THESIS

# KINEMATIC AND KINETIC ANALYSIS OF CANINE THORACIC LIMB AMPUTEES AT A TROT

Submitted by

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## ABSTRACT

### KINEMATIC AND KINETIC ANALYSIS OF CANINE THORACIC LIMB AMPUTEES AT A TROT

Most dogs appear to adapt well to the removal of a thoracic limb, but clinically there is a particular subset of dogs that still have problems with gait that seem to be unrelated to age, weight, or breed. The purpose of this study was to objectively characterize biomechanical changes in gait associated with amputation of a thoracic limb. Sixteen amputees and 24 control dogs of various breeds with similar stature and mass greater than 14 kg were recruited and participated in the study. Dogs were trotted across three in-series force platforms as spatial kinematic and ground reaction force data were recorded during the stance phase. Ground reaction forces, impulses, and stance durations were computed as well as stance widths, stride lengths, limb and spinal joint angles. Kinetic results show that thoracic limb amputees have increased stance times and vertical impulses. The remaining thoracic limb and pelvic limb ipsilateral to the side of amputation compensate for the loss of braking, and the ipsilateral pelvic limb also compensates the most for the loss of propulsion. The carpus, and ipsilateral hip and stifle joints are more flexed during stance, and the T1, T13, and L7 joints experience significant differences in spinal motion in both the sagittal and horizontal planes throughout the gait cycle stance phases. The spine, carpus, and ipsilateral hip and stifle joints are of most concern when considering the biomechanical impact that a thoracic limb amputation may have for a given dog.

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# I. INTRODUCTION

Limb amputation is standard treatment along with adjuvant chemotherapy for dogs with appendicular osteosarcoma.[1-4] This is the most common type of primary bone tumor in dogs[5,6] with over 6,000 new diagnoses made each year.[7] Most dogs seem to adapt well to the removal of a thoracic limb.[8,9] However, clinically there is a particular subset of dogs that do not return to normal or near-normal function even after the expected adaptation period of one month.[10] Many propose that age, bodyweight, and breed will affect the dog's functionality post-amputation,[3,10-14] but bodyweight has not been shown to be a contributing factor.[10] Additionally, owner surveys encompassing a wide variety of breeds and ages of dogs do not give any indication that these factors negatively impact the ability of a dog to adapt to the loss of a limb.[8,9] With these factors unlikely to be the source of poor adaptation for amputees, there must be other factors related to gait that contribute to decreased mobility.

It has been suggested that unless there is severe musculoskeletal or neurologic disease already present, any dog should be able to adapt well to a three-legged gait.[3] However, there is no clear distinction between severe and moderate degrees of lameness as these are determined clinically through physical examination. One must therefore question whether any degree of musculoskeletal or neurologic disease present in the limbs or spine before amputation could predispose a dog to problems in adapting to a three-legged gait. Osteosarcoma patients often have signs of significant degenerative joint disease in at least one other limb,[1] making this a concerning issue for these dogs.

Understanding compensatory changes in gait is also important for dogs that have had an amputation due to other reasons, such as traumatic injury, nerve damage, or infection.[8,10] Currently, dogs with osteosarcoma rarely live long enough for degenerative conditions such as osteoarthritis to develop secondary to amputation,[7,15] but dogs with amputations for other reasons often live many years after amputation[8] when these conditions might begin to appear.[15]

Alternative treatments to limb amputation are available, such as limb-sparing surgery.[3,16] However, this aggressive procedure is much more expensive,[3] has a high risk of complication,[1-3,16] and has not been shown to result in a significantly greater lifespan for the dog.[3,16] Less than 10% of dogs with osteosarcoma survive beyond three years,[7] but advances in cancer detection and treatment could extend the life expectancy. In the future, more amputees may live longer and begin to experience problems associated with altered gait. This is especially important for thoracic limb amputees since the majority of osteosarcoma diagnoses are located in the distal radius and humerus.[17]

Current knowledge of compensation strategies in thoracic limb amputees is limited to kinetic data evaluating ground reaction forces (GRF), impulses, and stance durations in a group of five dogs at the walk.[18] Significant differences were found in weight distribution and stance durations where thoracic limb amputees, in comparison to controls, exert an extra 16% of bodyweight on the remaining thoracic limb and an extra 7% of bodyweight on each pelvic limb while applying similar peak vertical GRFs over a shortened stance duration.[18] Differences also exist in how amputees compensate for the loss of thoracic limb braking by spending more time than normal braking with the remaining thoracic limb rather than distributing more of the braking impulse to the pelvic limbs.[18]

With such limited data on amputee gait, there is a need to better understand in a larger population of thoracic limb amputees the compensatory mechanisms used that alter loading in the remaining limbs. Analysis of the GRFs only provides a small portion of the picture in understanding amputee gait, and thus a kinematic analysis of the limbs and spine is needed.

Kinematic analysis has been used to evaluate gait in dogs that are either clinically normal, have hip dysplasia, or cranial cruciate ligament rupture,[15,19-33] but data on amputee kinematics is lacking. Any alteration to normal limb kinematics can significantly change the distribution of force through a joint.[34-36] This may lead to instability, muscle dysfunction, pain and decreased range of motion as well as abnormal biological changes such as cartilage degradation, impaired synthesis, and inflammation,[35,36] both in the joint of interest and possibly other adjacent joints as well.[37] Evidence of changes in maximum and minimum joint angles as well as ranges of motion combined with the knowledge of GRFs would indicate that there are indeed alterations in how the joints are being loaded in amputee gait.

As with altered kinematics in the limbs, increased spinal motion may also lead to degenerative changes and issues with muscular control of the joints.[27,35,36] Kinematic studies in dogs with hip dysplasia have shown significant differences in lateral pelvic movement, coxofemoral joint abduction-adduction and angular accelerations of the hip.[19,32] With these types of compensatory changes appearing in dogs with an intact but diseased limb, one could assume that even greater changes may appear in thoracic limb amputees as well, but perhaps more localized to the thoracic region.

Analysis of both the GRF kinetic and angular joint kinematic compensatory changes occurring in thoracic limb amputees will provide clinicians with a more robust understanding of amputee gait, highlighting areas where both joint loading and motion are altered. This will not only be influential in deciding a course of treatment for osteosarcoma within a given patient, but it will also support further research in osteoarthritis and long-term outcomes of amputee dogs. The purpose of this study is therefore to objectively characterize the changes in gait associated with amputation of a thoracic limb. Our hypothesis is that there are significant differences in GRFs and joint angular kinematics of thoracic limb amputee gait compared to a similar control population with four intact limbs.

*Specific Hypotheses.* In particular, we expect to see significant alterations in spinal movement in both the sagittal and horizontal planes. Additionally, we expect to see significant differences in minimum, maximum, and average joint angles as well as changes in range of motion during the stance phase in the remaining limbs. It has been previously shown in a small sample of subjects[18] that there are significant changes in weight distribution and a decrease in stance duration without a significant increase in peak vertical force in each limb. Along with our expectation that these changes are characteristic of our larger sample size, we predict that there will also be a significant decrease in the stance width for the remaining thoracic limb and an increase in stance width in the pelvic limbs as the dogs adjust their weight distribution to maintain balance with an altered center of mass.

## II. LITERATURE REVIEW

In order to understand the importance of identifying the compensatory changes dogs make after the loss of a thoracic limb, it is beneficial to have a thorough understanding of the related literature. In particular, it is helpful to explore the prevalence and treatment of osteosarcoma in dogs, previous clinical impressions on adaptation to a three-legged gait, the implications of altered gait, past research in amputee kinetics, and relevant kinematic studies in four-limbed dogs as these issues are directly relevant to our study of thoracic limb amputees.

In dogs, osteosarcoma comprises 85% of the tumors originating in the skeleton with over 6,000 new diagnoses made each year;[7] 90% of which are in dogs greater than 20 kg.[12,38] The most common site for osteosarcoma in dogs is the distal radius of the thoracic limb.[3,39,40] Some speculate that this is a result of carrying twenty percent more bodyweight on the thoracic limbs than the pelvic limbs[6,39,40] since most cases of osteosarcoma in humans appear in the higher weight-bearing, lower extremities.[6] Appendicular osteosarcoma in dogs is most frequently treated with chemotherapy and limb amputation.[1-4,16] Limb-sparing surgery is now becoming a common procedure as well, particularly for thoracic limb amputees;[1-3,16] however, advanced treatments such as this are significantly more expensive than amputation,[3] have a high risk of complication,[1-3,16] and have not been shown to result in a significantly greater lifespan for the dog.[3,16]

While there are many aspects of health and quality of life to consider when making the decision to amputate a limb, it is important to understand the gait changes that these dogs will make to compensate for the missing limb as they could potentially result in increased pain, lameness and decreased quality of life. Previous studies focused on clinical impressions and client surveys have shown subjectively that functional outcome of a limb amputation secondary to osteosarcoma is very good regardless of breed, size, or age.[8-10] It is believed that unless there is severe musculoskeletal or neurologic disease already present, such as ataxia, any dog should be able to adapt well to ambulating on three limbs.[3] However, there is no clear distinction between severe and moderate degrees of lameness as these are determined clinically through physical examination. Some conditions such as hip dysplasia may not always be accompanied by obvious pain and lameness,[19] but could be factors that will later contribute to difficulty in adapting to three limbs. One must therefore question whether any degree of musculoskeletal or neurologic disease or lameness present in the limbs or spine before amputation could predispose the dog to difficulties in adapting to a three-legged gait.

Understanding compensatory changes in amputees is also important for dogs that have had a limb removed for reasons other than osteosarcoma, such as traumatic injury, nerve damage, or infection.[8,10] Previous studies on the adaptation of dogs to amputation of a limb[8,10] indicate that dogs whose amputations are not a result of osteosarcoma generally live normal lifespans in comparison to dogs with osteosarcoma, where only 10% currently survive beyond three years after diagnosis with standard-of-care.[7] Therefore, consideration of both acute and long-term impacts of altered gait must be taken into account since some amputee patients may live many years after limb amputation.

Any alteration to normal gait can significantly change the distribution of forces through a joint,[34-36] and the way in which muscles control joint motion.[41] It is unknown the degree to which amputee dogs may adjust their stance width to maintain balance with an altered center of mass. One or more limbs could therefore be positioned such that a joint is forced into a more valgus position, which could cause increased stress on the ligaments stabilizing the joint. Valgus collapse of the knee has been associated with non-contact anterior cruciate ligament injury in humans,[42-44] and could be a concern for some amputee dogs as well. Muscles which control the extremities must be properly recruited and activated in order to absorb and generate GRFs to protect the limb articulations from injury.[44] The ability of a muscle to generate force is dependent on both its length and velocity of contraction.[45] Muscles generate decreasingly smaller amounts of force as they shorten or lengthen beyond their optimal lengths.[45] Additionally, the moment arm of a muscle changes as a function of the joint angle.[46] A dog with a limb that is more extended than normal throughout the gait cycle could therefore have difficulties generating adequate forces and moments to properly stabilize the joints, predisposing it to injury and lameness. Similarly, the ability of muscles to generate force also decreases with increasing velocity.[45] The faster the muscle contraction, the less force that can be generated. It has previously been suggested that thoracic limb amputees increase the cadence of limb movement as one of their compensation strategies.[18] This could also inhibit dynamic stability of the joints, making them more susceptible to acute or overuse injuries.

Proprioceptors detect altered joint position and movement between limb segments, and are important in maintaining coordinated limb motion should the mechanics or environment of the limb change.[47] The motor control system has been shown to have a high degree of adaptability to mechanical change, but this is limited when altered proprioceptive information occurs.[48] This further supports the need to develop quantitative knowledge of amputee gait to which pre-amputation physical examinations or assessment of proprioception and motor control can be compared.

While osteoarthritis has been shown to take up to three years to develop in dogs with induced cranial cruciate ligament rupture,[49] dogs with four limbs typically continue to use an injured limb for support,[21,32,49,50] and may therefore be developing degenerative joint disease at a slower rate than what might be expected for an amputee. When exposed to cyclic mechanical stress, such as walking or trotting, cartilage degradation is accelerated under higher loading conditions in osteoarthritic joints.[34,51] Significant osteoarthritis in at least one other limb prior to amputation is common among dogs with osteosarcoma.[1] A remaining limb already affected by osteoarthritis at the time of amputation will experience an even greater rate of cartilage degradation[51] after surgery due to altered range of motion and increased weight distribution to the limb .[18] This could have a significant impact on an amputee's quality of life.

Current knowledge of compensation strategies in thoracic limb amputees is limited to kinetic data in a small number of dogs, and clinical impressions of how well they seem to adapt to three limbs. Quantitative analysis of both the kinetic and kinematic compensatory changes occurring in thoracic limb amputees as well as comparison with physical examination findings will provide clinicians with a more robust understanding of amputee gait. This will highlight areas where both loading and joint motion are altered after the adaptation to a three-legged gait. Not only will this be influential in deciding a course of treatment for osteosarcoma in a given patient, but it will also support further research in osteoarthritis and the long-term outcomes of amputee dogs.

Several studies have analyzed GRFs and other kinetic parameters in dogs,[18,50,52-57] however only one study[18] has characterized the kinetic aspects of gait in amputees, reporting solely on the findings of five thoracic limb and five pelvic limb large-breed amputees, in comparison to 22 healthy adult Labrador retrievers at the walk. Although stance duration has previously been found to inversely correlate with peak vertical force in normal dogs,[52,55] the thoracic limb amputees were not found to have this correlation.[18] Instead they seem to be distributing the same amount of force over a shorter period of time within each limb. In healthy dogs, stance time also inversely correlates with velocity.[55] Therefore it is expected that at a trot, amputees will have shorter stance times in comparison to the stance times found for amputees at a walk.[18]

Healthy dogs are also known to have greater braking forces in the thoracic limbs with greater propulsive forces in the pelvic limbs.[52,54,58] Typically, the thoracic limbs spend 56% of their stance duration in the braking phase, while the pelvic limbs spend 61% of their stance duration in the propulsive phase. [54] After the loss of a thoracic limb, amputees compensate by reducing the propulsive forces on the non-amputated side such that the sum of the remaining contralateral thoracic limb and contralateral pelvic limb equal that of the ipsilateral pelvic limb.[18] (Note: unless specifically indicated, further use of “ipsilateral” is in reference to the amputated side while “contralateral” is in reference to the non-amputated side). Dogs with a thoracic limb amputation tend to spend even more time braking with the remaining thoracic limb (67% versus 56% of the thoracic limb contact time) and less time braking with each pelvic limb (25% of the ipsilateral pelvic limb contact time and 22% of the contralateral pelvic limb contact time, versus 38% in a four-limbed dog).[18]

Significant differences also exist in how thoracic limb amputees adjust the weight distribution among the limbs while walking as compared to healthy four-legged dogs. According to Kirpensteijn et al. this redistribution amounts to 46% on the remaining thoracic limb, and 27% on each pelvic limb.[18] Given that non-athletic dogs typically carry 30% of bodyweight on each thoracic limb and 20% of bodyweight on each pelvic limb,[6,39,40] the redistribution seen in thoracic limb amputees puts increased stress on all remaining limbs, especially the remaining thoracic limb. This likely makes the dog more susceptible to common musculoskeletal disorders[35,59] such as ligament injury or osteoarthritis.[17]

Before reviewing past research related to kinematics in dogs, it is important to discuss marker attachment to the skin and fur. Noninvasive placement of reflective markers on the skin/fur is the most common way of obtaining kinematic data in the veterinary field,[19-22,24-27,29,30,32,33] however as the dog walks or trots, this method can result in artifact error due to movement of fur or soft tissue over the bony landmarks used for marker placement. One study which modeled marker placement error found potential for significant differences between invasive and noninvasive methods of marker placement, specifically at the greater trochanter in the pelvic limb.[60] In particular, changes in marker location at the hip were greatest in the craniocaudal direction, which could result in exaggerated measures of stifle angles.[60] Artifact error can be reduced by using invasive methods for attaching markers directly to the bone, but this can result in pain and inflammation at the site where the markers are attached and could negatively impact gait patterns.[61,62] The implication of artifact error in noninvasive marker placement is still an important consideration when making conclusions about significantly different joint angles in a particular sample of dogs. However, artifact error due to soft tissue and fur movement was less than two percent in a previous study,[63] and likely affects all kinematic data collected to some degree for a given patient. Although variations in the measurement of joint angles may still exist as a result of artifact error, it has been accepted by previous studies that overall assessment of flexion and extension movement acquired from noninvasive kinematic data is still useful in analyzing normal and abnormal gait.[19,21,60]

Abnormal motion of the spine can lead to significant degenerative changes and decreased range of motion as a result of spondylosis and osteophyte formation.[27] This may result in compression of adjacent neural structures and ultimately increased pain and spinal dysfunction.[35] Likewise, alterations to normal limb kinematics can affect the distribution of force through a joint[34-36] which may result in instability and muscle dysfunction, as well as cartilage degradation and inflammation.[35,36] Evidence of changes in maximum and minimum joint angles as well as changes in ranges of motion would indicate that there are indeed alterations to how the joints are being loaded in amputee gait. While information on kinematic changes occurring in amputee dogs is currently lacking, there are studies in four-legged dogs which provide some insight on how amputees might be expected to compensate for a missing thoracic limb.

Studies in spinal kinematics have shown that healthy four-legged dogs have a preexisting natural rotation of the thoracic region of the spine with a preferred direction to the right.[31] The largest horizontal movement in the spine occurs at the caudal thoracic vertebrae and beginning of the lumbar vertebrae. The smallest horizontal and sagittal angular ranges of motion occur at the thoracolumbar junction.[27] In particular, mean joint angles defined by T6-T13-L3 and L3-L7-S3 during the stance phase at a walk have been found in the horizontal plane to be approximately 6 degrees at both locations, where full extension is 0 degrees. Over the entire gait cycle, these joints also had ranges of motion in the horizontal plane of 11 degrees and 12 degrees, respectively.[27] In the sagittal plane during the stance phase at a walk, the T6-T13-L3 mean joint angle was 2 degrees with a range of 4 degrees over the full gait cycle, while the L3-L7-S3 mean joint angle was 3 degrees with a range of 5 degrees over the full gait cycle.[27]

Poy et al. looked at kinematic changes in trotting dogs with hip dysplasia.[32] Affected dogs have shown significantly greater lateral pelvic movement and significant differences in coxofemoral joint abduction-adduction[19,32] and angular accelerations.[32] With these types of compensatory changes occurring in dogs with an intact but diseased limb, one could assume that even greater changes would appear in amputees. Studies on hip dysplasia are most relevant to pelvic limb amputees, but significant differences seen where the affected proximal limb interacts with the spine indicate that thoracic limb amputees could also exhibit similar differences localized to the thoracic region. While pelvic limb amputees would be expected to have significant differences in lateral pelvic movement and coxofemoral joint abduction-adduction like dogs with hip dysplasia, thoracic limb amputees may have significant differences in lateral movement at the T1 region.

Another expectation of the Poy et al. study[32] was that there would be detectable differences in mediolateral foot movement as an indication of a narrow-based stance due to lameness associated with hip dysplasia, but this was not the case. Perhaps the presence of a limb, even with a high level of lameness, gives the dog enough postural stability to maintain a normal stance width during a trot. In an amputee however, the center of mass moves away from the site of amputation.[18] It would therefore make sense that without a fourth limb there will be a significant difference in stance width as the dog maintains balance and redistributes weight among the remaining limbs. Stance width, as mentioned previously, is yet another variable which indicates changes in joint kinematics that could alter forces experienced within the joints.

In comparison to controls, kinematic evaluation of the limbs has shown significantly different angular displacements in the ipsilateral shoulder after taping of the carpus to prevent joint motion in a study with eight sound Labrador retrievers.[25] At the shoulder, elbow, and carpus, mean joint angles during the stance phase at a walk in normal dogs have been found to be 130 degrees, 137 degrees, and -6 degrees, respectively, where 180 degrees defines full extension for the shoulder and elbow, and 0 degrees is full extension at the carpus.[29] These joints also had ranges of motion of 19 degrees at the shoulder, 29 degrees at the elbow, and 79 degrees at the carpus during the stance phase.[29] In the pelvic limbs, the hip, stifle and hock mean joint angles during the stance phase at a walk in normal dogs have been found to be 120 degrees, 134 degrees, and 146 degrees, respectively, where 180 degrees defines full extension.[29] These joints had ranges of motion during the stance phase of 27.6 degrees at the hip, 22.8 degrees at the stifle, and 27.4 degrees at the hock. Amputees exhibiting changes in joint angles from these normal kinematic patterns will provide additional data suggesting that amputee gait is significantly altered and potentially problematic.

Knowledge of compensatory changes to a three-legged gait in dogs is clearly lacking. Relevant data is sparse and limited to small sample sizes and specific breeds, often focusing on clinically normal dogs. Little kinetic data is available and no quantitative assessments on kinematic changes in amputees currently exist. Analysis of both the kinetic and kinematic compensatory changes occurring in thoracic limb amputees will provide clinicians with a more robust understanding of amputee gait to which they can compare pre-amputation clinical exam findings. This will not only be influential in deciding a course of treatment for osteosarcoma in a given patient, but will also support further research in osteoarthritis and the long-term outcomes of amputee dogs. More importantly, it will ensure that dogs with osteosarcoma receive a treatment based on both qualitative and quantitative data in amputee gait which is expected to provide them with the best quality of life.

# III. MATERIALS AND METHODS

## Subjects

The control group consisted of 31 four-legged dogs, many previously diagnosed with cancer. The amputee group enrolled in the study consisted of 11 left thoracic limb amputees and 8 right thoracic 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 to limit variability and facilitate kinematic data processing. Amputees must have had an 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[10]. 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 either the control or the amputee group. The goal of the study was to provide a clinically relevant investigation and as a result, the control group was not designed to be without any orthopedic, neurologic or other physical impairments; thus comparing dogs that have lost a limb due to osteosarcoma to a comparable group of dogs with four limbs. All dogs underwent complete physical, orthopedic, and neurologic examinations before gait analysis to confirm enrollment the study. Researchers performing the kinetic and kinematic analysis were blinded to the results of the exams until the statistical analysis portion of the study was complete.

**Subject Measurements**

Immediately prior to gait analysis, both wither height and body mass measurements were recorded for each dog. 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 coordinate locations and calculate joint angles for the limbs and spine, 25 markers were placed on each control dog and 20 markers 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 over palpable bony landmarks along the spine and joint centers of rotation in the thoracic and pelvic limbs (Figure III-I) using double-sided carpet seam tape (Roberts, Q.E.P., Boca Raton, FL). On the thoracic limbs, markers were placed on skin/fur 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 on skin/fur 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 on the skin/fur over the occipital protuberance, the dorsal spinous process of T1, the dorsal spinous process of the T13 vertebrae, the dorsal spinous process of the L7 vertebrae, and the sacral apex. A scapula marker was also placed on the side of amputation where the scapular spine would be in relation to the contralateral side.

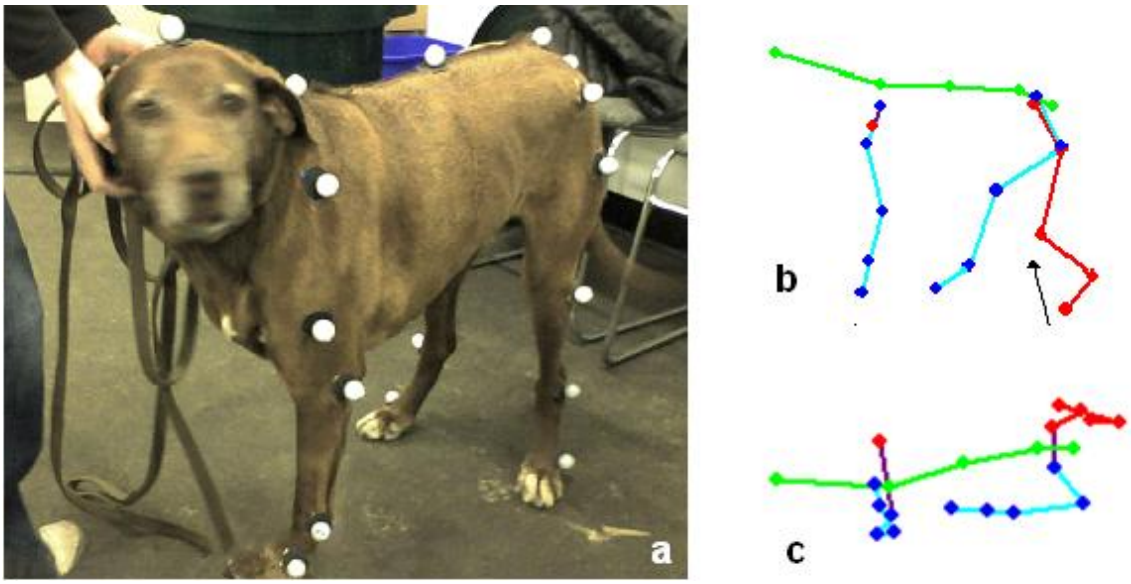


**Figure III-I. Thoracic limb amputee with a full set of retro-reflective markers applied to bony landmarks along the spine, pelvic and thoracic limbs (a). Sagittal (b) and horizontal (c) plane reconstructions of marker segments during a trotting trial providing full view of the markers. Green markers and segments represent the spine, while red represents the right limbs and blue represents the left limbs.**

**Data Collection**

Data collection took place at the Gait Analysis Laboratory at the Orthopaedic 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 III-II).

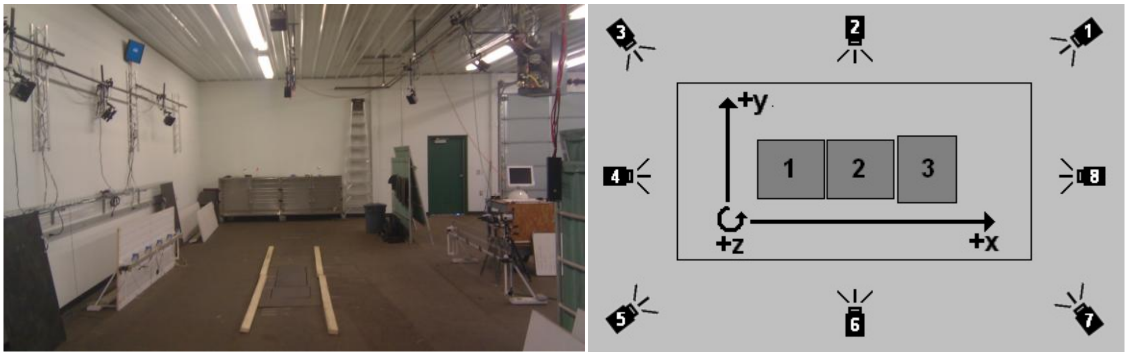


**Figure III-II. For each trial, dogs started at the far end of the walkway in the gait analysis laboratory and trotted toward the control center at the front of the lab (out of view) (left), running from plate 1 to plate 3 (right). Wooden boards placed parallel to the force platforms were used to guide the dogs across the force platforms. Timing lights were mounted to the left of the force platforms with reflectors placed in similar intervals on the right side of the walkway. Vertical GRFs are analyzed in the +Z direction, braking GRFs in the –X direction and propulsive GRFs in the +X direction.**

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 typically averaged 91.50 cm with a 1$^{st}$ standard deviation of 0.09 cm during daily calibration. Coordinate data were captured using eight optical motion cameras at 200 Hz (Motus 9.0, Vicon Motion Systems, Inc., Centennial, CO). Raw 3-D 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.

Five timing lights (Mekontrol, MEK-92-PAD, Richardson, TX) spaced at intervals of 0.5 m were used to instantaneously provide gait velocity and acceleration. Dog handlers were instructed to maintain velocities between 2.2 and 2.6 m/s and accelerations between -0.5 m/s$^2$ and 0.5 m/s$^2$ for the data collection. Trials were excluded if the handler and dog were not moving at the same pace, acceleration was outside of the acceptable range, the dog pulled on the leash while trotting, or the dog's head movement was excessive. Trials were also excluded if the velocity of a trial was not within ±0.4 m/s of that dog's other trials. This allowed for a slightly wider velocity range to accommodate amputees that could not get successful paw strikes within the range of 2.2-2.6 m/s. The dogs were trotted down the track 3 to 5 times before data collection to allow them to acclimate to the laboratory environment, marker attachment, and walkway. Subjects were trotted through the capture window until five successful trials were captured or until the dog was too exhausted to continue. Several minutes of rest were allowed between acclimation to the laboratory and between trials as needed. For the control group, trials were 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 range. Paw strikes were considered valid when the full paw landed on one platform and the GRF overlap between the first paw leaving the platform and the second paw landing on the platform was less than 25 N. For the amputee group, trials were considered successful if paw strikes were valid and the velocities and accelerations were within the acceptable range.

**Gait Parameter Definitions**

Gait analysis focused on the stance phase which was defined as the period of time during which the paw was in contact with the force platform and when GRFs were above the threshold value of 25 N. Stride lengths were defined as the craniocaudal 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 based on the lateral distance in the mediolateral direction between the center of pressure of the fore paw and the ipsilateral scapular marker for the thoracic limbs, and between the center of pressure of a hind paw and its ipsilateral ilial marker for the pelvic limbs. Joint angles for the limbs and spine were calculated using the locations of the markers (Figure III-III).

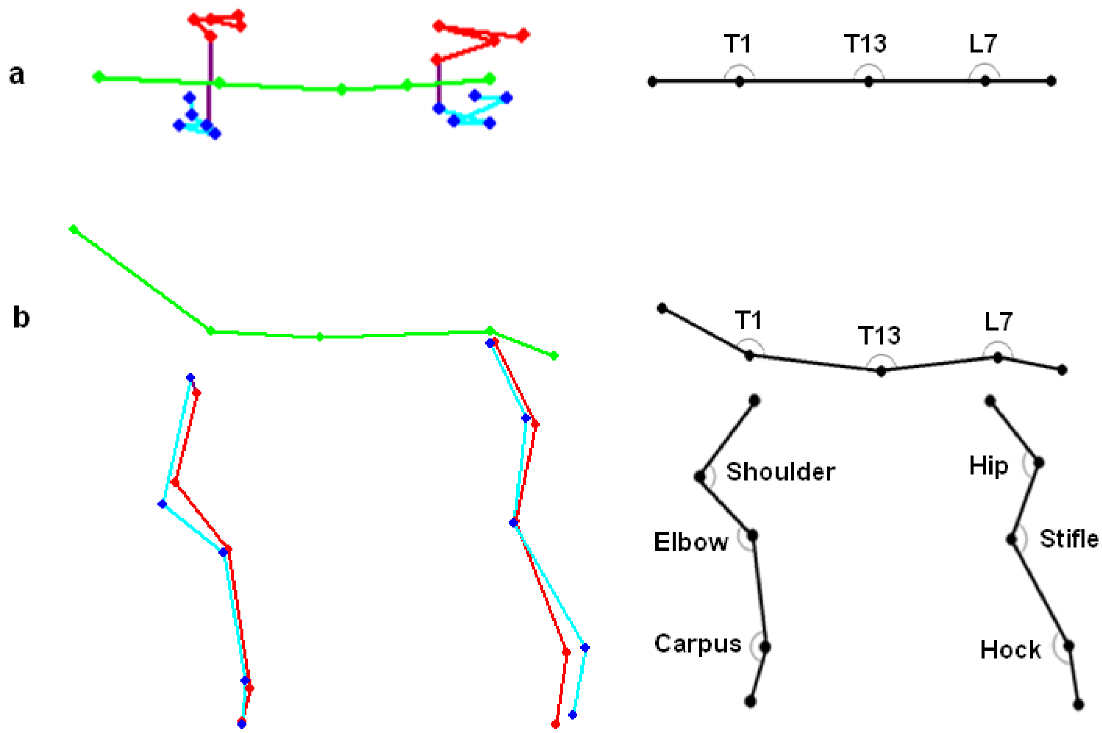


**Figure III-III. Spine angles were calculated from spinal markers in both the horizontal (a) and sagittal (b) planes. Thoracic limb and pelvic limb joint angles were calculated in the sagittal plane using markers placed on bony landmarks at joint centers of rotation (b).**

With these definitions for the joint angles of the limbs, where 180 degrees represents full extension, an increase in the joint angle indicates extension, while a decrease in joint angle indicates flexion. This is the case for all of the limb joint angles with the exception of the carpus where increased joint angles indicate carpal flexion and decreased joint angles indicate carpal extension. At the spine, full extension is also defined as 180 degrees in both sagittal and horizontal planes. 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, while a decrease in joint angle represents right lateral bending.

In order to compare the joint angles in the horizontal plane between left and right thoracic limb amputees, the horizontal joint angles for all left side amputees were subtracted from 360 degrees. In this way, compensation in the horizontal plane by a left limb amputee would be comparable to the exact opposite compensation by a right limb amputee. Without performing this adjustment, consistent compensations based on the amputated limb by right and left limbed dogs would have canceled each other out. While spinal motion will be described in reference to specific joints (T1, T13, and L7), the specific changes in joint angles are really a representation of spinal motion at that region of the spine, rather than just at the specific spinal process identified. For each joint angle, the mean, standard deviation, maximum, minimum, and range (maximum minus minimum) values were calculated during the stance phase. Peak vertical, braking, and propulsive GRFs and impulses were also 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 GRF in the craniocaudal direction. As such, the braking forces and impulses were described using negative values to indicate the direction of the force. For each parameter analyzed in either the control or amputee group, a minimum of three trials were pooled for each dog to create representative values, followed by pooling all of the dogs' representative trials to obtain respective group values. All forces and impulses were normalized by percent body mass for comparison purposes.

**Statistics**

Descriptive statistics were calculated for age, height, and mass of the dogs in the control and amputee groups. Values for each parameter were compared between amputee and control groups using independent measures t-tests. Once t-tests were complete, a Bonferroni adjustment was made on the alpha value for each parameter based on the number of different sub-parameters associated with each. Differences for age, height, and mass were considered significant for $P<0.05/n$ where $n=3$. 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 exams before gait analysis.

For the control group, the left and right sides were determined to have no significant differences using repeated measures t-tests ($P>0.05/n$; $n=4$ accounting for maximum, minimum, average, and range values of each variable). Therefore, the front two limbs and the hind two limbs were averaged to obtain representative values for each parameter for a control front limb and a control hind limb, respectively. The majority of the data for each parameter in each group were found to be normal using the Shapiro-Wilk test. Each amputee limb was then individually compared against the controls using independent measure t-tests. In addition, the contralateral and ipsilateral limbs in the amputees were compared to each other using repeated measures t-tests to determine any significant differences. Peak GRFs and times to peak GRF with vertical, braking, and propulsion components as well as weight distribution were significant for $P<0.05/n$ where $n=3$. Kinetic impulses with vertical, braking, propulsion, and craniocaudal (net braking/propulsion) components as well as kinematic variables with an average, maximum, minimum, and range, were considered significant for $P<0.05/n$ where $n=4$. Stance durations, stride lengths, stance widths, and velocity were also considered significant for $P<0.05/n$ where $n=4$.

# IV. RESULTS

## Subjects

Of the dogs enrolled in the study, 17 thoracic limb amputees (Table IV-I) and 24 control dogs (Table IV-II) were included in analysis. The dogs excluded from analysis (2 amputees and 7 controls) did not have the minimum of three trials of data needed for analysis due to long fur obstructing markers or failure to acclimate to the laboratory and markers. There were no significant differences in average body mass or wither height between the amputees and the control group ($p \geq 0.21$), however there was a significant difference in age ($p = 0.02$) where the amputees were slightly older (Table IV-I and Table IV-II).

**Table IV-I Thoracic limb amputee group signalment.**

| Patient ID | Breed | Sex | Age (years) | Wither Height (cm) | Mass (kg) |
|---|---|---|---|---|---|
| 1 | Mixed breed | MC | 5.7 | 64.8 | 25.2 |
| 2 | Mixed breed | MC | 6.7 | 72.4 | 42.3 |
| 3 | Australian shepherd | MC | 7.7 | 59.7 | 32.5 |
| 4 | Mixed breed | MC | 9.2 | 58.4 | 30.1 |
| 5 | Mixed breed | FS | 11.9 | 63.5 | 33.6 |
| 6 | Great Dane | FS | 6.2 | 80.0 | 51.3 |
| 7 | Labrador retriever | MC | 9.2 | 63.5 | 55.8 |
| 8 | Boxer | FS | 1.7 | 53.3 | 16.6 |
| 9 | Mixed breed | FS | 9.2 | 54.6 | 42.4 |
| 10 | Labrador retriever | FS | 7.8 | 63.5 | 35.0 |
| 11 | Labrador retriever | FS | 10.3 | 62.2 | 37.5 |
| 12 | Mixed breed | MC | 11.1 | 64.8 | 29.5 |
| 13 | Border collie | FS | 13.5 | 55.9 | 23.3 |
| 14 | Golden retriever | FS | 8.2 | N/A | 36.1 |
| 15 | Portuguese waterdog | MC | 9.3 | 52.1 | 26.8 |
| 16 | Greyhound | MC | 10.3 | 71.1 | 29.2 |
| 17 | Coonhound | FS | 9.0 | N/A | 22.6 |
| **Average** | | | 8.7 | 62.7 | 33.5 |
| **Standard Deviation** | | | 2.7 | 7.6 | 10.2 |
| **Maximum** | | | 13.5 | 80.0 | 55.8 |
| **Minimum** | | | 1.7 | 52.1 | 16.6 |
| **Range** | | | 11.9 | 27.9 | 39.2 |

FS = female spayed, MC = male castrated, N/A = not available

**Table IV-II. Control group signalment.**

| Subject ID | Breed | Sex | Age (years) | Wither Height (cm) | Mass (kg) |
|---|---|---|---|---|---|
| 1 | Bull mastiff | FS | 7.3 | 61.0 | 43.5 |
| 2 | Mixed breed | FS | 9.1 | 59.7 | 20.0 |
| 3 | Staffordshire terrier | MC | 5.1 | 54.6 | 28.6 |
| 4 | Mixed breed | MC | 9.1 | 58.4 | 37.1 |
| 5 | Mixed breed | FS | 6.8 | 67.3 | 35.1 |
| 6 | Labrador retriever | FS | 4.1 | 57.2 | 29.3 |
| 7 | Labrador retriever | FI | 6.0 | 50.8 | 25.7 |
| 8 | Weimaraner | MC | 5.7 | 61.0 | 30.0 |
| 9 | German shepherd | MC | 8.1 | 69.9 | 39.8 |
| 10 | Labrador retriever | FS | 12.1 | 57.2 | 34.3 |
| 11 | Labrador retriever | MI | 3.6 | 57.2 | 32.0 |
| 12 | Labrador retriever | FS | 1.0 | 59.7 | 21.1 |
| 13 | American bulldog | FS | 2.9 | 63.5 | 37.8 |
| 14 | Mixed breed | MC | 2.4 | 61.0 | 64.0 |
| 15 | Labrador retriever | FS | 6.5 | 53.3 | 33.2 |
| 16 | Mixed breed | MC | 3.0 | 64.8 | 38.3 |
| 17 | Great Dane | MC | 10.1 | 77.5 | 50.9 |
| 18 | Dalmatian | FS | 7.9 | 54.6 | 25.1 |
| 19 | Border collie | MC | 6.3 | 54.6 | 27.7 |
| 20 | Golden retriever | FS | 12.3 | 52.1 | 28.7 |
| 21 | Mixed breed | FS | 10.0 | 53.3 | 24.4 |
| 22 | Rottweiler | FS | 3.1 | N/A | 32.7 |
| 23 | German wirehaired pointer | MC | 5.1 | 61.0 | 14.6 |
| 24 | Golden retriever | MC | 3.7 | 61.0 | 33.9 |
| **Average** | | | 6.3 | 59.6 | 32.8 |
| **Standard Deviation** | | | 3.4 | 7.5 | 12.3 |
| **Maximum** | | | 12.3 | 77.5 | 64.0 |
| **Minimum** | | | 1.0 | 50.8 | 14.6 |
| **Range** | | | 11.3 | 26.7 | 49.4 |

FS = female spayed, FI = female intact, MC = male castrated, MI = male intact, N/A = not available

Subject 4 was the only dog that participated first as a control dog, and later as an amputee. The majority of the amputee group had limb amputations as a result of osteosarcoma in the radius or humerus of the thoracic limb (Table IV-III). However, two dogs had limb amputations as a result of soft tissue sarcoma in the thoracic limb.

**Table IV-III. Causes and locations of amputation for each dog.**

| Subject ID | Reason for Amputation | Location | Days Since Amputation |
|---|---|---|---|
| 1 | osteosarcoma | L proximal humerus | 213 |
| 2 | osteosarcoma | L proximal humerus | 94 |
| 3 | osteosarcoma | L distal radius | 159 |
| 4 | soft tissue sarcoma | L antebrachium | 39 |
| 5 | osteosarcoma | L distal radius | 169 |
| 6 | osteosarcoma | R distal radius | 28 |
| 7 | osteosarcoma | L proximal humerus | 35 |
| 8 | osteosarcoma | R distal radius | 62 |
| 9 | osteosarcoma | L distal radius | 98 |
| 10 | osteosarcoma | R distal radius | 37 |
| 11 | osteosarcoma | L proximal humerus | 57 |
| 12 | osteosarcoma | L distal radius | 54 |
| 13 | osteosarcoma | R proximal humerus | 41 |
| 14 | soft tissue sarcoma | R distal limb | 217 |
| 15 | osteosarcoma | R distal radius | 55 |
| 16 | osteosarcoma | L distal radius | 84 |
| 17 | osteosarcoma | R distal radius | 124 |
| **Average** | | | 92 |
| **Standard Deviation** | | | 63 |
| **Maximum** | | | 217 |
| **Minimum** | | | 28 |
| **Range** | | | 189 |

Complete physical examination findings for each dog in the amputee and control groups are presented in Appendix II. A summary of the number of dogs exhibiting clinical pathologies to a degree that would not generally be considered by most clinicians as a contraindication for amputation is shown in Figure IV-I for the neurologic system, spine, and joints of the thoracic and pelvic limbs. The total numbers of abnormalities specifically found in each forelimb amputee are compiled in Figure IV-II. The control group had a similar distribution of total number of abnormalities ranging from 0 to 8 total abnormalities in each dog. Control subjects 2-3, 6-7, 10-14, and 22-24 had two abnormalities or less, while subjects 1, 4-5, 8-9, 17, and 19-20 had 3-5 abnormalities, and subjects 15, 18, and 21 had 6-8 abnormalities present.

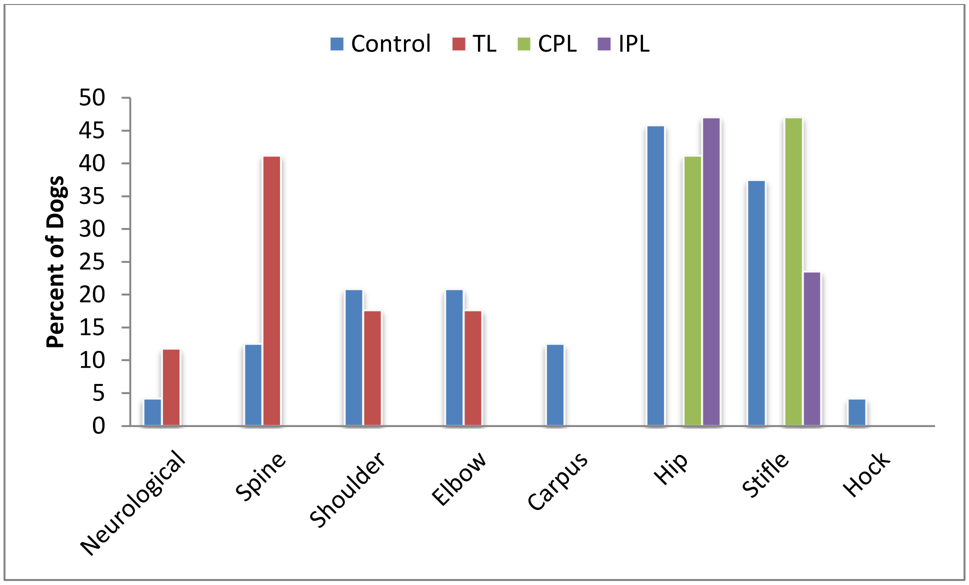


**Figure IV-I. Percentage of dogs in each group with impairments to the neurologic system, spine, and limb joints determined immediately prior to gait analysis based on physical examination. Values for the control group are a percentage of total number of controls (24 dogs), and values for the amputee limbs are a percentage of the total number of amputees (17 dogs). TL = thoracic limb, CPL = contralateral pelvic limb, IPL = ipsilateral pelvic limb.**

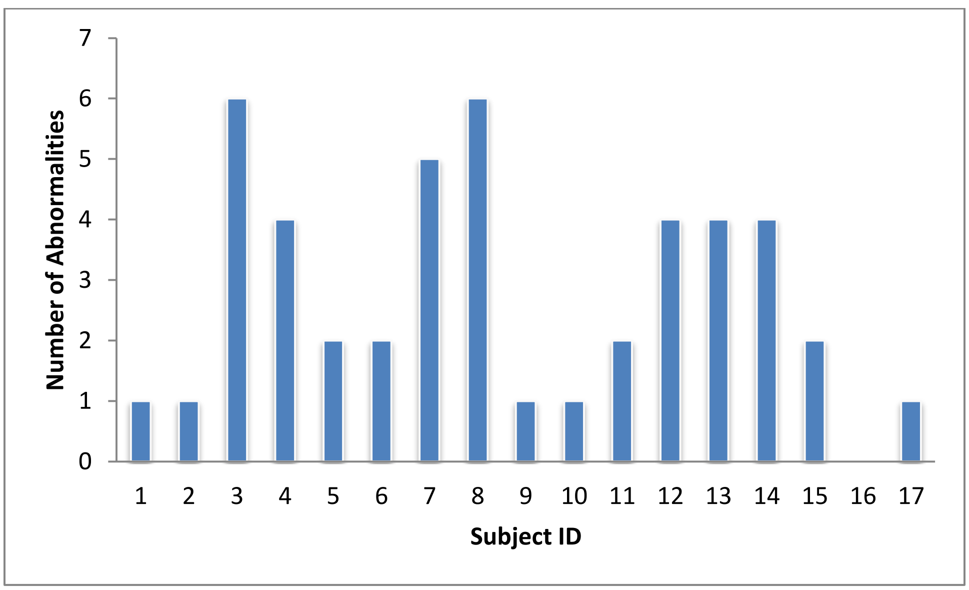


**Figure IV-II. Cumulative number of abnormalities in the neurologic system, spine, and limbs compiled for each thoracic limb amputee as determined immediately prior to gait analysis based on physical examination.**

**Kinetic Data**

Not all dogs were able to maintain velocities in the 2.2-2.6 m/s range and achieve successful paw strikes. Since this was particularly an issue for the amputees, individual trials for a given dog slightly outside of the specified velocity range were kept if they were within ± 0.4 m/s of each other. The true velocity ranges were 1.97-2.57 m/s for the controls and 1.87-2.71 m/s for the amputees. No significant differences were found in average trotting velocity (2.29 ± 0.15 m/s for controls, 2.18 ±0.28 m/s for amputees) between the control and amputee groups ($p = 0.11$).

Peak braking GRFs were greater in the remaining thoracic limb ($p < 0.001$) and the ipsilateral pelvic limb ($p = 0.003$) of the amputees when compared to control thoracic limbs and pelvic limbs, respectively (Table IV-IV). Peak propulsion GRF was found to be greater than control pelvic limbs in the ipsilateral pelvic limb only ($p = 0.003$). Time to peak braking GRF was significantly smaller in each limb while time to peak propulsion GRF was significantly greater in each limb compared to the corresponding limbs of the control group ($p < 0.001$). Within the amputee group, the contralateral pelvic limb was also found to have a significantly greater time to peak braking GRF when compared to the ipsilateral pelvic limb ($p = 0.005$). Compared to the control thoracic limb, the propulsion impulse was smaller in the amputee thoracic limb ($p = 0.003$), but greater than controls in both of the amputee pelvic limbs ($p \leq 0.005$). The net craniocaudal impulse was significantly greater in the amputee thoracic limb and ipsilateral pelvic limb showing increased net braking on the thoracic limb, and increased net propulsion on the ipsilateral pelvic limb, compared to the controls ($p < 0.001$).

Thoracic limb amputees in comparison to controls were found to have significantly decreased stance durations and significantly greater vertical impulses in all limbs ($p \leq 0.001$). Overlap between paw strikes was a common issue for the amputees unlike the control group, particularly with respect to the ipsilateral pelvic limb (Figure IV-III and Figure IV-IV). The remaining values were not different between the control group and the amputee group ($p \geq 0.013$), or between the two pelvic limbs of the amputee group ($p \geq 0.025$).

**Table IV-IV. Mean (SD) kinetic output parameters for thoracic limb amputees and control dogs at a trot.**

| | CONTROLS | | AMPUTEES | | |
|---|---|---|---|---|---|
| | TL | PL | TL | CPL | IPL |
| **Peak Vertical GRF** | 113.62 (16.37) | 74.08 (16.06) | 122.77 (31.78) | 76.74 (23.20) | 80.99 (20.87) |
| **Peak Braking GRF** | -15.67 (2.80) | -5.53 (2.28) | -28.82 (9.18)* | -7.74 (5.62) | -9.67 (5.64)* |
| **Peak Prop. GRF** | 9.15 (3.38) | 10.80 (3.80) | 6.47 (4.07) | 13.60 (6.95) | 16.45 (6.97)* |
| **TTP Vertical GRF** | 0.11 (0.02) | 0.09 (0.01) | 0.12 (0.03) | 0.09 (0.02) | 0.08 (0.02) |
| **TTP Braking GRF** | 0.13 (0.04) | 0.08 (0.03) | 0.07 (0.02)* | 0.04 (0.02)*‡ | 0.02 (0.01)* |
| **TTP Prop. GRF** | 0.11 (0.04) | 0.07 (0.03) | 0.19 (0.06)* | 0.15 (0.04)* | 0.15 (0.02)* |
| **Vertical Impulse** | 15.45 (3.09) | 8.83 (2.11) | 20.62 (5.24)† | 12.10 (3.48)† | 12.06 (3.33)† |
| **Cr/Cd Impulse** | -0.64 (0.29) | 0.68 (0.44) | -2.34 (0.91)† | 1.03 (0.83) | 1.60 (0.73)† |
| **Braking Impulse** | -1.15 (0.23) | -0.18 (0.09) | -1.87 (1.40) | -0.33 (0.48) | -0.23 (0.18) |
| **Prop. Impulse** | 0.51 (0.30) | 0.86 (0.42) | -0.46 (1.43)† | 1.37 (0.62)† | 1.82 (0.73)† |
| **Stance Dur.** | 0.23 (0.03) | 0.20 (0.02) | 0.27 (0.04)* | 0.27 (0.04)* | 0.24 (0.04)* |

Peak GRFs normalized to body mass (N/kg), Time to peak (TTP) GRFs (seconds), Impulses (Ns/kg)
TL = thoracic limb, PL = pelvic limb, CPL = contralateral pelvic limb, IPL = ipsilateral pelvic limb
Cr/Cd = net cranial/caudal impulse
P<0.05/n where *n=3 compared to controls, †n=4 compared to controls, ‡n=3 CPL compared to IPL

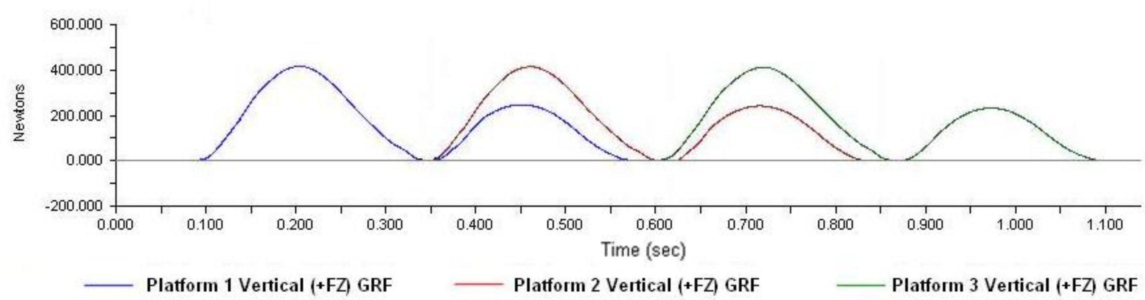


**Figure IV-III. Representative single trial vertical GRF plot of a control dog single trial. Strike patterns on each force platform begin with a thoracic limb, followed by the ipsilateral pelvic limb. Note that the GRF magnitudes have not been normalized to body mass.**

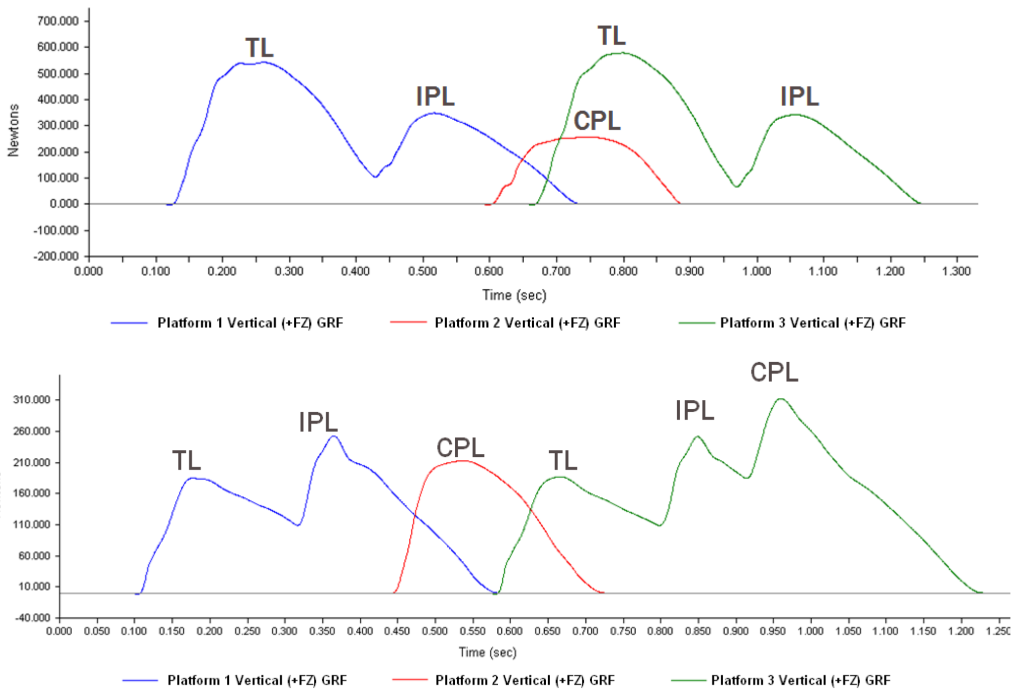


**Figure IV-IV. Representative vertical GRF plot for two different thoracic limb amputees. Strike patterns on each force platform are indicated where TL = thoracic limb, IPL = ipsilateral pelvic limb, and CPL = contralateral pelvic limb. Note that the GRF magnitudes have not been normalized to body mass.**

Weight distribution was calculated by dividing the average peak vertical GRF of each limb by the total average peak vertical GRF of all limbs, as previously described.[18] Amputees were shown to have significantly increased weight distribution to all limbs when compared to the controls ($p < 0.001$) (Table IV-V). No significant difference was seen between the contralateral and ipsilateral pelvic limbs within the amputee group ($p = 0.170$). The resulting combined weight distribution to the pelvic limbs was 55. 9%.

**Table IV-V. Mean (SD) mass distribution of the control and amputee group as a percentage of total body mass.**

| | CONTROLS | | AMPUTEES | | |
|---|---|---|---|---|---|
| | **TL** | **PL** | **TL** | **CPL** | **IPL** |
| **% Distribution** | 30.4 (2.1) | 19.7 (2.1) | 44.1 (5.8)* | 27.0 (3.9)* | 28.9 (3.2)* |
| **% Increase From Controls** | | | 13.8 | 7.3 | 9.3 |

*P<0.05/n; n=3 compared to controls. No significant differences within amputee group.
TL = thoracic limb, PL = pelvic limb, CPL = contralateral pelvic limb, IPL = ipsilateral pelvic limb
% Distribution for controls are averages of the right and left limbs

**Kinematic Data**

*Limb Kinematics*

During the stance phase of the thoracic limb, a significantly increased range of motion was seen in the amputee carpal joint when compared to controls (p = 0.011), primarily due to greater extension during stance (Table IV-VI). The remaining limb joint angles during thoracic limb stance were not different between groups (p ≥ 0.043).

**Table IV-VI. Mean (SD) thoracic limb sagittal plane joint angles during stance.**

| Joint | Group | Avg (deg) | Max (deg) | Min (deg) | Range (deg) |
|---|---|---|---|---|---|
| **Carpus** | **Control** | 148.44 (10.03) | 169.97 (7.74) | 133.08 (13.49) | 36.97 (10.69) |
| | **Amputee** | 141.15 (10.29) | 170.62 (6.16) | 123.54 (10.38) | 47.08 (8.89)* |
| **Elbow** | **Control** | 138.74 (12.02) | 156.36 (12.27) | 123.04 (12.86) | 33.32 (8.57) |
| | **Amputee** | 136.52 (12.30) | 158.91 (12.52) | 119.18 (12.78) | 39.73 (10.36) |
| **Shoulder** | **Control** | 135.03 (12.87) | 152.22 (13.10) | 126.18 (13.20) | 26.04 (6.92) |
| | **Amputee** | 138.37 (13.82) | 154.83 (8.88) | 125.19 (15.77) | 26.64 (11.68) |

*P<0.05/n; n=4 compared to controls. No significant differences within amputee group

Significant differences in ranges of motion during the stance phase were seen at the ipsilateral hip and stifle due to smaller minimum joint angles indicating increased flexion when compared to controls (p ≥ 0.003) (Table IV-VII). Within the amputee group there was also a significantly greater range of motion in the ipsilateral stifle which indicated an increase in flexion compared to the contralateral stifle (p = 0.003).

**Table IV-VII. Mean (SD) pelvic limb sagittal plane joint angles during stance.**

| Joint | Limb | Avg (deg) | Max (deg) | Min (deg) | Range (deg) |
|---|---|---|---|---|---|
| **Hock** | **Control** | 131.20 (9.61) | 156.94 (8.22) | 112.86 (9.65) | 44.08 (5.86) |
| | **Amp CPL** | 133.07 (11.00) | 159.04 (9.18) | 114.16 (12.52) | 44.88 (10.31) |
| | **Amp IPL** | 125.59 (10.32) | 155.13 (8.99) | 105.30 (11.05) | 49.83 (6.76) |
| **Stifle** | **Control** | 127.75 (10.85) | 144.52 (10.84) | 119.75 (11.90) | 24.77 (5.10) |
| | **Amp CPL** | 125.59 (12.87) | 141.07 (13.96) | 116.10 (12.22) | 24.98 (5.61) |
| | **Amp IPL** | 116.31 (14.40) | 141.60 (12.04) | 104.24 (16.72)* | 37.36 (8.39)*† |
| **Hip** | **Control** | 112.12 (10.29) | 124.48 (10.22) | 100.55 (9.63) | 23.94 (3.98) |
| | **Amp CPL** | 108.13 (13.63) | 118.87 (15.07) | 96.58 (11.89) | 22.29 (7.50) |
| | **Amp IPL** | 108.91 (11.37) | 121.26 (9.97) | 92.57 (11.77) | 28.68 (3.91)* |

CPL = contralateral pelvic limb, IPL = ipsilateral pelvic limb
P<0.05/n where *n=4 compared to controls, †n=4 CPL compared to IPL

Stance widths and stride lengths were not found to be significantly different when compared to controls (p ≥ 0.017). No significant differences were found in either stance width or stride length when comparing the two pelvic limbs within the amputee group (p = 0.054) (Table IV-VIII).

**Table IV-VIII. Mean (SD) stance widths and stride lengths.**

| Limb | | Stance Width (m) | Stride Length (m) |
|---|---|---|---|
| **TL** | **Control** | 0.06 (0.03) | 1.16 (0.10) |
| | **Amputee** | 0.05 (0.03) | 1.12 (0.15) |
| **PL** | **Control** | 0.03 (0.03) | 1.13 (0.10) |
| | **Amp CPL** | 0.03 (0.02) | 1.13 (0.01) |
| | **Amp IPL** | 0.02 (0.03) | N/A |

CPL = contralateral pelvic limb, IPL = ipsilateral pelvic limb, N/A = not available
No significant differences for P<0.05/n; n=3 compared to controls or within amputee group

*Spinal Kinematics*

During the stance phase of the thoracic limb, no significant differences (p ≥ 0.024) in spinal motion were seen between the controls and amputees in the horizontal plane (Table IV-IX). In the sagittal plane, the T1 joint angle had a significantly lower minimum angle during the stance phase of the thoracic limb (Table IV-X), which resulted in a significantly greater range of motion due to increased extension in amputees compared to controls (p < 0.001). The remaining joint angles during thoracic limb stance in the sagittal plane were not significantly different compared to the controls (p ≥ 0.024) or between amputee pelvic limbs (p ≥ 0.014).

**Table IV-IX. Mean (SD) spinal joint angles in the horizontal plane during the stance phase of the thoracic limb.**

| Region | Group | Avg (deg) | Max (deg) | Min (deg) | Range (deg) |
|---|---|---|---|---|---|
| **T1** | **Control** | 183.00 (10.45) | 190.05 (10.66) | 175.67 (11.43) | 16.42 (9.12) |
| | **Amputee** | 182.41 (12.56) | 192.20 (13.38) | 169.08 (12.22) | 23.22 (7.18) |
| **T13** | **Control** | 179.21 (7.37) | 188.22 (8.70) | 169.84 (6.86) | 18.38 (7.27) |
| | **Amputee** | 179.00 (6.06) | 188.76 (4.92) | 171.15 (8.17) | 17.61 (5.86) |
| **L7** | **Control** | 180.01 (7.55) | 185.62 (7.21) | 174.75 (8.64) | 10.87 (4.94) |
| | **Amputee** | 175.80 (3.90) | 184.39 (5.98) | 169.63 (5.59) | 14.75 (8.09) |

No significant differences for P<0.05/n; n=4 compared to controls or within amputee group

**Table IV-X. Mean (SD) spinal joint angles in the sagittal plane during the stance phase of the thoracic limb.**

| Region | Group | Avg (deg) | Max (deg) | Min (deg) | Range (deg) |
|---|---|---|---|---|---|
| **T1** | **Control** | 178.31 (5.52) | 181.79 (5.63) | 174.05 (5.70) | 7.73 (2.55) |
| | **Amputee** | 173.73 (8.08) | 181.98 (8.96) | 162.11 (9.00)* | 19.87 (6.21)* |
| **T13** | **Control** | 176.23 (5.32) | 179.69 (5.17) | 173.17 (5.78) | 6.52 (1.78) |
| | **Amputee** | 178.63 (6.06) | 182.60 (5.86) | 174.32 (6.51) | 8.28 (2.33) |
| **L7** | **Control** | 195.37 (3.30) | 200.12 (3.96) | 191.45 (4.01) | 8.67 (4.00) |
| | **Amputee** | 197.09 (3.71) | 202.70 (4.02) | 191.61 (4.40) | 11.08 (3.78) |

*P<0.05/n; n=4 compared to controls. No significant differences within amputee group

In the horizontal plane, a significantly larger range of motion (p = 0.002) was found at T1 during the stance phase of the contralateral pelvic limb for the amputees primarily due to slightly higher maximum and slightly smaller minimum joint angles (Table IV-XI). This also resulted in a significantly smaller average joint angle (p = 0.006), indicating lateral flexion toward the side of amputation. A significantly smaller range of motion was found at the T13 joint due to a significantly larger minimum joint angle (p ≤ 0.001). This indicates that the T13 region has less lateral bending toward the side of amputation during contralateral pelvic limb stance.

During the stance phase of the ipsilateral pelvic limb, T1 had a significantly smaller average joint angle (p = 0.012) indicating increased lateral flexion toward the side of amputation. As with the T1 joint during contralateral pelvic limb stance, T13 also had a significantly larger range of motion during ipsilateral pelvic limb stance due to a significantly smaller minimum joint angle (p ≤ 0.002). The remaining joint angle values in the horizontal plane during the stance phases of the pelvic limbs were not significantly different compared to the controls (p ≥ 0.018) or between the pelvic limbs within the amputee group (p ≥ 0.037).

**Table IV-XI. Mean (SD) spinal joint angles in the horizontal plane during the stance phase of the pelvic limbs.**

| Joint | Limb | Avg (deg) | Max (deg) | Min (deg) | Range (deg) |
|---|---|---|---|---|---|
| **T1** | **Control** | 184.12 (11.17) | 190.46 (11.43) | 177.85 (11.43) | 12.61 (5.79) |
| | **Amp CPL** | 173.39 (10.42)* | 194.77 (11.45) | 175.03 (10.86) | 19.74 (7.60)* |
| | **Amp IPL** | 172.97 (12.31)* | 193.30 (12.11) | 181.71 (12.58) | 11.59 (3.71) |
| **T13** | **Control** | 179.18 (7.01) | 187.48 (8.27) | 170.67 (6.62) | 16.81 (6.43) |
| | **Amp CPL** | 181.11 (4.91) | 185.50 (5.77) | 177.46 (4.74)* | 8.05 (2.38)* |
| | **Amp IPL** | 181.73 (4.41) | 185.92 (4.81) | 178.10 (4.05)* | 7.82 (2.85)* |
| **L7** | **Control** | 178.79 (10.73) | 184.03 (9.80) | 173.76 (11.63) | 10.27 (5.06) |
| | **Amp CPL** | 169.92 (16.56) | 174.87 (15.98) | 164.91 (17.07) | 9.96 (4.23) |
| | **Amp IPL** | 171.38 (19.84) | 176.43 (18.84) | 166.83 (20.08) | 9.60 (6.11) |

CPL = contralateral pelvic limb, IPL = ipsilateral pelvic limb
P<0.05/n where *n=4 compared to controls

During the stance phase of the contralateral pelvic limb, a significantly smaller minimum joint angle in the sagittal plane resulted in a significantly smaller average angle and significantly larger range of motion ($p \leq 0.011$) indicating increased extension at the T1 joint (Table IV-XII). Significant differences were also found at the T13 and L7 joints where amputees had larger maximum joint angles, a larger range of motion (T13 only), and a larger average joint angle (L7 only) in the sagittal plane when compared to controls ($p \leq 0.011$). These differences indicate increased flexion at the T13 and L7 joints.

**Table IV-XII. Mean (SD) spinal joint angles in the sagittal plane during the stance phase of the pelvic limbs.**

| Joint | Limb | Avg (deg) | Max (deg) | Min (deg) | Range (deg) |
|---|---|---|---|---|---|
| **T1** | **Control** | 178.05 (5.29) | 180.95 (5.25) | 174.03 (5.52) | 6.92 (1.81) |
| | **Amp CPL** | 172.02 (8.63)* | 182.33 (10.02) | 162.59 (8.83)* | 19.74 (7.60)* |
| | **Amp IPL** | 168.55 (9.15)* | 174.39 (8.46)* | 164.00 (9.67)* | 10.39 (4.05)*† |
| **T13** | **Control** | 175.73 (5.21) | 179.03 (5.08) | 173.14 (5.50) | 5.89 (1.42) |
| | **Amp CPL** | 179.73 (5.04) | 183.56 (4.87)* | 175.52 (6.01) | 8.05 (2.38)* |
| | **Amp IPL** | 178.44 (4.48) | 182.56 (4.44) | 174.74 (4.97) | 7.82 (2.85)* |
| **L7** | **Control** | 194.70 (3.52) | 198.98 (3.92) | 191.03 (4.10) | 7.95 (3.53) |
| | **Amp CPL** | 198.34 (4.61)* | 203.26 (5.56)* | 193.30 (4.06) | 9.96 (4.23) |
| | **Amp IPL** | 200.36 (4.38)*† | 204.54 (5.92)* | 194.94 (4.49) | 9.60 (6.11) |

CPL = contralateral Pelvic limb, IPL = ipsilateral pelvic limb
P<0.05/n where *n=4 compared to controls, †n=4 CPL compared to IPL

During the stance phase of the ipsilateral pelvic limb, the T1 joint had a smaller maximum and minimum joint angle in the sagittal plane resulting in a smaller average joint angle and greater range of motion ($p \le 0.008$) showing increased extension (Table IV-XII). The range of motion was also significantly greater at the T13 joint, while significantly larger average and maximum joint angles were seen at the L7 joint ($p \le 0.011$), indicative of increased flexion. In comparing the two pelvic limbs within the amputee group, the T1 joint had an increased range of motion while the L7 joint had a higher average angle during ipsilateral pelvic limb stance ($p \le 0.002$). This indicates amputees had increased extension at T1 and increased flexion at L7 in the ipsilateral pelvic limb stance phase compared to the contralateral pelvic limb stance phase. The remaining joint angle values in the sagittal plane during the stance phases of the pelvic limbs were not significantly different compared to the controls ($p \ge 0.016$) or between pelvic limbs within the amputee group ($p \ge 0.014$).

# V. DISCUSSION

In an effort to better understand how dogs compensate for the loss of a limb, this study objectively characterized the changes in gait associated with amputation of a thoracic limb. Ground reaction forces, impulses, and stance times were significantly different in all limbs, with the remaining thoracic limb and ipsilateral pelvic limb most affected. Limb angular kinematics revealed significant differences in motion at the carpus and ipsilateral hip and stifle, while spinal angular kinematics indicated increased motion in both horizontal and sagittal planes throughout the various stance phases. The hypotheses supported in this study were that removal of a thoracic limb results in significant changes in motion of both the spine and limb joint angles. Stance width was also expected to change significantly in all limbs, but this was not the case in any limb. Weight distribution increased in all limbs as hypothesized, however stance duration increased rather than decreased while peak vertical GRFs remained unchanged.

Kinetic analysis revealed increased stance durations along with increased vertical impulse in all limbs. This indicates that an increased force is applied in each limb for a longer duration of time. Cartilage degradation has been shown to progress at a faster rate with increased load during cyclic movements such as walking.[51] This is a particular concern for dogs that already show signs of osteoarthritis in another limb prior to amputation. An inverse relation between stance time and peak vertical force has been found in normal dogs at both a walk and a trot.[52,54,55] However, another study found later that in thoracic limb amputees, stance duration decreased without an increase in peak vertical force,[18] and in our study we found that stance time increased without a decrease in peak vertical force. These changes indicate that thoracic limb amputees adopt different compensation strategies that may depend on gait velocity. The differences found in our results compared to Kirpensteijn et al.[18] could also be related to differences in dog groups. While they compared mixed breeds to clinically normal Labrador retrievers, our study compared two similar groups of large breed dogs that also exhibited a number of clinical abnormalities in the limbs and spine representative of a typical group that may undergo limb amputation.

Peak braking GRF increased significantly in both the thoracic limb and ipsilateral pelvic limb without increases in braking impulse. While only the ipsilateral pelvic limb had an increase in peak propulsive GRF, propulsive impulses decreased significantly in the remaining thoracic limb, and increased significantly in both pelvic limbs. The net craniocaudal impulse was also significantly higher in the thoracic limb and ipsilateral pelvic limb, indicating significantly more braking with the thoracic limb and significantly more propulsion with the ipsilateral pelvic limb. Normally, dogs use the thoracic limbs primarily for braking and the pelvic limbs primarily for propulsion.[52,54,58] In the case of a thoracic limb amputation, the dog compensates for the loss of braking primarily with the remaining thoracic limb and ipsilateral pelvic limb, while the ipsilateral pelvic limb also compensates the most for the loss of propulsion. Therefore, the ipsilateral pelvic limb is in a sense acting like a thoracic limb while still functioning as a hindlimb.

It was hypothesized that stance widths would be significantly decreased in the remaining thoracic limb, and significantly increased in both pelvic limbs as the dog maintains balance with an altered center of mass after amputation. This hypothesis was not supported, as all limbs maintained stance widths equivalent to that seen in the control group. Stance widths were measured based on the lateral distance between the center of pressure of the paw and either the ipsilateral scapula marker (thoracic limb stance width) or the ipsilateral ilium marker (pelvic limb stance width). The fact that no significant differences were seen in stance width may be in part due to this unconventional method of defining stance width as it would normally be measured as the lateral distance between two paws. Since each stance width was based on two points within the same limb, true stance width may be masked by the relative locations of the center of pressure and scapula/ilium marker. If the center of pressure is in fact changing significantly in the lateral direction, it could be that the scapula/ilium marker moves to the same degree. Defining the stance widths based on a spinal marker was considered as a possible option. However, it was unknown to what degree amputees compensate in spinal motion, and thus stance widths based on centers of pressure and scapula/ilium markers were deemed the best option. It is also interesting to note that while no differences were found in stride lengths, adequate data for analysis of stride length in the ipsilateral pelvic limb was not available. This is because in order to get a stride length, the ipsilateral pelvic limb had to have a valid paw strike on both the first and third force platforms. Very few amputees were able to accomplish this as the majority of the time the ipsilateral pelvic limb had significant overlap with the remaining thoracic limb and/or contralateral pelvic limb.

Weight distribution was significantly different in each limb compared to the controls where the remaining thoracic limb carried 44.1% of bodyweight and the pelvic limbs carried 55.9% of bodyweight with no significant difference between the contralateral and ipsilateral pelvic limbs. This is consistent with what has previously been reported for thoracic limb amputees.[18]

In the remaining thoracic limb, only the carpus exhibited a significant increase in range of motion compared to controls. As the paw contacts the ground, the carpus extends to a much greater degree due to the increased weight distribution and ground reaction forces experienced by that limb. It was expected that the elbow and shoulder would show similar increases in ranges of motion. However, the fact that they do not may be a result of stronger muscles stabilizing those joints, differences in the abilities of the ligaments to accommodate changes in range of motion, or differences in how the bones articulate with each other as compared to the carpus. In the pelvic limbs, the ipsilateral hip and stifle joints had increased ranges of motion due to greater flexion during stance, while the hock showed no significant differences. Although no significant differences were seen in the weight distribution between the ipsilateral and contralateral pelvic limbs, the ipsilateral pelvic limb did have a greater magnitude of weight distribution and could be a contributing factor as to why only the ipsilateral pelvic limb had greater ranges of motion in the hip and stifle. It could, however, also be due to the increased peak braking GRF on the ipsilateral pelvic limb as this was not a significant parameter for the contralateral pelvic limb.

The T1 joint angle had significantly greater ranges of motion during the stance phases of each limb in both the sagittal and horizontal planes, with the exception of thoracic limb stance in the horizontal plane. However, during data collection it appeared that the T1 marker may have had the greatest movement artifact error associated with it, particularly in the horizontal plane, although artifact error was not specifically evaluated in this study. Movement of the soft tissue covering the T1 joint can be quite significant in some dogs, especially when the head is elevated. Additionally, the T1 marker was positioned very close to the collar in some dogs which could have induced excess movement of the T1 marker while trotting. In order to minimize artifact error, the markers were attached as close to the skin as possible and the dog handler was instructed not to pull on the leash. While marker motion artifact error may be resulting in greater observed ranges of motion than what is truly characteristic of these dogs, this was an issue common to both the amputee and control groups. Artifact error can be reduced by using invasive methods for marker attachment directly to the bone. However, this was not considered as a feasible option for the present study as these dogs were client-owned, and such methods can result in pain and inflammation at the site where the markers are attached and could have a significant impact on gait patterns.[61,62]

The T13 and L7 joint angles were not significantly different compared to controls during thoracic limb stance in either the sagittal or the horizontal plane, but they were significant during the pelvic limb stance phases. In particular, during the stance phases of the pelvic limbs, T13 had greater range of motion in the sagittal plane, while L7 operated at a higher average joint angle with a similar range of motion compared to controls. In the horizontal plane, the T13 region exhibited decreased range of motion with less lateral flexion, while L7 had no significant differences. With spinal motion changing most notably during the pelvic limb stance phases, it may be that the increased flexion in the ipsilateral hip and stifle as well as the increased peak GRFs are causing the dog to arch its back into a more extended position at these points in the gait cycle. Furthermore, the thoracic limb needs to be able to clear the ground in going from one stance phase to the next, so in the absence of another thoracic limb, the hindlimbs must elevate the body more which subsequently alters spinal motion, particularly in the sagittal plane. With increased motion in the spine, amputees could be more susceptible to muscle strain as a result of high eccentric contractions stabilizing those joints.[64]

In general, the T1 joint angles tend to flex toward the side of amputation during thoracic limb stance, and in the opposite direction during the stance phase of the ipsilateral pelvic limb.

However, there is no clear trend throughout the various stance phases in the direction of lateral movement at T13 and L7 with respect to side of amputation. For example, some left thoracic limb amputees had a slight increase in flexion to the right at T13, while other left thoracic limb amputees had slight increases in flexion to the left at T13 during the same stance phase. This was true of the right thoracic limb amputees as well. Lateral movement of the spine in any direction may still have a significant impact over time as it could affect muscular control of spinal motion[64] and potentially lead to increased cartilage degradation.[51]

The most important outcome of this study is to provide clinicians with information that will allow them to make more objective decisions on the appropriateness of amputation for a given patient. In thoracic limb amputees, all limbs are affected by altered GRFs and stance times, particularly the remaining thoracic limb and ipsilateral pelvic limb. Furthermore, the carpus and ipsilateral hip and stifle, as well as each of the spinal regions (T1, T13, and L7) had increased ranges of motion throughout the stance phases of each limb. Signs of osteoarthritis already present in one of the limbs will progress at an even faster rate after amputation due to the increased loading in each limb.[34,51] Susceptibility to acute injury may also increase at these locations as altered kinematics change the way load passes through the joints and how the muscles act to stabilize them.[34-36,41] The increased spinal motion could have damaging effects as well leading to spondylosis and osteophyte formation, as well as increased susceptibility to eccentric contractions that may result in muscle strain.[64] Therefore, any clinical pathologies in one of these joints prior to amputation should be taken into consideration before making the decision to amputate.

All but 5 control dogs and 1 amputee had some degree of lameness in the neurologic system and/or one of the joints of the spine and limbs. The greatest number of abnormalities were seen at the hip, stifle, and spine, generally attributable to pain and resistance to extension, which is consistent with the areas identified as most susceptible to lameness secondary to limb amputation. In the amputee group, subjects 3, 7, and 8 had the highest total number of clinical abnormalities present. During data collection, subjects 3 and 7 appeared to have more difficulty trotting on three limbs than the majority of the remaining thoracic limb amputee group. Subject 8, however, appeared to have no problems trotting with three limbs. Although age and weight have not been shown to be determining factors in a dog's ability to ambulate on three limbs,[10] subjects 3 and 7 were 7 and 9 years old, respectively, while subject 8 was just under 2 years of age at the time of data collection. Additionally, subject 8 had the smallest body mass of the entire amputee group, while subject 7 had the highest body mass of the amputee group.

Although pre-amputation gait analysis is preferred when comparing compensation strategies,[21] most dogs that will undergo amputations due to osteosarcoma have too much lameness in that limb to be able to successfully complete a session of gait analysis.[18] This study was fortunate, however, to have one subject that participated both as a control and an amputee (Subject 4). Prior to amputation, this subject was found to have "mild" pain with extension at both stifle joints. One month after amputation immediately prior to gait analysis, pain in the ipsilateral pelvic limb had elevated to a "moderate" level and pain had also developed at the shoulder. This is consistent with the predictions of this study that the ipsilateral pelvic limb and thoracic limb are particularly susceptible to lameness secondary to amputation.

The goal of this study was to provide clinically relevant data on amputee gait, but the variability in subject characteristics does present some limitation. While body mass was used to normalize the GRFs and impulses, breed-specific studies could reduce some of the variability attributable to size and stature variances. Similarly, focusing on patients with no clinical pathologies or limiting enrollment to only study dogs with a particular pathology could reduce the variability seen in the physical examinations. Clinical pathologies are common amongst osteosarcoma patients,[1] so although the control and amputee groups were not perfectly healthy groups of dogs as far as other orthopedic or neurologic conditions, they represented typical groups of dogs that undergo amputation. They also represented a wide variety of breeds, each of which may have more specific compensatory gait strategies that cannot be identified from this set of data. The amputee group had an average age that was 2.4 years older than the control group which could be another limitation of this study. Older dogs may have more difficulty with mobility simply due to slowing down with age,[59] and this could be a contributing factor to some of the differences seen in this study between the two groups.

The velocity range was intended to be within 2.2-2.6 m/s to reduce variability associated with velocity. However, many amputees were not able to trot within 2.2-2.6 m/s and get successful paw strikes. For this reason, the velocity range was widened as long as each dog's trials were within $\pm$0.4 m/s of each other to keep variability to a minimum while allowing more dogs to be included in the study. Without widening the velocity range, nearly half of the amputees included in this study would have to be eliminated from analysis. Stance time has been shown to inversely correlate with velocity. [55] Although the average velocities of the amputee and control groups were not significantly different, some differences in stance time may be attributable to differences in velocity.

It is possible that while the amputees did not differ in average velocity from the controls, their gait may not be that of a true "trot." During normal trotting, a dog alternates diagonal pairs of limbs during each stance phase.[65] Thoracic limb amputees, however, often had significant overlap between the stance phases of the two pelvic limbs, which is more characteristic of a galloping pattern.[65] A galloping pattern is usually accompanied by a faster gait velocity, [65] but walking has significant periods of overlap as well at slower velocities. Typically the thoracic limb stance phase in the amputees was followed by the ipsilateral pelvic limb and then the contralateral pelvic limb, where the ipsilateral pelvic limb overlapped with the stance phases of both. With the ipsilateral pelvic limb taking on the role of both a thoracic limb and a pelvic limb in terms of GRFs, the gait pattern of thoracic limb amputees is really a blend of walking, trotting, and galloping at a velocity similar to that of a normal dog at a trot.

Adaptation to amputation has only been described subjectively,[10] however a quantitative assessment as soon as possible after amputation could reveal other changes that dogs adapt early on which are different from those once they've become more accustomed to ambulating with three limbs. Likewise, studies which are specific to time since amputation could reveal similar findings. The dogs in this study had amputations anywhere from one month to just over seven months prior to gait analysis. Although not evidenced in this study, it is possible that adaptation takes longer than one month as previously suggested[10] and that the changes seen may not be as easy to detect clinically after that first month.

Analysis of the swing phase would also be another aspect to consider in future studies in amputee gait. Data on the swing phase was collected in this study, however due to issues with skin motion artifact and fur obstructing some of the markers in the swing phase, it was very difficult to obtain enough complete data for analysis of this group of dogs. Finally, a more in-depth biomechanical analysis using inverse dynamics and electromyography would reveal changes occurring within the individual joints and muscles. This would be particularly influential in determining which joints are most susceptible to acute injury.

## VI. CONCLUSION

This study has shown that thoracic limb amputees have significant changes in kinetic and kinematic aspects of gait which differ from that of a similar control group. In particular, the following conclusions were made about kinetics, and limb and spine kinematics during stance:

- Kinetics
    - All limbs experience increased stance times and vertical impulses
    - Loss of braking from the amputated thoracic limb is compensated for by the remaining thoracic limb and ipsilateral pelvic limb
    - The loss of propulsion by the amputated thoracic limb is mostly compensated for by the ipsilateral pelvic limb
- Limb Kinematics
    - The carpus has greater range of motion during stance due to increased hyperextension
    - The ipsilateral stifle and hip are more flexed during stance with increased ranges of motion
- Spinal kinematics
    - The T1 and T13 regions have increased range of motion in the sagittal and horizontal planes
    - The L7 region is generally more flexed in the sagittal plane, but operates in the same range

- The T1 region shifts toward the side of amputation during thoracic limb stance and away from the side of amputation during ipsilateral pelvic limb stance
- There are no apparent trends in direction of lateral movement at the T13 and L7 spinal regions

This data provides quantitative knowledge of thoracic limb amputee gait which clinicians can compare with pre-amputation physical examinations. This will not only be influential as clinicians and owners decide upon a course of treatment for osteosarcoma in a given patient, but will also support further research in osteoarthritis and the long-term outcomes of amputee dogs.

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## VIII. 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: Kerry Engle / ERK
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

Colorado State University

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

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

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**Effective Date:** 11-AUG-10
**Renewal Date:** 18-AUG-10
**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 / ERK

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

# IX. APPENDIX II: SUMMARY OF PATIENT EXAMINATION FINDINGS

**CONTROLS**

| Subject ID | 1 | 2 | 3 |
|---|---|---|---|
| **Past ortho Hx** | | right femur fracture 9 years ago | |
| **Med Hx** | | | |
| **Dx** | lymphoma, hypertension, early dilated cardiomyopathy | | LF antebrachial sarcoma, recently started deracoxib |
| **Gait** | slight shuffling and slapping of HL, normal gait rhythm | normal | normal |
| **Comments** | | | 5 x 13 cm tumor at L caudal antebrachium just below elbow |
| **Cervical pain** | | | |
| **Spinal pain** | | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | mild resistance with flexion | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | mild crepitus | | moderate medial buttress |
| **L hip** | marked discomfort with extension | slight resistance to extension | mild discomfort with extension L>R |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | mild crepitus | | moderate medial buttress, pain with hyperextension |
| **R hip** | marked discomfort with extension | slight resistence to extension | mild discomfort with extension L>R |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis

**CONTROLS**

| Subject ID | 4 | 5 | 6 |
|---|---|---|---|
| **Past ortho Hx** | | | R femoral head and neck ostectomy 9/09 |
| **Med Hx** | | hip dysplasia, left patella lateral laxity | |
| **Dx** | | | |
| **Gait** | normal | normal | normal |
| **Comments** | hates lying down | | |
| **Cervical pain** | | | |
| **Spinal pain** | | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | mild crepitus and slight decreased ROM | |
| **L elbow** | | | slight discomfort with pressure over medial coronoid in flexion |
| **L shoulder** | | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | | grade 2 laterally luxating patella | |
| **L hip** | does not like hip extension, no pain | marked discomfort with extension | |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | | grade 1 laterally luxating patella | |
| **R hip** | does not like hip extension, no pain | marked discomfort with extension | slight resistance with extension |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis, ROM = range of motion

**CONTROLS**

| **Subject ID** | **7** | **8** | **9** |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | | pannus, R anal sac mass |
| **Dx** | | | |
| **gait** | normal | normal | slightly lower carriage of pelvis to ground |
| **Comments** | | | trying to bite |
| **Cervical pain** | | | |
| **Spinal pain** | | | pain with hyperelevation of tail, pain at L4/L5 region |
| **Neuro status** | | | slight crossing over HLs, HL weakness, CPs intactx4 |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | mild shoulder discomfort worse in R | | |
| **LF other** | | | unable to finish |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | mild shoulder discomfort worse in R, mild decrease ROM | | |
| **RF other** | | | unable to finish |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | | | |
| **L hip** | | | |
| **LH other** | | | unable to complete ortho exam, decreased pelvic limb muscles |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | | | |
| **R hip** | | | |
| **RH other** | | | unable to complete ortho exam, decreased HL muscles |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis, CP = conscious proprioception

**CONTROLS**

| Subject ID | 10 | 11 | 12 |
|---|---|---|---|
| **Past ortho Hx** | | | history of LH stiffness |
| **Med Hx** | | | |
| **Dx** | | | |
| **Gait** | mild bilateral HL lameness, stiff HL gait | normal | normal |
| **Comments** | decreased joint excursions when walking, good muscle mass in HLs | | slight decreased ROM of stifles at the walk |
| **Cervical pain** | | | |
| **Spinal pain** | mild lumbar discomfort with palpation | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | | equivocal discomfort with flexion | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | painful with hyperextension, medial buttress and mild effusion present | | mild crepitus |
| **L hip** | resists hip extension | | |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | painful with hyperextension, medial buttress and mild effusion present | | mild crepitus |
| **R hip** | resists hip extension | | |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis, ROM = range of motion

**CONTROLS**

| **Subject ID** | **13** | **14** | **15** |
|---|---|---|---|
| **Past ortho Hx** | juvenile pubic symphiodesis 7/08, hip dysplasia, R partially TACL 10/09, bilateral ACL disease L>R 11/09, L tibial plateal leveling osteotomy 6/10 | | |
| **Med Hx** | | | multiple cutaneous masses, no medications |
| **Dx** | only on Dasuquin | | |
| **Gait** | after ortho exam, mild RH weight bearing lameness | normal | normal |
| **Comments** | | | |
| **Cervical pain** | | | |
| **Spinal pain** | | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | decreased flexion |
| **L elbow** | | | slight discomfort with ROM |
| **L shoulder** | | | pain with extension R >L |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | decreased flexion |
| **R elbow** | | | |
| **R shoulder** | | | pain with extension R>L |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | moderate medial buttress and TPLO plate, mild pain with hyperextension | | pain, unable to fully hyperextend, effusion and medial buttress present |
| **L hip** | | | |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | marked medial buttress, moderate pain with hyperextension | | |
| **R hip** | | | |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis, ROM = range of motion
TACL = torn anterior cruciate ligament, TPLO = tibial plateal leveling osteotomy

**CONTROLS**

| **Subject ID** | **16** | **17** | **18** |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | poor vision, multiple fatty masses | |
| **Dx** | | | |
| **Gait** | normal | normal | normal |
| **Comments** | | shoulders more sore than hips | |
| **Cervical pain** | | | possible decreased bilateral lateral cervical motion |
| **Spinal pain** | | | mild discomfort with palpation L5/L6 region |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | | resistance to extend | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | slight decreased flexion, marked crepitus, moderate discomfort with flexion |
| **R shoulder** | | resistance to extend | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | | | |
| **L hip** | | resistance to extend | mild discomfort with extension |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | | | mild discomfort with hyperextension |
| **R hip** | | resistance to extend | mild discomfort with extension |
| **RH other** | | | |

Abbreviations:
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Mx = medical history, Dx = diagnosis

**CONTROLS**

| Subject ID | 19 | 20 | 21 |
|---|---|---|---|
| **Past ortho Hx** | crepitus left hock since 2005 | | |
| **Med Hx** | | | |
| **Dx** | gets occasional carprofen | | |
| **Gait** | normal | normal | slight short-strided HL gait |
| **Comments** | very nervous | | |
| **Cervical pain** | | | |
| **Spinal pain** | | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | decreased ROM, mild crepitus |
| **L elbow** | | stiff, mild effusion | slight discomfort with flexion, slight thickening |
| **L shoulder** | | stiff shoulder | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | mild decreased ROM, mild crepitus |
| **R elbow** | | | slightly less discomfort with flexion, less thickening |
| **R shoulder** | | stiff shoulder | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | slight crepitus, marked decreased ROM | | |
| **L stifle** | | | medial buttress, very mild discomfort with hyperextension R>L |
| **L hip** | unable to assess hip fully | | mild discomfort with full extension |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | marked decreased flexion | | |
| **R stifle** | | | very mild discomfort with hyperextension R>L |
| **R hip** | unable to assess hip fully | | mild discomfort with full extension |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis, ROM = range of motion

**CONTROLS**

| **Subject ID** | **22** | **23** | **24** |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | | |
| **Dx** | | | |
| **Gait** | normal | normal | normal |
| **Comments** | Different clinician did exam | | |
| **Cervical pain** | | | |
| **Spinal pain** | | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | mild right carpal pain | | |
| **R elbow** | | | |
| **R shoulder** | | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | | | |
| **L hip** | | | |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | | | |
| **R hip** | | | |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis

AMPUTEES

| Subject ID | 1 | 2 | 3 |
|---|---|---|---|
| Past ortho Hx | | | |
| Med Hx | | | |
| Dx | osteosarcoma L proximal humerus, six cycles carboplatin | osteosarcoma L proximal humerus, had four cycles carboplatin | osteosarcoma L distal radius, had six cycles carboplatin, now tires easily, lies down on walks |
| Gait | "normal" | "normal" | "normal" |
| Comments | | strongly ambulatory, brings LH forward to balance | |
| Cervical pain | | | |
| Spinal pain | | | possible hyperpathia L5/L6 region |
| Neuro status | | | |
| L manus | | | |
| L carpus | | | |
| L elbow | | | |
| L shoulder | | | resents full extension |
| LF other | | | |
| R manus | | | |
| R carpus | | | |
| R elbow | | | |
| R shoulder | | | |
| RF other | | | |
| L pes | | | |
| L tarsus | | | |
| L stifle | | | medial buttress |
| L hip | | | mild resistance with extension |
| LH other | | | |
| R pes | | | |
| R tarsus | | | |
| R stifle | mild crepitus, mild discomfort with hyperextension | mild crepitus, mild discomfort with hyperextension | medial buttress |
| R hip | | | mild resistance with extension |
| RH other | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis

**AMPUTEES**

| **Subject ID** | **4** | **5** | **6** |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | | |
| **Dx** | soft tissue sarcoma L antebrachium | osteosarcoma R distal radius, recent right hind lameness which carprofen has been helping | osteosarcoma R distal radius |
| **Gait** | "normal" | "normal" | "normal" |
| **Comments** | vigorous gait with slight stiffness in RH | | ambulating well |
| **Cervical pain** | | mild resistance to dorsal and ventral cervical flexion | |
| **Spinal pain** | | | mild discomfort over L2 region |
| **Neuro status** | | mild increase in right patellar reflex | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | slight resistance with flexion |
| **L shoulder** | | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | mild discomfort with full extension and flexion | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | | | |
| **L hip** | moderate discomfort with extension | | |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | moderate stifle effusion, pain with hyperextension | | |
| **R hip** | mild discomfort with extension | | |
| **RH other** | | | |

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Mx = medical history, Dx = diagnosis

**AMPUTEES**

| Subject ID | 7 | 8 | 9 |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | | |
| **Dx** | osteosarcoma L proximal humerus, had received one cycle carboplatin | osteosarcoma R distal radius, had two cycles carboplatin | osteosarcoma L distal radius, had four cycles carboplatin |
| **Gait** | "normal" | occasionally skips on RH | "normal" |
| **Comments** | | ambulating well | ambulating well |
| **Cervical pain** | | | |
| **Spinal pain** | mild discomfort over L6 | discomfort over L5/L6 region | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | | discomfort with extension | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | mild discomfort with flexion | | mild crepitus |
| **R shoulder** | mild discomfort with extension | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | | equivocal discomfort with hyperextension | |
| **L hip** | moderate resistance with extension | mild discomfort with extension | |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | | equivocal discomfort with hyperextension | |
| **R hip** | moderate resistance with extension | mild discomfort with extension | |
| **RH other** | | | |

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Mx = medical history, Dx = diagnosis

**AMPUTEES**

| **Subject ID** | **10** | **11** | **12** |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | | |
| **Dx** | osteosarcoma R proximal humerus, had received one cycle carboplatin | osteosarcoma L proximal humerus, had received two cycles carboplatin | osteosarcoma L distal radius, had one cycle carboplatin, on carprofen |
| **Gait** | "normal" | LH lameness and moderate shifting HL gait | mild LH weightbearing lameness |
| **Comments** | | | |
| **Cervical pain** | | | |
| **Spinal pain** | | pain at L5 region | |
| **Neuro status** | | | possibly increased left patellar and cranial reflexes |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | pain with hyperextension, subtle effusion | | |
| **L hip** | | | moderate crepitus |
| **LH other** | | pain at distal femur | slight increased muscle atrophy |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | | | |
| **R hip** | | | moderate crepitus |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis

**AMPUTEES**

| **Subject ID** | **13** | **14** | **15** |
|---|---|---|---|
| **Past ortho Hx** | | | |
| **Med Hx** | | | |
| **Dx** | soft tissue sarcoma R distal limb | osteosarcoma R distal radius, had six cycles carboplatin,having some episodes of falling down at home | osteosarcoma R distal humerus, had received two cycles carboplatin |
| **Gait** | bilateral HL lameness, R lateralizing | bunny-hopping in HLs | "normal" |
| **Comments** | | ambulating but HL are moving mostly together | ambulating well, short strided in HL |
| **Cervical pain** | | mild cervical discomfort bilaterally | |
| **Spinal pain** | | | |
| **Neuro status** | | | |
| **L manus** | | | |
| **L carpus** | | | |
| **L elbow** | | | |
| **L shoulder** | | | |
| **LF other** | | | |
| **R manus** | | | |
| **R carpus** | | | |
| **R elbow** | | | |
| **R shoulder** | | | |
| **RF other** | | | |
| **L pes** | | | |
| **L tarsus** | | | |
| **L stifle** | mild discomfort with hyperextension | pain with hyperextension R>L, chronic medial buttress | |
| **L hip** | mild discomfort w/extension R>L | | resistant to full extension, mild discomfort |
| **LH other** | | | |
| **R pes** | | | |
| **R tarsus** | | | |
| **R stifle** | marked pain w/hypertext., medial buttress, surgical crimp felt | pain with hyperextension R>L, chronic medial buttress | |
| **R hip** | mild discomfort with extension R>L | resists extension | resistant to full extension, mild discomfort |
| **RH other** | | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis

**AMPUTEES**

| Subject ID | 16 | 17 |
|---|---|---|
| **Past ortho Hx** | | |
| **Med Hx** | | Addison's disease, receiving prednisone and DOCP, has blood in urine today |
| **Dx** | osteosarcoma L distal radius, had received two cycles doxorubicin, has renal disease and hypertension | osteosarcoma L distal radius, had four cycles of carboplatin |
| **Gait** | "normal" | "normal" |
| **Comments** | normal exam | Other clinician did exam |
| **Cervical pain** | | |
| **Spinal pain** | | |
| **Neuro status** | | |
| **L manus** | | |
| **L carpus** | | |
| **L elbow** | | |
| **L shoulder** | | |
| **LF other** | | |
| **R manus** | | |
| **R carpus** | | |
| **R elbow** | | |
| **R shoulder** | | |
| **RF other** | | muscle atrophy over scapula, prominent scapular spine |
| **L pes** | | |
| **L tarsus** | | |
| **L stifle** | | |
| **L hip** | | |
| **LH other** | | |
| **R pes** | | |
| **R tarsus** | | |
| **R stifle** | | |
| **R hip** | | |
| **RH other** | | |

Abbreviations:
L(H) = left (hind), R(H) = right (hind)
Mx = medical history, Dx = diagnosis