32,33]. It is interesting to see that, although not statistically significant, the two surgical groups had a more adducted stifle than the control group. This is contrary to Tashman's findings that showed a more abducted stifle 2 years after CCL rupture when compared to a normal control [33]. It is difficult to compare these two studies, however, because Tashman's subjects did not have a stabilization repair performed and there is a difference in the follow-up time between the two groups. With increased adduction of the stifle, there is likely more compression in the medial compartment. It is interesting that the suture group has less adduction than the TPLO group, and we can speculate that the presence of a suture (and subsequent scar tissue) on the lateral aspect of the joint helps to reduce this movement. The TPLO surgery is designed to inhibit cranial translation of the tibia, but should not significantly reduce any movement in either of the other two planes. If the CCL has any restraint in motion in the frontal and transverse planes, there may be differences between the two surgical procedures. It is interesting that the surgical groups hold their hip joints in a more adducted position compared to the controls. This was not statistically significant, and these motions should not be overanalyzed, but it is interesting if this is in response to or a cause of changes commonly seen in the medial compartment of the stifle with stifle OA.

The one statistically significant variable found in the frontal plane was a burst of concentric power by the abductors of the lateral suture group. The difference was significant between the lateral suture and both the TPLO and control groups ($p=0.021$ and $p=0.015$ respectively). When the data were analyzed, it is obvious that this pattern was due to the influence of one of the six dogs in the lateral suture group. This dog showed a consistent peak of concentric power as the other dogs' power was decreasing after a smaller peak in concentric activity. When scrutinized, there was nothing abnormal about this dog's trials – no aberrant movement and no other obvious differences in kinetic or kinematic data. This reveals a limitation of having a small population of subjects. The data from this one dog influenced the mean results of all six subjects to cause this one variable to be statistically significant between these two groups.

In the transverse plane, internal rotation of the tibia was observed for the first 50% of stance phase in all three groups; however, for the remainder of stance phase, the surgical groups appeared to have changes that caused internal rotation before that seen in the control group. Also, both surgical groups maintained a less externally rotated stifle throughout ROM when compared to the controls. Although these changes were not statistically significant, these discrepancies in waveforms may be related to subtle changes in the arthritic or CCL deficient stifle. Interestingly the TPLO group deviated more from the control group than the suture group did. This may be because of the lack of any stabilization that would limit internal or external rotation of the stifle joint with this surgical procedure. It is possible that the suture procedure allowed for more restricted stifle motion in terms of internal or external motion. These findings are different from those of Tashman et al. who found a trend (non-significant) toward reduced internal rotation in an unstabilized CCL deficient stifle [33].

It is worth comparing our results to two other studies that have examined the canine pelvic limb in three dimensions. Chailleux et al used a 3D electromagnetic tracking system to perform a cadaveric study examining canine stifles immediately after a TPLO or lateral suture surgery [30]. This group found both surgical groups had increased external rotation of the tibia when compared to a normal control. Our study showed both groups to be less externally rotated compared to controls. Both of our surgical groups also had increased tibial adduction compared to the controls. Chailleux's results showed increased tibial adduction in the TPLO group but increased abduction in the suture group. It is difficult to compare these two studies considering the post-operative time difference between the two studies, and also considering the cadaveric nature of Chailleux's work. Future in vivo studies are needed to compare these two procedures immediately after surgery and beyond.

Recently another group reported on the three dimensional kinematics of the canine pelvic limb during walking and trotting [31]. Fu's group provided the first veterinary research known to us to perform a static trial in dogs for the purposes of examining 3D motion by using joint centers. In the sagittal plane, their dogs' hock angles were much more flexed and did not have the excursion that our dogs had. The stifle and hip total joint excursions were similar to our study; however, the hip was more extended by approximately 15 degrees in their study. In the frontal plane the hock patterns were similar in both groups but the stifle and hips were quite different between the two studies. Where our normal subjects' stifles began in slight abduction (5 degrees) and adducted for the first 50% of stance phase, the other group was very adducted at toe down (20 degrees) and abducted slightly throughout stance phase. It is unclear which markers were used in their study to determine joint angles. If they were using an external hip marker, it is strange that their stifle angle was so much more adducted compared to ours. Differences throughout these two studies may be attributable to marker placement and use of different joint centers for measurement of joint angles. Both groups' hip angles abducted by about 10 degrees through the stance phase, however Fu's subjects began at nearly 15 degrees more abduction. In the transverse plane, our dogs' hocks entered stance with 15 degrees greater internal rotation and rotated externally throughout stance phase compared to a 10 degree external rotation (25 degree difference) starting point for the other group with the first 50% of stance phase experiencing internal rotation and the second half external rotation. The stifle joints of the dogs in the other study began internally rotated, rotated externally and then rotated internally again during stance phase. Our dogs' stifles tended to enter stance at a neutral angle and externally rotated about 10 degrees for the duration of stance phase. The slight internal rotation of the hip during stance phase was similar between both studies.

It is very difficult to compare differences between veterinary inverse dynamics studies as well as those studies describing movement in three dimensions. This is a relatively new area of study to veterinary medicine and more standardized methods to collect data should be further discussed and adopted before meaningful comparisons can be made. Until a reasonable, clinically applicable, and non-invasive means to collect morphometric data from subjects is developed, it will remain difficult to compare kinetic results between different breeds of dogs. Furthermore, methods of kinematic data collection to reduce skin motion artifact and to better characterize the motion of the skeleton must continue to improve. Human and equine research are able to place clusters of reflective spheres over the muscle groups found in middle of each segment. This allows for a redundancy of markers, so that if one is out of view or a collection error is made, other markers remain to represent the segment. Also, by placing the cluster over a large muscle mass, it may be less prone to skin motion artifact when compared to markers placed over boney prominences and may better represent the underlying skeletal motion. We attempted to duplicate this method but due to the morphometry of our subjects, we were unable to devise a means to maintain the clusters in place and have adequate separation between markers to avoid the problem of overlapping or hidden markers.

Ground reaction force is a major factor in the calculation of the moment and power across a joint. We compared ground reaction forces in the cranio-caudal and vertical directions, as well as the impulses (area under the curve) of both of these in the three groups of dogs. Comparison of discrete points at the minimums and maximums and impulse values of all data sets revealed no significant differences between the three groups. We are aware of only two studies that have compared post-operative ground reaction forces of TPLO and lateral suture to stabilize the stifle in patients with cranial cruciate ligament rupture. One study followed these two groups for six months after surgery and evaluated peak vertical force differences between them at a walk[42]. They found no differences between the two surgical groups, however they had fewer dogs return to normal function in the short 6 month post-operative evaluation period compared to our surgical groups. 14.9% of the lateral suture dogs and 10.9% of the TPLO dogs returned to normal function based on ground reaction forces and impulses[42]. Comparing the mean ground reaction forces and impulses between the groups in our study revealed no difference between groups. It is possible that 6 months after stifle stabilization surgery is still too soon for a dog to regain normal activity. Another group compared the same two procedures at a walk up to 2 years post-operatively[41]. They did not compare to a healthy control, but similarly found that at all time points up to and including the 2 year post-operative time, there was no difference in peak vertical force between these groups. One group of dogs that had experimentally transected CCLs and repair of stifle instability with a TPLO procedure had no significant differences at a trot between 18 week post-operative and pre-operative peak vertical forces and impulses [129]. Another group found similar results when comparing the lateral suture technique in trotting dogs [130]. Results of this study showed dogs repaired with the lateral suture technique returned to pre-operative peak vertical force levels by 20 weeks post-operatively. Finally, Budsberg studied an OA model two years after transection of the CCL with no repair and found ground reaction forces in trotting dogs to be a reasonable means to study return to function in the arthritic model [131]. He found that these dogs had a tendency to plateau in recovery, as determined by peak vertical force, at 10 months after transection of the CCL and that the subjects had very little improvement beyond this point up to 2 years after transection.

There are limitations to our study. The number of subjects we had was low, especially in the control and LFS groups, and may have reduced the opportunity to detect statistical differences among groups. The differences that we found may have been spurious instead of real differences. We noted how one dog's frontal plane motion influenced the mean stifle power of the entire group. Also, we used 4 cameras which limited us to collecting data for only one side of the dog at one time. Due to the sensitivity of the camera setup, and the need to move cameras to new locations for each side of data collection, as well as outfitting and calibrating 25 dogs per side, we were unable to collect both sides of one dog at the same time. This forced the study of the same dog (both sides) to occur over different days. Although the severity of radiographic OA is not predictive of weightbearing ground reaction forces [132], it would have been helpful to grade the level of radiographic OA to help understand how these two surgical procedures may result in different rates of radiographic progression of OA over time. We analyzed discrete portions of the kinetic and kinematic waveforms in order to compare the three groups. Although this resulted in a vast amount of data to compare, there are other methods to analyze waveforms. Principal component analysis [133], polynomial equations [134,135], Fourier analysis [28,136–138], and generalized indicator function analysis (GIFA) [34], have all been used to study gait waveforms successfully. It is possible that these methods have helped identify differences among these groups that were undetectable by our method. We used historical morphometric data of Labrador Retrievers that were not specific to our subjects. Our subjects were hound-type dogs and we are uncertain if the morphometric data we used affects our results in any way. Prior studies have used cadaveric data for morphometric information [37,114]. We did not want to euthanize our subjects in order to obtain specific morphometric data from them, considering that a database for a similar sized dog was available [37]. Since the beginning of this study, a noninvasive computed tomography-dependent means for collecting veterinary morphometric data has been developed [44]. Hopefully this will progress to a means of collecting subject specific inverse dynamics data in a clinically relevant means. Until further research is done to either categorize breed specific morphometric data or allow for a clinically relevant means to acquire these data noninvasively, we will be required to extrapolate from the database available to us. However, although the accuracy of the results for moment and power may be affected by using historical morphometric data, the results should be proportional in dogs of similar body type used in a study. Lastly, EMG was not used in this study. EMG monitoring would help us better understand muscle contraction patterns and timing of contraction activity of specific muscles studied here. Without EMG data we are left with information regarding net moments across the joints without knowing specifically which muscles are contracting when they produce the moments. EMG research is also very new to veterinary medicine with only a couple of reports available in canine subjects [139,140]. This research requires more refinement and understanding before becoming a standard part of veterinary biomechanical studies.

In conclusion, we examined 3D kinetics, through the inverse dynamics method, of the canine hock, stifle, and hip joints. Based on our data, it appears that TPLO and lateral suture stabilization techniques have similar outcomes and compare favorably to normal control dogs. Similar to other studies that have compared the TPLO and lateral suture techniques[27,33,41–43], we found no significant difference between the two procedures that would suggest that one procedure results in a return to normal function more than the other. In fact, based on inverse dynamics study, subjects in both surgical groups move similar to normal controls approximately 5 years post-operatively. We recognize that these subjects are unlike clinical patients in that they did not have instability of the stifle for any length of time prior to stabilization, and they did not have the onset of secondary OA during a period of instability as a clinical patient would. However, we are content to show that both of these procedures, given a similar presentation and with the same post-operative housing and exercise conditions, can have the same prognosis for return to function.

LIST OF REFERENCES

1. Berchuck M, Andriacchi TP, Bach BR, Reider B. Gait adaptations by patients who have a deficient anterior cruciate ligament. *J Bone Joint Surg Am*. 1990;72(6):871–7.

2. Andriacchi TP, Birac D. Functional testing in the anterior cruciate ligament-deficient knee. *Clin Orthop Relat Res*. 1993;(288):40–7.

3. Hurwitz DE, Andriacchi TP, Bush-Joseph CA, Bach BR. Functional adaptations in patients with ACL-deficient knees. *Exerc Sport Sci Rev*. 1997;25:1–20.

4. Muneta T, Ogiuchi T, Imai S, Ishida A. Measurements of joint moment and knee flexion angle of patients with anterior cruciate ligament deficiency during level walking and on one leg hop. *Biomed Mater Eng*. 1998;8(3-4):207–18.

5. Noyes FR, Schipplein OD, Andriacchi TP, Saddemi SR, Weise M. The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. *Am J Sports Med*. 1992;20(6):707–16.

6. Wexler G, Hurwitz DE, Bush-Joseph CA, Andriacchi TP, Bach BR. Functional gait adaptations in patients with anterior cruciate ligament deficiency over time. *Clin Orthop Relat Res*. 1998;(348):166–75.

7. Ferber R, Osternig LR, Woollacott MH, Wasielewski NJ, Lee J-H. Gait mechanics in chronic ACL deficiency and subsequent repair. *Clin Biomech (Bristol, Avon)*. 2002;17(4):274–85.

8. Roberts CS, Rash GS, Honaker JT, Wachowiak MP, Shaw JC. A deficient anterior cruciate ligament does not lead to quadriceps avoidance gait. *Gait & Posture*. 1999;10(3):189–199.

9. Rudolph K, Eastlack M, Axe M, Snyder-Mackler L. 1998 Basmajian Student Award Paper - Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J. Electromyogr. Kinesiol.* 1998;8(6):349–362.

10. Fisher NM, White SC, Yack HJ, Smolinski RJ, Pendergast DR. Muscle function and gait in patients with knee osteoarthritis before and after muscle rehabilitation. *Disabil Rehabil*. 1997;19(2):47–55.

11. Kaufman KR, Hughes C, Morrey BF, Morrey M, An KN. Gait characteristics of patients with knee osteoarthritis. *J Biomech*. 2001;34(7):907–915.

12. Messier SP, Loeser RF, Hoover JL, Semble EL, Wise CM. Osteoarthritis of the knee: effects on gait, strength, and flexibility. *Arch Phys Med Rehabil*. 1992;73(1):29–36.

13. Baratta R, Solomonow M, Zhou BH, et al. Muscular coactivation. *The American Journal of Sports Medicine*. 1988;16(2):113–122.

14. Boerboom AL, Hof AL, Halbertsma JP, et al. Atypical hamstrings electromyographic activity as a compensatory mechanism in anterior cruciate ligament deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2001;9(4):211–6.

15. Kellis E, Baltzopoulos V. The effects of antagonist moment on the resultant knee joint moment during isokinetic testing of the knee extensors. *Eur J Appl Physiol Occup Physiol*. 1997;76(3):253–9.

16. Kellis E, Baltzopoulos V. The effects of the antagonist muscle force on intersegmental loading during isokinetic efforts of the knee extensors. *J Biomech*. 1999;32(1):19–25.

17. Limbird TJ, Shiavi R, Frazer M, Borra H. EMG profiles of knee joint musculature during walking: changes induced by anterior cruciate ligament deficiency. *J Orthop Res*. 1988;6(5):630–8.

18. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med*. 1989;15(3):207–13.

19. Button K, van Deursen R, Price P. Recovery in functional non-copers following anterior cruciate ligament rupture as detected by gait kinematics. *Phys Ther Sport*. 2008;9(2):97–104.

20. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther*. 2005;85(8):740–9; discussion 750–4.

21. DeVita P, Hortobagyi T, Barrier J. Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. *Med Sci Sports Exerc*. 1998;30(10):1481–8.

22. Osternig LR, Ferber R, Mercer J, Davis H. Human hip and knee torque accommodations to anterior cruciate ligament dysfunction. *Eur J Appl Physiol*. 2000;83(1):71–6.

23. Fanchon L, Grandjean D. Accuracy of asymmetry indices of ground reaction forces for diagnosis of hind limb lameness in dogs. *American journal of veterinary research*. 2007;68(10):1089–1094.

24. Madore E, Huneault L, Moreau M, Dupuis J. Comparison of trot kinetics between dogs with stifle or hip orthrosis. *VETERINARY AND COMPARATIVE ORTHOPAEDICS AND TRAUMATOLOGY*. 2007;20(2):102.

25. Bockstahler BA, Henninger W, Müller M, et al. Influence of borderline hip dysplasia on joint kinematics of clinically sound Belgian Shepherd dogs. *American journal of veterinary research*. 2007;68(3):271–276.

26. Poy NSJ, DeCamp CE, Bennett RL, Hauptman JG. Additional kinematic variables to describe differences in the trot between clinically normal dogs and dogs with hip dysplasia. *American Journal of Veterinary Research*. 2000;61(8):974–978.

27. de Medeiros M, Sánchez Bustinduy M, Radke H, Langley-Hobbs S, Jeffery N. Early kinematic outcome after treatment of cranial cruciate ligament rupture by tibial plateau levelling osteotomy in the dog. *Veterinary and Comparative Orthopaedics and Traumatology*. 2011;24(3):178–184.

28. DeCamp C, Riggs C, Olivier N, et al. Kinematic evaluation of gait in dogs with cranial cruciate ligament rupture. *American journal of veterinary research*. 1996;57(1):120.

29. Sanchez-Bustinduy M, De Medeiros MA, Radke H, et al. Comparison of Kinematic Variables in Defining Lameness Caused by Naturally Occurring Rupture of the Cranial Cruciate Ligament in Dogs. *Veterinary Surgery*. 2010;39(4):523–530.

30. Chailleux N, Lussier B, De Guise J, Chevalier Y, Hagemeister N. In vitro 3-dimensional kinematic evaluation of 2 corrective operations for cranial cruciate ligament-deficient stifle. *Canadian journal of veterinary research*. 2007;71(3):175.

31. Fu YC, Torres BT, Budsberg SC. Evaluation of a three-dimensional kinematic model for canine gait analysis. *American journal of veterinary research*. 2010;71(10):1118–1122.

32. Korvick DL, Pijanowski GJ, Schaeffer DJ. Three-dimensional kinematics of the intact and cranial cruciate ligament-deficient stifle of dogs. *J Biomech*. 1994;27(1):77–87.

33. Tashman S, Anderst W, Kolowich P, Havstad S, Arnoczky S. Kinematics of the ACL-deficient canine knee during gait: serial changes over two years. *J Orthop Res*. 2004;22(5):931–41.

34. Torres BT, Punke JP, Fu YC, et al. Comparison of canine stifle kinematic data collected with three different targeting models. *Veterinary Surgery*. 2010;39(4):504–512.

35. Colborne G, Durant A, Millis D, et al. Are sound dogs mechanically symmetric at trot? No, actually. *Vet Comp Orthop Traumatol*. 2008;21:294–301.

36. Colborne GR, Good L, Cozens LE, Kirk LS. Symmetry of hind limb mechanics in orthopedically normal trotting Labrador Retrievers. *American Journal of Veterinary Research*. 2011;72(3):336–344.

37. Colborne GR, Innes JF, Comerford EJ, Owen MR, Fuller CJ. Distribution of power across the hind limb joints in Labrador Retrievers and Greyhounds. *Am J Vet Res*. 2005;66(9):1563–71.

38. Colborne GR, Walker AM, Tattersall AJ, Fuller CJ. Effect of trotting velocity on work patterns of the hind limbs of Greyhounds. *Am J Vet Res*. 2006;67(8):1293–8.

39. Dogan S, Manley PA, Vanderby R, et al. Canine intersegmental hip joint forces and moments before and after cemented total hip replacement. *J Biomech*. 1991;24(6):397–407.

40. Ragetly CA, Griffon DJ, Mostafa AA, Thomas JE, Hsiao-Wecksler ET. Inverse Dynamics Analysis of the Pelvic Limbs in Labrador Retrievers With and Without Cranial Cruciate Ligament Disease. *Veterinary Surgery*. 2010;39(4):513–522.

41. Au KK, Gordon-Evans WJ, Dunning D, et al. Comparison of Short-and Long-term Function and Radiographic Osteoarthrosis in Dogs After Postoperative Physical Rehabilitation and Tibial Plateau Leveling Osteotomy or Lateral Fabellar Suture Stabilization. *Veterinary Surgery*. 2010;39(2):173–180.

42. Conzemius MG, Evans RB, Besancon MF, et al. Effect of surgical technique on limb function after surgery for rupture of the cranial cruciate ligament in dogs. *Journal of the American Veterinary Medical Association*. 2005;226(2):232–236.

43. Lazar TP, Berry CR, Dehaan JJ, Peck JN, Correa M. Long-Term Radiographic Comparison of Tibial Plateau Leveling Osteotomy Versus Extracapsular Stabilization for Cranial Cruciate Ligament Rupture in the Dog. *Veterinary Surgery*. 2005;34(2):133–141.

44. Ragetly CA, Griffon DJ, Thomas JE, et al. Noninvasive determination of body segment parameters of the hind limb in Labrador Retrievers with and without cranial cruciate ligament disease. *Am J Vet Res*. 2008;69(9):1188–96.

45. Sigward SM, Powers CM. The influence of gender on knee kinematics, kinetics and muscle activation patterns during side-step cutting. *Clin Biomech (Bristol, Avon)*. 2006;21(1):41–8.

46. Hurwitz DE, Hulet CH, Andriacchi TP, Rosenberg AG, Galante JO. Gait compensations in patients with osteoarthritis of the hip and their relationship to pain and passive hip motion. *J Orthop Res*. 1997;15(4):629–35.

47. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol*. 1998;8(6):349–62.

48. Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. *J Electromyogr Kinesiol*. 2005;15(1):83–92.

49. Li G, Rudy TW, Sakane M, et al. The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. *J Biomech*. 1999;32(4):395–400.

50. Papadonikolakis A, Cooper L, Stergiou N, Georgoulis AD, Soucacos PN. Compensatory mechanisms in anterior cruciate ligament deficiency. *Knee Surg Sports Traumatol Arthrosc*. 2003;11(4):235–43.

51. Torry MR, Decker MJ, Ellis HB, et al. Mechanisms of compensating for anterior cruciate ligament deficiency during gait. *Med Sci Sports Exerc*. 2004;36(8):1403–12.

52. Waite JC, Beard DJ, Dodd CAF, Murray DW, Gill HS. In vivo kinematics of the ACL-deficient limb during running and cutting. *Knee Surg Sports Traumatol Arthrosc*. 2005;13(5):377–84.

53. Williams GN, Snyder-Mackler L, Barrance PJ, Buchanan TS. Quadriceps femoris muscle morphology and function after ACL injury: a differential response in copers versus non-copers. *J Biomech*. 2005;38(4):685–93.

54. Tsepis E, Vagenas G, Giakas G, Georgoulis A. Hamstring weakness as an indicator of poor knee function in ACL-deficient patients. *Knee Surg Sports Traumatol Arthrosc*. 2004;12(1):22–9.

55. Arvidsson I, Eriksson E, Haggmark T, Johnson R. Isokinetic thigh muscle strength after ligament reconstruction in the knee joint: results from a 5-10 year follow-up after reconstructions of the anterior cruciate ligament in the knee joint. *Int J Sports Med*. 1981;2(1):7–11.

56. Seto JL, Orofino AS, Morrissey MC, Medeiros JM, Mason WJ. Assessment of quadriceps/hamstring strength, knee ligament stability, functional and sports activity levels five years after anterior cruciate ligament reconstruction. *Am J Sports Med*. 1988;16(2):170–80. Available at: http://www.ncbi.nlm.nih.gov/pubmed/3377102 [Accessed April 10, 2009].

57. Snyder-Mackler L, Ladin Z, Schepsis AA, Young J. Electrical stimulation of the thigh muscles after reconstruction of the anterior cruciate ligament: effects of electrically elicited contraction of the

quadriceps femoris and hastring muscles on gait and on strength of thigh muscles. *Journal of bone and joint surgery. American volume*. 1991;73(7):1025–1036.

58. Tibone JE, Antich TJ. Electromyographic analysis of the anterior cruciate ligament-deficient knee. *Clin Orthop Relat Res*. 1993;(288):35–9.

59. Kvist J. Sagittal plane translation during level walking in poor-functioning and well-functioning patients with anterior cruciate ligament deficiency. *Am J Sports Med*. 2004;32(5):1250–1255.

60. Isaac DL, Beard DJ, Price AJ, et al. In-vivo sagittal plane knee kinematics: ACL intact, deficient and reconstructed knees. *Knee*. 2005;12(1):25–31.

61. Bryant AL, Creaby MW, Newton RU, Steele JR. Dynamic restraint capacity of the hamstring muscles has important functional implications after anterior cruciate ligament injury and anterior cruciate ligament reconstruction. *Arch Phys Med Rehabil*. 2008;89(12):2324–31.

62. Hiemstra LA, Webber S, MacDonald PB, Kriellaars DJ. Hamstring and quadriceps strength balance in normal and hamstring anterior cruciate ligament-reconstructed subjects. *Clin J Sport Med*. 2004;14(5):274–80.

63. Kellis E, Katis A. Quantification of functional knee flexor to extensor moment ratio using isokinetics and electromyography. *J Athl Train*. 2007;42(4):477–85.

64. Aagaard P, Simonsen E, Andersen J, et al. Antagonist muscle coactivation during isokinetic knee extension. *Scandinavian journal of medicine & science in sports*. 2000;10(2):58–67.

65. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. *The American journal of sports medicine*. 2005;33(10):1579.

66. Al-Zahrani KS, Bakheit AMO. A study of the gait characteristics of patients with chronic osteoarthritis of the knee. *Disabil Rehabil*. 2002;24(5):275–280.

67. Messier SP, DeVita P, Cowan RE, et al. Do older adults with knee osteoarthritis place greater loads on the knee during gait? A preliminary study. *Arch Phys Med Rehabil*. 2005;86(4):703–709.

68. Childs JD, Sparto PJ, Fitzgerald GK, Bizzini M, Irrgang JJ. Alterations in lower extremity movement and muscle activation patterns in individuals with knee osteoarthritis. *Clinical Biomechanics*. 2004;19(1):44–49.

69. Lewek MD, Rudolph KS, Snyder-Mackler L. Control of frontal plane knee laxity during gait in patients with medial compartment knee osteoarthritis. *Osteoarthr. Cartil*. 2004;12(9):745–751.

70. Hurd WJ, Snyder-Mackler L. Knee instability after acute ACL rupture affects movement patterns during the mid-stance phase of gait. *J Orthop Res*. 2007;25(10):1369–77.

71. Hall KD, Hayes KW, Falconer J. Differential strength decline in patients with osteoarthritis of the knee: revision of a hypothesis. *Arthritis Care Res*. 1993;6(2):89–96.

72. Hassan B, Mockett S, Doherty M. Static postural sway, proprioception, and maximal voluntary quadriceps contraction in patients with knee osteoarthritis and normal control subjects. *Annals of the rheumatic diseases*. 2001;60(6):612–618.

73. Hurley M. The effects of joint damage on muscle function, proprioception and rehabilitation. *Manual therapy*. 1997;2(1):11–17.

74. Lewek MD, Rudolph KS, Snyder-Mackler L. Quadriceps femoris muscle weakness and activation failure in patients with symptomatic knee osteoarthritis. *J. Orthop. Res*. 2004;22(1):110–115.

75. Lim BW, Hinman RS, Wrigley TV, Sharma L, Bennell KL. Does knee malalignment mediate the effects of quadriceps strengthening on knee adduction moment, pain, and function in medial knee osteoarthritis? A randomized controlled trial. *Arthritis Rheum*. 2008;59(7):943–51.

76. Astephen JL, Deluzio KJ, Caldwell GE, Dunbar MJ. Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity. *J. Orthop. Res*. 2008;26(3):332–341.

77. Briem K, Snyder-Mackler L. Proximal gait adaptations in medial knee OA. *J. Orthop. Res*. 2009;27(1):78–83.

78. McGibbon CA, Krebs DE. Compensatory gait mechanics in patients with unilateral knee arthritis. *J. Rheumatol*. 2002;29(11):2410–2419.

79. Chang A, Hayes K, Dunlop D, et al. Hip abduction moment and protection against medial tibiofemoral osteoarthritis progression. *Arthritis Rheum*. 2005;52(11):3515–9.

80. Thorstensson CA, Henriksson M, von Porat A, Sjodahl C, Roos EM. The effect of eight weeks of exercise on knee adduction moment in early knee osteoarthritis--a pilot study. *Osteoarthritis Cartilage*. 2007;15(10):1163–70.

81. Ramsey DK, Snyder-Mackler L, Lewek M, Newcomb W, Rudolph KS. Effect of anatomic realignment on muscle function during gait in patients with medial compartment knee osteoarthritis. *Arthritis Rheum*. 2007;57(3):389–97.

82. Kean CO, Birmingham TB, Garland JS, et al. Moments and muscle activity after high tibial osteotomy and anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2009;41(3):612–9.

83. Arendt E, Dick R. Knee Injury Patterns Among Men and Women In Collegiate Basketball and Soccer - NCAA Data and Review of Literature. *Am. J. Sports Med.* 1995;23(6):694–701.

84. Arendt E, Bershadsky B, Agel J, others. Periodicity of noncontact anterior cruciate ligament injuries during the menstrual cycle. *The journal of gender-specific medicine: JGSM: the official journal of the Partnership for Women’s Health at Columbia*. 2002;5(2):19.

85. Harmon KG, Ireland ML. Gender differences in noncontact anterior cruciate ligament injuries. *Clinics in sports medicine*. 2000;19(2):287–302.

86. Myklebust G, Maehlum S, Holm I, Bahr R. A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scandinavian journal of medicine & science in sports*. 1998;8(3):149–153.

87. Beynnon B, Slauterbeck J, Padua D, Hewett T. Update on ACL risk factors and prevention strategies in the female athlete. In: *National Athletic Trainers' Association 52nd Annual Meeting and Clinical Symposia*.; 2001:15–18.

88. Uhorchak J, Scoville C, Williams G, et al. Risk factors associated with noncontact injury of the anterior cruciate ligament - A prospective four-year evaluation of 859 West Point cadets. *Am. J. Sports Med.* 2003;31(6):831–842.

89. Ireland ML, others. The female ACL: why is it more prone to injury? *The Orthopedic clinics of North America*. 2002;33(4):637.

90. Shambaugh JP, Klein A, Herbert JH, others. Structural measures as predictors of injury basketball players. *Medicine and science in sports and exercise*. 1991;23(5):522.

91. Haycock CE, Gillette JV. Susceptibility of women athletes to injury. *JAMA: the journal of the American Medical Association*. 1976;236(2):163.

92. Zelisko JA, Noble HB, Porter M. A comparison of men's and women's professional basketball injuries. *The American journal of sports medicine*. 1982;10(5):297.

93. Nagano Y, Ida H, Akai M, Fukubayashi T. Gender differences in knee kinematics and muscle activity during single limb drop landing. *Knee*. 2007;14(3):218–23. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17215126 [Accessed March 26, 2009].

94. Gray J, Taunton J, McKenzie D, et al. A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. *Int J Sports Med*. 1985;6(6):314–316.

95. Nielsen JM, Hammar M. Sports injuries and oral contraceptive use. Is there a relationship?. *Sports Medicine*. 1991;12(3):152–160.

96. Slauterbeck JR, Hardy DM. Sex hormones and knee ligament injuries in female athletes. *Am J Med Sci*. 2001;322(4):196–9.

97. Chandy T, Grana W. Secondary school athletic injury in boys and girls: a three-year comparison. *Journal of Pediatric Orthopaedics*. 1985;5(5):629.

98. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. *The American journal of sports medicine*. 1996;24(4):427.

99. Weesner CL, others. A Comparison of Anterior and Posterior Cruciate Ligament Laxity Between Female and Male Basketball Players. *Physician and Sportsmedicine*. 1986.

100. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *J Electromyogr Kinesiol*. 2001;11(4):263–8.

101. Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Gender differences exist in neuromuscular control patterns during the pre-contact and early stance phase of an unanticipated side-cut and cross-cut maneuver in 15-18 years old adolescent soccer players. *J Electromyogr Kinesiol*. 2008.

102. Myer GD, Ford KR, Hewett TE. The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position. *Journal of Electromyography and Kinesiology*. 2005;15(2):181–189.

103. Rozzi SL, Lephart SM, Gear WS, Fu FH. Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players. *The American journal of sports medicine*. 1999;27(3):312.

104. Hewett TE, Myer GD, Ford KR, Slauterbeck JR. Dynamic neuromuscular analysis training for preventing anterior cruciate ligament injury in female athletes. *Instr Course Lect*. 2007;56:397–406.

105. Liu-Ambrose T, Taunton JE, MacIntyre D, McConkey P, Khan KM. The effects of proprioceptive or strength training on the neuromuscular function of the ACL reconstructed knee: a randomized clinical trial. *Scand J Med Sci Sports*. 2003;13(2):115–23.

106. Myer GD, Ford KR, Brent JL, Hewett TE. Differential neuromuscular training effects on ACL injury risk factors in"high-risk" versus "low-risk" athletes. *BMC Musculoskelet Disord*. 2007;8:39.

107. Myer GD, Ford KR, Palumbo JP, Hewett TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res*. 2005;19(1):51–60.

108. Zebis MK, Bencke J, Andersen LL, et al. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. *Clin J Sport Med*. 2008;18(4):329–37.

109. Burton NJ, Dobney JA, Owen MR, Colborne GR. Joint angle, moment and power compensations in dogs with fragmented medial coronoid process. *Vet Comp Orthop Traumatol*. 2008;21(2):110–8.

110. Clayton HM, Lanovaz JL, Schamhardt HC, Willemen MA, Colborne GR. Net joint moments and powers in the equine forelimb during the stance phase of the trot. *Equine Vet J*. 1998;30(5):384–9.

111. Colborne GR, Lanovaz JL, Sprigings EJ, Schamhardt HC, Clayton HM. Forelimb joint moments and power during the walking stance phase of horses. *Am J Vet Res*. 1998;59(5):609–14.

112. Lanovaz JL, Clayton HM, Colborne GR, Schamhardt HC. Forelimb kinematics and net joint moments during the swing phase of the trot. *Equine Vet J Suppl*. 1999;30:235–9.

113. Mostafa AA, Griffon DJ, Thomas MW, Constable PD. Morphometric Characteristics of the Pelvic Limb Musculature of Labrador Retrievers with and without Cranial Cruciate Ligament Deficiency. *Veterinary Surgery*. 2010;39(3):380–389.

114. Nielsen C, Stover SM, Schulz KS, Hubbard M, Hawkins DA. Two-dimensional link-segment model of the forelimb of dogs at a walk. *American journal of veterinary research*. 2003;64(5):609–617.

115. Gradner G, Bockstahler B, Peham C, Henninger W, Podbregar I. Kinematic study of back movement in clinically sound malinois dogs with consideration of the effect of radiographic changes in the lumbosacral junction. *Veterinary Surgery*. 2007;36(5):472–481.

116. Johnson JA, da Costa RC, Bhattacharya S, Goel V, Allen MJ. Kinematic Motion Patterns of the Cranial and Caudal Canine Cervical Spine. *Veterinary Surgery*. 2011.

117. Durant A, Millis D, Headrick J. Kinematics of stair ascent in healthy dogs. *VCOT*. 2011;10:03–0038.

118. Millard R, Headrick J, Millis D. Kinematic analysis of the pelvic limbs of healthy dogs during stair and decline slope walking. *Journal of Small Animal Practice*. 2010;51(8):419–422.

119. Marsolais GS, McLean S, Derrick T, Conzemius MG. Kinematic analysis of the hind limb during swimming and walking in healthy dogs and dogs with surgically corrected cranial cruciate ligament rupture. *Journal of the American Veterinary Medical Association*. 2003;222(6):739–743.

120. Owen M, Richards J, Clements D, et al. Kinematics of the elbow and stifle joints in greyhounds during treadmill trotting-An investigation of familiarisation. *Veterinary and Comparative Orthopaedics and Traumatology*. 2004;17(3):141–145.

121. Feeney LC, Lin CF, Marcellin-Little DJ, et al. Validation of two-dimensional kinematic analysis of walk and sit-to-stand motions in dogs. *American journal of veterinary research*. 2007;68(3):277–282.

122. Agostinho F, Rahal S, Miqueleto N, et al. Kinematic analysis of Labrador Retrievers and Rottweilers trotting on a treadmill. *VCOT*. 2007;10:03–0039.

123. Clayton HM, Hodson E, Lanovaz JL. The forelimb in walking horses: 2. Net joint moments and joint powers. *Equine Vet J*. 2000;32(4):295–300.

124. Clayton HM, Hoyt DF, Wickler SJ, Cogger EA, Lanovaz JL. Hindlimb net joint energies during swing phase as a function of trotting velocity. *Equine Vet J Suppl*. 2002;(34):363–367.

125. Burton NJ, Owen MR, Kirk LS, Toscano MJ, Colborne GR. Conservative Versus Arthroscopic Management for Medial Coronoid Process Disease in Dogs: A Prospective Gait Evaluation. *Veterinary Surgery*. 2010.

126. Aragon CL, Budsberg SC. Applications of Evidence-Based Medicine: Cranial Cruciate Ligament Injury Repair in the Dog. *Veterinary Surgery*. 2005;34(2):93–98.

127. Slocum B, Slocum TD. Tibial plateau leveling osteotomy for repair of cranial cruciate ligament rupture in the canine. *Vet Clin North Am Small Anim Pract*. 1993;23(4):777–95.

128. Kim J, Rietdyk S, Breur GJ. Comparison of two-dimensional and three-dimensional systems for kinematic analysis of the sagittal motion of canine hind limbs during walking. *American journal of veterinary research*. 2008;69(9):1116–1122.

129. Ballagas AJ, Montgomery RD, Henderson RA, Gillette R. Pre-and Postoperative Force Plate Analysis of Dogs with Experimentally Transected Cranial Cruciate Ligaments Treated Using Tibial Plateau Leveling Osteotomy. *Veterinary surgery*. 2004;33(2):187–190.

130. Jevens DJ, DeCamp CE, Hauptman J, et al. Use of force-plate analysis of gait to compare two surgical techniques for treatment of cranial cruciate ligament rupture in dogs. *American journal of veterinary research*. 1996;57(3):389.

131. Budsberg SC. Long-term temporal evaluation of ground reaction forces during development of experimentally induced osteoarthritis in dogs. *American journal of veterinary research*. 2001;62(8):1207–1211.

132. Gordon WJ, Conzemius MG, Riedesel E, et al. The relationship between limb function and radiographic osteoarthrosis in dogs with stifle osteoarthrosis. *Veterinary Surgery*. 2003;32(5):451–454.

133. Williams G, Silverman B, Wilson A, Goodship A. Disease-specific changes in equine ground reaction force data documented by use of principal component analysis. *American journal of veterinary research*. 1999;60(5):549.

134. Allen K, DeCamp C, Braden T, Bahns M, others. Kinematic gait analysis of the trot in healthy mixed breed dogs. *Veterinary and comparative orthopaedics and traumatology: VCOT*. 1994;7(4):148.

135. DeCamp C, Soutas-Little R, Hauptman J, et al. Kinematic gait analysis of the trot in healthy greyhounds. *American journal of veterinary research*. 1993;54(4):627.

136. Bennett R, DeCamp C, Flo G, Hauptman J, Stajich M. Kinematic gait analysis in dogs with hip dysplasia. *American journal of veterinary research*. 1996;57(7):966.

137. Hottinger H, DeCamp C, Olivier N, Hauptman J, Soutas-Little R. Noninvasive kinematic analysis of the walk in healthy large-breed dogs. *American journal of veterinary research*. 1996;57(3):381.

138. Schaefer S, DeCamp C, Hauptman J, Walton A. Kinematic gait analysis of hind limb symmetry in dogs at the trot. *American journal of veterinary research*. 1998;59(6):680.

139. Bockstahler BB, Gesky R, Mueller M, et al. Correlation of Surface Electromyography of the Vastus Lateralis Muscle in Dogs at a Walk with Joint Kinematics and Ground Reaction Forces. *Veterinary Surgery*. 2009;38(6):754–761.

140. Lauer SK, Hillman RB, Li L, Hosgood GL. Effects of treadmill inclination on electromyographic activity and hind limb kinematics in healthy hounds at a walk. *American journal of veterinary research*. 2009;70(5):658–664.

APPENDICES

APPENDIX A: RESULTS OF STATISTICAL ANALYSIS OF VARIABLES IN SAGITTAL PLANE

Sagittal Plane Statistical Variables' Abbreviations

xAROM = Hock Range of Motion
xAAngMax = Hock Maximum Angle
xAAngOn = Hock Angle at Onset
xAAngOff = Hock Angle at Offset
xAMomMin = Hock Minimal Moment
xAPoMin1 = Hock First Minimal Power
xAPoNegImp = Hock Negative Power Area Under Curve
xAPoMax = Hock Maximal Power
xAPoPosImp = Hock Positive Power Area Under Curve
xKROM = Stifle Range of Motion
xKAngMin = Stifle Minimal Angle
xKAngOn = Stifle Angle at Onset
xKAngOff = Stifle Angle at Offset
xKMoMax = Stifle Maximal Moment
xKMoNegImp = Stifle Negative Moment Area Under Curve
xKPoMax1 = Stifle First Maximal Power
xKPoMin1 = Stifle First Minimal Power
xKPoMax2 = Stifle Second Maximal Power
xKPoPosImp = Stifle Postitive Power Area Under Curve
xKPoNegImp = Stifle Negative Power Area Under Curve
xHAngOn = Hip Angle at Onset
xHAngOff = Hip Angle at Offset
xHROM = Hip Range of Motion
xHMoMin = Hip Minimal Moment
xHMoMax = Hip Maximal Moment
xHPoMax1 = Hip First Maximal Power
xHPoPosImp = Hip Positive Power Area Under Curve
xHPoMin1 = Hip First Minimal Power
xHPoNegImp = Hip Negative Power Area Under Curve
GRFZMax = Vertical Ground Reaction Force Maximum
GRFZRate = Rate Vertical Ground Reaction Force
GRFZImp = Ground Reaction Force Area Under Curve
GRFYMin = MedioLateral Ground Reaction Force Minimum
GRFYMax = MedioLateral Ground Reaction Force Maximum
GRFYNegImp = Negative MedioLateral Ground Reaction Force Area Under Curve
GRFPosImp = Positive MedioLateral Ground Reaction Force Area Under Curve

Statistical Variables for Hock of Left Pelvic Limb in Sagittal Plane

Dog	Group	Leg	xAROM	xAAngMax	xAAngOn	xAAngOff	xAMomMin	xAPoMin1	xAPoNegImp	xAPoMax	xAPoPosImp
1	N	L	45.19	51.86	22.17	6.67	-0.54	-3.87	-0.18	3.23	0.19
2	S	L	41.27	36.76	4.84	-4.51	-0.46	-2.82	-0.16	2.68	0.15
3	T	L	38.31	37.04	13.42	-1.26	-0.35	-2.17	-0.10	1.71	0.10
4	T	L	31.86	31.86	0.10	0.00	-0.34	-2.37	-0.12	1.45	0.08
5	S	L	29.86	28.20	8.20	-1.66	-0.53	-2.78	-0.12	2.29	0.11
6	S	L	39.65	40.08	16.95	0.42	-0.31	-1.52	-0.09	1.03	0.06
7	N	L	51.70	49.48	21.34	-2.23	-0.47	-2.94	-0.14	2.85	0.17
8	N	L	48.36	40.84	21.58	-7.52	-0.29	-1.34	-0.07	1.66	0.08
9	S	L	41.13	37.68	3.37	-3.45	-0.89	-5.49	-0.27	3.81	0.25
10	N	L	33.28	42.67	18.89	9.40	-0.47	-2.74	-0.13	2.19	0.10
11	T	L	38.69	32.16	2.57	-6.53	-0.48	-3.21	-0.16	2.28	0.12
12	T	L	47.01	39.11	20.64	-7.90	-0.26	-1.70	-0.06	0.92	0.07
13	T	L	28.65	24.99	3.82	-3.66	-0.26	-1.41	-0.07	1.10	0.06
14	S	L	42.14	36.68	2.83	-5.46	-0.55	-4.40	-0.23	3.00	0.15
15	T	L	45.54	38.50	4.17	-7.04	-0.42	-3.16	-0.16	2.07	0.12
16	T	L	43.22	47.55	14.62	4.33	-0.68	-5.21	-0.25	3.17	0.16
17	N	L	38.56	42.19	12.07	3.63	-0.58	-3.85	-0.18	3.07	0.16
18	T	L	34.92	35.54	10.27	0.62	-0.18	-0.82	-0.04	0.66	0.02
19	T	L	33.26	36.72	14.67	3.46	-0.76	-3.49	-0.17	3.32	0.15
20	T	L	40.61	30.96	5.70	-9.65	-0.36	-2.10	-0.10	1.23	0.09
21	S	L	44.58	32.54	-6.96	-12.05	-0.43	-3.92	-0.21	2.13	0.09
22	N	L	42.01	42.16	17.57	0.16	-0.43	-2.39	-0.11	2.28	0.13
23	T	L	42.54	22.75	0.11	-19.80	-0.46	-2.12	-0.12	2.05	0.10
24	T	L	37.67	33.10	3.21	-4.57	-0.49	-2.74	-0.16	1.73	0.12
25	T	L	33.33	14.92	-16.86	-18.41	-0.95	-4.78	-0.27	3.03	0.20

N = Normal S = Suture T = TPLO

Statistical Variables for Hock of Right Pelvic Limb in Sagittal Plane

Dog	Group	Leg	xAROM	xAAngMax	xAAngOn	xAAngOff	xAMomMin	xAPoMin1	xAPoNegImp	xAPoMax	xAPoPosImp
1	N	R	49.01	36.55	-1.94	-12.47	-0.45	-3.77	-0.19	2.46	0.13
2	S	R	23.74	27.92	4.18	-11.29	-0.36	-1.85	-0.10	1.74	0.09
3	T	R	29.01	27.75	-1.26	0.56	-0.54	-3.69	-0.16	2.56	0.12
4	T	R	19.26	24.86	5.60	-6.41	-0.36	-1.92	-0.08	1.76	0.07
5	S	R	22.71	32.13	9.42	3.46	-0.46	-2.80	-0.13	1.73	0.08
6	S	R	29.45	31.23	1.79	-6.16	-0.64	-4.45	-0.21	2.81	0.15
7	N	R	25.27	53.32	28.04	1.87	-0.47	-2.36	-0.13	2.47	0.16
8	N	R	17.02	29.71	12.69	-7.09	-0.31	-1.34	-0.06	1.29	0.06
9	S	R	32.06	42.92	10.86	5.23	-0.51	-3.73	-0.18	2.74	0.14
10	N	R	20.18	43.22	23.05	5.17	-0.23	-1.24	-0.06	1.12	0.04
11	T	R	22.94	29.12	6.18	-9.25	-0.37	-1.89	-0.09	1.83	0.08
12	T	R	15.59	35.46	19.87	3.51	-0.37	-2.04	-0.08	1.19	0.08
13	T	R	40.40	43.24	2.84	-13.65	-1.32	-10.69	-0.59	7.80	0.43
14	S	R	27.96	37.32	9.35	1.90	-0.44	-3.13	-0.14	2.34	0.10
15	T	R	33.81	39.28	5.47	-18.59	-0.45	-3.22	-0.17	2.03	0.14
16	T	R	38.95	45.87	6.92	2.59	-0.54	-4.19	-0.25	1.96	0.14
17	N	R	20.00	29.13	9.13	-5.41	-0.36	-1.87	-0.08	1.57	0.08
18	T	R	31.29	37.28	5.99	-3.78	-0.46	-3.29	-0.15	2.57	0.13
19	T	R	18.46	42.31	23.85	4.26	-0.60	-2.83	-0.14	2.43	0.12
20	T	R	31.97	37.09	5.12	2.38	-0.56	-3.56	-0.20	2.21	0.11
21	S	R	29.86	28.50	-1.37	-6.12	-0.27	-2.50	-0.11	1.14	0.04
22	N	R	18.87	27.21	8.34	-12.87	-0.37	-1.70	-0.08	1.75	0.11
23	T	R	32.59	18.57	-14.03	-22.05	-0.48	-3.49	-0.18	2.14	0.13
24	T	R	24.59	30.97	6.38	-5.17	-0.52	-2.78	-0.15	2.22	0.13
25	T	R	26.68	23.22	-3.46	-24.26	-0.60	-3.11	-0.16	3.08	0.21

N = Normal   S = Suture   T = TPLO

Statistical Variables for Stifle of Left Pelvic Limb in Sagittal Plane

Dog	Group	Leg	xKROM	xKAngMin	xKAngOn	xKAngOff	xKMoMax	xKMoNegImp	xKPoMax1	xKPoMin1	xKPoMax2	xKPoPosImp	xKPoNegImp
1	N	L	19.03	-49.05	-30.02	-41.33	0.18	-0.0044	0.66	-0.11	0.40	0.0400	-0.0027
2	S	L	22.67	-53.96	-31.28	-43.36	0.30	-0.0012	0.45	-0.58	0.69	0.0508	-0.0286
3	T	L	21.41	-60.82	-39.41	-56.47	0.35	-0.0002	0.26	-0.84	0.21	0.0094	-0.0502
4	T	L	21.01	-37.74	-16.73	-33.92	0.21	-0.0034	0.90	-0.20	0.21	0.0345	-0.0055
5	S	L	11.11	-38.07	-26.97	-38.07	0.21	-0.0051	0.68	-0.13	0.19	0.0252	-0.0047
6	S	L	17.99	-33.77	-15.78	-28.42	0.25	-0.0022	0.41	-0.31	0.48	0.0316	-0.0187
7	N	L	21.27	-59.25	-37.98	-50.07	0.31	-0.0003	0.22	-0.57	0.83	0.0368	-0.0368
8	N	L	23.16	-60.65	-37.49	-53.80	0.45	-0.0003	0.70	-0.86	0.00	0.0345	-0.0504
9	S	L	27.95	-50.22	-22.27	-47.69	0.48	-0.0043	0.64	-0.63	0.45	0.0361	-0.0318
10	N	L	17.38	-55.65	-38.27	-49.98	0.41	-0.0002	0.32	-0.59	0.14	0.0161	-0.0322
11	T	L	19.47	-42.42	-22.95	-40.03	0.10	-0.0115	1.14	-0.01	0.13	0.0561	-0.0001
12	T	L	12.45	-50.18	-37.73	-46.42	0.19	-0.0006	0.54	-0.19	0.21	0.0177	-0.0104
13	T	L	20.90	-59.15	-38.25	-54.55	0.20	-0.0001	0.01	-0.61	0.27	0.0080	-0.0345
14	S	L	23.05	-50.68	-27.63	-46.62	0.28	-0.0041	0.51	-0.21	0.35	0.0292	-0.0085
15	T	L	19.09	-67.55	-48.46	-61.57	0.37	-0.0014	0.76	-0.53	0.52	0.0270	-0.0239
16	T	L	25.96	-53.80	-27.84	-49.20	0.44	-0.0077	0.80	-0.82	0.69	0.0553	-0.0336
17	N	L	23.93	-61.87	-37.94	-53.67	0.39	0.0000	0.03	-0.80	0.53	0.0258	-0.0443
18	T	L	19.03	-58.89	-39.86	-56.79	0.37	-0.0004	0.26	-0.63	0.28	0.0129	-0.0330
19	T	L	20.45	-56.76	-36.31	-51.82	0.71	-0.0017	0.46	-0.97	0.85	0.0380	-0.0396
20	T	L	13.32	-53.32	-40.00	-46.24	0.16	-0.0016	0.27	-0.05	0.31	0.0231	-0.0023
21	S	L	26.99	-38.04	-11.05	-25.96	0.21	-0.0033	1.17	-0.41	0.62	0.0496	-0.0147
22	N	L	15.67	-54.73	-39.07	-48.32	0.26	-0.0030	0.50	-0.18	0.50	0.0370	-0.0069
23	T	L	17.17	-53.09	-35.92	-49.63	0.27	-0.0021	0.26	-0.18	0.31	0.0230	-0.0072
24	T	L	20.99	-52.79	-31.80	-49.22	0.18	-0.0074	0.67	-0.07	0.12	0.0356	-0.0028
25	T	L	22.72	-57.61	-34.89	-53.31	0.48	-0.0047	0.82	-0.43	0.52	0.0480	-0.0183

N = Normal S = Suture T = TPLO

Statistical Variables for Stifle of Right Pelvic Limb in Sagittal Plane

Dog	Group	Leg	xKROM	xKAngMin	xKAngOn	xKAngOff	xKMoMax	xKMoNegImp	xKPoMax1	xKPoMin1	xKPoMax2	xKPoPosImp	xKPoNegImp
1	N	R	24.58	-55.05	-30.46	-46.76	0.25	-0.0027	0.65	-0.50	0.53	0.0365	-0.0255
2	S	R	20.87	-55.05	-34.18	-44.33	0.38	-0.0001	0.06	-0.80	0.54	0.0307	-0.0457
3	T	R	17.87	-67.46	-49.59	-67.46	0.29	-0.0014	0.39	-0.67	0.03	0.0062	-0.0339
4	T	R	18.09	-52.98	-34.90	-46.03	0.39	-0.0026	0.72	-0.65	0.71	0.0427	-0.0193
5	S	R	20.69	-51.89	-31.20	-47.01	0.31	-0.0018	0.46	-0.62	0.14	0.0098	-0.0306
6	S	R	16.85	-44.55	-27.71	-34.51	0.24	-0.0099	1.31	-0.10	0.59	0.0713	-0.0021
7	N	R	24.12	-59.73	-35.61	-51.25	0.33	-0.0011	0.46	-0.30	0.73	0.0441	-0.0183
8	N	R	18.42	-36.88	-18.46	-35.09	0.21	-0.0047	0.57	-0.36	0.20	0.0242	-0.0142
9	S	R	24.23	-57.28	-33.05	-53.11	0.31	-0.0005	0.27	-0.60	0.37	0.0147	-0.0403
10	N	R	15.09	-55.36	-40.26	-45.89	0.45	-0.0007	0.97	-0.76	0.27	0.0527	-0.0276
11	T	R	18.49	-60.70	-42.20	-55.68	0.34	0.0000	0.46	-0.59	0.20	0.0149	-0.0443
12	T	R	7.96	-42.66	-34.70	-40.98	0.17	-0.0049	0.51	-0.12	0.26	0.0306	-0.0041
13	T	R	25.67	-55.71	-30.04	-45.45	0.54	-0.0117	1.25	-0.50	1.47	0.1252	-0.0174
14	S	R	18.07	-56.02	-37.95	-54.07	0.44	-0.0010	0.36	-0.79	0.20	0.0105	-0.0469
15	T	R	25.15	-50.46	-25.31	-40.26	0.34	-0.0031	1.04	-0.41	0.77	0.0540	-0.0200
16	T	R	32.56	-67.87	-35.30	-62.25	0.26	-0.0071	1.36	-0.58	0.42	0.0570	-0.0296
17	N	R	13.53	-53.52	-39.99	-48.46	0.42	0.0000	0.13	-0.70	0.39	0.0207	-0.0286
18	T	R	17.54	-49.80	-32.26	-46.60	0.31	-0.0001	0.08	-0.51	0.14	0.0044	-0.0356
19	T	R	18.11	-58.50	-40.39	-47.03	0.77	-0.0010	1.90	-1.25	-0.02	0.0945	-0.0630
20	T	R	19.10	-34.41	-15.32	-29.15	0.12	-0.0135	1.18	-0.06	0.25	0.0648	-0.0009
21	S	R	22.46	-46.67	-24.21	-40.18	0.30	-0.0012	0.27	-0.69	0.35	0.0180	-0.0283
22	N	R	12.19	-54.72	-42.53	-50.68	0.34	-0.0003	0.38	-0.31	0.01	0.0195	-0.0172
23	T	R	21.12	-56.33	-35.21	-52.96	0.22	-0.0040	1.17	-0.25	0.29	0.0405	-0.0079
24	T	R	20.50	-52.60	-32.10	-50.23	0.18	-0.0053	0.45	-0.13	0.28	0.0320	-0.0040
25	T	R	21.22	-58.61	-37.39	-54.86	0.50	-0.0022	0.67	-0.48	0.53	0.0347	-0.0304

N = Normal S = Suture T = TPLO

Statistical Variables for GRF and Hip of Left Pelvic Limb in Sagittal Plane

Dog	Group	Leg	xHAngOn	xHAngOff	xHROM	xHMoMin	xHMoMax	xHPoMax1	xHPoPosImp	xHPoMin1	xHPoNegImp	GRFZMax	GRFZRate	GRFZImp	GRFYMin	GRFYMax	GRFYNegImp	GRFPosImp
1	N	L	79.95	56.60	23.35	-0.32	0.08	0.56	0.0389	-0.30	-0.0146	0.67	8.01	0.08	-0.10	0.07	-0.0045	0.0045
2	S	L	68.94	52.92	16.02	-0.25	0.13	0.37	0.0181	-0.37	-0.0215	0.66	6.54	0.09	-0.05	0.08	-0.0023	0.0062
3	T	L	70.07	56.34	13.73	-0.37	0.10	0.59	0.0159	-0.25	-0.0131	0.65	8.43	0.08	-0.05	0.07	-0.0025	0.0052
4	T	L	55.90	41.63	14.27	-0.32	0.12	0.13	0.0080	-0.26	-0.0146	0.63	7.21	0.08	-0.05	0.07	-0.0031	0.0050
5	S	L	52.13	36.81	15.32	-0.39	0.20	0.55	0.0258	-0.32	-0.0151	0.78	11.46	0.08	-0.01	0.14	-0.0002	0.0109
6	S	L	53.43	30.38	23.05	-0.19	0.24	0.48	0.0162	-0.50	-0.0435	0.45	4.47	0.07	-0.03	0.06	-0.0009	0.0053
7	N	L	67.00	45.64	21.37	-0.28	0.23	0.41	0.0139	-0.56	-0.0472	0.65	7.57	0.08	-0.04	0.10	-0.0017	0.0076
8	N	L	72.06	50.85	21.21	-0.25	0.23	0.69	0.0285	-0.72	-0.0454	0.62	6.88	0.08	-0.03	0.10	-0.0015	0.0078
9	S	L	75.48	57.07	18.41	-0.50	0.23	0.26	0.0136	-0.61	-0.0451	0.65	6.38	0.09	-0.06	0.08	-0.0024	0.0059
10	N	L	67.78	49.42	18.36	-0.31	0.16	0.53	0.0235	-0.42	-0.0251	0.60	6.90	0.08	-0.02	0.09	-0.0007	0.0080
11	T	L	60.81	43.23	17.58	-0.42	0.12	0.55	0.0478	-0.19	-0.0056	0.65	8.01	0.08	-0.03	0.09	-0.0013	0.0071
12	T	L	61.16	37.62	23.54	-0.33	0.15	0.61	0.0131	-0.49	-0.0324	0.47	6.10	0.07	-0.05	0.06	-0.0023	0.0057
13	T	L	66.01	44.41	21.59	-0.23	0.16	0.29	0.0095	-0.51	-0.0396	0.44	5.65	0.06	-0.02	0.06	-0.0009	0.0045
14	S	L	66.95	48.70	18.25	-0.67	0.14	0.63	0.0414	-0.25	-0.0118	0.80	9.06	0.10	-0.02	0.12	-0.0010	0.0099
15	T	L	74.86	48.21	26.66	-0.48	0.13	0.92	0.0598	-0.40	-0.0224	0.63	7.29	0.08	-0.04	0.10	-0.0015	0.0080
16	T	L	56.48	35.93	20.55	-0.49	0.09	0.72	0.0580	-0.23	-0.0115	0.62	6.12	0.08	-0.04	0.08	-0.0015	0.0061
17	N	L	64.11	49.13	14.98	-0.31	0.12	0.21	0.0119	-0.34	-0.0164	0.79	9.51	0.09	-0.07	0.10	-0.0027	0.0073
18	T	L	68.30	50.01	18.30	-0.25	0.10	0.41	0.0185	-0.40	-0.0186	0.65	7.72	0.08	-0.06	0.08	-0.0032	0.0046
19	T	L	63.51	39.75	23.76	-0.43	0.31	0.93	0.0375	-0.77	-0.0537	0.67	7.01	0.07	-0.05	0.10	-0.0016	0.0074
20	T	L	66.22	44.40	21.82	-0.25	0.08	0.53	0.0284	-0.28	-0.0112	0.55	6.48	0.08	-0.05	0.07	-0.0021	0.0071
21	S	L	61.33	42.39	18.94	-0.34	0.16	0.36	0.0190	-0.41	-0.0250	0.79	9.61	0.09	-0.05	0.09	-0.0025	0.0062
22	N	L	80.03	58.23	21.79	-0.35	0.15	0.77	0.0471	-0.36	-0.0186	0.63	6.92	0.08	-0.02	0.09	-0.0009	0.0071
23	T	L	50.70	33.96	16.74	-0.18	0.22	0.25	0.0163	-0.32	-0.0164	0.63	7.15	0.08	-0.03	0.09	-0.0012	0.0068
24	T	L	66.99	48.73	18.25	-0.40	0.06	0.52	0.0446	-0.19	-0.0102	0.66	6.47	0.10	-0.06	0.09	-0.0036	0.0081
25	T	L	55.92	34.83	21.09	-0.51	0.21	0.79	0.0456	-0.56	-0.0346	0.70	6.35	0.10	-0.03	0.10	-0.0019	0.0093

N = Normal S = Suture T = TPLO

Statistical Variables for GRF and Hip of Right Pelvic Limb in Sagittal Plane

Dog	Group	Leg	xHAngOn	xHAngOff	xHROM	xHMoMin	xHMoMax	xHPoMax1	xHPoPosImp	xHPoMin1	xHPoNegImp	GRFZMax	GRFZRate	GRFZImp	GRFYMin	GRFYMax	GRFYNegImp	GRFPosImp
1	N	R	65.43	41.02	24.41	-0.41	0.10	0.90	0.0456	-0.26	-0.0157	0.65	8.88	0.08	-0.08	0.07	-0.0050	0.0033
2	S	R	70.60	49.72	20.88	-0.22	0.22	0.59	0.0229	-0.62	-0.0522	0.66	7.92	0.09	-0.08	0.06	-0.0038	0.0038
3	T	R	64.93	46.59	18.35	-0.34	0.11	0.82	0.0400	-0.15	-0.0080	0.63	9.00	0.06	-0.04	0.06	-0.0033	0.0017
4	T	R	64.31	46.43	17.88	-0.41	0.06	0.59	0.0366	-0.26	-0.0080	0.79	10.39	0.08	-0.04	0.11	-0.0073	0.0010
5	S	R	74.29	56.78	17.51	-0.32	0.18	0.47	0.0222	-0.36	-0.0192	0.71	9.91	0.08	-0.06	0.09	-0.0057	0.0018
6	S	R	68.69	39.57	29.12	-0.60	0.21	1.51	0.0889	-0.69	-0.0387	0.70	7.74	0.09	-0.07	0.09	-0.0064	0.0017
7	N	R	65.10	40.56	24.54	-0.26	0.16	0.61	0.0406	-0.47	-0.0288	0.60	6.04	0.09	-0.03	0.11	-0.0098	0.0010
8	N	R	69.05	46.03	23.03	-0.33	0.17	0.72	0.0363	-0.48	-0.0256	0.55	6.56	0.07	-0.02	0.08	-0.0060	0.0007
9	S	R	71.43	49.70	21.73	-0.25	0.23	0.55	0.0310	-0.45	-0.0262	0.66	7.83	0.08	-0.04	0.07	-0.0046	0.0021
10	N	R	72.28	50.56	21.72	-0.35	0.18	0.71	0.0313	-0.48	-0.0304	0.63	7.95	0.07	-0.03	0.11	-0.0077	0.0008
11	T	R	66.64	48.04	18.61	-0.29	0.15	0.31	0.0132	-0.41	-0.0235	0.66	8.07	0.08	-0.03	0.10	-0.0082	0.0008
12	T	R	65.13	42.87	22.26	-0.28	0.15	1.04	0.0493	-0.42	-0.0291	0.55	6.79	0.07	-0.06	0.05	-0.0040	0.0032
13	T	R	66.66	41.68	24.98	-0.78	0.37	1.44	0.1033	-1.02	-0.0633	0.82	8.87	0.11	-0.08	0.11	-0.0093	0.0039
14	S	R	71.70	52.20	19.49	-0.32	0.24	1.22	0.0486	-0.30	-0.0203	0.73	9.11	0.08	-0.03	0.10	-0.0070	0.0007
15	T	R	63.39	41.16	22.24	-0.61	0.20	1.04	0.0468	-0.49	-0.0319	0.64	6.93	0.10	-0.04	0.09	-0.0085	0.0016
16	T	R	75.07	54.45	20.62	-0.39	0.00	0.84	0.0714	-0.03	-0.0087	0.69	7.37	0.11	-0.09	0.06	-0.0050	0.0066
17	N	R	75.24	56.17	19.07	-0.23	0.10	0.35	0.0156	-0.28	-0.0166	0.71	9.64	0.08	-0.07	0.08	-0.0053	0.0025
18	T	R	61.53	43.01	18.51	-0.17	0.20	0.29	0.0109	-0.43	-0.0322	0.66	8.57	0.07	-0.05	0.07	-0.0040	0.0026
19	T	R	69.34	44.40	24.93	-0.50	0.24	0.87	0.0418	-0.81	-0.0452	0.64	7.25	0.08	-0.05	0.09	-0.0062	0.0024
20	T	R	57.53	34.91	22.63	-0.49	0.09	1.23	0.0626	-0.24	-0.0120	0.62	7.32	0.08	-0.04	0.08	-0.0064	0.0017
21	S	R	64.45	45.84	18.61	-0.25	0.12	0.92	0.0430	-0.14	-0.0079	0.69	9.39	0.07	-0.07	0.06	-0.0036	0.0027
22	N	R	67.83	44.75	23.08	-0.21	0.16	0.18	0.0114	-0.52	-0.0365	0.57	6.53	0.07	-0.04	0.08	-0.0067	0.0014
23	T	R	64.11	42.65	21.46	-0.32	0.11	0.59	0.0451	-0.28	-0.0138	0.60	7.32	0.08	-0.07	0.06	-0.0035	0.0046
24	T	R	61.91	44.76	17.14	-0.35	0.10	0.65	0.0449	-0.18	-0.0087	0.67	7.89	0.09	-0.05	0.09	-0.0079	0.0024
25	T	R	69.33	46.13	23.20	-0.41	0.20	0.45	0.0310	-0.49	-0.0301	0.61	5.66	0.09	-0.06	0.08	-0.0065	0.0031

N = Normal   S = Suture   T = TPLO

APPENDIX B: RESULTS OF STATISTICAL ANALYSIS OF VARIABLES IN FRONTAL PLANE

Frontal Plane Statistical Variables Abbreviations

yAROM = Hock Range of Motion
yAAngOn = Hock Angle at Onset
yAAngOff = Hock Angle at Offset
yAMoMin = Hock Minimal Moment
yAPoMin = Hock Minimal Power
yANegImp = Hock Negative Power Area Under Curve
yAPoMax = Hock Maximal Power
yAPosImp = Hock Positive Power Area Under Curve
yKROM = Stifle Range of Motion
yKAngOn = Stifle Angle at Onset
yKAngOff = Stifle Angle at Offset
yKAngMax = Stifle Maximal Angle
yKMoMax = Stifle Maximal Moment
yKMoMin = Stifle Minimal Moment
yKPoMax = Stifle Maximal Power
yKPoPosImp = Stifle Positive Power Area Under Curve
yHROM = Hip Range of Motion
yHAngOn = Hip Angle at Onset
yHAngOff = Hip Angle at Offset
yHMoMin = Hip Minimal Moment
yHPoMax = Hip Maximal Power
yHPoPosImp = Hip Positive Power Area Under Curve

Statistical Variables for Hock of Left Pelvic Limb in Frontal Plane

Dog	Group	Leg	yAROM	yAAngOn	yAAngOff	yAMoMin	yAPoMin	yANegImp	yAPoMax	yAPosImp
1	N	L	3.41	-6.67	-3.26	0.01	0.00	-0.0078	0.01	0.0012
2	S	L	10.43	-9.83	0.61	-0.12	-0.10	-0.0051	0.08	0.0040
3	T	L	6.36	-2.78	3.58	-0.23	-0.88	-0.0108	0.13	0.0388
4	T	L	5.99	-3.95	2.04	0.05	0.02	-0.0161	0.19	0.0035
5	S	L	19.85	-7.18	12.66	0.04	0.09	-0.0113	0.07	0.0020
6	S	L	7.44	-5.65	1.79	0.06	-0.07	-0.0107	0.14	0.0022
7	N	L	8.81	-7.14	1.67	-0.05	-0.11	-0.0033	0.11	0.0057
8	N	L	6.75	-5.62	1.12	-0.16	-0.71	-0.0041	0.29	0.0321
9	S	L	8.35	-5.75	2.60	-0.09	0.21	-0.0164	-0.23	0.0191
10	N	L	1.77	-0.74	1.03	-0.07	-0.25	-0.0113	0.15	0.0220
11	T	L	15.26	-5.43	9.83	0.05	0.12	-0.0167	0.14	0.0020
12	T	L	11.64	-13.87	-2.23	-0.01	0.01	-0.0019	0.00	0.0010
13	T	L	9.48	-4.84	4.64	-0.04	-0.02	-0.0039	0.04	0.0038
14	S	L	8.72	-2.16	6.56	-0.23	-0.45	-0.0253	0.25	0.0212
15	T	L	1.80	-6.32	-4.52	-0.27	-0.76	-0.0254	0.37	0.0443
16	T	L	9.47	-7.71	1.76	0.17	0.03	-0.0530	0.88	0.0063
17	N	L	7.72	-4.15	3.58	-0.15	-0.42	-0.0001	0.52	0.0265
18	T	L	1.58	3.79	5.37	-0.29	-2.04	-0.0739	1.16	0.1020
19	T	L	12.02	-8.49	3.53	-0.04	-0.23	-0.0026	-0.01	0.0106
20	T	L	4.43	1.08	5.51	-0.04	-0.20	-0.0042	0.02	0.0086
21	S	L	21.26	-7.60	13.66	-0.05	-0.02	-0.0007	-0.16	0.0125
22	N	L	10.60	-10.88	-0.28	0.05	0.04	-0.0135	0.04	0.0006
23	T	L	19.48	-1.30	18.18	0.17	-0.38	-0.0460	0.72	0.0182
24	T	L	5.56	2.88	8.44	0.03	0.00	-0.0055	0.06	0.0065
25	T	L	18.56	0.40	18.95	0.07	-0.06	-0.0286	0.51	0.0053

N = Normal   S = Suture   T = TPLO

Statistical Variables for Hock of RIght Pelvic Limb in Frontal Plane

Dog	Group	Leg	yAROM	yAAngOn	yAAngOff	yAMoMin	yAPoMin	yANegImp	yAPoMax	yAPosImp
1	N	R	7.06	2.57	9.62	-0.08	-0.29	-0.0141	0.01	0.0011
2	S	R	12.68	-13.45	-0.76	-0.22	-1.05	-0.0561	0.27	0.0101
3	T	R	11.71	-6.49	5.22	-0.04	-0.11	-0.0041	0.01	0.0010
4	T	R	4.21	-4.36	-0.15	0.03	0.02	-0.0015	0.07	0.0039
5	S	R	19.53	-11.15	8.38	-0.03	-0.14	-0.0088	-0.05	0.0005
6	S	R	15.17	-7.66	7.51	0.20	0.03	-0.0102	0.62	0.0316
7	N	R	7.59	-17.19	-9.59	0.01	0.01	-0.0019	0.03	0.0122
8	N	R	10.74	-0.96	9.78	-0.05	-0.14	-0.0081	0.11	0.0002
9	S	R	8.21	-8.91	-0.69	-0.12	-0.26	-0.0250	-0.14	0.0037
10	N	R	1.95	4.07	2.12	-0.08	-0.26	-0.0122	0.27	0.0010
11	T	R	13.08	-10.80	2.28	-0.20	-1.15	-0.0627	0.13	0.0084
12	T	R	13.97	-11.55	2.42	0.13	-0.06	-0.0080	0.14	0.0240
13	T	R	22.72	-9.95	12.77	0.35	-0.30	-0.0552	2.30	0.1435
14	S	R	12.31	-3.86	8.46	-0.13	-0.17	-0.0199	-0.07	0.0001
15	T	R	8.35	7.28	-1.07	-0.18	-0.44	-0.0469	0.22	0.0595
16	T	R	7.66	-5.51	2.15	-0.05	-0.07	-0.0047	0.00	0.0023
17	N	R	5.33	-8.76	-3.42	-0.11	-0.23	-0.0149	-0.02	0.0002
18	T	R	9.56	0.11	9.67	-0.12	-0.24	-0.0169	-0.01	0.0043
19	T	R	7.17	-7.72	-0.56	0.00	-0.04	-0.0079	0.12	0.0089
20	T	R	4.55	-1.18	3.37	-0.05	-0.09	-0.0122	-0.12	0.0041
21	S	R	3.49	3.34	6.83	-0.23	-0.61	-0.0292	0.39	0.0231
22	N	R	1.26	-4.95	-3.69	-0.05	0.01	-0.0022	0.08	0.0014
23	T	R	10.20	1.92	12.12	-0.04	0.03	-0.0028	-0.02	0.0049
24	T	R	11.02	-1.84	9.18	-0.03	0.03	-0.0017	0.01	0.0046
25	T	R	4.88	-9.41	-4.53	-0.10	-0.25	-0.0077	-0.01	0.0002

N = Normal S = Suture T = TPLO

Statistical Variables for Stifle of Left Pelvic Limb in Frontal Plane

Dog	Group	Leg	yKROM	yKAngOn	yKAngOff	yKAngMax	yKMoMax	yKMoMin	yKPoMax	yKPoPosImp
1	N	L	6.78	6.17	10.31	12.95	-0.05	-0.10	0.01	0.0049
2	S	L	1.25	7.05	7.41	8.30	-0.02	0.02	0.11	0.0036
3	T	L	1.45	-5.70	-16.32	-4.25	0.01	-0.14	0.82	0.0048
4	T	L	4.79	5.89	5.94	10.68	0.02	-0.04	0.01	0.0016
5	S	L	9.86	13.03	17.13	22.89	-0.02	-0.09	0.05	0.0053
6	S	L	8.50	3.21	6.04	11.71	0.00	-0.02	0.01	0.0007
7	N	L	2.61	-15.89	-20.16	-18.50	0.19	-0.05	-0.16	0.0133
8	N	L	5.01	-14.06	-17.12	-9.06	0.08	-0.09	-0.53	0.0017
9	S	L	6.85	-8.39	-0.10	-1.54	0.00	-0.13	0.41	0.0004
10	N	L	1.54	-6.86	-14.15	-5.32	0.09	-0.08	-0.11	0.0033
11	T	L	14.72	13.70	21.25	28.42	0.00	-0.02	0.00	0.0099
12	T	L	9.05	-1.30	1.56	7.74	0.00	-0.06	0.19	0.0055
13	T	L	5.04	-24.54	-33.11	-29.58	0.11	0.18	-0.12	0.0177
14	S	L	3.55	-10.54	-10.52	-6.99	0.01	-0.30	1.67	0.0028
15	T	L	6.10	1.94	-4.05	-4.15	0.00	-0.14	-0.31	0.0083
16	T	L	12.01	8.56	11.49	20.57	0.00	-0.13	-0.01	0.0050
17	N	L	2.16	-22.26	-20.92	-20.10	0.11	-0.10	-0.37	0.0010
18	T	L	12.35	4.04	-2.47	-8.31	-0.02	-0.15	0.02	0.0010
19	T	L	10.67	12.54	6.79	23.22	0.01	-0.41	-0.02	0.0394
20	T	L	0.66	6.25	6.46	6.91	0.00	-0.12	0.05	0.0064
21	S	L	1.55	2.51	-0.46	4.06	0.01	-0.19	0.08	0.0020
22	N	L	4.30	-0.53	2.50	3.77	0.01	-0.05	-0.02	0.0004
23	T	L	10.88	-7.17	-3.96	3.71	0.00	0.02	-0.14	0.0015
24	T	L	13.10	5.67	12.79	18.78	-0.04	-0.13	-0.16	0.0189
25	T	L	4.82	6.48	6.11	11.30	0.00	-0.24	-0.01	0.0206

N = Normal S = Suture T = TPLO

Statistical Variables for Stifle of Right Pelvic Limb in Frontal Plane

Dog	Group	Leg	yKROM	yKAngOn	yKAngOff	yKAngMax	yKMoMax	yKMoMin	yKPoMax	yKPoPosImp
1	N	R	1.57	-3.03	-9.20	-4.60	-0.02	-0.07	0.06	0.0016
2	S	R	3.73	-13.93	-16.68	-17.66	0.21	-0.04	0.33	0.0248
3	T	R	7.17	3.47	-4.17	10.64	-0.04	-0.14	0.14	0.0114
4	T	R	2.06	11.96	14.21	14.02	-0.01	-0.16	0.15	0.0123
5	S	R	3.45	8.62	5.85	12.06	0.10	-0.14	0.22	0.0080
6	S	R	10.76	10.06	16.39	20.82	0.07	-0.16	0.11	0.0104
7	N	R	19.61	-16.20	-2.87	3.41	-0.06	-0.07	-0.03	0.0089
8	N	R	10.75	7.42	8.97	18.16	0.00	-0.02	0.07	0.0065
9	S	R	4.56	-11.15	-12.23	-6.59	0.19	-0.11	0.27	0.0140
10	N	R	4.79	-3.55	-5.63	1.25	-0.04	-0.06	0.00	0.0031
11	T	R	7.49	-11.91	-14.28	-4.42	-0.09	-0.13	0.03	0.0080
12	T	R	8.56	11.05	12.96	19.62	-0.04	-0.09	0.22	0.0058
13	T	R	12.43	-7.78	0.09	4.65	0.67	-0.36	0.72	0.0294
14	S	R	1.07	0.20	-6.35	-0.87	0.37	-0.29	0.39	0.0181
15	T	R	0.84	-10.17	-11.20	-9.33	0.77	-0.16	1.41	0.0358
16	T	R	16.35	-2.95	6.92	13.40	0.00	0.01	0.06	0.0034
17	N	R	1.23	4.13	10.07	2.91	-0.03	-0.08	0.01	0.0019
18	T	R	2.91	-6.90	-13.81	-9.82	-0.05	-0.06	0.26	0.0187
19	T	R	5.32	-2.31	-3.44	3.01	0.13	-0.11	0.07	0.0084
20	T	R	2.98	9.29	10.72	12.27	-0.02	-0.17	0.22	0.0066
21	S	R	0.18	-3.70	-8.92	-3.52	0.76	-0.13	0.80	0.0452
22	N	R	0.69	2.69	2.91	2.00	-0.05	-0.09	0.01	0.0015
23	T	R	12.37	9.11	12.76	21.48	0.00	-0.08	0.10	0.0017
24	T	R	15.73	15.98	17.37	31.71	-0.01	-0.14	0.01	0.0000
25	T	R	8.50	-4.94	0.27	3.57	0.00	-0.01	0.02	0.0010

N = Normal S = Suture T = TPLO

Statistical Variables for Hip of Left Pelvic Limb in Frontal Plane

Dog	Group	Leg	yHROM	yHAngOn	yHAngOff	yHMoMin	yHPoMax	yHPoPosImp
1	N	L	15.58	-7.94	-23.52	-0.02	0.08	0.0022
2	S	L	10.04	-7.83	-17.87	-0.09	0.10	0.0003
3	T	L	18.15	7.99	-10.16	-0.09	0.49	0.0006
4	T	L	15.22	0.70	-14.52	-0.03	0.03	0.0008
5	S	L	12.56	11.37	-1.19	-0.08	0.65	0.0002
6	S	L	7.92	-3.36	-11.28	0.02	0.11	0.0071
7	N	L	12.81	-6.86	-19.67	-0.06	0.11	0.0001
8	N	L	12.67	-6.55	-19.23	-0.10	0.29	0.0054
9	S	L	20.01	3.81	-16.20	-0.08	0.02	0.0005
10	N	L	8.67	-8.09	-16.77	-0.03	0.01	0.0045
11	T	L	9.59	-4.33	-13.92	0.00	0.16	0.0040
12	T	L	9.06	2.36	-6.70	-0.01	0.15	0.0046
13	T	L	1.99	-1.45	-3.45	-0.01	-0.01	0.0013
14	S	L	4.14	6.68	2.54	-0.20	1.65	0.0006
15	T	L	25.82	4.58	-21.24	-0.08	0.11	0.0000
16	T	L	10.56	0.17	-10.39	-0.05	0.18	0.0001
17	N	L	14.88	4.63	-10.26	-0.06	0.52	0.0007
18	T	L	5.73	-9.87	-15.60	-0.06	0.18	0.0037
19	T	L	12.81	-4.15	-16.96	-0.06	0.44	0.0106
20	T	L	5.12	-4.75	-9.87	-0.06	0.00	0.0005
21	S	L	4.30	1.11	-3.19	-0.11	0.29	0.0015
22	N	L	9.90	-12.30	-22.20	-0.05	0.06	0.0033
23	T	L	14.23	6.18	-8.05	-0.05	0.07	0.0011
24	T	L	8.98	-3.85	-12.83	-0.04	0.23	0.0012
25	T	L	5.48	-5.26	-10.74	-0.14	0.06	0.0013

N = Normal S = Suture T = TPLO

Statistical Variables for Hip of Right Pelvic Limb in Frontal Plane

Dog	Group	Leg	yHROM	yHAngOn	yHAngOff	yHMoMin	yHPoMax	yHPoPosImp
1	N	R	6.52	-2.12	-8.64	-0.03	0.02	0.0018
2	S	R	5.53	-15.37	-20.91	-0.07	0.12	0.0085
3	T	R	2.49	1.54	-0.95	-0.06	0.26	0.0140
4	T	R	8.20	-4.48	-12.68	-0.01	0.09	0.0072
5	S	R	6.10	7.92	1.83	0.00	0.43	0.0186
6	S	R	1.38	-10.68	-12.06	-0.04	0.21	0.0117
7	N	R	8.00	-6.97	-14.98	-0.13	0.37	0.0167
8	N	R	13.42	11.07	-2.36	-0.06	0.15	0.0138
9	S	R	12.59	-0.45	-13.03	-0.10	0.55	0.0391
10	N	R	0.62	-13.94	-13.32	-0.10	0.34	0.0150
11	T	R	12.07	6.17	-5.89	-0.12	0.92	0.0652
12	T	R	0.53	-19.09	-19.62	-0.03	0.08	0.0041
13	T	R	5.35	0.56	-4.79	-0.02	0.85	0.0392
14	S	R	5.90	-6.81	-0.91	-0.09	0.19	0.0092
15	T	R	5.15	1.28	-3.87	-0.10	0.32	0.0334
16	T	R	2.22	-7.38	-5.16	0.09	-0.07	0.0000
17	N	R	0.58	-5.94	-6.52	-0.08	0.10	0.0107
18	T	R	3.46	-10.10	-6.64	-0.07	0.16	0.0069
19	T	R	2.59	-5.22	-7.81	-0.15	0.52	0.0321
20	T	R	1.20	-3.00	-1.80	-0.04	0.04	0.0054
21	S	R	0.35	-10.16	-9.80	-0.06	0.03	0.0008
22	N	R	2.80	-8.25	-11.05	-0.10	0.08	0.0085
23	T	R	4.46	-16.50	-12.03	-0.03	0.04	0.0011
24	T	R	0.82	-4.01	-4.83	-0.04	0.27	0.0094
25	T	R	-5.60	-9.38	-3.79	-0.09	0.29	0.0119

N = Normal   S = Suture   T = TPLO

APPENDIX C: RESULTS OF STATISTICAL ANALYSIS OF VARIABLES IN TRANSVERSE PLANE

Transverse Plane Statistical Variables Abbreviations

zAROM = Hock Range of Motion
zAAngOn = Hock Angle at Onset
zAAngOff = Hock Angle at Offset
zAMoMin = Hock Minimal Moment
zAMoMax = Hock Maximal Moment
zAPoMin = Hock Minimal Power
zAPoMax = Hock Maximal Power
zKROM = Stifle Range of Motion
zKAngOn = Stifle Angle at Onset
zKAngOff = Stifle Angle at Offset
zKMoMax = Stifle Maximal Moment
zKPoMin = Stifle Minimal Power
zKPoNegImp = Stifle Negative Power Area Under Curve
zHROM = Hip Range of Motion
zHAngOn = Hip Angle at Onset
zHAngOff = Hip Angle at Offset
zHMoMin = Hip Minimal Moment
zHPoMin = Hip Minimal Power
zHPoMax = Hip Maximal Power

Statistical Variables for Hock of Left Pelvic Limb in Transverse Plane

Dog	Group	Leg	zAROM	zAAngOn	zAAngOff	zAMoMin	zAMoMax	zAPoMin	zAPoMax
1	N	L	12.27	17.99	7.80	-0.07	0.00	-0.21	-0.08
2	S	L	13.82	9.83	-1.75	-0.07	0.01	-0.23	-0.01
3	T	L	9.01	-0.12	-4.02	-0.10	0.00	-0.21	0.39
4	T	L	13.72	5.19	-8.53	-0.02	0.03	-0.08	0.01
5	S	L	8.21	-1.90	-10.11	-0.05	0.02	0.00	0.15
6	S	L	21.73	26.77	5.04	-0.01	0.02	-0.04	0.26
7	N	L	18.64	11.36	-0.93	-0.04	0.04	-0.09	0.01
8	N	L	20.48	29.86	9.93	-0.07	0.00	-0.06	0.09
9	S	L	10.91	16.11	5.20	-0.06	0.02	-0.02	0.04
10	N	L	13.91	12.14	-1.78	-0.08	0.05	-0.23	0.74
11	T	L	11.09	-4.54	-10.31	-0.05	0.02	-0.08	0.18
12	T	L	4.56	5.76	12.27	-0.03	0.01	-0.04	0.12
13	T	L	10.97	4.67	-5.78	-0.01	0.06	-0.09	0.17
14	S	L	6.42	-7.31	-8.69	-0.13	0.00	-0.23	0.55
15	T	L	2.97	-7.37	1.57	-0.12	0.00	0.01	0.46
16	T	L	23.40	15.15	-6.69	-0.11	0.07	-0.41	0.03
17	N	L	10.68	10.03	-0.08	-0.11	0.00	-0.13	-0.02
18	T	L	13.66	15.34	6.93	-0.14	-0.02	-0.04	-0.04
19	T	L	27.88	21.49	-0.18	-0.12	0.05	-0.34	0.00
20	T	L	15.05	1.60	-4.99	-0.09	-0.01	-0.22	0.07
21	S	L	18.31	11.04	-6.30	-0.07	0.00	-0.32	0.27
22	N	L	10.49	1.10	-7.66	-0.03	0.04	-0.05	0.03
23	T	L	7.40	-5.23	-12.21	-0.03	0.08	-0.03	0.00
24	T	L	9.91	2.87	-2.25	-0.08	-0.01	-0.20	0.02
25	T	L	9.43	-4.44	-12.83	-0.11	0.01	-0.23	0.09

N = Normal S = Suture T = TPLO

Statistical Variables for Hock of Right Pelvic Limb in Transverse Plane

Dog	Group	Leg	zAROM	zAAngOn	zAAngOff	zAMoMin	zAMoMax	zAPoMin	zAPoMax
1	N	R	25.18	36.00	24.44	-0.05	0.02	-0.06	0.25
2	S	R	17.10	12.86	-2.79	-0.09	0.00	-0.10	0.14
3	T	R	2.78	-75.31	-75.48	-0.07	0.01	-0.07	0.02
4	T	R	14.70	-6.60	-1.16	-0.04	0.01	-0.02	0.41
5	S	R	14.94	46.95	38.81	-0.05	0.01	0.01	0.11
6	S	R	11.63	-2.97	-14.60	-0.10	0.04	-0.01	0.18
7	N	R	11.63	-32.64	-39.83	-0.05	0.04	-0.02	0.13
8	N	R	13.58	60.76	47.18	-0.03	0.01	0.04	0.10
9	S	R	16.69	10.46	-4.05	-0.07	0.00	-0.12	0.12
10	N	R	8.46	4.21	-0.18	-0.02	0.02	-0.01	0.01
11	T	R	15.46	41.53	29.33	-0.10	-0.01	0.00	0.15
12	T	R	9.35	40.07	30.72	-0.05	0.01	-0.09	0.20
13	T	R	10.85	39.04	31.00	-0.19	0.04	-0.27	0.36
14	S	R	15.53	-24.83	-39.37	-0.08	0.00	-0.13	0.12
15	T	R	14.41	29.41	34.98	-0.09	0.00	-0.07	0.27
16	T	R	12.48	16.06	4.17	-0.02	0.09	-0.03	0.08
17	N	R	11.22	13.53	4.34	-0.04	0.01	0.00	0.10
18	T	R	4.22	-13.18	-16.12	-0.09	0.00	-0.21	0.04
19	T	R	21.15	67.84	51.27	-0.04	0.06	-0.02	0.17
20	T	R	10.75	27.20	15.48	-0.07	0.07	-0.05	0.20
21	S	R	7.65	-23.88	-16.23	-0.09	0.00	-0.79	-0.02
22	N	R	9.09	18.60	14.13	-0.05	0.02	0.00	0.09
23	T	R	2.57	-26.29	-28.86	-0.05	0.02	-0.13	0.03
24	T	R	8.87	-15.97	-24.84	-0.06	0.00	-0.14	0.09
25	T	R	12.62	21.69	11.68	-0.01	0.06	-0.05	0.02

N = Normal S = Suture T = TPLO

Statistical Variables for Stifle of Left Pelvic Limb in Transverse Plane

Dog	Group	Leg	zKROM	zKAngOn	zKAngOff	zKMoMax	zKPoMin	zKPoNegImp
1	N	L	5.00	-0.76	-4.97	0.03	0.00	-0.0002
2	S	L	10.87	11.35	5.30	0.03	0.00	-0.0003
3	T	L	26.78	1.39	-10.73	0.07	0.05	-0.0025
4	T	L	2.25	-10.51	-6.32	0.01	-0.03	-0.0006
5	S	L	20.45	5.15	-1.93	0.04	0.02	-0.0006
6	S	L	18.13	11.59	3.55	0.01	-0.03	-0.0012
7	N	L	10.99	16.30	3.71	0.02	-0.01	-0.0017
8	N	L	23.47	4.64	-12.80	0.06	-0.06	-0.0015
9	S	L	31.43	23.79	-3.80	0.04	-0.04	-0.0010
10	N	L	22.04	8.46	2.68	0.05	-0.04	-0.0014
11	T	L	13.31	1.61	0.27	0.03	0.02	-0.0010
12	T	L	24.08	10.83	-1.78	0.01	0.00	-0.0001
13	T	L	13.12	13.81	0.69	0.01	-0.04	-0.0014
14	S	L	37.92	39.72	8.98	0.10	0.00	-0.0025
15	T	L	9.51	-5.78	-14.85	0.09	-0.09	-0.0046
16	T	L	10.29	1.75	-1.43	0.04	0.00	-0.0002
17	N	L	22.89	26.98	8.89	0.05	-0.02	0.0000
18	T	L	1.38	-30.97	-28.40	0.07	-0.18	-0.0129
19	T	L	1.65	-1.27	3.03	0.06	-0.05	-0.0007
20	T	L	2.93	5.70	10.35	0.04	-0.06	-0.0023
21	S	L	20.65	25.70	18.26	0.05	-0.05	-0.0024
22	N	L	12.04	10.75	0.66	0.03	0.00	0.0000
23	T	L	19.31	22.88	11.42	0.02	0.01	-0.0004
24	T	L	2.06	13.31	7.68	0.07	-0.03	-0.0016
25	T	L	3.08	11.02	9.60	0.08	-0.03	-0.0023

N = Normal S = Suture T = TPLO

Statistical Variables for Stifle of Right Pelvic Limb in Transverse Plane

Dog	Group	Leg	zKROM	zKAngOn	zKAngOff	zKMoMax	zKPoMin	zKPoNegImp
1	N	R	3.92	-6.85	-1.28	0.01	-0.02	-0.0017
2	S	R	21.31	18.10	6.42	0.01	-0.05	-0.0042
3	T	R	11.32	7.01	-0.39	0.05	-0.14	-0.0082
4	T	R	4.27	2.64	-3.35	0.06	-0.23	-0.0048
5	S	R	8.98	0.62	-8.36	0.05	-0.08	-0.0054
6	S	R	13.81	21.27	7.46	0.07	-0.23	-0.0148
7	N	R	28.48	22.97	-9.87	0.03	-0.19	-0.0144
8	N	R	5.13	-26.22	-25.45	0.02	-0.04	-0.0017
9	S	R	17.71	15.96	4.83	0.04	-0.19	-0.0104
10	N	R	8.47	-13.50	-17.32	0.05	-0.10	-0.0068
11	T	R	10.97	6.01	-0.43	0.07	-0.25	-0.0140
12	T	R	9.98	6.69	5.36	0.01	-0.13	-0.0036
13	T	R	32.26	46.02	13.76	0.08	-0.64	-0.0293
14	S	R	12.01	9.62	8.37	0.04	-0.14	-0.0071
15	T	R	20.02	16.86	-0.63	0.05	-0.18	-0.0121
16	T	R	9.47	-16.40	-23.15	0.05	-0.11	-0.0036
17	N	R	6.69	-20.41	-27.10	0.04	-0.03	-0.0013
18	T	R	17.99	31.86	23.58	0.02	-0.05	-0.0039
19	T	R	1.68	0.92	-1.46	0.08	-0.22	-0.0128
20	T	R	3.74	0.33	3.63	0.07	-0.15	-0.0063
21	S	R	36.66	20.50	8.15	0.03	-0.23	-0.0135
22	N	R	1.41	-12.13	-14.82	0.03	-0.01	-0.0007
23	T	R	8.93	-5.58	-8.52	0.04	-0.11	-0.0070
24	T	R	15.32	-10.63	-1.99	0.03	-0.16	-0.0092
25	T	R	2.87	-15.94	-21.00	0.05	-0.13	-0.0056

N = Normal S = Suture T = TPLO

Statistical Variables for Hip of Left Pelvic Limb in Transverse Plane

Dog	Group	Leg	zHROM	zHAngOn	zHAngOff	zHMoMin	zHPoMin	zHPoMax
1	N	L	12.61	-13.43	-0.82	-0.10	-0.33	0.02
2	S	L	17.96	-24.38	-6.43	-0.13	-0.10	0.08
3	T	L	15.32	-42.32	-27.00	-0.11	-0.18	0.06
4	T	L	5.78	-1.47	4.32	-0.07	-0.12	0.01
5	S	L	20.76	5.65	26.40	-0.05	-0.04	0.12
6	S	L	13.92	-9.04	4.88	-0.01	-0.11	0.03
7	N	L	9.64	-54.30	-44.67	-0.08	-0.05	0.04
8	N	L	23.71	-53.43	-29.71	-0.13	-0.10	0.18
9	S	L	31.85	-40.59	-8.73	-0.15	-0.40	0.21
10	N	L	10.87	-41.90	-31.03	-0.07	-0.10	0.07
11	T	L	19.55	0.27	19.83	-0.01	-0.07	0.03
12	T	L	24.74	-31.49	-6.75	-0.05	-0.01	0.13
13	T	L	16.15	-60.71	-44.57	-0.03	0.00	0.02
14	S	L	33.17	-55.76	-22.60	-0.12	-0.20	0.29
15	T	L	8.46	-23.20	-14.74	-0.08	-0.20	0.08
16	T	L	20.74	-14.58	6.15	-0.11	-0.06	0.16
17	N	L	24.74	-58.37	-33.64	-0.11	-0.04	0.15
18	T	L	9.12	-17.56	-8.44	-0.09	-0.36	0.16
19	T	L	11.20	-8.35	2.85	-0.06	-0.13	0.23
20	T	L	15.24	-1.47	13.77	-0.13	-0.05	0.11
21	S	L	15.03	-30.07	-15.04	-0.09	-0.05	0.11
22	N	L	10.53	-25.25	-14.72	-0.07	-0.12	0.04
23	T	L	11.36	-20.79	-9.43	-0.05	-0.03	0.25
24	T	L	24.76	-15.60	9.17	-0.08	-0.15	0.20
25	T	L	13.02	-3.10	9.92	-0.09	-0.04	0.15

N = Normal S = Suture T = TPLO

Statistical Variables for Hip of Right Pelvic Limb in Transverse Plane

Dog	Group	Leg	zHROM	zHAngOn	zHAngOff	zHMoMin	zHPoMin	zHPoMax
1	N	R	5.15	-27.33	-22.18	-0.05	0.00	0.11
2	S	R	20.00	-65.80	-45.80	-0.06	0.00	0.02
3	T	R	14.21	-30.88	-16.67	-0.04	-0.06	0.03
4	T	R	8.28	-12.30	-4.02	-0.03	-0.02	0.12
5	S	R	30.59	-20.47	10.12	-0.04	-0.11	0.12
6	S	R	16.30	-22.83	-6.54	-0.06	-0.17	0.06
7	N	R	30.80	-57.41	-26.60	-0.10	-0.24	0.24
8	N	R	13.18	-6.62	6.56	-0.07	-0.22	0.11
9	S	R	25.57	-54.44	-28.88	-0.13	-0.20	0.07
10	N	R	12.99	-38.14	-25.15	-0.10	-0.01	0.04
11	T	R	35.08	-53.59	-18.51	-0.08	-0.26	-0.01
12	T	R	13.23	-10.14	3.09	-0.07	-0.12	0.03
13	T	R	38.89	-53.74	-14.85	-0.07	-0.13	0.14
14	S	R	15.66	-43.61	-27.95	-0.10	-0.31	0.01
15	T	R	18.57	-53.71	-35.14	-0.11	-0.15	0.08
16	T	R	23.23	-19.00	4.24	0.03	-0.02	0.06
17	N	R	15.11	-31.75	-16.63	-0.11	-0.06	0.05
18	T	R	10.48	-64.56	-54.08	-0.09	-0.19	0.05
19	T	R	11.19	-29.55	-18.36	-0.14	-0.15	0.19
20	T	R	9.32	-13.30	-3.98	-0.03	-0.12	0.06
21	S	R	7.73	-57.55	-49.82	-0.06	-0.06	0.05
22	N	R	10.71	-24.55	-13.83	-0.11	-0.06	0.12
23	T	R	7.00	-7.14	-0.14	-0.07	-0.11	0.02
24	T	R	16.96	-1.86	15.09	-0.05	-0.14	0.00
25	T	R	17.36	-28.19	-10.83	-0.09	-0.08	0.03

N = Normal S = Suture T = TPLO

VITA

Dr. Jason Headrick is originally from Manitowoc, Wisconsin. He attended Marquette University where he received Bachelor of Arts degrees in psychology and philosophy in 1995. He earned his doctor of veterinary medicine degree from the University of Wisconsin – Madison in 2003. His veterinary training continued with a rotating internship at the University of Missouri – Columbia, a surgical internship at Gulf Coast Veterinary Hospital in Houston, Texas, and an orthopedic fellowship at the University of Tennessee. He remained at the University of Tennessee to pursue his residency training in small animal surgery and doctorate in comparative and experimental medicine with a concentration in biomechanics.