Kinematic and kinetic analysis of dogs during trotting after amputation of a thoracic limb

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Objective—To characterize biomechanical differences in gait between dogs with and without an amputated thoracic limb.

Animals—Client-owned dogs (16 thoracic-limb amputee and 24 quadruped [control] dogs).

Procedures—Dogs were trotted across 3 in-series force platforms. Spatial kinematic and kinetic data were recorded for each limb during the stance phase.

Results—Amputees had significant increases in stance duration and vertical impulse in all limbs, compared with values for control dogs. Weight distribution was significantly increased by 14% on the remaining thoracic limb and by a combined 17% on pelvic limbs in amputees. Braking ground reaction force (GRF) was significantly increased in the remaining thoracic limb and pelvic limb ipsilateral to the amputated limb. The ipsilateral pelvic limb had a significantly increased propulsive GRF. The carpus and ipsilateral hip and stifle joints had significantly greater flexion during the stance phase. The cervicothoracic vertebral region had a significantly increased overall range of motion (ROM) in both the sagittal and horizontal planes. The thoracolumbar vertebral region ROM increased significantly in the sagittal plane but decreased in the horizontal plane. The lumbosacral vertebral region had significantly greater flexion without a change in ROM.

Conclusions and Clinical Relevance—Compared with results for quadruped dogs, the vertebral column, carpus, and ipsilateral hip and stifle joints had significant biomechanical changes after amputation of a thoracic limb. The ipsilateral pelvic limb assumed dual thoracic and pelvic limb roles because the gait of a thoracic limb amputee during trotting appeared to be a mixture of various gait patterns. (*Am J Vet Res* 2013;74:1155–1163)

Abbreviations

CTVR	Cervicothoracic vertebral region
GRF	Ground reaction force
LSVR	Lumbosacral vertebral region
ROM	Range of motion
TLVR	Thoracolumbar vertebral region

Most dogs appear to adapt well to the removal of a thoracic limb[1,2]; appropriate adaptation may be influenced by conscientious presurgical selection of patients for amputation. Anecdotally, some dogs have difficulties with locomotion following thoracic limb amputation. In 1 survey,[3] some clients indicated that their dogs were not able to return to normal locomotive function, even after a 4-week adaptation period following amputation. It has been hypothesized that age, body weight, and breed may affect a dog's functionality after amputation,[3–8] although body weight has not been found to be a factor that contributes to subsequent disability.[3] Additionally, owner surveys[1,2] encompassing dogs of a wide variety of ages and breeds do not indicate that these factors negatively impact the ability of a dog to adapt to the loss of a thoracic limb. On the basis of this information, other factors related to gait are thought to contribute to a decrease in mobility and activities in some canine amputees.

It is important that clinicians and researchers understand the compensatory changes in gait for dogs that have undergone thoracic limb amputation.[1,3] Currently, information about compensatory gait strategies in thoracic limb amputees is limited to kinetic data evaluations of GRF, impulse duration, and stance duration in 5 amputee dogs during walking.[9] In comparison with

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results for control dogs, thoracic limb amputees distribute an additional 17% of body weight to the remaining thoracic limb and an additional 13% of body weight to the pelvic limbs during the stance phase while maintaining similar peak vertical GRFs over a shorter stance duration.[9] Amputees also compensate for the loss of a thoracic limb by increasing the braking duration of the remaining thoracic limb instead of distributing more of the braking demands to the pelvic limbs.[9]

A need exists to better understand the compensatory mechanisms that alter loading and joint motion of the remaining limbs in amputee dogs. Although the gait has been evaluated in amputee dogs during walking,[9] the authors are not aware of any prior gait analysis of amputees during trotting, a motion whereby limbs may have higher GRFs and possible periods of support on a single limb. The GRF analysis provides a limited understanding of the gait in amputees; therefore, kinematic analysis of the limbs and vertebral column is needed to fully assess potential strategies for musculoskeletal compensation. Any alteration to normal limb kinematics can impact the distribution of joint forces,[10–12] which can lead to gross instability, muscle dysfunction, pain, and a decrease in ROM of joints. There may be increases in inflammation, impaired synthesis of cartilage, and cartilage degradation[11,12] within the joint of interest, which possibly could also affect adjacent joints.[13] Evidence of altered joint angles and ROMs combined with GRF analysis will help to identify joint loading patterns and compensatory strategies in the gait of amputee dogs.[10–12] Altered limb kinematics and increased motion of the vertebral column may also lead to degenerative changes and altered muscular control of the remaining limbs.[11,12,14]

The extent of compensatory strategies in the gait of amputee dogs is unknown. The purpose of the study reported here was to objectively compare differences in gait between dogs that underwent thoracic limb amputation and a clinically relevant cohort of quadruped control dogs that had orthopedic, neurologic, or other related comorbidities similar to those of the amputee dogs, thus reflecting patient conditions in a clinical environment.

Materials and Methods

Animals—Thirty-one quadruped control dogs and 19 thoracic limb amputees (11 with amputation of the left thoracic limb and 8 with amputation of the right thoracic limb) were enrolled in the study during the period from November 2009 through April 2011. All dogs were client-owned patients recruited through the Colorado State University Flint Animal Cancer Center and were simultaneously receiving standard treatment for naturally occurring disease. None of the control dogs had neoplasms that affected the neurologic or musculoskeletal systems. Some control dogs were apparently free of any neoplasm but were examined as a part of diligent health screening, some had multiple benign cutaneous masses that were being monitored, and some had various cancers, including anal sac apocrine gland adenocarcinoma, lymphoma, and soft tissue sarcoma. All clients were given a written description of the project; clients provided written consent prior to enrollment of dogs in the study. All procedures were approved by an institutional animal care and use committee and by the veterinary teaching hospital clinical board.

Dogs were eligible for inclusion if they were > 1 year old (to limit inclusion of skeletally immature dogs) and weighed > 14 kg. Amputee dogs were eligible for inclusion if the thoracic limb amputation was performed ≥ 4 weeks before gait analysis to allow an adequate period to adapt to a 3-limbed gait.[10] All eligible dogs underwent complete physical, orthopedic, and neurologic examinations performed by a board-certified veterinary surgeon engaged exclusively in small animal surgical oncology. Control dogs were excluded from the study if clinical assessment determined that a dog would have been an unsuitable candidate for amputation; thus, the control group was subjectively similar to the amputee group with regard to degree of preexisting lameness and associated clinical decisions. Examples of signs of an unsuitable candidate for limb amputation included preexisting neurologic abnormalities that exceeded mild limb ataxia or preexisting osteoarthritis associated with marked weight-bearing or nonweight-bearing lameness despite medical management. Amputees were excluded from further gait analysis if the examiner determined that gait analysis would be harmful to the dog as determined on the basis of clinical examination findings, including suspicion of pulmonary or skeletal metastasis. Dogs were also excluded from further gait analysis if they were unable to complete the study because of signs of pain or discomfort in the joints or had long hair that prevented proper attachment of retroreflective markers. Investigators performing the kinetic and kinematic analysis were unaware of clinical examination findings. Height (distance from the ground to the most dorsal point between the scapulae [ie, withers]) and body weight were recorded for each dog.

Gait protocol—To measure coordinate locations and calculate joint angles for the limbs and vertebral column, 25-mm spherical retroreflective markers were affixed to the skin over palpable bony landmarks along the vertebral column and at joint centers of rotation in the thoracic and pelvic limbs with double-sided carpet tape.[a] Twenty-five markers were placed on each control dog and 20 markers on each amputee dog **(Figure 1)**. Kinematic and kinetic data were collected synchronously[b] in a calibrated volume of 1 × 1 × 2 m centered over 3 in-series force platforms[c,d] mounted in a 12-m walkway. Digital video recordings[e] obtained from the center of the walkway were used to visually verify paw strikes. Three-dimensional coordinate data were recorded at 200 Hz with 8 optical cameras. Raw data were filtered with a recursive fourth-order Butterworth filter with a cutoff frequency of 15 Hz. Kinetic analogue data were recorded at 2,000 Hz and filtered with the same Butterworth filter at 40 Hz. Calibration of the recorded volume yielded an accuracy within 0.09 cm.

Five timing lights[f] were placed at 0.5-m intervals along the walkway and used to instantaneously provide data on gait velocity and acceleration. Range of the target velocity was 2.2 to 2.6 m/s, and acceleration was strictly maintained between ± 0.5 m/s^2 for data collection. If the target velocity could not be achieved, a velocity within ± 0.4 m/s of the target velocity range was considered to yield acceptable trials for a specific dog. Trials were excluded if the handler and dog were not moving at the same velocity, acceleration was not within the acceptable range, the dog pulled on the leash while trotting, or the dog became distracted and moved its head to look down or to the side (ie, head movement out of the midsagittal plane) within the established data collection volume.

All dogs were allowed to trot down the walkway 3 to 5 times to provide acclimation to the laboratory environment and attached retroreflective markers prior to collection of data. Each dog then trotted down the walkway until a minimum of 5 successful trials were recorded or until the dog was deemed too tired to continue. Dogs were allowed several minutes of rest between acclimation and the start of the trials and between subsequent trials; the amount of rest time was dependent on the dog. Paw strikes were considered valid when the full paw landed on 1 platform and the GRF overlap between successive paw strikes was < 25 N.

Gait analysis—Gait analysis focused on the stance phase, which was defined as the period during which a paw had a vertical GRF greater than a threshold value of 25 N. Stride length was defined as the craniocaudal distance between the initiation of the stance phase of 2 consecutive steps for a given paw as determined on the basis of center-of-pressure locations. Thoracic limb axial foot displacement (ie, orientation of a thoracic limb within the transverse plane) was determined via the mediolateral distance between the center of pressure of the remaining forelimb paw calculated from the force platform and the ipsilateral scapular marker for the thoracic limbs. Pelvic limb axial foot displacement (ie, orientation of a pelvic limb within the transverse plane) was calculated from the center of pressure of a specific hind limb paw and its ipsilateral ilial marker. Stride length and axial foot displacement were normalized on the basis of height to account for variation in size among the dogs.

Joint angles for the limbs and vertebral column were calculated with marker locations. For all limbs, an angle of 180° was considered full extension and joint angles < 180° corresponded to flexion (Figure 1). Motion of the cervical, thoracic, and lumbosacral vertebral regions was measured in reference to vertebral column markers located at T1 (CTVR), T13 (TLVR), and L7 (LSVR). Full extension of the vertebral column was defined as 0° in both sagittal and horizontal planes. In the sagittal plane, positive joint angles indicated extension of a vertebral region and negative joint angles indicated flexion of a vertebral region. In the horizontal plane, positive angles for a vertebral region represented right lateral bending (or toward the side of amputation) and negative angles represented left lateral bending (or away from the side of amputation). To compare horizontal joint angles between left and right thoracic limb amputees, angles for the vertebral regions for all left limb amputees were mirrored to the right side such that all dogs were analyzed as if they were right thoracic limb amputees. For each joint angle, the mean, maximum, minimum, and range values were calculated during the stance phase of each limb.

Peak vertical, braking, and propulsive GRFs and impulses as well as the craniocaudal (net braking or net propulsion) impulse were measured for each paw strike and normalized on the basis of the percentage of body weight. Time to peak GRF was also measured for the vertical, braking, and propulsive components. Body weight distribution was calculated by dividing the mean peak vertical GRF of a limb by the total mean peak vertical GRF of all limbs.[9] For each variable, the mean value for a minimum of 3 and a maximum of 7 trials was calculated for each dog, which was followed by pooling of values to obtain a single representative value for each group.

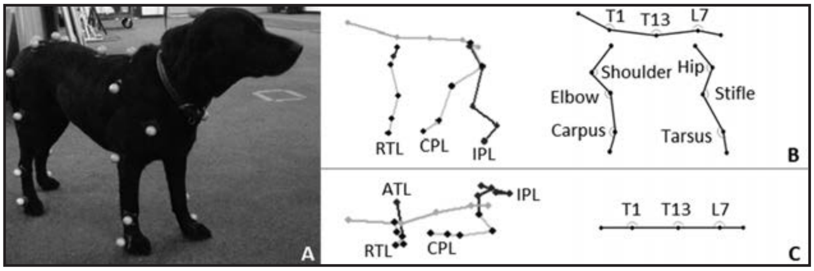

Figure 1—Photograph of a quadraped (control) dog with a set of retroreflective markers affixed to the skin over bony landmarks at joint centers of rotation along the thoracic and pelvic limbs and vertebral column (A) and the sagittal (B) and horizontal (C) plane reconstructions of marker segments during trotting. On the thoracic limb, markers were placed on the skin over the distolateral aspect of the fifth metacarpal bone, ulnar styloid process, lateral epicondyle of the humerus, greater tubercle of the humerus, and dorsal aspect of the scapular spine. On the pelvic limb, markers were placed on the skin over the distolateral aspect of the fifth metatarsal bone, lateral malleolus of the fibula, lateral femoral condyle, greater trochanter of the femur, and iliac crest. On the vertebral column, markers were placed on the skin over the occipital protuberance; the spinous processes of T1, T13, and L7; and the dorsal sacral apex. For thoracic-limb amputees, a marker was also placed on the side of the thoracic limb amputation on the skin over the point at which the scapular spine typically would be relative to the contralateral side. ATL = Amputated thoracic limb. CPL = Contralateral pelvic limb. IPL = Ipsilateral pelvic limb. RTL = Remaining thoracic limb.

Statistical analysis—Statistical analyses were conducted with commercially available software.[g] Normal distribution of data was confirmed with Shapiro-Wilk tests. Descriptive statistics for the control and amputee groups were calculated for age, height, and body weight. Clinical examination findings were compared qualitatively. Mean differences were compared between groups with independent (control vs amputee) and paired (amputee group, contralateral vs ipsilateral limbs relative to the side of amputation) *t* tests with Bonferroni corrections ($P < 0.05/n$, where n represents the number of categories of data analyzed for a given variable) to account for multiple comparisons and to partially control for overall error rates. The GRF and impulse values were considered significant at $P < 0.017$ ($n = 3$, which accounted for vertical, braking, and propulsion values). Limb and vertebral kinematics for the stance duration, stride length, stance width, and velocity were considered significant at $P < 0.013$ ($n = 4$, which accounted for maximum, minimum, mean, and range of values for each). For the control group, thoracic and pelvic limb kinematics and GRFs were evaluated separately by means of paired *t* tests to detect differences between the left and right sides; values for which no differences existed between the right and left side were pooled to create a single value for the thoracic or pelvic limbs.

Results

Animals—Fifty dogs (31 control dogs and 19 thoracic limb–amputee dogs) were enrolled in the study; however, only 24 control dogs and 16 amputee dogs were included in the analysis (**Table 1**). Ten dogs were excluded from analysis because they did not meet minimum requirements for inclusion as a result of obstruction of reflective markers (1 amputee and 3 control dogs), failure to acclimate to the experimental procedures during the practice trials (3 control dogs), or poor placement of reflective markers and errors in data collection (1 control and 2 amputee dogs). The 24 control dogs were included as the control group in another study[15] conducted by our research group.

Table 1—Signalment and velocity characteristics of 24 quadruped (control) dogs and 16 thoracic limb–amputee dogs used for kinematic and kinetic analysis during trotting.

Variable	Control	Amputee
Sex		
Male	10	5
Female	14	11
Age (y)*	6.3 ± 3.4 (1.0–12.3)[a]	8.6 ± 2.8 (1.7–13.5)[b]
Body weight (kg)*	32.8 ± 12.3 (14.6–64.0)	34.2 ± 10.2 (16.6–55.8)
Height (cm)*	59.6 ± 7.5 (51.0–78.0)	62.7 ± 7.6 (52.0–80.0)
Side of amputation		
Right	NA	7
Left	NA	10
Time since amputation (d)*	NA	90 ± 64 (28–217)
Velocity (m/s)*	2.3 ± 0.1 (2.0–2.6)	2.2 ± 0.3 (1.9–2.7)

Height is the distance from the ground to the most dorsal point between the scapulae (ie, withers).

*Values reported are mean ± SD (range).

NA = Not applicable.

[a,b]Values with different superscript letters differ significantly ($P < 0.017$).

The amputee group was significantly ($P = 0.017$) older than the control group (Table 1). In addition, several dogs included in the analysis had insufficient data for ≥ 1 variable as a result of marker obstruction and partial or overlapping paw strikes. Thus, statistical analysis of kinetic data comprised 12 amputee and 24 control dogs, limb kinematic data comprised 11 amputee and 23 control dogs, and vertebral column kinematic data comprised 11 amputee and 24 control dogs.

All limbs were amputated because of osteosarcoma in the radius or humerus, except for 2 dogs that had limb amputations because of soft tissue sarcomas. All dogs, except for 1 amputee and 5 control dogs, had some type of orthopedic abnormality localized to 1 or more joints of the limbs or vertebral column. These orthopedic abnormalities were manifested as signs of pain during palpation, palpable periarticular fibrosis, palpable crepitus, or an altered ROM. Neurologic abnormalities included mild ataxia or mild conscious proprioceptive deficits (2 control dogs) and altered peripheral reflexes (2 amputee dogs). Of the 24 control dogs, 2 had joint abnormalities in 4 limbs, 4 had joint abnormalities in 3 limbs, 11 had joint abnormalities in 2 limbs, and 2 had joint abnormalities in 1 limb; the 5 remaining control dogs had no apparent joint abnormalities. Of the 16 amputee dogs, 2 had abnormalities in all 3 limbs, 5 had abnormalities in 2 limbs, and 7 had abnormalities in 1 limb; the remaining 2 amputee dogs had no apparent joint abnormalities, but 1 had a vertebral column abnormality. Bilateral joint abnormalities were common in a total of 15 control dogs and 7 amputee dogs in the shoulder joints (3 control dogs), elbow joints (1 control dog), carpi (1 control dog), hip joints (8 control and 5 amputee dogs), stifle joints (7 control and 4 amputee dogs), and tarsal joints (1 control dog).

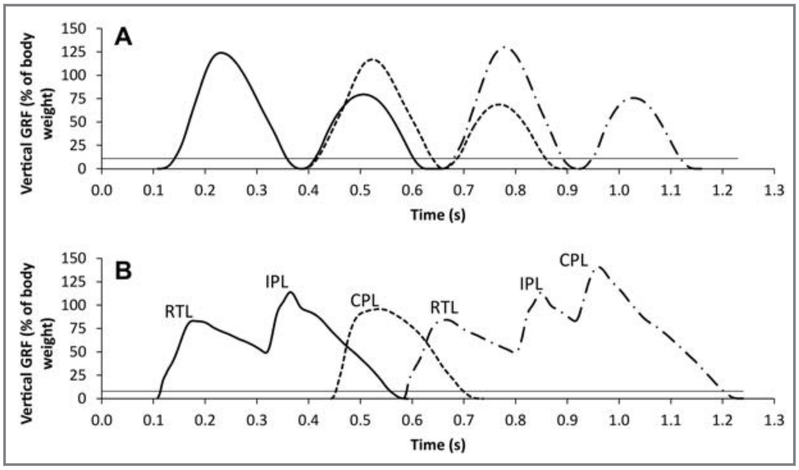

Figure 2—Graphs of a vertical GRF tracing of a single trial from a representative control dog (A) and thoracic limb–amputee dog (B) trotting across 3 in-series force platforms (FPs). In panel A, notice that each FP (FP1 [solid line], FP2 [dashed line], and FP3 [dashed-and-dotted line]) has a thoracic limb paw strike (first inflection) followed by an IPL paw strike (second smaller inflection). In panel B, notice that there is substantial overlap of the stance phase between the remaining thoracic limb and the IPL on FP1 and for all 3 limbs on FP3. The CPL had a single vertical GRF on FP2. Notice the wider and more rounded shape of the CPL GRF, compared with the GRFs of the control dogs. A threshold of 25 N of vertical GRF (thin horizontal line) was used to define overlapping paw strikes within a trial; paw-off and paw-strike events for each limb could not be accurately determined above this threshold. *See* Figure 1 for remainder of key.

GRF kinetics—Ten amputee and 5 control dogs were not able to achieve or maintain velocity within the intended range of 2.2 to 2.6 m/s while achieving successful paw strikes. The velocity these dogs could maintain was within ± 0.4 m/s of the target velocity range and was used instead (Table 1). Mean trotting velocity was not significantly ($P = 0.111$) different between the amputee and control groups. Most amputee dogs had overlapping paw strikes, which were most frequently detected between the ipsilateral pelvic limb and 1 or both of the other remaining limbs (**Figure 2**). To account for overlapping paw strikes, we adjusted gait velocity or starting position (or both) for each trial, except for 7 amputees that had 1 or 2 limbs that could not be included in kinetic analysis because of overlap that was consistently greater than the allowable established threshold.

Table 2—Mean ± SD values for kinetic and temporospatial variables for limbs during trotting in 24 control dogs and 16 thoracic limb–amputee dogs.

	Thoracic limbs		Pelvic limbs		
				Amputee	
Variable	**Control***	**Amputee**	**Control***	**Ipsilateral**	**Contralateral**
Peak GRF (% of body weight)					
Vertical	113.6 ± 16.4	122.8 ± 31.8	74.1 ± 16.1	82.0 ± 20.9	76.7 ± 23.2
Braking	–15.7 ± 2.8	–28.8 ± 9.2†	–5.5 ± 2.3	–9.7 ± 5.6†	–7.7 ± 5.6
Propulsion	9.2 ± 3.4	6.5 ± 4.1	10.8 ± 3.8	16.5 ± 7.0†	13.6 ± 7.0
Time to peak GRFs (s)					
Vertical	0.11 ± 0.02	0.12 ± 0.03	0.09 ± 0.01	0.08 ± 0.02	0.09 ± 0.02
Braking	0.13 ± 0.04	0.07 ± 0.02†	0.08 ± 0.03	0.02 ± 0.01†	0.04 ± 0.02‡
Propulsion	0.11 ± 0.04	0.19 ± 0.06†	0.07 ± 0.03	0.15 ± 0.02†	0.15 ± 0.04†
Impulse (% of body weight•s)					
Vertical	15.5 ± 3.1	20.6 ± 5.2§	8.8 ± 2.1	12.1 ± 3.3§	12.1 ± 3.5§
Craniocaudal	–0.6 ± 0.23	–2.3 ± 0.9§	0.7 ± 0.4	1.6 ± 0.7§	1.0 ± 0.8
Braking	–1.1 ± 0.2	–1.9 ± 1.4	–0.2 ± 0.1	–0.2 ± 0.2	–0.3 ± 0.5
Propulsion	0.5 ± 0.3	–0.5 ± 1.4§	0.9 ± 0.4	1.8 ± 0.7§	1.4 ± 0.6§
Stance duration (s)	0.23 ± 0.03	0.27 ± 0.04†	0.20 ± 0.02	0.24 ± 0.04†	0.27 ± 0.04†
Axial foot displacement (m/m)	0.09 ± 0.05	0.08 ± 0.06	0.04 ± 0.05	0.03 ± 0.04	0.04 ± 0.04
Stride length (m/m)	1.95 ± 0.29	1.84 ± 0.38	1.94 ± 0.32	ND	ND

Axial foot displacement and stride length are normalized on the basis of height to account for variation in size among dogs. Stride length was calculated on the basis of paw-strike and paw-off events in the GRF data.

*Represents a pooled value for the left and right sides. †Within a row within the thoracic or pelvic limbs, value differs significantly ($P < 0.017$) from the value for the control dogs. ‡Within a row, value differs significantly ($P < 0.017$) from the value for the ipsilateral amputee pelvic limb. §Within a row within the thoracic or pelvic limbs, value differs significantly ($P < 0.013$) from the value for the control dogs.

ND = Not determined because most amputees had substantial overlap of the stance phase between the ipsilateral pelvic limb and the remaining thoracic limb or contralateral pelvic limb.

No significant differences between the left and right sides were found in the GRFs of the control group, so values for the left and right thoracic and pelvic limbs were pooled for the control dogs (**Table 2**). Peak braking GRF was significantly increased in the remaining thoracic limb ($P < 0.001$) and ipsilateral pelvic limb ($P = 0.003$) of the amputees, compared with values for the control dogs. Peak propulsive GRF was also significantly ($P = 0.003$) increased in the ipsilateral pelvic limb in amputees, compared with the value for the control dogs, which indicated both increased propulsive and braking functions of this limb. There was a significant increase in vertical impulse ($P < 0.001$) and stance duration ($P = 0.004$) in all limbs of the amputees, compared with values for the control dogs. Propulsive impulse was significantly ($P = 0.003$) decreased in the remaining thoracic limb but significantly ($P = 0.005$) increased in both pelvic limbs of amputees, compared with values for the control dogs. Craniocaudal impulse was significantly ($P < 0.001$) increased in the remaining thoracic limb and ipsilateral pelvic limb of amputees, compared with values for the control dogs. Amputee dogs had a significant ($P < 0.001$) increase in the percentage of weight distribution to all remaining limbs, compared with values for the control dogs (**Figure 3**). The percentage of weight distribution did not differ significantly ($P = 0.170$) between the contralateral and ipsilateral pelvic limbs of the amputee group. Mean ± SD pooled weight distribution on the pelvic limbs was 56 ± 5.8% for the amputee group and 40 ± 4.2% for the control group.

Joint kinematics—Joint kinematics was determined for the limbs and for regions of the vertebral column.

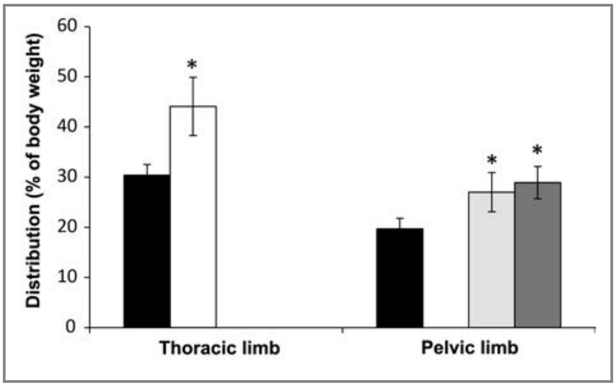

Figure 3—Mean ± SD values for the percentage of body weight distribution for the thoracic and pelvic limbs of quadruped control dogs (black bars) and the RTL (white bar), CPL (light gray bar), and IPL (dark gray bar) of thoracic limb–amputee dogs. For the control dogs, values for the left and right sides did not differ significantly ($P < 0.05$); therefore, a pooled value was used. Values represent a percentage of total mean peak GRF of all limbs calculated as described elsewhere.[9] *Within a limb, value differs significantly ($P < 0.017$) from the value for the control limbs. *See* Figure 1 for remainder of key.

LIMB KINEMATICS

No significant differences between the right and left side were found in the limb kinematics for the control group; thus, values for the left and right thoracic and pelvic limb were pooled for the control dogs. During the stance phase of the thoracic limb, a significant ($P = 0.011$) increase in overall joint ROM was detected for the carpus in amputees, compared with the overall joint ROM for the carpus in control dogs, primarily attributable to greater extension during the stance phase (**Table 3**). Significant ($P = 0.003$) differences in ROM during the stance phase were detected for the ipsilateral hip and stifle joints in amputee dogs, compared with values in control dogs, because of smaller mini-

Table 3—Mean ± SD joint angles (°) in the sagittal plane for limbs of 24 control dogs and 16 thoracic limb–amputee dogs during the stance phase while trotting.

Joint	Group	Side	Mean	Maximum	Minimum	Range
Shoulder	Control	Pooled	135.0 ± 12.9	152.2 ± 13.1	126.2 ± 13.2	26.0 ± 6.9
	Amputee	Remaining	138.4 ± 13.8	154.8 ± 8.9	125.2 ± 15.8	26.6 ± 11.7
Elbow	Control	Pooled	138.7 ± 12.0	156.4 ± 12.2	123.0 ± 12.9	33.3 ± 8.6
	Amputee	Remaining	136.5 ± 12.3	158.9 ± 12.5	119.2 ± 12.8	39.7 ± 10.4
Carpus	Control	Pooled	211.6 ± 10.0	190.0 ± 7.7	226.9 ± 13.5	323.0 ± 10.7
	Amputee	Remaining	218.8 ± 10.3	189.4 ± 6.2	236.5 ± 10.4	312.9 ± 8.9*
Hip	Control	Pooled	112.1 ± 10.3	124.5 ± 10.2	100.6 ± 9.6	23.9 ± 4.0
	Amputee	Ipsilateral	108.9 ± 11.4	121.3 ± 10.0	92.6 ± 11.8	28.7 ± 3.9*
	Amputee	Contralateral	108.1 ± 13.6	118.9 ± 15.1	96.6 ± 11.9	22.3 ± 7.5
Stifle	Control	Pooled	127.8 ± 10.9	144.5 ± 10.8	119.8 ± 11.9	24.8 ± 5.1
	Amputee	Ipsilateral	116.3 ± 14.4	141.6 ± 12.0	104.2 ± 16.7*	37.4 ± 8.4*
	Amputee	Contralateral	125.6 ± 12.9	141.1 ± 14.0	116.1 ± 12.2	25.0 ± 5.6†
Tarsus	Control	Pooled	131.2 ± 9.6	156.9 ± 8.2	112.9 ± 9.7	44.1 ± 5.9
	Amputee	Ipsilateral	125.6 ± 10.3	155.1 ± 9.0	105.3 ± 11.1	49.8 ± 6.8
	Amputee	Contralateral	133.1 ± 11.0	159.0 ± 9.2	114.2 ± 12.5	44.9 ± 10.3

*Within a column within a joint, value differs significantly ($P < 0.013$) from the control value. †Within a column within a joint, value differs significantly ($P < 0.013$) from the value for the ipsilateral amputee pelvic limb.

Table 4—Mean ± SD angle (°) of the vertebral column in the sagittal plane of 24 control dogs and 16 amputee dogs during the stance phase for each thoracic or pelvic limb during trotting.

Vertebral region	Group	Side	Mean	Maximum	Minimum	Range
Thoracic limb						
T1	Control	Pooled	1.7 ± 5.5	5.9 ± 5.7	–1.8 ± 5.6	7.7 ± 2.6
	Amputee	Remaining	6.3 ± 8.1	17.9 ± 9.0*	–2.0 ± 9.0	19.9 ± 6.2*
T13	Control	Pooled	3.8 ± 5.3	6.8 ± 5.8	0.3 ± 5.2	6.5 ± 1.8
	Amputee	Remaining	1.4 ± 6.1	5.7 ± 6.5	–2.6 ± 5.9	8.3 ± 2.3
L7	Control	Pooled	–15.4 ± 3.3	–11.5 ± 4.0	–20.1 ± 4.0	8.7 ± 4.0
	Amputee	Remaining	–17.1 ± 3.7	–11.6 ± 4.4	–22.7 ± 4.0	11.1 ± 3.8
Pelvic limb						
T1	Control	Pooled	1.9 ± 5.3	6.0 ± 5.5	–0.9 ± 5.3	6.9 ± 1.8
	Amputee	Ipsilateral	11.5 ± 9.2*	16.0 ± 9.7*	5.6 ± 8.5*	10.4 ± 4.1*
	Amputee	Contralateral	8.0 ± 8.6*	17.4 ± 8.8*	–2.3 ± 10.0	19.7 ± 7.6*†
T13	Control	Pooled	4.3 ± 5.2	6.9 ± 5.5	1.0 ± 5.1	5.9 ± 1.4
	Amputee	Ipsilateral	1.6 ± 4.5	5.3 ± 5.0	–2.6 ± 4.4	7.8 ± 2.9*
	Amputee	Contralateral	0.3 ± 5.0	4.5 ± 6.0	–3.6 ± 4.9*	8.1 ± 2.4*
L7	Control	Pooled	–14.7 ± 3.5	–11.0 ± 4.1	–19.0 ± 3.9	8.0 ± 3.5
	Amputee	Ipsilateral	–20.4 ± 4.4*	–14.9 ± 4.5	–24.5 ± 5.9*	9.6 ± 6.1
	Amputee	Contralateral	–18.3 ± 4.6*†	–13.3 ± 4.1	–23.3 ± 5.6*	10.0 ± 4.2

Positive angles indicate extension of the vertebral column within the vertebral region, and negative values indicate flexion of the vertebral column within the vertebral region.

*Within a column within a vertebral region, value differs significantly ($P < 0.013$) from the control value. †Within a column within a vertebral region, value differs significantly ($P < 0.013$) from the value for the ipsilateral amputee pelvic limb.

mum joint angles that indicated increased flexion in the amputee dogs. In the amputee group, there was also a significant ($P = 0.003$) increase in overall joint ROM in the ipsilateral stifle joint, compared with the value in the control dogs, as a result of an increase in flexion in the amputee dogs.

REGIONAL VERTEBRAL KINEMATICS

In the sagittal plane, the CTVR in amputee dogs had a significant ($P < 0.001$) increase in overall ROM, compared with that of the control dogs, because of cervicothoracic extension during the stance phase of the thoracic limb in the amputee group (**Table 4**). During the stance phase of the ipsilateral pelvic limb in the amputee group, the CTVR and TLVR had a significant ($P = 0.008$) increase in overall ROM and the LSVR had a significant ($P < 0.001$) increase in mean joint angle, compared with values for the control dogs, which indicated increased flexion in the joints of the amputee dogs. During the stance phase of the contralateral pelvic limb in the amputee group, there was a significant increase in mean CTVR angle ($P = 0.011$) as well as overall ROM ($P = 0.001$), compared with values for the control dogs, which indicated increased cervicothoracic extension in the amputee dogs (Table 4). Significant differences were also found at the TLVR and LSVR where amputees had a significant ($P = 0.001$) increase in overall ROM at the TLVR region and a significant ($P = 0.009$) increase in the mean angle at the LSVR region, compared with values for the control dogs. These differences indicated an increase in extension at the TLVR region and an increase in flexion at the LSVR in the amputee group. Comparison of the ipsilateral and contralateral pelvic limbs of the amputee group revealed that the CTVR had a significant ($P = 0.009$) increase in overall ROM in the sagittal plane and the LSVR had a significant ($P = 0.002$) increase in mean angle during the stance phase of the ipsilateral pelvic limb, compared with values for the control dogs, which indicated an increase in extension at the CTVR and flexion at the LSVR in amputee dogs.

Table 5—Mean ± SD angle (°) of the vertebral column in the horizontal plane of 24 control dogs and 16 amputee dogs during the stance phase for each thoracic or pelvic limb during trotting.

Vertebral region	Group	Side	Mean	Maximum	Minimum	Range
Thoracic limb						
T1	Control	Pooled	–3.0 ± 10.5	4.3 ± 11.4	–10.1 ± 10.7	16.4 ± 9.1
	Amputee	Remaining	–2.4 ± 12.6	10.9 ± 12.2	–12.2 ± 13.4	23.2 ± 7.2
T13	Control	Pooled	0.8 ± 7.4	10.2 ± 6.9	–8.2 ± 8.7	18.4 ± 7.3
	Amputee	Remaining	1.0 ± 6.1	8.8 ± 8.2	–8.8 ± 4.9	17.6 ± 5.9
L7	Control	Pooled	0.0 ± 7.6	5.3 ± 8.6	–5.6 ± 7.2	10.9 ± 4.9
	Amputee	Remaining	4.2 ± 3.9	10.4 ± 5.6	–4.4 ± 6.0	14.8 ± 8.1
Pelvic limb						
T1	Control	Pooled	–4.1 ± 11.2	2.2 ± 11.4	–10.5 ± 11.4	12.6 ± 5.8
	Amputee	Ipsilateral	7.0 ± 12.3*	–1.7 ± 12.6	–13.3 ± 12.1	11.6 ± 3.7
	Amputee	Contralateral	6.6 ± 10.4*	5.0 ± 10.9	–14.8 ± 11.5	19.7 ± 7.6*
T13	Control	Pooled	0.8 ± 7.0	9.3 ± 6.6	–7.5 ± 8.3	16.8 ± 6.4
	Amputee	Ipsilateral	–1.7 ± 4.4	1.9 ± 4.1*	–5.9 ± 4.8	7.8 ± 2.9*
	Amputee	Contralateral	–1.1 ± 4.9	2.5 ± 4.7*	–5.5 ± 5.8	8.1 ± 2.4*
L7	Control	Pooled	1.2 ± 10.7	6.2 ± 11.6	–4.0 ± 9.8	10.3 ± 5.1
	Amputee	Ipsilateral	8.6 ± 19.8	13.2 ± 20.1	3.6 ± 18.8	9.6 ± 6.1
	Amputee	Contralateral	10.1 ± 16.6	15.1 ± 17.1	5.1 ± 16.0	10.0 ± 4.2

Positive angles indicate right lateral bending (or toward the side of amputation) for each vertebral region, and negative values indicate left lateral bending (or away from the side of amputation) for each vertebral region.

See Table 4 for remainder of key.

During the stance phase of the ipsilateral pelvic limb in amputee dogs, the CTVR had a significant (*P* = 0.013) change in mean joint angle, compared with the value for the control dogs, which indicated an increase in lateral flexion (ie, bending) toward the side of amputation, whereas control dogs typically had flexion toward the side of the thoracic limb currently in the stance phase. The TLVR also had a significant (*P* = 0.006) decrease in overall ROM during the stance phase of the ipsilateral pelvic limb, compared with the value for the control dogs, as a result of a significant (*P* = 0.002) increase in lateral bending toward the side of amputation (**Table 5**). During the stance phase of the contralateral pelvic limb, a significant (*P* = 0.002) increase in overall ROM was found at the CTVR of amputee dogs, compared with the value in control dogs, which possibly indicated more side-to-side sway in amputee dogs. This also resulted in a significantly (*P* = 0.006) smaller mean joint angle in the amputee dogs than in the control dogs, which indicated lateral flexion toward the side of amputation. A significant ($P < 0.001$) decrease in overall ROM was found at the TLVR in the horizontal plane of amputee dogs, compared with the value in control dogs, because of a significantly (*P* = 0.001) smaller minimum joint angle in the amputee group, which indicated a decrease in lateral bending toward the side of amputation.

Discussion

In the present study, gait alterations associated with thoracic limb amputation were objectively characterized in an effort to increase the information about the manner in which dogs compensate for loss of a limb. Compensation strategies for thoracic limb amputees included significantly altered GRFs, impulses, and stance durations within all limbs; the remaining thoracic limb and ipsilateral pelvic limb were most affected in amputees, but all limbs had an increase in weight distribution. These findings are consistent with those of another study.[9] In the present study, analysis of limb angular kinematics revealed a significant alteration in motion at the carpus and ipsilateral hip and stifle joints of the amputees, whereas analysis of vertebral angular kinematics revealed altered motion in both the horizontal and sagittal planes at each region of interest in the vertebral column. Compensation for the amputated thoracic limb appeared to primarily involve the ipsilateral pelvic limb in addition to the remaining thoracic limb as amputees adopted a unique blending of gait patterns.

An inverse relationship between stance duration and peak vertical force has been reported in clinically normal dogs during both walking and trotting, whereby increasing peak vertical force generally correlates with a decrease in stance duration.[16–18] However, a study[9] of thoracic limb amputees found that stance duration during walking decreased without a concurrent increase in peak vertical force, which resulted in a decrease in vertical impulse. In contrast, the kinetic analysis of trotting amputee dogs in the present study revealed that stance duration increased without a change in peak vertical force, which resulted in an increase in vertical impulse and indicated that thoracic limb amputees adopt different compensation strategies that may depend on gait type, velocity, or both. Furthermore, the rounded GRF curves that resulted from the increased stance durations were an indication that a higher load was applied over a longer duration throughout the stance phase. This is an important issue for these dogs because many of them have signs of osteoarthritis and joint dysfunction, and cartilage degradation is presumed to progress at a faster rate with increased loading during cyclic movements such as walking.[19]

In addition to increased limb loading, there was an increase of approximately 55% in peak braking GRFs of both the remaining thoracic limb and the ipsilateral pelvic limb of the amputee group. Without a concurrent increase in braking impulse, these increased peak braking GRFs indicated that higher forces were being distributed over a shorter duration. Typically, the thoracic limbs are used primarily for braking and the pelvic limbs primarily for propulsion, although both sets of limbs participate in both braking and propulsive functions.[16,17,20] The amputee group had this pattern of craniocaudal forces during trotting; however, the pattern for these functions had 2 important alterations that had little impact on the contralateral pelvic limb. First, the remaining thoracic limb functioned almost entirely in braking and contributed less to propulsion. Second, the ipsilateral pelvic limb adopted the role of both a thoracic and a pelvic limb in that it had increased braking and propulsive GRFs as well as an increase in propulsive impulse. Although the remaining thoracic limb certainly had to withstand greater demands than usual, the ipsilateral pelvic limb may be more susceptible to acute and chronic injuries as a result of the dual roles it provides in amputees.

In the remaining thoracic limb in amputee dogs, the carpus had an increase in overall joint ROM and hyperextension during the stance phase attributable to an increase in the percentage of body weight distribution and GRFs for that limb. The lack of significant differences in joint kinematics at the shoulder and elbow joints indicated that these joints remained relatively extended during the stance phase, which was similar to results for the control dogs, and did not aid the carpus in providing additional elastic recoil (which is lost with the amputation of a thoracic limb) that is needed for the paw to clear the ground with each step. Therefore, the carpus of a thoracic limb amputee undergoes increased stress and strain, particularly at increased gait velocities whereby GRFs are higher and joint motion becomes more rapid. Kinematics of the ipsilateral hip and stifle joints of the amputees had an increase in overall joint ROMs because of the increase in flexion during the stance phase, whereas the tarsal joint had no significant compensatory changes. Although no significant differences were detected between the ipsilateral and contralateral pelvic limbs with regard to weight distribution among the amputee group, the ipsilateral pelvic limb did have greater magnitudes of weight distribution and peak GRFs, which could have been contributing factors to the increase in joint ROMs detected at the hip and stifle joints of the ipsilateral pelvic limb.

Although mean velocity did not differ significantly between amputee and control dogs, the gait of amputees may not have been that of a true trot. During trotting, a dog typically alternates diagonal limb pairs during each stance phase.[21] However, thoracic limb amputees in the present study often had substantial overlap between the stance phases of the 2 pelvic limbs, which is more characteristic of a hopping or galloping gait pattern typically associated with faster gait velocities.[21] The stance phase of the thoracic limb was typically followed by ground contact of the ipsilateral pelvic limb and then the contralateral pelvic limb, whereby the ipsilateral pelvic limb overlapped with the stance phases of both the preceding and following limbs. When the ipsilateral pelvic limb was forced to take on the increased demands and function of both a thoracic and pelvic limb in terms of increased GRFs, the gait pattern of a thoracic limb amputee had little in common with that of a clinically normal dog during trotting. Instead, the gait of amputees becomes a blend of characteristics associated with other clearly defined gait patterns.

The pattern of diagonal limb support during a gait cycle in clinically normal trotting dogs helps to maintain a balance of forces that would otherwise cause abnormal rotation of the trunk.[22] Thoracic limb amputees lose this balance of rotational forces and have an increase in sagittal and horizontal motion of the vertebral column that is most pronounced during the stance phase of the pelvic limbs. A position with an extended head and neck combined with a flexed lumbosacral region causes a caudal shift in the center of gravity. This is likely an effort to remove weight from the remaining thoracic limb and to place the ipsilateral pelvic limb in a more protracted position under the trunk to improve stability. Furthermore, the limbs need to clear the ground between stance phases. In dogs with an amputated thoracic limb, the pelvic limbs are recruited to provide an increase in elevation of the body (ie, center of mass), which subsequently increases extension in the TLVR and flexion in the lumbar vertebral region. Altered motion of the vertebral column may have a long-term impact for an amputee because of increased demands on muscular control and trunk strength (ie, core stability).[23]

During data collection, it was apparent that some skin markers may have caused more artifact error than others. In particular, it appeared that the reflective marker at T1 may have had the greatest movement artifact error as a result of increased soft tissue movement and interference from each dog's collar, particularly within the horizontal plane; however, skin movement artifact error was not specifically evaluated in the present study.

Ideally, clinically normal purpose-bred dogs with controlled age and body weight that were subjected to gait analysis before and after amputation would serve as the best study population. This was not possible because of limited resources and animal welfare concerns associated with subjecting clinically normal dogs to medically unnecessary limb amputations.

Preexisting musculoskeletal injuries and lameness are common among osteosarcoma patients[24] and older patients; thus, the imperfect physical condition of the control and amputee dogs in the present study was believed to be representative of the general patient population that typically undergoes limb amputation. The greatest numbers of musculoskeletal abnormalities in both the amputee and control groups were localized to the hip and stifle joints and vertebral column. These clinical findings were consistent with the body regions identified kinetically and kinematically in the present study as being the most susceptible to an increase in loading and to potential lameness after thoracic limb amputation.

The objective of the study reported here was to provide clinically relevant data on the gait of thoracic limb–amputee dogs; however, variation among subjects resulted in limitations that, in retrospect, might have been reduced with a case-control study design. In future studies, investigators may find it beneficial to limit enrollment to subjects without concurrent musculoskeletal or neurologic abnormalities or to subjects with a single, specific injury (eg, cruciate ligament tear), thereby reducing variation attributable to numerous preexisting physical conditions. However, such limitations to enrollment criteria will be at the expense of a decrease in the clinical relevance and will increase the challenge of finding suitable patients that meet those criteria.

Dogs of the amputee group were a mean of 2.4 years older than the dogs of the control group, which was not surprising because of the fact that osteosarcoma patients typically are older. This could have added bias to the data because some older dogs may have reduced joint mobility and increased compensatory gait changes as a result of increasing severity of musculoskeletal disorders,[25] and this may have reflected heterogeneity between the subject groups. An increase in stance duration and impulse variation may have been attributable to the increased range of gait velocities allowed for the amputee group because stance duration is inversely correlated with velocity.[18] Although a walking gait may have allowed for a more consistent range of velocities, we believed that the analysis of subjects during trotting would provide important new information about the gait of canine amputees for a more intense activity in which these dogs typically engage. The dogs in the present study underwent thoracic limb amputations 1 to 7 months prior to gait analysis; it has been suggested that 1 month is needed as an adaptation period after limb amputation.[3] Although not evident in the present study, it is possible that complete adaptation to limb amputation may require longer than 1 month and that additional gait alterations and compensatory strategies may place these dogs at an increased risk for musculoskeletal injury in one of the remaining limbs. Future studies focused on analyzing kinetic and kinematic changes at multiple time points after amputation would help to determine the extent of progressive or regressive compensatory changes over time because it is not clear whether amputation of a limb results in accelerated wear on any of the remaining limbs following an initial period of tripedal adaption.

In the present study, the ipsilateral pelvic limb took on dual thoracic and pelvic limb roles, and gait of forelimb amputees during trotting appeared to be a blend of various gait patterns. Compared with results for quadruped control dogs, the vertebral column, carpus, and ipsilateral hip and stifle joints had significant biomechanical changes following thoracic limb amputation. Results of this study can be used to determine anatomic areas that may have increased changes during tripedal adaption after forelimb amputation for a given patient. In addition, it also provides a basis for further research into long-term outcome measures of the gait of thoracic limb amputees as well as the gait of dogs undergoing alternative forelimb salvage procedures.

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a. Roberts indoor/outdoor double-sided carpet tape, QEP, Boca Raton, Fla.
b. Motus 9.0, Vicon Motion Systems Inc, Centennial, Colo.
c. Model BP400600-1000 force platforms, AMTI Inc, Watertown, Mass.
d. Model OR6-5-1000 force platforms, AMTI Inc, Watertown, Mass.
e. Dinion, Bosch Security Systems Inc, Fairport, NY.
f. MEK-92-PAD, Mekontrol Inc, Richardson, Tex.
g. Matlab, R2010a, MathWorks, Natick, Mass.

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