THESIS

KINEMATIC AND KINETIC ANALYSIS OF CANINE PELVIC LIMB AMPUTEES AT A TROT

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ABSTRACT

KINEMATIC AND KINETIC ANALYSIS OF CANINE PELVIC LIMB AMPUTEES AT A TROT

Osteosarcoma is the most common form of bone tumors in dogs. Treatment options include palliative or curative-intent options. Of the curative-intent treatments, the most common is amputation, due to lower cost and the ability to perform the procedure on all osteosarcoma patients irrespective of tumor location, as opposed to limb-sparing options which can only be used when the tumor is located at the distal radius or ulna of the thoracic limb. Overall, dogs with amputations adjust well to the loss of the limb; however, there still remains a subset of patients which do not. In this study, the ground reaction force kinetics and joint angular kinematics of pelvic limb amputees and four-legged dogs were compared to identify compensation strategies adopted by amputees after the loss of a pelvic limb. It was hypothesized that there would be increased flexion and extension of all limbs within the amputees, as well as increased spinal motion. In addition, it was hypothesized that there would be decreased vertical impulses in all limbs of amputees, as well as, decreased propulsion forces within the thoracic limbs of amputees, as compared to controls.

The four-legged control population consisted of 24 dogs and the pelvic limb amputee population consisted of 12 dogs. Both populations had dogs of varying breeds. Ground reaction force data were captured using three serial force platforms while dogs were trotted down

an over-ground walkway. Concurrently, joint angular kinematic data were captured by motion capture software using retroreflective markers affixed to bony landmarks along the limbs and axial skeleton.

Peak ground reaction forces and impulses were slightly different between pelvic limb amputees and four-legged dogs. Pelvic limb amputees had increased peak braking forces in the contralateral thoracic limb and increased peak propulsion in both the ipsilateral thoracic limb and remaining pelvic limb. In addition, amputees had increased peak vertical force and propulsion impulse in the remaining pelvic limb. Time to peak braking force was significantly decreased in all limbs of the amputees, while time to peak propulsion ground reaction force was increased in all limbs of the amputees.

Limb kinematics of pelvic limb amputees were very similar to the kinematics of four-legged dogs. The only compensatory strategy adopted within the limbs of the amputee was increased range of motion of the hock joint within the remaining pelvic limb. However, the pelvic limb amputees had various spinal compensatory changes within the sagittal plane. Amputees had increased regional spinal motion about both the T1 and T13 markers and increased extension about the L7 marker, compared to four-legged controls. The motion of the spine in the horizontal plane varied only in the regional angular motion about the L7 marker.

Overall, ground reaction force kinetic and joint angular kinematic gait analysis of pelvic limb amputees showed that there are various compensation strategies adopted by pelvic limb amputees to adjust for the loss of a limb. Combined, these compensation strategies allow for successful adaptation to a three-legged gait pattern after the removal of a pelvic limb. Clinically, this information will be valuable for determining factors related to adaptive strategies with pelvic limb amputees. This information can also be used to create a set of quantitative measures needed to classify canine amputees into adapted or poorly adapted gait parameters.

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INTRODUCTION

Osteosarcoma is the most common type of bone cancer in dogs with 6,000-8,000 new cases of osteosarcoma diagnosed each year [1]. Treatment for the disease can either be palliative or curative-intent [2]. Palliative treatments work to treat painful symptoms arising from the tumor and decrease the severity without providing a cure, while curative-intent therapy works to control the local disease and prevent it from becoming metastatic [2]. In most cases, curative-intent is the best option for both the patient and owner. Curative-intent therapy includes limb amputation, limb-sparing surgery, as well as radiation therapy, all followed by chemotherapy [2]. Of these, limb amputation is currently the most common procedure for appendicular osteosarcoma, not only because it is less expensive than limb-sparing surgery (i.e. approximately $1,800 compared to $7,500 to spare the limb), it is also an option for most osteosarcoma patients regardless of tumor location [3,4]. Limb-sparing surgery is usually only recommended for dogs with tumors located at the distal radius or ulna of the thoracic limb [4]. While most dogs adapt well to the loss of the limb, returning to near normal levels of activity within a month after surgery, a clinically important subset of patients do not adapt well, in all cases, not returning to normal levels of activity after amputation [5,6]. Most likely the dogs that do not adjust well have concurrent musculoskeletal or neurologic conditions prior to the amputation that hinder adoption of appropriate compensatory strategies.

After limb amputation due to osteosarcoma followed by adjuvant chemotherapy, 50% of dogs live one year, less than 30% survive two years, and less than 10% live for three years [1]. Osteoarthritis, which may be a risk factor for dogs following amputation, is a degenerative and typically progressive condition which starts in a mild form during early growth and continues to get worse over the course of the dog life [7]. For dogs who already have clinical signs of osteoarthritis before amputation, such as joint pain or lameness, the signs may only be intermittent, occurring after long periods of activity and will not become severe, activity-limiting, until later in life [7]. One study transected the cranial cruciate ligament in the canine stifle to cause osteoarthritis [8]. In this model, the osteoarthritis remained mild for three years before becoming severe and hindering mobility [8]. As a result, the development of severe osteoarthritis in limb amputees due to osteosarcoma may be of less clinical importance due to their short life span after amputation. However, other conditions may require limb amputation at a younger age which would allow time for osteoarthritis to develop. Limb can also be a result of severe trauma, ischaemic necrosis, intractable orthopedic infections, disability due to arthritis, or congenital deformities [9]. In some of these conditions, the dogs are expected to live much longer than three years post-limb amputation and would have the potential to develop secondary joint pain and degeneration over time as a result of compensatory strategies adopted following the loss of a limb, even when able to adequately adjust soon after surgery.

Limb amputations occur in either the thoracic limb or pelvic limb, depending on the individual clinical situation. Amputation of a pelvic limb is thought to reduce balance and locomotor function in dogs due to increased weight on the thoracic limbs and potentially more spinal motion due to the loss of symmetry in strength and propulsion caused by the amputated limb [10,11]. At present, the known compensation strategies of pelvic limb amputees are limited to the changes in ground reaction forces and stance phase timing and duration. One previous study showed that peak vertical forces and impulses for all limbs in pelvic limb amputees are comparable to control dogs while stance duration is decreased at a walk, indicating that the same amount of force is still being applied to the limbs, but over a shorter period of time [10]. In four-legged dogs, decreased stance duration is accompanied by an increased velocity; however, in pelvic limb amputees, the decreased stance duration is not accompanied by an increased velocity [10]. Therefore, the decreased stance duration in pelvic limb amputees is a result of an increase in cadence [10]. Decreased stance duration accompanied by faster moving limbs, is expected to cause significant differences in limb kinematics between pelvic limb amputees and four-legged dogs as the amputees would be expected to decrease the range of motion within the joints, specifically the stifle, to adjust to a faster loading time as seen in human athletes [12].

Kinetic analysis on four-legged dogs show that the pelvic limb horizontal ground reaction forces are dominated by propulsion, while thoracic limb horizontal ground reaction forces are dominated by braking [13]. One study indicates that pelvic limb amputees retain the same amount of propulsion in the remaining pelvic limb as compared to four-legged dogs while decreasing the amount of propulsion in their thoracic limbs [10]. Also, dogs with pelvic limb amputations take longer to reach their peak braking force in their thoracic limbs and less time to peak braking force in their remaining pelvic limb due to the loss of braking from the amputated pelvic limb [10]. The ability to develop compensatory changes in propulsion and braking forces for the remaining limbs could be a reason why some dogs adapt more efficiently to limb amputation than others. Another study indicates that pelvic limb amputees have difficulty accelerating immediately after amputation due to difficulties adapting to changes in braking and propulsion, which would be a significant problem for those dogs that cannot adapt and increase the loads applied to the joints [10].

Pelvic limb amputees also adapt to their missing limb by redistributing their bodyweight due to changes in center of mass. Normal canine gait kinetics show that 60 percent of bodyweight is supported by the thoracic limbs and 40 percent is supported by the pelvic limbs [14]. Pelvic limb amputees compensate by increasing weight bearing on the thoracic limbs to 74 percent and 26 percent supported by the pelvic limb at a walk [10]. Theoretically, the center of mass is located three-fifths of the distance between the pelvic limbs and the thoracic limbs [10]. Therefore, by amputating a pelvic limb, the center of mass is moved more toward the thoracic limbs, increasing the amount weight bore by the thoracic limbs. Increased weight bearing on the thoracic limbs results in a greater load applied to the soft tissues and joints and therefore, dogs with lameness or osteoarthritis in the elbow or shoulder joints pre-surgery may have more difficulty adjusting to the pelvic limb amputation due to increased weight bearing on already abnormal joints.

In order to more completely understand the ramifications of altered limb loading after amputation, the effects of changes in limb and spinal kinematics also need to be examined. Studies on canine balance show that forces that rotate the body about its transverse axis while trotting, causing the body to fall forward or backward, are opposed by the thoracic limb or pelvic limb of a support pair [11]. Forces that rotate the body about the sagittal axis, causing the body to rotate to the left or the right while trotting, can be opposed by the right or left limb of a support pair (left or right thoracic limbs in this case) [11]. When a pelvic limb amputee loses the member of one of the above mentioned support pairs, compensation must be made to regain balance and prevent rotation about the transverse or sagittal axes of the body, which can be quantitatively measured using spinal kinematics. In addition, with increased velocity, especially running, the pelvic limbs are used for increased propulsion and the trunk extends to increase stride length [11]. As discussed previously, pelvic limb amputees have decreased propulsive forces, which could then result in decreased trunk extension. Decreased balance in addition to decreased trunk extension could result in a more rigid spine and potentially a stiff-legged gait in the remaining pelvic limb in order to get the remaining pelvic limb off the ground quickly.

A stiff-legged gait in the remaining pelvic limb of amputees would increase concussive forces on the joints and decrease flexion in all joints due to the increased propulsion needed to get the limb off the ground [12]. In addition, a stiff-legged gait in the remaining pelvic limb would provide for less control in the hind-quarters as the limb would have significantly increased loading over a short amount of time. Human studies have shown that stiff-legged gait results in greater abduction at the hip during stance phase, which in canine pelvic limb amputees would create a state of unbalance as it would move the pelvic limb away from the center of the body without having the stability of a contralateral pelvic limb [15]. This could result in greater motion in the caudal thoracolumbar spine as the pelvic limb is less compliant and more rigid, with less motion within the joints [12]. A more compliant gait pattern would allow for more efficient loading of the remaining pelvic limb due to increased range of motion of the joints, which would provide more control during both stance and swing phases and potentially less spinal motion while trotting. Limb and spinal kinematics would provide useful and much needed information on what type of gait patterns are typically adapted and how this may improve the successful adaption to a three-legged gait.

The purpose of this study was to examine the kinematic and kinetic differences between four-legged dogs and pelvic limb amputees to examine the adaptive and maladaptive compensation strategies adopted after losing a limb. It was hypothesized that there will be a decreased joint range of motion in all limbs during the stance phase for pelvic limb amputees, as compared to controls due to the decreased stance duration and increased cadence previously defined by Kirpensteijn et al (2000) [10]. In addition, the ipsilateral thoracic limb will have a increased range of motion during stance phase than the contralateral thoracic limb due to the lack of support from the missing pelvic limb at a trot. Also, spinal motion would be increased in pelvic limb amputees with decreased stance width in the remaining pelvic limb to create balance while trotting. Within the amputee group, there will be greater spinal motion while the contralateral thoracic limb is in stance phase compared to the ipsilateral thoracic limb. These results will serve as a basis for quantifying adoptive compensation strategies of pelvic limb amputees; advancing our understanding of why some dogs adapt well to pelvic limb amputation and to assess which joints may be at risk for developing or aggravating osteoarthritis in the longer-lived population.

LITERATURE REVIEW

Over the past couple of decades, canine gait studies have become increasingly more important, both to the overall understanding of how dogs walk, but also to the treatment of various musculoskeletal diseases, such as hip dysplasia, osteosarcoma, and stifle injuries [8,10,16]. Considerable information is known about the ground reaction forces and impulses of normal canine gait and only one study has analyzed the ground reaction forces of amputee gait [10]. Less is known about the limb and spinal kinematics of both normal dogs and amputees, though they are becoming more prevalent. Following the loss of a pelvic limb, amputees must learn to compensate both kinematically and kinetically due to changes in balance as a result of weight distribution changes [10,17].

Understanding compensation strategies adopted by pelvic limb amputees is important clinically as it would help to identify why some dogs adapt more effectively to limb amputation than others. If clinicians knew the details of adoptive strategies present after limb amputation, that information could be used to determine which characteristics are present before surgery that could be aggravated post-amputation due to maladaptive compensations, in turn making the lameness worse. A few studies on stifle injuries and hip dysplasia examine limb kinematics of the pelvic limbs and a couple of studies have described spinal motion of the clinically normal canine spine, though research has yet to look at the limb and spinal kinematics of limb amputees [8,16,18]. More information on the kinetics and kinematics of canine amputee gait are needed for clinicians to be able to better understand the compensation strategies of pelvic limb amputees and to help optimize functional performance. The goal of the following literature review is to present current findings on canine appendicular osteosarcoma, pelvic limb amputee ground reaction force and impulse kinetics, and normal canine ground reaction force and impulse kinetics in order to demonstrate the importance of studying the ground reaction force and impulse kinetics and kinematics of canine pelvic limb amputee gait for clinical use.

Osteosarcoma and Treatment

Appendicular osteosarcoma is a malignant tumor that has a high potential for metastasis [2]. It is the most common canine primary bone tumor, with 6,000-8,000 new cases diagnosed each year [1]. Osteosarcoma can be treated using palliative or curative-intent therapy [2]. Palliative treatments focus on treating painful symptoms arising from the tumor and decreasing the severity of pain or lameness without providing a cure [2]. Curative-intent therapy focuses on controlling the local disease and preventing it from metastasis [2]. The most common form of curative-intent therapy and gold standard of care for local management of osteosarcoma is limb amputation followed by chemotherapy [1]. Amputation of a limb is also commonly used to treat cases of severe trauma, ischaemic necrosis, intractable orthopedic infections, and congenital deformities [9].

In cases where limb amputation is either not possible due to conditions such as neurologic disease, severe osteoarthritis or morbid obesity, or is simply not desired as a treatment option by the owners, other limb-sparing options are available, which include limb-sparing surgery or stereotactic therapy [2]. Limb-sparing surgery is often performed in patients with tumors on the distal radius and ulna of the thoracic limb [2]. In this procedure, a marginal resection of the soft tissue is performed followed by the placement of an allograft, autograft, or metal implant [4]. As with amputation and other osteosarcarma treatments, limb-sparing surgery is also followed by chemotherapy [2]. Another limb-sparing, option is stereotactic radiation therapy. In stereotactic radiation, the entire dose of radiation is delivered in three treatments using multiple, nonplanar radiation beams stereotactically focused on the tumor [19]. This minimizes the damage to the healthy tissues surrounding the tumor and results in fewer anesthetic episodes with the possibility of having a significant biological effect on the tumor [19].

Though recovery largely depends on the individual, studies show overall recovery after the limb amputation in dogs is usually satisfactory with dogs returning to activity levels similar to pre-amputation within a month after surgery [5]. One study by Carberry and Harvey asked a group of dog and cat owners who had previously had pets undergo a limb amputation about their satisfaction with the limb amputation and 72 of the 74 who had responded stated they were satisfied with the procedure [5]. In addition, most of the dogs returned to normal activity, in some cases going hunting or performing field trial work [5]. The study also found that the level of activity and functionality was only slightly impacted by bodyweight and not by whether it was a thoracic limb or a pelvic limb that was amputated [5]. Overall, many of the owners surveyed stated that despite the difficult decision to go through with the limb amputation, they did not regret the decision and were “impressed with how quickly their pets adjusted” [5,6].

Another study by Kirpenteijn et al. (1999) solicited a similar survey with dog owners who had pets with recent limb amputations [6]. Their survey showed that there was a positive relationship between owners with positive attitudes about the amputation and how quickly their pet recovered from surgery [6]. Pet owners who believed their pet would adjust well after amputation had dogs return to normal activity faster than those who were less optimistic [6]. In addition, it also showed that most owners were satisfied with the adaptation and functionality of their pet after the limb amputation [6]. These two surveys show that the majority of dogs undergoing limb amputation recover well, though it is still not understood what causes some dogs to better adapt to amputation than others. Increased knowledge of the compensatory strategies adapted by pelvic limb amputees would provide much needed information on why some dogs adjust better to limb amputation than others.

Osteoarthritis

Approximately 10-12 million dogs (20% of the total canine population) over the age of one year have some degree of osteoarthritis [20,21]. As a result, it is important to consider the potential for dogs to develop osteoarthritis after the limb amputation. Osteoarthritis is typically a slowly progressive disease that can vary in severity from a mild condition that causes limited discomfort and disability to a state of constant pain and severe disability [21]. Some of the conditions that are thought to contribute to the development of osteoarthritis include defective articular cartilage structure and biosynthesis, joint trauma, joint instability, inflammatory conditions, and congenital and developmental abnormalities [13]. In most cases osteoarthritis develops secondary to trauma [20]. After transection of the cranial cruciate ligament, osteoarthritis remained mild for three years before becoming severe and reducing mobility [8]. Treatment for osteoarthritis is often palliative and includes weight management or reduction, exercise, physical therapy, and medications [21]. There is very little evidence that moderate or prolonged, vigorous use of a normal joint results in osteoarthritis, though the same use of an abnormal or diseased joint could induce the development and progression of osteoarthritis [20]. Therefore, dogs undergoing amputation that do not already have osteoarthritis and have normal joints would most likely not develop osteoarthritis in the joints due to their short lifespan after amputation.

Ground Reaction Force Kinetics

Various studies have examined the kinetics of four-legged canine gait, though only a few studies have examined changes after limb amputation. Kirpensteijn et al. (2000) examined bodyweight distribution in a clinically normal population of Labrador Retrievers and found that normal dogs bear 60 percent of their body weight on their thoracic limbs and 40 percent on their pelvic limbs at a walk [10]. This study also examined the adjustments in bodyweight support made by dogs after limb amputation. They found that pelvic limb amputees carry 74 percent of their body weight on their thoracic limbs and 26 percent on the remaining pelvic limb, with each of the thoracic limbs supporting equal weight [10].

After limb amputation, changes in forces and impulses of the remaining limbs have been reported. Kirpensteijn et al. (2000) examined the adaptations of canine amputees to the loss of a limb as well as the impact those changes had on the kinetics of their gait [10]. In four-legged dogs, there is an inverse relationship between the stance duration and the peak vertical force at both walking and trotting velocities [10,22,23]. This relationship was not seen in limb amputees [10]. The decrease in stance duration did not result in increased peak vertical force or impulse [10]. However, there were significant decreases in the vertical impulse of all three limbs and the peak vertical ground reaction force of the contralateral thoracic limb, indicating that the same force exerted by control dogs was distributed over a shorter period of time in pelvic limb amputees [10]. In pelvic limb amputees, peak braking forces and impulses of all limbs did not change as compared to four-legged dogs while thoracic limb peak propulsive forces and impulses significantly decreased [10]. Pelvic limb amputees exhibited decreased propulsion in both their ipsilateral and contralateral thoracic limbs as compared to four-legged dogs [10]. Also, pelvic limb amputees took longer to reach their peak braking force in the thoracic limbs and less time in the pelvic limb indicating that it took longer to brake in amputees than in controls [10].

Joint Angular Kinematics

Over the past few years, kinematic studies of the canine limbs have become more common. There are a few considerations that need to be made in designing kinematic studies in order to reduce experimental errors. For example, all trials must be completed at a constant velocity in a symmetrical gait pattern, such as a trot [24]. Variation of more than 0.6 m/s in the velocity of trials has been shown to induce unnecessary experimental error [25]. Several studies on the symmetry of canine gait in clinically normal, four-legged dogs have shown that although there are slight asymmetries in individual dogs, the group differences between left and right sides are typically small [24]. A dog with three limbs would most likely not be able to maintain a symmetrical gait pattern due to the missing rhythm from the amputated pelvic limb.

Marker placement is important to the overall quality of kinematic data as well. One recent study showed that marker placement does affect calculation of joint angles [26]. Torres et al. showed errors in the dorso-ventral direction produce no significant differences in the models, while errors in the cranio-caudal direction do [26]. Marker reapplication during a study can also potentially result in significant differences and errors in the joint measurements, an important concern for canine studies as markers secured to hair and not firmly to the skin are not always secure for the entirety of a trial, resulting in motion artifact [26]. With the new studies more information is now known about the effects of marker placement on the overall outcome of kinematic studies; however, this will continue to be an issue in creating a better, more accurate standard for kinematic analysis in dogs.

Another potential source of error in kinematic analysis is using different breeds of dogs in the same study [24]. Bertram et al. showed differences in the gait at a trot for Labrador Retrievers and Greyhounds were mainly due to size; however, they still moved in a “dynamically similar way” [27]. Another study five years later did not support this conclusion by showing significant differences in pelvic limb kinematics between the two breeds [28]. Both of these studies show the importance of examining the differences between breeds, such as ground reaction forces, size, back conformations, and gait patterns, to determine whether or not studies using multiple breeds to make general conclusions for all dogs are accurate or if it would be better to do studies using a single breed.

Joint Kinematics and Stance Width

Very few studies have examined the kinematics of canine gait and no studies to date have looked at the differences in canine limb kinematics after limb amputation as compared to a control population for normal, four-legged dogs. Feeney et al. examined the limb angles of clinically normal Labrador Retrievers at a walk using two-dimensional video analysis. In this study, joint angles were calculated by multiple individuals using 2D video analysis and then compared to each other to validate 2D methods [29]. Angles of flexion and extension during walking ranged from 128°-239° in the carpus, 91°-146° in the elbow, 88°-125° in the shoulder, 111°-145° in the tarsus, 111°-146° in the stifle, and 111°-147° in the hip, where zero degrees indicates full flexion and 180 degrees indicates full extension [29]. All joint ranges of motion of the pelvic limb were within 1.1-2.9° of previous studies and joint ranges of motion of the thoracic limbs were within 6.7-19.8° [29]. Studies of human kinematics during walking compared to running show little change in the hip joint angle between the two speeds, the joint range of motion at the knee is significantly decreased with increased speed, and maximum dorsiflexion in the ankle is decreased while running [12]. As a result, decreased range of motion at the stifle joint and an increased maximum joint angle at the hock joint might then be expected in dogs at a trot.

Stance width has also been studied in various studies in order to determine how canines compensate for other orthopedic conditions, such as hip dysplasia, though the changes in canine pelvic limb amputees have not yet been determined. Poy et al. examined the kinematic differences between clinically normal dogs and those with lameness due to hip dysplasia [30]. In their study they found that dogs with lameness had a greater degree of pelvic limb adduction and kept their femurs closer to their midlines than the control group consisting of clinically normal, non-purpose-bred large breed dogs; a mechanism to reduce pain and discomfort in the pelvic limb [30]. This could also be the case in pelvic limb amputees; however, instead of moving the pelvic limb toward the midline to reduce pain and discomfort, it could be a mechanism to increase stability while trotting, though has not been investigated in previous studies.

Ligaments, Muscles, and Tendons

Altered joint motion in amputees not only affects the bones and cartilage due to increased loads on the joints, it could also potentially lead to significant changes in the muscles, ligaments, and tendons acting on the joints. The muscular moment about a joint is not only determined by the force of the muscle, but the moment arm of the muscle as well. Muscle moment arms vary with changes in joint angle and are therefore an important component of the joint moment. Williams et al examined the changes in muscle moment arms of muscles in the pelvic limbs of Greyhounds [31]. They found that the moment arm of the biceps femoris muscle remained constant as the hip joint angle changed, while the semimembranosus muscle moment arm increased slightly with increased hip extension [31]. The limited amount of change in the biceps femoris muscle is likely a mechanism to increase versatility of the muscle as it is required to produce a significant force throughout each stride cycle and it is likely that the biceps femoris muscle acts as several distinct regions rather than as a single unit due to its large size [31]. The middle gluteal and semitendinosus moment arms were small with hip flexion, but increased with hip extension and had their maximum moment arm at maximum extension [31]. The semitendinosus has the greatest change during hip joint motion and the greatest maximum moment arm, indicating that it plays a large role in creating muscle torque at the hip, especially during propulsion [31]. An increase in the range of motion at the hip joint in the remaining pelvic limb of amputees could then result in significant overuse and strain of the semitendinosus muscle and therefore produce pain and instability at the hip joint.

Force-velocity and force-length relationships of the muscles are also an important consideration when examining the altered gait of amputees. The force-velocity relationship states that the amount of force generated by a muscle is dependent on the number of cross-bridges and as velocity increases, the amount of force decreases due to the filaments moving past each other without attaching [32]. As discussed earlier, pelvic limb amputees have an increased cadence in all limbs and increased limb loading [10]. As a result, the muscles may be shortening quickly and therefore not able to produce adequate force while trotting due to a lack of cross-bridges forming, which could potentially lead to joint degeneration over time due to the lack of muscle strength and joint instability. The force-length relationship also has significant importance to the amputee population. For each muscle, there is an ideal length at which it reaches its greatest active force [32]. When the muscle is stretched beyond that point or below that point, the maximum force that can be generated is decreased [32]. In joints where the muscles are lengthened or shortened beyond that of a normal joint, the maximum force generated by the muscle will decrease. If the muscle doesn't create the necessary force to support the joint, there could be instability and damage at the joint over time due to a loss of protective mechanisms.

Ligament and tendon injuries are also common at the stifle joint in dogs. The cranial and caudal cruciate ligaments located within the stifle joint work together to maintain the strict alignment of the femur and tibia and prevent cranio-caudal translation [33]. During stifle flexion, the ligaments twist on each other to prevent inward rotation of the tibia with respect to the femur [33]. Then during stifle extension, the cranial and caudal cruciate ligaments untwist and the collateral ligaments that connect the femur to the tibia are then responsible for stabilizing the joint [33]. Increased extension in the stifle of the remaining pelvic limb in amputees could then result in overuse injuries to the cranial and caudal cruciate ligaments as well as the collateral ligaments.

Spinal Kinematics

There have not been any studies performed on the kinematics of the canine spine after limb amputation; however, a few studies have described the kinematics of the clinically normal canine spine. Back problems are one of the most common reasons for working dogs to go into retirement and the abnormal motion in the spine can lead to spondylosis and osteophyte formation, which reduces the overall spinal range of motion [34,35]. Due to the large clinical impact of abnormal spinal motion, Gradner et al. examined clinically sound Malinois dogs in order to provide standardized kinematic measurements [18]. They found the highest range of motion in the transverse place was found at the T6, T13, and L3 markers, while the highest range of motion in the sagittal plane was found at the S3 marker [18]. The smallest angular range of motion was found from the thoracic to the lumbar vertebrae in both the horizontal and sagittal planes [18]. Overall, the study showed a coefficient of correlation of 0.86 for the marker locations and 0.68 for the angles of the spine in the transverse plane with decreased coefficients in the vertical plane, possibly due to increased flexibility of the spine, showing the variability in the different planes [18]. Extreme deviations from a coefficient of correlation of 1.0 were thought to be caused by joint flexion and extension differences due to orthopedic problems [18]. Deviations in the spinal curvature, such as increased flexion or extension, of an amputee population as compared to a control population would be valuable information for clinicians in evaluating why some dogs adapt more efficiently to amputation than others.

Another study on the biomechanics of the spine shows that the spine alone is not responsible for keeping a quadruped balanced and in a correct posture, but that muscles and ligaments of the limbs and abdomen also play a large role [17]. Important muscles for flexion or extension of the spine include the iliopsoas, the epaxial, and the psoas minor muscles [36]. The iliopsoas muscle works to flex the vertebral column ventrally when the pelvic limb is weight bearing and draws the femur cranially when the pelvic limb is in swing phase [36]. The epaxial muscles extend the vertebral column dorsally when both left and right sides are contracting and laterally flexes the vertebral column when only one side contracts [36]. Additionally, the psoas minor muscle flexes the lumbar portion of the vertebral column [36]. These muscles, combined with the muscles of the abdomen, which flex the spine ventrally, work to flex and extend the spine in order to maintain posture and balance while trotting. Changes in the actions of these muscles in pelvic limb amputees would be apparent through a spinal kinematic analysis.

Summary

With the large number of appendicular osteosarcoma cases being diagnosed each year, it is important to continually evaluate the efficacy of the various treatment methods. As more limb-sparing options become available, the need to amputate limbs may become obsolete, but until then, it is still many times the best option for treatment. In order to create the best possible scenario for successful adaptation after limb amputation, full evaluation of the compensation strategies, both kinetically and kinematically, used by dogs after losing a limb are needed and very helpful clinically. With this knowledge, clinicians would be better able to determine why some dogs are able to better adapt to a missing limb than others.

MATERIALS AND METHODS

Dog Population

The goal of the study was to be clinically relevant and as a result, the control group was not designed to be without any orthopedic, neurologic or other physical impairments; therefore comparing dogs who have lost a limb due to osteosarcoma to a similar group with four limbs. The control group consisted of 27 four-legged dogs, three previously diagnosed with cancer and currently undergoing treatment. The amputee group consisted of 13 pelvic limb amputees, 7 left pelvic limb and 6 right pelvic limb amputees. All dogs were client-owned, recruited through the Colorado State University (CSU) Animal Cancer Center and received standard of care for spontaneously-occurring disease. Owners signed Institutional Animal Care and Use Committee (IACUC) approved written consent (Appendix I) for their dogs to be included in the study and were given a written summary of the project before participating.

Dogs were considered for inclusion in the study if they were older than one year and weighed more than 14 kg. Dogs had to be of a certain height for gait analysis in order to properly strike the plates and for markers to be identifiable using the motion capture system. Amputees must have had a pelvic limb amputation at CSU at least one month prior to the gait analysis, as this amount of time post-amputation has been shown to be adequate for adaptation to a three-legged gait [6]. Exclusion from the study for control dogs was based on whether the dog could be an amputee candidate. Therefore, some lameness ranging from mild discomfort with palpation to a marked decrease in range of motion could be present in the control group. All dogs underwent a complete physical, orthopedic, and neurologic examination before gait analysis in order to confirm that there were no unknown conditions that would prevent inclusion in the study. Unknown conditions would have included and inability to complete the study due to pain or discomfort in the joints or long hair that would prevent proper marker attachment. Operators performing the kinetic and kinematic analysis were blinded to the results of the physical exam findings until the study was completed.

Subject Measurements

Immediately prior to gait analysis, both wither height and body mass measurements were recorded for each dog. Body mass was used to normalize ground reaction force data so all dogs could be compared. Wither height was measured on a level surface from the ground to the top of the shoulder blade using an inextensible tape measure.

Marker Placement

To measure three-dimensional coordinate locations and calculate joint angles for the limbs and spine, 25 retro-reflective markers were placed on each control dog and 20 on each amputee. The spherical retro-reflective markers, 25.4 mm in diameter (Vicon Motion Systems, Inc., Centennial, CO), were placed on unclipped fur as close as possible to the skin at standard palpable bony landmarks along the spine and thoracic and pelvic limbs (Figure 3.1) using double-sided carpet seam tape (Q.E.P., Boca Raton, FL). On the thoracic limbs, markers were placed over the distal lateral aspect of the fifth metacarpal bone, the ulnar styloid process, the lateral epicondyle of the humerus, the greater tubercle of the humerus, and the dorsal aspect of the scapular spine. On the pelvic limbs, markers were placed over the distal lateral aspect of the fifth metatarsal bone, the lateral malleolus of the fibula, the lateral femoral condyle, the greater trochanter of the femur, and the iliac crest. On the spine, markers were placed over the sacral apex, the dorsal spinous process of the L7 vertebrae, the dorsal spinous process of the T13 vertebrae, the dorsal spinous process of T1, and the occipital protuberance. For pelvic limb amputees, an iliac crest marker was placed on the side of amputation.

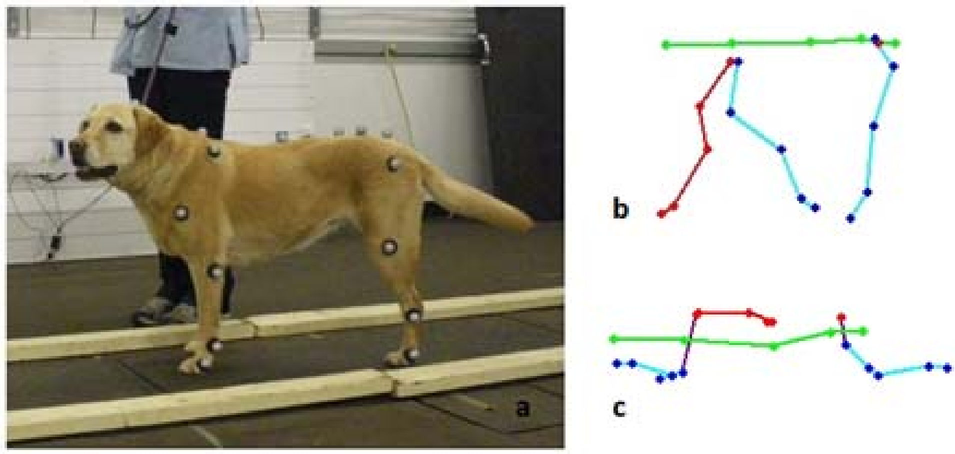

Figure 3.1 (a) Photo of a right pelvic limb amputee standing on two serial force platforms within the capture volume with a full set of retro-reflective markers applied to bony landmarks along the spine, pelvic and thoracic limbs. Sagittal (b) and horizontal (c) plane reconstructions during a trotting trial allowing full view of the markers. Green markers and lines represent the spine, red markers and lines the right limbs and blue markers and lines the left limb.

Data Collection

Data collection took place at the Gait Analysis Laboratory at the CSU Orthopedic Research Center. This facility is designed for simultaneous kinetic and kinematic data collection. Data were collected in a calibration volume of 1 x 1 x 2 meters centered over three in-series force platforms (AMTI, two model BP400600-1000 and one model OR6-5-1000, Watertown, MA) mounted in the center of a 12 m walkway (Figure 3.2).

Kinematic and kinetic data were synchronized in Vicon Motus (Motus 9.0, Vicon Motion Systems, Inc., Centennial, CO) and a Bosch Dinion camera (Bosch Security Systems Inc., Fairport, NY) located at the center of the walkway was used to visually verify pawstrikes. Within the kinematic capture volume, a 91.50 cm wand was measured to be 91.50 cm long with an average first standard deviation of 0.09 cm during daily calibration of motion capture system. Coordinate data were captured at 200 Hz using eight optical cameras (Motus 9.0, Vicon Motion Systems, Inc., Centennial, CO). Three-dimensional raw coordinate data were filtered to remove noise with a recursive 4^{th}-order Butterworth filter with cutoff frequency of 15 Hz. Kinetic analog data were captured at a frequency of 2000 Hz and filtered with a Butterworth filter at 40 Hz.

Figure 3.2 For each trial, dogs started at the far end of the walkway in the gait analysis laboratory and trotted toward the control center at the front of the lab (out of view). Boards were placed parallel to the force platforms to guide the dogs across the force platforms. A series of 5 timing lights were placed to the left of the force platforms with reflectors placed in similar intervals on the right side of the walkway.

Five timing lights (Mekontrol, MEK-92-PAD, Richardson, TX) spaced at intervals of 0.5 m were used to instantaneously provide measures of velocity and acceleration. Dog handlers were instructed to maintain velocities as close as possible to 2.2-2.6 m/s and accelerations between -0.5 m/s^2 and 0.5 m/s^2 for the data collection. In some cases, dogs were unable to reach the specified velocity range, in which case, dogs were trotted as close to the velocity range as possible while still maintaining a 0.4 m/s range in order to prevent variation within trials for the individual dog. Trials were excluded if the handler and dog were not moving at the same pace, the velocity or acceleration was outside of the acceptable range, the dog pulled on the leash while trotting, or the dog's head movement was not held constant or was excessive. The dogs were trotted down the track 3 to 5 times before data collection to allow the dogs to acclimate to the laboratory, marker attachment, and walkway setting. Subjects were trotted through the capture window until five successful trials were captured or until the dog was too exhausted to continue. Several minutes, usually 3-5 minutes, of rest were allowed between acclimation to the lab setting and between trials as needed. For the control group, trials were considered successful when each force platform had valid paw strikes from a front paw followed by the ipsilateral hind paw and the velocities and accelerations were within the acceptable ranges. Paw strikes were considered valid when the full paw landed on one platform and the overlap in vertical ground reaction force tracings between the first paw leaving the platform and the second paw landing on the platform was less than 25 N (Figure 3.3).

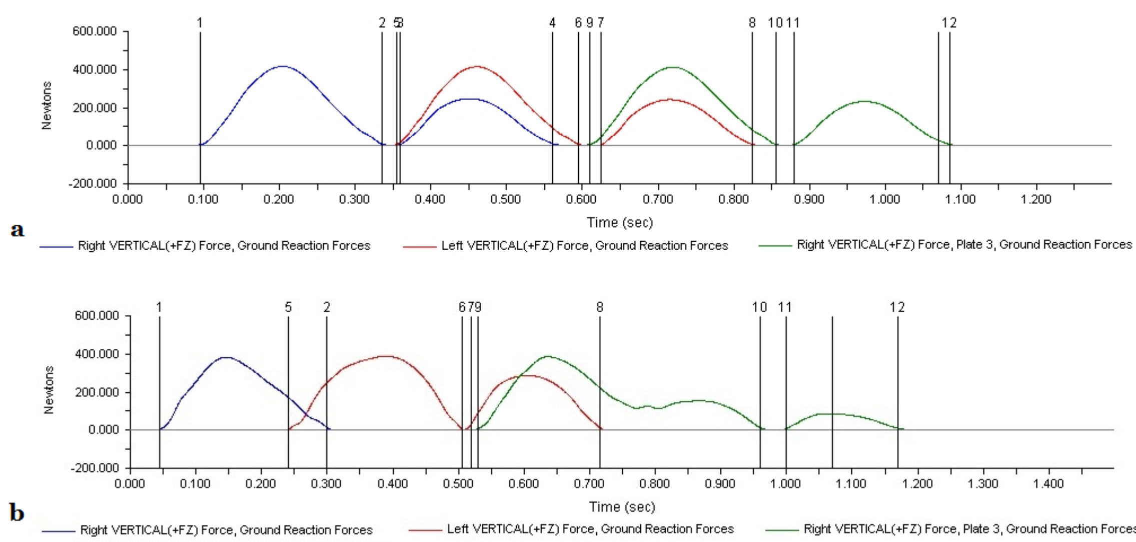

Figure 3.3 (a) Valid kinetic trials with no overlap in paw strikes and each paw hit one platform. (b) Invalid kinetic trials with more than 25 N of overlap between the first paw leaving the platform and the second paw landing on the platform. In this case, there is overlap between the first and second paw strikes on the third plate as seen by the first green parabola.

Gait Parameter Definitions

The stance phase is defined as the period of time during which the paw is in contact with the force platform. The swing phase is defined as the period of time between paw off and paw strike of the ipsilateral limb. In this study, swing phase is not considered due to a lack of usable data. Stride lengths are defined as the cranio-caudal distance between the initiation of the stance phase and the conclusion of the swing phase for a given paw based on the locations of the centers of pressure on the force platforms. Stance widths were determined by taking the lateral distance in the medial-lateral direction between the center of pressure of each thoracic paw and the ipsilateral scapula marker, and between the center of pressure of each pelvic paw and the ipsilateral ilium marker. Joint angles for the limbs and spine were calculated using the locations of the joint markers (Figure 3.4).

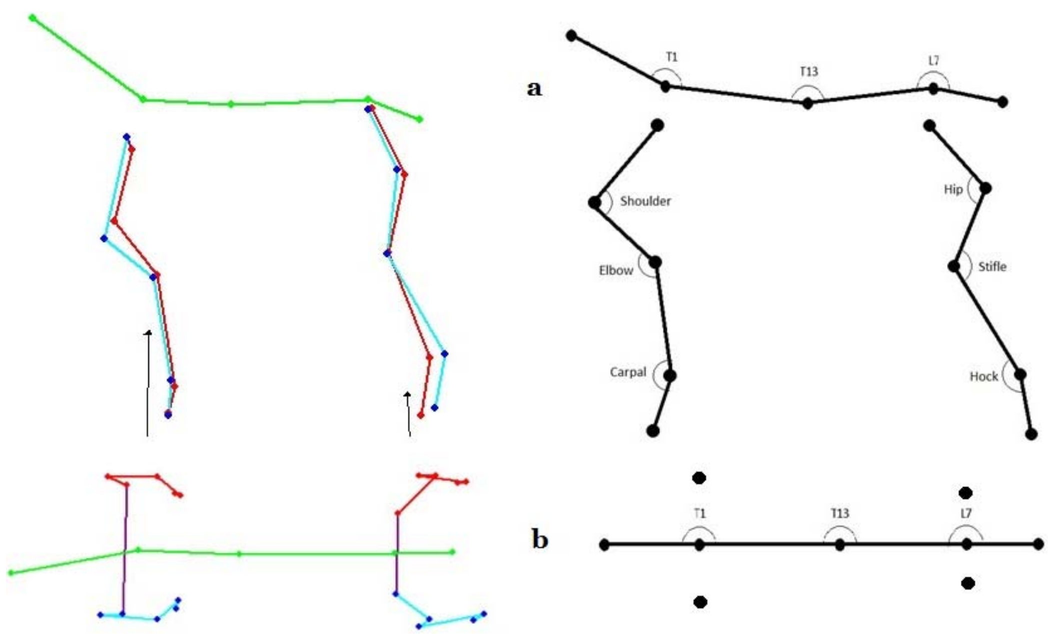

Figure 3.4 Regional spinal angles were calculated from spinal markers in both the sagittal (a) and horizontal (b) planes. Thoracic limb and pelvic limb joint angles were calculated using markers placed on bony landmarks.

Limb joint angles and regional spinal motion were all calculated using the markers placed on palpable bony landmarks. Hip angles were measured using the angle of the iliac crest, greater trochanter, and lateral femoral condyle markers of the pelvic limb. Stifle angles were measured based on the greater trochanter, lateral femoral condyle, and lateral malleolus of the fibula markers. Hock angles were calculated using the lateral femoral condyle, lateral malleolus of the fibula, and lateral fifth metatarsal bone markers of the pelvic limb. Shoulder angles were calculated using the scapula marker, greater tubercle of the humerus, and lateral epicondyle of the humerus markers. Elbow angles were calculated using the greater tubercle of the humerus, lateral epicondyle of the humerus, and ulnar styloid process markers. Carpus angles were calculated using the lateral epicondyle of the humerus, ulnar styloid process, and fifth metacarpal bone markers. Markers placed along the spine were used to calculate regional spine motion between the markers. Angular movements about the T1 marker represent the overall spinal motion between the occiput and T13 markers. Similarly, angular movements about the T13 marker reflect the overall spinal motion between the T1 and L7 markers. Angular movements about the L7 markers represent the overall spinal motion between the T13 and sacrum markers.

A joint angle of 180 degrees was considered full extension and an increase in the limb joint angle indicated extension. A decrease in limb joint angle indicated flexion. At the spine, full extension is also defined as 180 degrees. In the sagittal plane, an increase in joint angle indicates flexion, while a decrease in joint angle indicates extension. In the horizontal plane, an increase in joint angle represents left lateral bending and a decrease in joint angle represented a right lateral bending. In order to compare the joint angles in the horizontal plane between left and right side pelvic limb amputees, the horizontal joint angles for all left side amputees were subtracted from 360 degrees. For each joint angle, the mean, standard deviation, maximum, minimum, and range (maximum minus minimum) were calculated during the stance phase. In addition to kinematics, peak vertical, braking, and propulsive ground reaction forces as well as vertical, braking and propulsive impulses were extracted from the force platform data for each paw strike. Peak propulsive and peak braking forces are the maximum and minimum values, respectively, of the ground reaction force in the cranio-caudal direction (Figure 3.5). The braking forces and impulses are described using negative values to indicate the negative direction of the force. A minimum of three trials were averaged for each dog to create representative values, followed by pooling within groups to obtain respective group values. All forces and impulses were normalized by percent body mass for comparison.

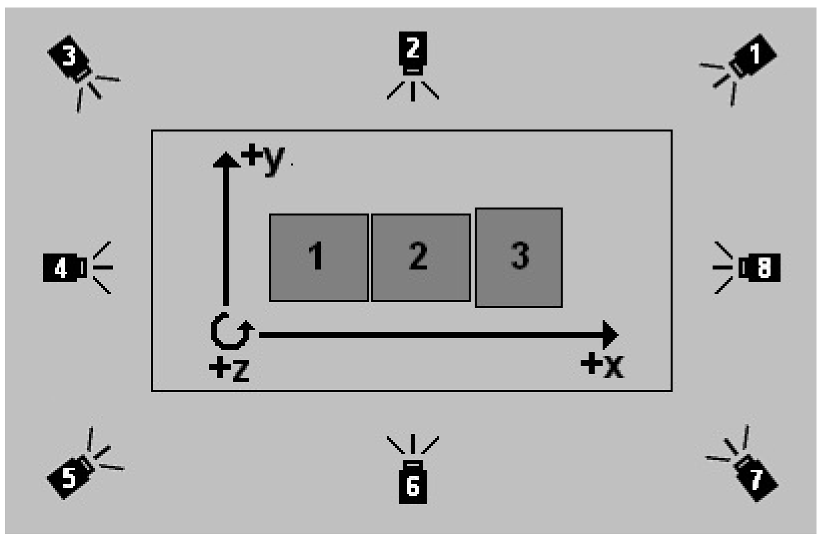

Figure 3.5 Vertical ground reaction forces represent the force in the positive z-direction. Braking and propulsion forces describe the direction of the force in the x-direction; braking is in the negative x-direction and is therefore described using negative values.

Statistics

Descriptive statistics were calculated for age, height, and mass of the dogs within the control and amputee groups. Values for each parameter were compared between amputee and control groups using independent t-tests. Bonferroni post hoc adjustments were made to counteract any error due to multiple comparisons by calculating a new pairwise alpha to maintain a familywise alpha value of 0.05. Differences for age, height, and mass were considered significant for P<0.05/n where n=3 (P=0.0167). The mean ± standard deviation values were used as the main comparison for each parameter. Abnormalities in the joints of the two groups were compared qualitatively using clinical descriptions from physical examination findings prior to gait analysis.

For the control group, the left and right side joint angles and ground reaction forces were determined to have no significant differences using repeated measures t-tests (P>0.05/n; n=4, P=0.0125, accounting for maximum, minimum, average, and range values of each variable) and therefore the thoracic limbs and the pelvic limbs were pooled to obtain representative values for each parameter for a control thoracic limb and a control pelvic limb, respectively. The majority of the data for each parameter in each group was found to have a normal distribution using the Shapiro-Wilk test. Each limb amputee parameter was then compared against the control values using independent t-tests. In addition, the contralateral and ipsilateral limbs in the amputees were compared using repeated measures t-tests to determine significant differences. Limb and spinal kinematic variables with an average, maximum, minimum, and range, and were considered significant for P<0.05/n where n=4 (P=0.0125). Peak ground reaction forces with vertical, braking, and propulsion components were significant for P<0.05/n where n=3 (P=0.0167). Similarly, time to peak ground reaction force for vertical, braking and propulsion components were significant for P<0.05/n where n = 3 (P=0.0167). Kinetic impulses with vertical, braking and propulsion components were also considered significant for P<0.05/n where n = 3 (P=0.0167). Stance durations, stride lengths, stance widths, and velocity were considered significant for P<0.05/n where n=4 (P=0.0125).

RESULTS

Dog Population

The control group consisted of 24 four-legged dogs (Table 4.1). There were 27 control dogs enrolled in the study; however, one dog could not acclimate to the lab, one had too much hair to be able to use markers, and one dog could not reach an appropriate speed to be included in the study. The amputee group consisted of 12 pelvic limb amputees with limbs removed for various types of cancer, 7 left pelvic limb and 5 right pelvic limb amputees (Table 4.2). There were 13 pelvic limb amputees enrolled in the study; however, one dog could not be used due to an invalid data collection. Age, height, and mass were not significantly different between the two groups (P > = 0.095). The physical examination findings showed abnormalities in the joints of the limbs and spine in 19 of 24 (79%) control dogs (Figure 4.1) and 10 of 12 (83%) amputees (Figure 4.2). Abnormalities of the joints included thickened joints, decreased range of motion, and discomfort upon forced flexion or extension (Appendix II).

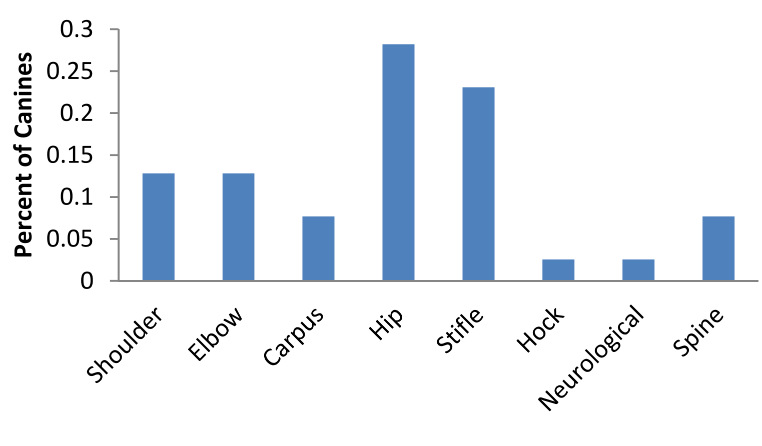

Figure 4.1 Physical examination findings in joints of the limbs and spine, as well as neurologic concerns as percent of total group for control group.

Table 4.1 Characteristics of control group.

Dog	Breed	Age (yrs)	Height (in)	Mass (kg)	Gait Pattern
C1	Labrador Retriever	1	23.5	21.1	Normal
C2	Mixed Breed	2	24	64	Normal
C3	American Bulldog	3	25	37.8	Normal
C4	Mixed Breed	3	25.5	38.3	Normal
C5	Rottweiler	3	N/A	32.7	Normal
C6	Labrador Retriever	4	22.5	32	Normal
C7	Golden Retriever	4	24	30	Normal
C8	Labrador Retriever	4	22.5	29.3	Normal
C9	Staforsdshire Terrier	5	21.5	28.6	Normal
C10	German Pointer	5	24	14.6	Normal
C11	Weimaraner	6	21	24.4	Normal
C12	Labrador Retriever	6	27.5	39.8	Normal
C13	Border Collie	6	23.5	20	Normal
C14	Labrador Retriever	7	21	33.2	Normal
C15	Mixed Breed	7	20	25.7	Normal
C16	Bull Mastiff	7	24	43.5	Normal
C17	Dalmatian	8	21.5	25.1	Normal
C18	German Shepherd	8	24	33.9	Carriage of pelvis lower to ground
C19	Mixed Breed	9	23	37.1	Normal
C20	Mixed Breed	9	22.5	34.3	Normal
C21	Mixed Breed	10	20.5	28.7	Slightly shortened stride in pelvic limb
C22	Great Dane	10	21.5	27.7	Normal
C23	Labrador Retriever	12	22.5	34.3	Mild bilateral pelvic limb lameness causing stiff gait
C24	Golden Retriever	12	30.5	50.9	Normal
	Average	6.31	23.3	32.8	
	Standard Deviation	3.08	2.35	10.3	
	Maximum	12.3	30.5	64.0	
	Minimum	1.01	20.0	14.6	
	Range	11.3	10.5	49.4	

C indicates control dog
N/A indicates data that was not recorded during gait analysis

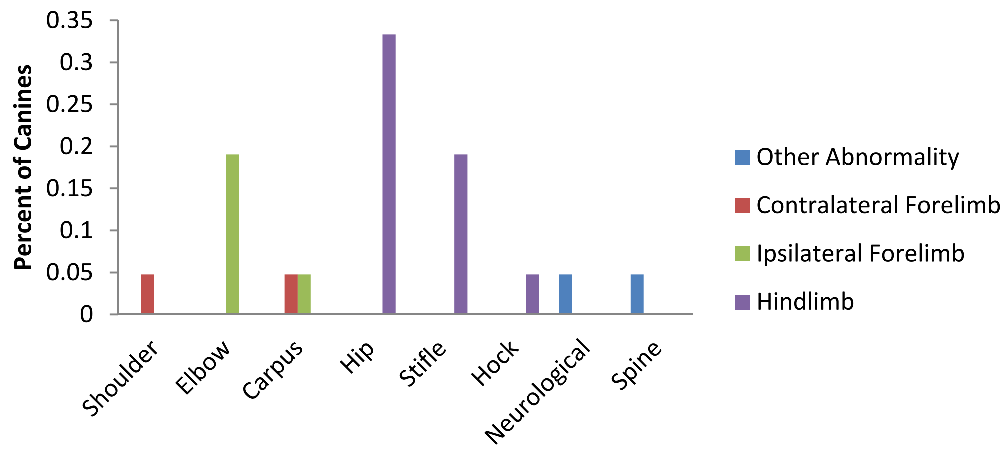

Figure 4.2 Physical examination findings in the joints of the limbs and spine, as well as neurologic concerns as percent of total group for amputee group.

Table 4.2 Characteristics of pelvic limb amputee group.

Dog	**Breed**	**Age (yrs)**	**Height (in)**	**Mass (kg)**	**Time since Amputation (months)**	**Reason for Amputation**
L1	Saint Bernard	5	29	41.1	2.01	Osteosarcoma
L2	Labrador Retriever	6	25	34.1	3.95	Histiocytic sarcoma
L3	Greyhound	8	26	23.3	1.18	Osteosarcoma
L4	Siberian Husky	9	23	25.2	5.82	Osteosarcoma
L5	Golden Retriever	9	23	24	3.12	Soft tissue sarcoma
L6	Mixed Breed	10	22	20.2	3.29	Osteosarcoma
L7	Mixed Breed	11	20.5	22.6	4.44	Anaplastic sarcoma
R1	Staffordshire Terrier	5	N/A	25.1	1.12	Osteosarcoma
R2	Golden Retriever	7	24	38.9	1.58	Osteosarcoma
R3	Saint Bernard	7	31	53	3.45	Osteosarcoma
R4	Labrador Retriever	9	21.5	25.4	4.04	Osteosarcoma
R5	Labrador Retriever	10	24	36.1	1.97	Osteosarcoma
	Average	8.00	24.5	30.8	3.00	
	Standard Deviation	2.00	3.18	9.90	1.45	
	Maximum	11.5	31.0	53.0	5.82	
	Minimum	5.22	20.5	20.2	1.12	
	Range	6.28	10.5	32.8	4.70	

L indicates left pelvic limb amputee
R indicates right pelvic limb amputee
N/A indicates data that was not recorded during gait analysis

Velocity and Limb Position

Average trotting velocities were not significantly different between amputee and control groups (2.25 ± 0.19 m/s and 2.29 ± 0.15 m/s, respectively; P = 0.520). There were no significant differences in stance duration (P > = 0.042) for all limbs of the amputees compared to control dogs (Table 4.3). In addition, there were no significant differences in stride length or stance width (P > = 0.060) for all limbs of the amputees compared to those of control dogs (Table 4.3). No significant differences were found in stance duration, stance width, or stride length (P > = 0.647) for the contralateral thoracic limb compared to the ipsilateral thoracic limb in the amputee group (Table 4.3).

Table 4.3 Stance duration and stride length for amputee and control groups.

	Stance Duration (s)	Stance Width (m)	Stride Length (m)
Control Pooled Thoracic limb	0.234 ± 0.027	0.055 ± 0.028	1.155 ± 0.098
Amputee Contralateral Thoracic limb	0.248 ± 0.081	0.061 ± 0.042	1.128 ± 0.098
Amputee Ipsilateral Thoracic limb	0.238 ± 0.086	0.061 ± 0.016	1.253 ± 0.157
Control Pooled Pelvic limb	0.197 ± 0.022	0.025 ± 0.028	1.125 ± 0.091
Amputee Contralateral Pelvic limb	0.175 ± 0.037	0.004 ± 0.030	1.145 ± 0.133

*No significant differences between amputee and control groups or within amputee group (p<0.05/n; n=3)

Ground Reaction Forces and Impulses

All limbs of the amputee group carried significantly more weight (P < = 0.001) than the limbs of the control dogs (Table 4.4). There was no significant difference in the amount of weight bearing (P = 0.303) between the contralateral and ipsilateral thoracic limbs.

Table 4.4 Body weight distributions for pelvic limb amputees and controls based on peak vertical ground reaction forces of each limb compared to total vertical ground reaction forces of all limbs combined.

	Body Weight Support (% Total Peak Vertical GRF)
Control Pooled Thoracic limb	30.4 ± 2.1
Amputee Contralateral Thoracic limb	35.8 ± 2.2*
Amputee Ipsilateral Thoracic limb	37.1 ± 2.6*
Control Pooled Pelvic limb	19.7 ± 2.1
Amputee Contralateral Pelvic limb	27.1 ± 3.1*

*Indicates a significant difference between amputee and control groups (p<0.05/n; n=3)
**No significant differences within amputee group (p<0.05/n; n=3)

Peak vertical ground reaction force (GRF) was significantly greater in the remaining pelvic limb of amputees (P = 0.004) compared to the peak vertical force of control pelvic limbs (Table 4.5). In addition, peak braking force was significantly greater in the contralateral thoracic limb (P = 0.012) than in control dogs and peak propulsion force was significantly greater in both the ipsilateral thoracic limb and the remaining pelvic limb (P < = 0.013) as compared to the control dogs (Table 4.5). Time to peak braking force was significantly decreased in all limbs of the amputees (P < = 0.002) compared to the control dogs. In addition, the time to peak propulsion was significantly greater in all limbs of the amputees (P < = 0.012) as compared to the control dogs (Table 4.6). There were no significant differences in peak ground reaction forces or time to peak ground reaction forces (P > = 0.153) between the contralateral and ipsilateral thoracic limbs (Table 4.5 and 4.6).

Table 4.5 Peak ground reaction forces (mean ± SD) for pelvic limb amputees, compared to controls.

	Peak Vertical GRF (N/BW %)	Peak Braking GRF (N/BW %)	Peak Propulsion GRF (N/BW %)
Control Pooled Thoracic limb	113.6 ± 16.4	-15.7 ± 2.8	9.2 ± 3.4
Amputee Contralateral Thoracic limb	117.5 ± 16.7	-19.2 ± 4.8*	10.6 ± 3.5
Amputee Ipsilateral Thoracic limb	126.3 ± 14.0	-17.6 ± 4.3	12.3 ± 2.6*
Control Pooled Pelvic limb	74.1 ± 16.1	-5.5 ± 2.3	10.8 ± 3.8
Amputee Contralateral Pelvic limb	92.3 ± 13.9*	-8.5 ± 4.7	16.8 ± 5.3*

*Indicates a significant difference between control and amputee groups (p<0.05/n; n=3)
**No significant differences within amputee group (p<0.05/n; n=3)

Table 4.6 Time to peak ground reaction forces (mean ± SD) for pelvic limb amputees, compared to controls.

	Time to Peak Vertical GRF (s)	Time to Peak Braking GRF (s)	Time to Peak Propulsion GRF (s)
Control Pooled Thoracic limb	0.11 ± 0.02	0.13 ± 0.04	0.11 ± 0.04
Amputee Contralateral Thoracic limb	0.13 ± 0.04	0.08 ± 0.03*	0.19 ± 0.08*
Amputee Ipsilateral Thoracic limb	0.12 ± 0.04	0.08 ± 0.03*	0.17 ± 0.07*
Control Pooled Pelvic limb	0.09 ± 0.01	0.08 ± 0.03	0.07 ± 0.03
Amputee Contralateral Pelvic limb	0.09 ± 0.01	0.03 ± 0.03*	0.11 ± 0.04*

*Indicates a significant difference between control and amputee groups (p<0.05/n; n=3)
**No significant differences within amputee group (p<0.05/n; n=3)

The propulsion impulses of both the ipsilateral thoracic limb and remaining pelvic limb of amputees were significantly greater (P < = 0.014) than that of control dogs (Table 4.7). Additionally, the vertical impulses of both the contralateral thoracic limb and the remaining pelvic limb of amputees were significantly higher (P < = 0.015) than control dogs (Table 4.7). Impulses of the contralateral and ipsilateral thoracic limbs of amputees were not significantly different (P > = 0.029) (Table 4.7).

Table 4.7 Impulses (mean ± SD) for all limbs of amputees and controls.

	Vertical Impulse (Ns/BW %)	Braking Impulse (Ns/BW %)	Propulsion Impulse (Ns/BW %)
Control Pooled Thoracic limb	15.5 ± 3.1	-1.2 ± 0.2	0.5 ± 0.3
Amputee Contralateral Thoracic limb	19.4 ± 5.8*	-1.6 ± 0.9	0.6 ± 0.5
Amputee Ipsilateral Thoracic limb	18.8 ± 5.7	-1.4 ± 0.7	0.9 ± 0.4*
Control Pooled Pelvic limb	8.8 ± 2.1	-0.2 ± 0.1	0.9 ± 0.4
Amputee Contralateral Pelvic limb	10.8 ± 1.7*	-0.1 ± 0.1	1.3 ± 0.5*

* Indicates a significant difference between control and amputee groups (p<0.05/n; n=3)
**No significant differences within amputee group (p<0.05/n; n=3)

Limb Angular Kinematics

The shoulder, elbow, and carpal joints of the contralateral thoracic limb had no significant differences in maximum or minimum joint angle or range of motion (P > = 0.021) from control group (Table 4.8). Similarly, the same joints of the ipsilateral thoracic limb were not significantly different in range of motion or maximum or minimum joint angle (P > = 0.048) as compared to controls (Table 4.8). Also, there were no significant differences in the thoracic limb joints (P > = 0.037) between the contralateral and ipsilateral thoracic limbs of amputees (Table 4.8).

Table 4.8 Sagittal plane joint angles (mean ± SD) of thoracic limbs of control group compared to contralateral and ipsilateral thoracic limbs of pelvic limb amputee group.

Joint	Thoracic limb	Avg (°)	Max (°)	Min (°)	ROM (°)
Shoulder	Pooled Control	135.0 ± 12.9	152.2 ± 13.1	126.2 ± 13.2	26.0 ± 6.9
	Amputee Contralateral	143.3 ± 9.9	155.2 ± 11.9	132.8 ± 9.4	22.3 ± 9.4
	Amputee Ipsilateral	131.6 ± 14.1	148.3 ± 13.1	122.1 ± 15.3	26.1 ± 11.2
Elbow	Pooled Control	138.7 ± 12.0	156.4 ± 12.3	123.0 ± 12.9	33.3 ± 8.6
	Amputee Contralateral	138.7 ± 9.6	155.1 ± 10.6	124.1 ± 9.8	31.1 ± 9.5
	Amputee Ipsilateral	140.1 ± 11.4	155.6 ± 8.9	124.5 ± 15.4	31.1 ± 9.1
Carpus	Pooled Control	148.4 ± 10.0	170.0 ± 7.7	133.1 ± 13.5	37.0 ± 10.7
	Amputee Contralateral	143.4 ± 9.7	168.8 ± 7.1	127.4 ± 14.0	41.4 ± 16.4
	Amputee Ipsilateral	140.4 ± 11.4	167.6 ± 5.7	120.6 ± 16.7	47.0 ± 14.7

*No significant differences between amputee and control groups (p<0.05/n; n=4)
**No significant differences within amputee group (p<0.05/n; n=4)

In the remaining pelvic limb of amputees, the hock joint had significantly greater range of motion (P = 0.012) than those of control dogs (Table 4.8). Range of motion at the hip and stifle joints were not significantly different (P > = 0.113) than control group (Table 4.9).

Table 4.9 Sagittal plane joint angles (mean ± SD) of pelvic limbs of control group compared to remaining pelvic limb of amputees.

Joint	Pelvic limb	Avg (°)	Max (°)	Min (°)	ROM (°)
Hip	Pooled Control	112.1 ± 10.3	124.5 ± 10.2	100.6 ± 9.6	23.9 ± 4.0
	Amputee Contralateral Pelvic limb	120.5 ± 11.4	133.5 ± 11.0	107.3 ± 14.2	26.2 ± 8.8
Stifle	Pooled Control	127.8 ± 10.9	144.5 ± 10.8	119.8 ± 11.9	24.8 ± 5.1
	Amputee Contralateral Pelvic limb	127.0 ± 12.9	145.8 ± 11.6	117.2 ± 14.9	28.7 ± 8.2
Hock	Pooled Control	131.2 ± 9.6	156.9 ± 8.2	112.9 ± 9.7	44.1 ± 5.9
	Amputee Contralateral Pelvic limb	124.7 ± 12.0	157.5 ± 7.3	104.1 ± 17.0	53.3 ± 14.0*

* Indicates a significant difference between amputee and control groups (p<0.05/n; n=4)
**No significant differences within amputee group (p<0.05/n; n=4)

Spine Angular Kinematics

There were no significant differences found in the maximums, minimums, or range of regional angular motion in the horizontal plane about the T1 or T13 markers of the amputees during thoracic limb or pelvic limb stance (P > = 0.032) as compared to the control dogs (Table 4.10). About the L7 marker, there was a significant increase in the maximum angle in the horizontal plane during ipsilateral thoracic limb stance (P = 0.010). Additionally, the average and minimum values for the regional angular motion about the L7 marker in the horizontal plane were significantly higher during ipsilateral thoracic limb stance (P < = 0.008) than during contralateral thoracic limb stance [Table 4.10).

Table 4.10 Joint angle measurements (mean ± SD) for the spine in the horizontal plane during thoracic limb and pelvic limb stance for amputees compared to controls.

Site	Limb	Avg (°)	Max (°)	Min (°)	ROM (°)
T1	Control Pooled Thoracic limb	183.0 ± 10.5	190.0 ± 10.7	175.7 ± 11.4	16.2 ± 9.1
	Amputee Contralateral Thoracic limb	189.1 ± 22.6	199.3 ± 20.1	175.7 ± 25.0	23.6 ± 12.0
	Amputee Ipsilateral Thoracic limb	183.8 ± 18.0	196.1 ± 16.3	174.2 ± 20.6	21.9 ± 11.6
	Control Pooled Pelvic limb	184.1 ± 11.2	190.5 ± 11.4	177.9 ± 11.4	12.6 ± 5.8
	Amputee Contralateral Pelvic limb	183.0 ± 19.0	193.0 ± 17.5	175.5 ± 20.2	17.5 ± 8.9
T13	Control Pooled Thoracic limb	179.2 ± 7.37	188.2 ± 8.7	169.8 ± 6.9	18.4 ± 7.3
	Amputee Contralateral Thoracic limb	173.6 ± 10.4	185.3 ± 11.2	163.3 ± 9.4	21.9 ± 10.5
	Amputee Ipsilateral Thoracic limb	173.7 ± 9.53	183.5 ± 9.3	162.9 ± 11.5	20.6 ± 7.8
	Control Pooled Pelvic limb	179.2 ± 7.01	187.5 ± 8.3	170.7 ± 6.6	16.8 ± 6.4
	Amputee Contralateral Pelvic limb	175.1 ± 11.1	182.8 ± 10.5	164.4 ± 11.0	18.4 ± 5.4
L7	Control Pooled Thoracic limb	180.0 ± 7.55	185.6 ± 7.2	174.8 ± 8.64	10.9 ± 4.9
	Amputee Contralateral Thoracic limb	**185.8 ± 12.9	193.3 ± 14.2	**179.6 ± 11.4	13.8 ± 5.9
	Amputee Ipsilateral Thoracic limb	**188.5 ± 13.3	195.9 ± 14.9*	**181.4 ± 13.1	14.5 ± 8.9
	Control Pooled Pelvic limb	178.8 ± 10.7	184.0 ± 9.8	173.8 ± 11.6	10.3 ± 5.1
	Amputee Contralateral Pelvic limb	189.2 ± 15.2	195.3 ± 16.3	183.0 ± 13.2	12.3 ± 7.1

*Indicates a significant difference between amputee and control groups (p<0.05/n; n=4)
**Indicates a significant difference within amputee group (p<0.05/n; n=4)

In the sagittal plane, there was a significant increase in the range of regional angular motion about both the T1 and T13 markers during both thoracic limb and pelvic limb stance (P < = 0.003). In addition, there was a significant increase in the maximum angle about the L7 marker causing increased flexion in the amputee spine during contralateral thoracic limb stance (P < 0.001). In amputees, there were significantly greater maximum and minimum angles about the L7 marker during thoracic limb stance for the contralateral limb (P < = 0.003) as compared to the ipsilateral limb indicating greater flexion and decreased extensionion of the spine about the L7 marker (Table 4.11). Also, the minimum joint angle about the T13 marker is significantly greater in the contralateral thoracic limb (P = 0.009) compared to the ipsilateral thoracic limb in amputees indicating greater extension of the spine about the T13 marker while the ipsilateral thoracic limb was in stance phase (Table 4.11).

Table 4.11 Joint angles (mean ± SD) for regional spinal motion within the sagittal plane during thoracic limb and pelvic limb stance for amputees, compared to controls.

Site	Limb	Avg (°)	Max (°)	Min (°)	ROM (°)
T1	Control Pooled Thoracic limb	178.3 ± 5.5	181.8 ± 5.6	174.1 ± 5.7	7.7 ± 2.6
	Amputee Contralateral Thoracic limb	**172.0 ± 15.9	177.9 ± 16.1	165.6 ± 15.3	12.3 ± 5.8*
	Amputee Ipsilateral Thoracic limb	**178.1 ± 15.5	183.0 ± 14.4	170.3 ± 15.9	12.7 ± 4.4*
	Control Pooled Pelvic limb	178.1 ± 5.3	181.0 ± 5.3	174.0 ± 5.5	6.9 ± 1.8
	Amputee Contralateral Pelvic limb	177.4 ± 16.1	182.0 ± 15.6	170.4 ± 17.0	11.6 ± 3.5*
T13	Control Pooled Thoracic limb	176.2 ± 5.3	179.7 ± 5.2	173.2 ± 5.8	6.5 ± 1.8
	Amputee Contralateral Thoracic limb	188.7 ± 8.8*	194.6 ± 8.7*	**183.8 ± 9.1*	10.8 ± 5.0*
	Amputee Ipsilateral Thoracic limb	186.5 ± 8.6*	192.3 ± 7.9*	**181.3 ± 9.9*	11.0 ± 4.7*
	Control Pooled Pelvic limb	175.7 ± 5.2	179.0 ± 5.1	173.1 ± 5.5	5.9 ± 1.4
	Amputee Contralateral Pelvic limb	185.4 ± 8.9*	191.7 ± 7.8*	181.1 ± 9.2*	10.7 ± 4.1*
L7	Control Pooled Thoracic limb	195.4 ± 3.3	200.1 ± 4.0	191.5 ± 4.0	8.7 ± 4.0
	Amputee Contralateral Thoracic limb	**202.1 ± 5.9*	**207.4 ± 5.7*	**195.8 ± 8.3	11.6 ± 7.1
	Amputee Ipsilateral Thoracic limb	**198.1 ± 6.3	**204.2 ± 6.8	**191.9 ± 9.4	12.3 ± 7.4
	Control Pooled Pelvic limb	194.7 ± 3.5	199.0 ± 3.9	191.0 ± 4.1	8.0 ± 0.4
	Amputee Contralateral Pelvic limb	192.2 ± 15.9	198.0 ± 15.4	187.5 ± 17.0	10.5 ± 7.7

* Indicates a significant difference between amputee and control groups (p<0.05/n; n=4)
**Indicates a significant difference within amputee group (p<0.05/n; n=4)

DISCUSSION

The purpose of this study was to examine compensatory strategies adopted by dogs after pelvic limb amputation through examination of limb and spinal kinematics and ground reaction forces. Understanding mechanisms by which pelvic limb amputees adapt to the loss of a limb is critically important clinically in determining why some dogs adapt better than others. In this study, it was determined that pelvic limb amputees displayed several compensation strategies, that included increased range of motion of the hock, changes in the spinal kinematics within the sagittal plane, as well as changes in peak ground reaction forces (to include weight distribution) and the propulsion impulse in both the ipsilateral thoracic limb and the remaining pelvic limb that allowed the pelvic limb amputees to function well with the three remaining limbs.

Ground Reaction Force Kinetics

Following limb amputation, pelvic limb amputees must redistribute their body weight to maintain proper stability and balance. This study found that pelvic limb amputees adjust by supporting 73 percent of the weight with their thoracic limbs and 22 percent of their weight on their remaining pelvic limb. These results are similar to those found by Kirpensteijn et al (2000) [10]. In addition, the amount of weight supported by the contralateral and ipsilateral thoracic limbs are equal, which would indicate that the ground reaction forces of the two thoracic limbs should be similar.

Alterations in the kinetics of pelvic limb amputee gait have been described previously by Kirpensteijn et al [10]. According to that study, pelvic limb amputees adjust to the loss of a limb by decreasing the amount of propulsive forces and impulses in both thoracic limbs. In our study, amputees had increased peak propulsion force and impulse in both the ipsilateral thoracic limb and the remaining pelvic limb. The previous study also showed a decrease in the vertical impulse of all limbs in pelvic limb amputees; however, this study showed an increase in the vertical impulse of the contralateral thoracic limb as well as the remaining pelvic limb. Also, this study indicated increased peak braking force in the ipsilateral thoracic limb and increased vertical ground reaction force in the pelvic limb, neither of which were apparent in the previous study [10]. Time to peak braking force was decreased in all limbs of amputees in this study, while the study by Kirpensteijn, et al. found decreased time in the pelvic limb only, with increased time to peak braking force in both thoracic limbs. Additionally, our study found increased time to peak propulsion force in all limbs, while the previous study found no change in amputees as compared to controls.

Differences between the two studies could be due to sample size; our study had 12 amputees and 24 controls, while the Kirpensteijn study had only 5 amputees and 22 controls [10]. The control population of the Kirpensteijn study was comprised of all Labrador Retrievers ranging in mass from 25 to 39 kg with a median of 32 kg, while the control population of this study was comprised of various breeds ranging in mass from 14.6 to 64.0 kg and a median of 32.4 kg [10]. Amputee populations of both groups were of various breeds and weight distributions of 25.0 to 39.2 kg with a median of 31.0 kg in the Kirpensteijn study and 20.2 to 53.0 kg with a median of 25.3 kg in this study [10]. While the size differences should have been accounted for by normalizing the forces in both studies, differences in breed could affect gait GRF kinetics causing the two studies to have different results [28]. Also, the amputees studied in the Kirpensteijn study had no other orthopedic abnormalities in the remaining limbs, while many of the amputees in our study did. Other orthopedic abnormalities in the remaining limbs of the amputees could potentially cause the dogs to adjust differently to the amputation and therefore have different gait kinetics. One of the biggest differences in the two studies is that the dogs in the Kirpensteijn study were walked across the force platforms, while the dogs in this study were trotted across the force platforms. Studies on the impact of velocity on ground reaction forces in dogs show that there is a significant increase in peak vertical and peak braking ground reaction forces as velocity increases [25]. Additionally, vertical impulses as well as propulsion impulses decrease with increased velocity, while braking impulses consistently increase [25]. Therefore, the differences in speed could be a large reason for the differences between the two studies as the increased speed would increase the ground reaction forces needed in the limbs to maintain speed and clear the limbs. Though there are various differences between the studies, comparing the results could potentially give an indication of how ground reaction forces of pelvic limb amputees change when velocity increases as well as if the population of interest changes. Also, it could give an indication of the adaptations of our group of amputees that could be masked by the comparison to a control group with orthopedic abnormalities.

Joint Angular Kinematics

While there are various changes in the ground reaction forces of pelvic limb amputee gait as compared to the control group, there was only one significant change in the limb kinematics. Amputees had increased joint range of motion in the hock joint of the remaining limb. This is most likely a compensation strategy used to get the limb off the ground faster based on increased cadence of amputees found in previous studies [10]. The joint has slightly increased flexion in order to load the joint more effectively due to increased weight supported by the pelvic limb after amputation. Because the limb kinematics of pelvic limb amputees are so similar to that of the control dogs, it is likely that limb amputees do not compensate for the loss of a limb by changing their joint angular kinematics, but through other compensation strategies involving changes in ground reaction forces and spinal kinematics.

There were several changes in the spinal kinematics in both the horizontal and sagittal planes. In the horizontal plane, the regional angular motion about L7 marker is the only area of the spine that had a change in motion as compared to controls, indicating that the loss of a pelvic limb induces more motion in the hind quarters of dogs. Increased extension at about the L7 marker during ipsilateral thoracic limb stance indicates that the remaining pelvic limb is moving away from the center of the body at that time. If the remaining pelvic limb is moving away from the body, it would extend the spine beyond the L7 marker toward the limb, increasing the angle about the L7 marker. Also, increased extension about the L7 marker could indicate that the epaxial muscles are more active on the side contralateral pelvic limb, flexing the spine laterally toward the contralateral side. Slightly increased average angle about the L7 marker during ipsilateral thoracic limb stance than during contralateral thoracic limb stance would indicate that the remaining pelvic limb is further away from the center of the body during ipsilateral thoracic limb stance than contralateral thoracic limb stance.

In the sagittal plane, the increased range of regional angular motion about the T1 and T13 markers during the stance phase for all limbs could indicate increased flexion of the head during trotting. The amputees appear to move the head up when propelling off the ground and then down at the termination of swing to help propel them forward. Studies on trotting horses have shown that lameness in one thoracic limb causes horses to lower their head during the stance phase of that limb to unload the limb in an effort to reduce the amount of pain in the limb [37]. Similarly, canine amputees experiencing pain in the thoracic limbs during stance may have more dorso-ventral motion in the head in an attempt to reduce that pain in thoracic limbs. Increased regional angular motion about the T13 marker is likely due to the overall changes in the regional motion about the T1 and L7 markers. Additionally, there is increased flexion about the L7 marker of amputees during the stance phase of both the contralateral and ipsilateral thoracic limbs as compared to the control population; this change is greater in the contralateral limb. Increased flexion could be due to greater motion and instability of the remaining pelvic limb. While in stance phase, the contralateral limb also has decreased maximum flexion about the L7 marker as compared to the ipsilateral limb, indicating that the muscles in the remaining pelvic limb are potentially more active while the contralateral thoracic limb is in stance phase, pulling on the spine and therefore creating more flexion at the joint. Over time this could potentially become a source of pain or discomfort in the dog as it could put stress on the ligaments and muscles that support the spine on the dorsal side potentially causing strained muscles [38]. If the muscle is stretched beyond normal capacity, there is increased force and tension produced that is beyond the isometric maximum [39]. The magnitude of the peak force created then correlates to the amount of muscle injury [39]. Therefore, increased flexion of the spine could potentially result in injuries from extended strain and use of dorsal muscles. Clinically, this could determine why some amputees adjust more successfully to amputation than others. If dogs had stiffness in the spine prior to amputation, these adaptations would be difficult to make and could therefore hinder the process of adapting properly to a three-legged gait.

Prior to gait analysis all dogs underwent a physical examination to determine underlying conditions present in the dogs that could potentially affect their gait. The physical exam findings found significant pain and abnormalities in the limbs; however, very few dogs had discomfort in the spine. Only one of the twelve amputees (5%) had pain in the spine, located at the L6/S1 region. Our study found significant differences in the canine spine after the amputation of a pelvic limb, which would contradict the findings of the physical examinations. As a result, it is likely that the compensation strategies found in the spine of amputees are not inducing obvious pain; however, the sample size in this study may be too small to make that an affirmative statement. Additionally, our results showed a significantly greater range of motion of the hock joint during stance in the remaining pelvic limb of the amputees, which was not represented by pain or abnormalities upon physical examination. Of the twelve amputees used in the study, only one appeared to have a decreased range of motion upon flexion and bony thickening at the joint. Overall, the areas which were highlighted as abnormal or painful during physical examination are not the areas of significant difference from the controls suggesting that the alterations of the spine and the hock joint may not physically affect the actual joint, but the joints proximal to the joint of interest that must absorb the changes. Four of the amputees had pain of the stifle joint and seven of them had pain of the hip joint of the remaining limb. Similarly, there were five of the amputees that expressed discomfort in the joints of the thoracic limbs, suggesting that although the limb kinematics of the thoracic limbs were not significantly different than those of the control population, the increased force on those limbs may still be impacting the joints in a negative way.

While every attempt was made to create the best experimental conditions for optimal results, there were still various limitations in this study. The study was limited to dogs undergoing treatment at the CSU Veterinary Teaching Hospital, making it difficult to have large populations for comparison. Also, dogs had to be of a certain weight and height range to be included in the study. Dogs had to be of a certain size in order for their paw strikes to register on the force platforms and for the retro-reflective markers to be deciphered using motion analysis software. One significant limitation of the study was the varying levels of activity within the amputee group. Because each dog had a different level of endurance and ability, it was difficult to maintain the same velocity for all dogs adding another layer of variability. As a result, each dog was trotted as close as possible to our 2.2-2.6 m/s velocity range while maintaining a velocity range of 0.4 m/s in order to prevent unnecessary experimental error. Also, not knowing the medical and drug histories of the dogs before doing gait analysis was a limitation as it could have changed the dog's normal range of motion or ability. Abnormal joints in either the control group or the amputee group could have potentially hid adaptations of the amputees to the loss of a limb. Additionally, because the study included client-owned dogs, markers were placed on the hair as close to the skin as possible. Therefore, measurements based on marker location will have slight error due to skin and hair movement artifacts during gait analysis [26].

Clinically, this information can be used in many ways to benefit the amputee population. Currently there are ways in which to classify the adaptation of amputees qualitatively based on the ease of motion and the range of activities amputees can complete; however, it would be valuable to use the information from this study to begin creating a set of quantitative measures to classify the dogs as well adapted or poorly adapted. Quantitative measures would give a definitive measure of the abilities of the dog and would be a better comparison than pure observation. Dogs unable to adapt the compensation strategies described above could potentially have difficulty adapting overall to the amputation. Also, deviations from the set of compensation strategies described by this study could indicate that the dogs are poorly adapted and are potentially creating compensation strategies that could be detrimental over time. Also, the information gathered through this study could be used to determine if there are conditions prior to amputation that would cause dogs to not adjust properly to the loss of a limb based on the compensation strategies observed in this study.

Future Directions

With this information, there are various other studies that could be completed to further the knowledge of canine amputees and their compensation strategies. While this study was limited to examining stance phase only, it would be interesting to do a similar study of the limb and spinal kinematics during the swing phase. In this study, swing phase was not of significant concern during data collection and as a result, there were not enough valid trials to do analysis on the swing phase of limb amputees. Observationally, it appears that most of the spinal motion occurs during the swing phase; therefore, having more information on what occurs during that time would further explain how amputees compensate for the loss of a limb. Additionally, inverse dynamics and musculoskeletal modeling of the individual joints of the limbs would allow us to determine the forces and moments acting directly on the joints rather than on the limb as a whole. This would also give information on how the muscles are impacting the motion of the joint through generation of moments about the joint, as well as the individual forces acting on the joints to determine potential areas of overuse and stress. Forces acting on the joint would not only include the muscles, it would also include bone on bone forces and ligament forces. Excessive loading at the joint will eventually cause degeneration of the articular cartilage leading to loss of joint motion, instability, or pain of the affected joint [40]. Also, electromyography used to monitor the muscle activity in the limbs and spine would confirm the various adaptations of the muscles suggested in this study. As a whole, these studies would provide the information needed to determine why there are some dogs that adapt more effectively to amputation than others. Eventually, this information could be used to determine a set of parameters to quantify what makes a dog well adapted to then be used to determine whether or not a dog will be able to successfully adapt to the loss of a limb.

CONCLUSION

Pelvic limb amputees have various compensations strategies that allow for the best possible adaptation to a three-legged gait. Of these strategies, the most prevalent are changes in the gait kinetics and spinal kinematics within the sagittal plane. Increased propulsion of the remaining limbs allows the dogs to maintain forward velocity and appropriate cadence in order to successfully ambulate. Additionally, increased spine extension helps the dogs propel themselves forward and to maintain stability. Combined, these compensation strategies allow for successful adaptation to a three-legged gait pattern after the loss of a pelvic limb.

REFERENCES

[1] The National Canine Cancer Foundation, "Osteosarcoma." (2011) Visited on October 3, 2011. http://www.wearethecure.org/osteosarcoma.htm

[2] Liptak, Julius M. et al. "Canine Appendicular Osteosarcoma: Curative-Intent Treatment." *Compendium on Continuing Education for the Practicing* Veterinarian (2004) 186-197.

[3] "Amputation." Comparative Oncology Unit, Animal Cancer Center Pamphlet, Colorado State University (2007).

[4] "Limb Sparing Procedure for Osteosarcoma Patients." Animal Cancer Center Pamphlet, Colorado State University (2009).

[5] Carberry, C.A. and Harvey, H.J. "Owner Satisfaction with Limb Amputation in Dogs and Cats." *Journal of the American Animal Hospital Association* (1987) 23, 227-232.

[6] Kirpenstijn, J., van den Bos, R., and Endenburg, N. "Adaptation of Dogs to the Amputation of a Limb and Their Owners' Satisfaction with the Procedure." *The Veterinary Record* (1999) 144, 115-118.

[7] Marcellin-Little, Denis. "Managing Osteoarthritis – Everyone Gets Involved." College of Veterinary Medicine North Carolina State University, Raleigh, NC (2011). http://secure.aahanet.org/eweb/images/AAHAYC2011/pdfs/Marcellin-Little_ManagingOsteoarthritis_PainMgmt_Sy_206D.pdf

[8] Vilensky, Joel A. et al. "Serial Kinematic Analysis of the Unstable Knee after Transection of the Anterior Cruciate Ligament: Temporal and Angular Changes in a Canine Model of Osteoarthritis." *Journal of Orthopaedic Research* (1994) 12, 229-237.

[9] Withrow, S.J. and Hirsch, V.M. "Owner Response to the Amputation of a Pet's Leg." *Veterinary Medicine/Small Animal Clinician* (1979) 74, 332-334.

[10] Kirpensteijn, J., et al. "Ground Reaction Force Analysis of Large Breed Dogs When Walking After the Amputation of a Limb." *The Veterinary Record* (2000) 146, 155-159.

[11] Lee, David V., Bertram, John E., and Todhunter, Rory J. "Acceleration and Balance in Trotting Dogs." *The Journal of Experimental Biology* (1999) 202, 3565-3573.

[12] Novacheck, Tom F. "The Biomechanics of Running: Review Paper." *Gait & Posture* (1998) 7, 77-95.

[13] Aragon, Carlos L., Hofmeister, Erik H., and Budsberg, Steven C. “Systematic Review of Clinical Trials of Treatments for Osteoarthritis in Dogs.” *Journal of the American Veterinary Medical Association* (2007) 230, 514-521.

[14] Budsberg, S.C., Verstraete, M.C., and Soutas-Little, R. W. “Force Plate Analysis of the Walking Gait in Healthy Dogs.” *American Journal of Veterinary Research* (1987) 48, 915-918.

[15] Sutherland, David H. and Davids, Jon R. “Common Gait Abnormalities of the Knee in Cerebral Palsy.” *Clinical Orthopaedics and Related Research* (1993) 288, 139-147.

[16] Bennett, R.L., et al. “Kinematic Gait Analysis in Dogs with Hip Dysplasia.” *American Journal of Veterinary Research* (1996) 57, 966-971.

[17]Smit, Theo H. “The Use of a Quadruped as an In Vivo Model for the Study of the Spine – Biomechanical Considerations.” *European Spine Journal* (2002) 11, 137-144.

[18] Gradner, Gabriele, et al. “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, 472-481.

[19] Farese, James P., et al. “Stereotactic Radiosurgery for Treatment of Osteosarcomas Involving the Distal Portions of the Limbs in Dogs.” *Journal of the American Veterinary Medical Association* (2004) 225, 1567-1572.

[20] Johnston, Spencer A. “Osteoarthritis: Joint Anatomy, Physiology, and Pathobiology.” *Veterinary Clinics of North America: Small Animal Practice* (1997) 27, 699-723.

[21] Budsberg, Steven C. “Canine Osteoarthritis: Understanding the Etiology, Clinical Presentation, and Diagnosis.” *Veterinary Medicine* (2004).

[22]McLaughlin, R.M. and Roush, J.K. “Effects of Subject Stance Time and Velocity on Ground Reaction Forces in Clinically Normal Greyhounds at the Trot.” *American Journal of Veterinary Research* (1994) 55, 1666-1671.

[23]Roush, J.K. and McLaughlin, R.M. “Effects of Subject Stance Time and Velocity on Ground Reaction Forces in Clinically Normal Greyhounds at the Walk.” *American Journal of Veterinary Research* (1994) 55, 1672-1676.

[24] Gillette, Robert L. and Angle, T. Craig. “Recent Developments in Canine Locomotor Analysis: A Review.” *The Veterinary Journal* (2008) 178, 165-176.

[25] Riggs, CM, et al. “Effects of Subject Velocity on Force Plate-Measured Ground Reaction Forces in Healthy Greyhounds at the Trot.” *American Journal of Veterinary Research* (1993) 54, 1523-1526.

[26] Torres, Bryan T., et al. “The Effect of Marker Location Variability on Noninvasive Canine Stifle Kinematics.” *Veterinary Surgery* (2011) 40, 716-719.

[27] Bertram, John E.A., et al. “Comparison of the Trotting Gaits of Labrador Retrievers and Greyhounds.” *American Journal of Veterinary Research* (2000) 61, 832-838.

[28] Colborne, G. Robert, et al. “Distributions of Power Across the Hind Limb Joints of Labrador Retrievers and Greyhounds.” *American Journal of Veterinary Research* (2005) 66, 1563-1571.

[29] Feeney, Lauren C., et al. “Validation of Two-Dimensional Kinematic Analysis of Walk and Sit-to-Stand Motions in Dogs.” *American Journal of Veterinary Science* (2007) 68, 277-281.

[30] Poy, Nancy S.J., et al. “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, 974-978.

[31] Williams, SB, et al. “Functional Anatomy and Muscle Moment Arms of the Pelvic Limb of an Elite Sprinting Athlete: the Racing Greyhound (*Canis familiaris*).” *Journal of Anatomy* (2008) 213, 361-372.

[32] Winter, David A. *Biomechanics and Motor Control of Human Movement.* Fourth Edition. New York: Wiley, 2009.

[33] “Lameness in Dogs and Cats.” Newman Veterinary Medical Services. Seattle, WA. (1997-2011) Visited on October 11, 2011. http://www.newmanveterinary.com/lameness.html

[34] Moore, G.E., et al. “Causes of Death or Reasons for Euthanasia in Military Working Dogs: 927 Cases (1993-1996).” *Journal of the American Veterinary Association* (2001) 219, 209-214.

[35] Schmid, V and Lang, J. “Measurements on the Lumbosacral Junction in Normal Dogs and Those with Cauda Equina Compression.” *Journal of Small Animal Practice* (1993) 34, 437-442.

[36] Smith, Bonnie J. *Canine Anatomy*. Philadelphia, PA: Lippincott Williams & Wilkins, 1999.

[37] Peham, C, Scheidl, M, and Licka, Theresia. “A Method of Signal Processing in Motion Analysis of the Trotting Horse.” *Journal of Biomechanics* (1996) 29, 1111-1114.

[38]Steiss, Janet E. “Muscle Disorders and Rehabilitation in Canine Athletes.” *Veterinary Clinics of North America: Small Animal Practice* (2002) 32, 267-285.

[39] Stauber, William T. “Factors Involved in Strain-Induced Injury in Skeletal Muscles and Outcomes of Prolonged Exposures.” *Journal of Electromyography and Kinesiology* (2004) 14, 61-70.

[40] Buckwalter, Joseph A. “Mechanical Injuries of Articular Cartilage.” *The Iowa Orthopedic Journal* (1992) 12, 50-57.

APPENDIX I: IACUC APPROVAL

Colorado State University

Research Integrity & Compliance Review Office
Office of Vice President for Research
Fort Collins, CO 80523
(970) 491-1563
FAX (970) 491-2293

Colorado State University
Institutional Animal Care and Use Committee

Animal Research/Teaching Protocol Approval

ANIMAL WELFARE ASSURANCE NUMBER: A3572-01

Principal Investigator: Worley,Deanna R **Phone:** 970-297-4423
Co-Investigator(s):
Department: Clinical Sciences (1678)

Protocol Approval Number: 09-1300A

User Reference Number: 2690

Project Short Title: Kinematic and kinetic description of canine limb and spinal compensation changes following limb...

Project Long Title: Kinematic and kinetic description of canine limb and spinal compensation changes following limb amputation secondary to cancer

Approval Date: 11-AUG-10
Effective Date: 11-AUG-10
Renewal Date: 18-AUG-11
Expiration Date: 18-AUG-12
Inactive Date:

Funding Agency: CRC/Miki Society

Species:

Dog	Dog - 80 - Pain Category C	**Remaining Animals:** 60

If the number of animals ordered exceeds the number approved by 10%, a justification for more animals must be sent to the Regulatory Compliance Coordinator before further orders will be processed by the Laboratory Animal Resources.

This project was reviewed by the Institutional Animal Care and Use Committee and action taken as follows

Project Status: APPROVED

With the following conditions or comments:

Approval of annual renewal of protocol #09-1300A.

Chair: Jerry Engle / Sekh

Date: 8/11/10

Questions concerning this approval should be directed to Coordinator, Institutional Animal Care and Use Committee, 321 General Services Building, CD 2011 491-1553

August 11, 2010

Research Integrity &
Compliance Review Office
Office of Vice President for Research
Fort Collins, CO 80523
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Colorado State University
Institutional Animal Care and Use Committee

Animal Research/Teaching Protocol Approval

ANIMAL WELFARE ASSURANCE NUMBER: A3572-01

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Expiration Date: 18-AUG-12
Inactive Date:

Funding Agency: CRC/Miki Society

Species:

Dog	Dog - 80 - Pain Category C	**Remaining Animals:** 80

If the number of animals ordered exceeds the number approved by 10%, a justification for more animals must be sent to the Regulatory Compliance Coordinator before further orders will be processed by the Laboratory Animal Resources.

This project was reviewed by the Institutional Animal Care and Use Committee and action taken as follows

Project Status: APPROVED

With the following conditions or comments:

Approval of Amendment to add personnel to protocol (Laura Steele, Sarah Jarvis, Sara Hogy, and Kristen Weishaar).

Chair: Jerry Engle / EKK.

Date: 8/11/10

Questions concerning this approval should be directed to Coordinator, Institutional Animal Care and Use Committee, 321 General Services Building, CD 2011 491-1553

August 11, 2010

APPENDIX II: PHYSICAL EXAM RESULTS

Controls
C1 Past ortho history - history of LH stiffness Comments - slight decreased ROM of stifles at the walk L stifle - mild crepitus R stifle - mild crepitus
C2 No problems in physical exam
C3 Past ortho history - juvenille pubic symphiodesis 7/08, hip dysplasia, R partialy TACL 10/09, bilateral ACL disease L>R 11/09, L tibial plateal leveling osteotomy 6/10 Dx - only on Dasuquin Gait - after ortho exam, mild RH weightbearing lameness L stifle - moderate medial buttress and TPLO plate, mild pain with hyperextension R stifle - marked medial buttress, moderate pain with hyperextension
C4 No problems in physical exam
C5 R carpal - mild pain
C6 R shoulder - equivocal discomfort with flexion
C7 No problems in physical exam
C8 Past ortho history - R femoral head and neck ostectomy 9/09 L elbow - slight discomfort with pressure over medial coronoid in flexion R hip - slight resistence with extension
C9 Comments - hates lying down L hip - does not like hip extension, no pain R hip - does not like hip extension, no pain
C10 No problems in physical exam
C11 No problems in physical exam
C12 L shoulder - mild shoulder discomfort worse in R R shoulder - mild shoulder discomfort worse in R, mild decrease ROM
C13 Past ortho history - crepitus left hock since 2005 Dx - gets occasional carprofen Comments - very nervous L tarsus - slight crepitus, marked decreased ROM L hip - unable to assess hip fully R tarsus - marked decreased flexion R hip - unable to assess hip fully

C14	Medical history - multiple cutaneous masses, no medications L carpus - decreased flexion L elbow - slight discomfort with ROM L shoulder - pain with extension R >L R carpus - decreased flexion R shoulder - pain with extension R>L L stifle - pain, unable to fully hyperextend, effusion and medial buttress present
C15	Medical history - hip dysplasia, left patella lateral laxity L carpus - mild crepitus and slight decreased ROM L stifle - grade 2 laterally luxating patella L hip - marked discomfort with extension R stifle - grade 1 laterally luxating patella R hip - marked discomfort with extension
C16	Dx - lymphoma, hypertension, early dilated cardiomyopathy Gait - slight shuffling and slapping of HL, normal gait rhythm L shoulder - mild resistence with flexion L stifle - mild crepitus L hip - marked discomfort with extension R stifle - mild crepitus R hip - marked discomfort with extension
C17	Cervical pain - possible decreased bilateral lateral cervical motion Spinal pain - mild discomfort with palpation L5/L6 region R elbow - slight decreased flexion, marked crepitus, moderate discomfort with flexion L hip - mild discomfort with extension R stifle - mild discomfort with hyperextension R hip - mild discomfort with extension
C18	Medical history - pannus, R anal sac mass Gait - slightly lower carriage of pelvis to ground Comments - trying to bite Spine - pain with hyperelevation of tail, pain at L4/L5 region Neuro - slight crossing over HLs, HL weakness, CPs intactx4 Forelimbs - unable to complete exam Hindlimbs - unable to complete ortho exam, decreased HL muscles
C19	Dx - LF antebrachial sarcoma, recently started deracoxib Comments - 5 x 13 cm tumor at L caudal antebrachium just below elbow L stifle - moderate medial buttress L hip - mild discomfort with extension L>R R stifle - moderate medial buttress, pain with hyperextension R hip - mild discomfort with extension L>R
C20	Past ortho history - right femur fracture 9 years ago L hip - slight resistence to extension R hip - slight resistence to extension

C21	Gait - slight short strided HL gait L carpus - decreased ROM, mild crepitus L elbow - slight discomfort with flexion, slight thickening R carpus - mild decreased ROM, mild crepitus R elbow - slightly less discomfort with flexion, less thickening L stifle - medial buttress, very mild discomfort with hyperextension R>L L hip - mild discomfort with full extension R stifle - very mild discomfort with hyperextension R>L R hip - mild discomfort with full extension
C22	Medical history - poor vision, multiple fatty masses Comments - shoulders more sore than hips L shoulder - resistence to extend R shoulder - resistence to extend L hip - resistence to extend
C23	Gait - mild bilateral HL lameness, stiff HL gait Comments - decreased joint excursions when walking, good muscle mass in HLs Spine - mild lumbar discomfort with palpation L stifle - painful with hyperextension, medial buttress and mild effusion present L hip - resists hip extension R stifle - painful with hyperextension, medial buttress and mild effusion present R hip - resists hip extension
C24	L elbow - stiff, mild effusion L shoulder - stiff shoulder R shoulder - stiff shoulder

Amp-LH	
L1	
	Dx - osteosarcoma L proximal tibia, had one cycle carboplatin Comments - ambulating well L elbow - thickened R elbow - thickened R stifle - medial buttress
L2	
	Dx - histiocytic sarcoma L proximal tibial region, had seen CCNU, one cycle doxorubicin Comments - ambulating well L elbow - mildly thickened, discomfort with flexion, decreased ROM R elbow - mildly thickened, discomfort with flexion, decreased ROM R hip - pain with extension
L3	
	Dx - osteosarcoma L distal femur, had one cycle carboplatin Comments - ambulating well L carpus - decreased ROM R carpus - decreased ROM R tarsus - decreased ROM especially on flexion, bony thickening R hip - mild discomfort with extension
L4	
	Dx - osteosarcoma L distal femur, had five cycles carboplatin, on Palladia Comments - RH shifted to midline L elbow - equivocal discomfort with flexion R shoulder - equivocal discomfort with extension
L5	
	Dx - soft tissue sarcoma L lateral metatarsus
L6	
	Medical history - recently fell once at home Dx - osteosarcoma L proximal tibia, had four cycles carboplatin Comments - ambulating well, pulling dog handlers L elbow - pain with flexion, mild thickening R elbow - mild resistence with flexion R hip - stiff on extension
L7	
	Medical history - had R lateral thoracotomy 12/06/2010 for metastatic R midddle lung lobe and lymph node Dx - anaplastic sarcoma L proximal thigh, had one cycle CCNU Comments - ambulating well, jumping on sole RH R stifle - mild thickening, moderate discomfort with hyperextension R hip - mild discomfort with extension

Amp-RH
R1 Dx - osteosarcoma R proximal femur, had one cycle carboplatin Comments - ambulating well L stifle - thickening, moderate discomfort with hyperextension L hip - mild discomfort with extension
R2 Dx - osteosarcoma R femur, had one cycle carboplatin Comments - ambulating well L stifle - medial buttress, mild discomfort with hyperextension L hip - moderate discomfort with extension
R3 Dx - osteosarcoma R distal tibia, had four cycles carboplatin Comments - ambulating well R4 Dx - osteosarcoma R proximal femur, had five cycles carboplatin L hip - slight discomfort with extension
R5 Dx - osteosarcoma R distal tibia, had two cycles carboplatin Comments - ambulating well Spine - mild discomfort over L6/S1 region Neuro - slow conscious proprioception LH