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

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Objective—To evaluate biomechanical gait adaptations in dogs after amputation of a pelvic limb.

Animals—Client-owned dogs (12 pelvic 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—Pelvic limb amputees had increased peak braking forces in the contralateral thoracic limb and increased propulsive forces and impulses in both the ipsilateral thoracic limb and remaining pelvic limb. Time to peak braking force was significantly decreased, and time to peak propulsive force was significantly increased in all remaining limbs in amputees. Amputees had an increase in range of motion at the tarsal joint of the remaining pelvic limb, compared with results for the control dogs. Amputees had increased vertebral range of motion at T1 and T13 and increased vertebral extension at L7 within the sagittal plane. In the horizontal plane, amputees had increased lateral bending toward the remaining pelvic limb, which resulted in a laterally deviated gait pattern.

Conclusions and Clinical Relevance—Pelvic limb amputees adjusted to loss of a limb through increased range of motion at the tarsal joint, increased range of motion in the cervicothoracic and thoracolumbar vertebral regions, and extension of the lumbosacral vertebral region, compared with results for the control dogs. Amputees alternated between a laterally deviated gait when the pelvic limb was in propulsion and a regular cranially oriented gait pattern when either forelimb was in propulsion with horizontal rotation around L7. (*Am J Vet Res* 2013;74:1164–1171)

ABBREVIATIONS

CTL	Contralateral thoracic limb
CTVR	Cervicothoracic vertebral region
GRF	Ground reaction force
ITL	Ipsilateral thoracic limb
LSVR	Lumbosacral vertebral region
RPL	Remaining pelvic limb
TLVR	Thoracolumbar vertebral region

Most dogs adapt well to amputation of a limb and return to normal levels of activity within a month after surgical removal of a limb[1]; however, the biomechanical impact of limb amputation on the remaining musculoskeletal system is not known. Pelvic limb amputation is thought to impair balance and locomotor function as a result of increased weight bearing on the RPL and increased vertebral range of motion attributable to asymmetric support and propulsion of the pelvic limb.[2,3] Investigators in 1 study[2] found that peak vertical forces and impulses across all limbs are comparable between pelvic limb amputees and quadruped dogs. However, the stance duration is decreased in amputees, which indicates that the same force is still applied to the limbs but over a shortened time period.[2] In quadruped dogs, decreased stance duration is typically associated with increased velocity[2]; however, in pelvic limb amputees, the decreased stance duration is a result of an increase in limb cadence and not because of an increase in overall velocity.[2] Consequently, examining the adaptations made by amputees during trotting is of importance. Additionally, it has been proposed that as velocity increases, the rigor of the test also increases,[4] such that amputee dogs may have different adaptations during trotting than those observed for amputee dogs at a walking velocity.

Received November 12, 2012.
Accepted April 11, 2013.

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Supported in part by the College of Veterinary Medicine and Biomedical Sciences College Research Council and the Colorado State University Flint Animal Cancer Center.

This manuscript represents a portion of a thesis submitted by Ms. Hogy to the Colorado State University School of Biomedical Engineering as partial fulfillment of the requirements for a Master of Science degree.

The authors thank Kristen Weishaar, Kelly Carlsten, Laura Steele, and Laura Chubb for technical assistance.

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Pelvic limb amputation also causes a redistribution of weight bearing in the limbs in that 74% of body weight is supported by the 2 thoracic limbs and 26% is supported by the RPL during walking.[2] Analysis of gait kinetics indicates that a typical quadruped dog supports 60% of its body weight on the thoracic limbs and 40% on the pelvic limbs during walking.[2] To fully understand the effects of altered limb loading after amputation on the entire musculoskeletal system, additional alterations in limb and vertebral kinematics need to be examined. A study[3] on balance in trotting dogs reveals that rotational forces about the transverse and sagittal axes of the trunk are countered by placement of the diagonal limb pair during the stance phase. Pelvic limb amputation removes the contralateral limb support for one of the thoracic limbs; thus, there must be substantial limb or vertebral compensation to maintain balance and trunk support or core stability.

The purpose of the study reported here was to objectively characterize differences in the gait during trotting for client-owned pelvic limb–amputee dogs and a cohort of client-owned quadruped dogs that had orthopedic, neurologic, or other related comorbidities similar to those of the amputee dogs, thus reflecting patient conditions in a clinical environment. We hypothesized that limb loading and joint motion would be significantly increased in pelvic limb–amputee dogs, with an increased range of motion in the joints of the remaining limbs and increased GRFs in all limbs.

Materials and Methods

Animals—Thirty-one quadruped control dogs and 13 pelvic limb amputees (7 with amputation of the left pelvic limb and 6 with amputation of the right pelvic limb) were enrolled in the study. 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 (to minimize simultaneous paw strikes on the force platforms). Amputee dogs were eligible for inclusion if the pelvic limb amputation was performed ≥ 4 weeks before gait analysis to allow an adequate period to adapt to a 3-limbed gait.[5] 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. Gait, neurologic assessment, and orthopedic evaluations were categorized as normal or abnormal for each variable or anatomic region assessed; 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 dorsal aspect of 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 on each pelvic limb amputee (**Figure 1**). Kinematic and kinetic data were collected synchronously in a calibrated volume of 1 × 1 × 2 m centered over 3 in-series force platforms[b,c] mounted in a 12-m walkway equipped with an automatic video tracking program.[d] A digital color network camera[e] located in the center of the walkway was 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 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 en-

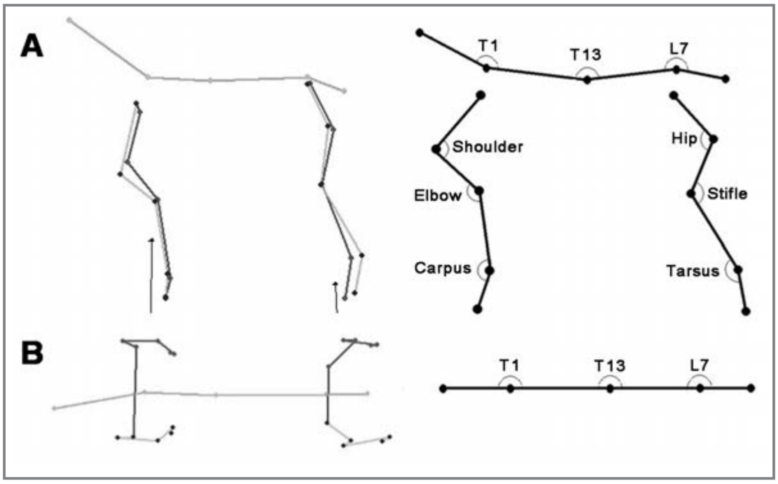

Figure 1—Schematic of the sagittal (A) and horizontal (B) plane reconstructions of the location of retroreflective markers affixed to the skin over bony landmarks at joint centers of rotation along the thoracic and pelvic limbs and vertebral column of quadruped (control) dogs and dogs after amputation of a pelvic limb. On the thoracic limbs, 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 limbs, 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; spinous processes of T1, T13, and L7; and the dorsal sacral apex. For pelvic-limb amputees, a marker was also placed on the side of the pelvic limb amputation on the skin over the point at which the greater trochanter typically would be relative to the contralateral side.

vironment and attached retroreflective markers prior to data collection. 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 a specific 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 the remaining 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 from the 3-D coordinates of the retroreflective markers (Figure 1). For all limbs, an angle of 180° was considered full extension and joint angles < 180° corresponded to flexion. 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 regional. In the horizontal plane, positive angles for a vertebral region represented right lateral bending (toward the side of amputation) and negative angles represented left lateral bending (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 were measured for each paw strike and normalized on the basis of the percentage of body weight. Braking forces and impulses were defined as negative values. Time to peak GRF was also measured for the vertical, braking, and propulsive components. Body weight distribution was defined as the ratio of the mean peak vertical GRF of a limb to the overall total mean peak vertical GRF of all limbs.[6] For each kinetic variable, the mean value for a minimum of 3 and a maximum of 10 trials was calculated for each dog to minimize error attributable to single-trial variation.

Statistical analysis—Normal distribution of data was assessed with Shapiro-Wilk tests. Descriptive statistics for the control and amputee groups were calculated for age, height, and body weight. Mean differences were compared between groups by means of independent *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.[5,7] 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 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. Power analyses were conducted with a statistics software program[g] for tests that yielded nonsignificant results.

Table 1—Signalment characteristics of 24 quadruped (control) dogs and 12 pelvic limb–amputee dogs used for kinematic and kinetic analysis during trotting.

Group	Variable	Mean ± SD	Maximum	Minimum	Range
Control	Age (y)	6.3 ± 3.1	12.3	1	11.3
	Height (cm)	59.2 ± 5.8	77.5	50.8	26.7
	Weight (kg)	32.8 ± 10.3	64	14.6	49.4
Amputee	Age (y)	8.0 ± 2.0	11.5	5.2	6.3
	Height (cm)	62.2 ± 8.1	78.7	51.3	26.7
	Weight (kg)	30.8 ± 9.9	53	20.2	32.8
	Time since amputation (mo)	3.0 ± 1.5	5.8	1.1	4.7

Height is the distance from the ground to the most dorsal point between the scapulae (ie, withers). For each variable, there were no significant ($P \geq 0.017$) differences between the amputee and control groups.

Results

Animals—Forty-four dogs (31 control dogs and 13 amputee dogs) were enrolled in the study; however, only 24 control dogs and 12 pelvic limb–amputee dogs were included in the analysis (**Table 1**). Eight dogs were excluded from analysis because they did not meet minimum requirements for inclusion as a result of obstruction of reflective markers (4 control dogs), failure to acclimate to the experimental procedures during the practice trials (2 control dogs), or errors in data collection (1 control and 1 amputee dog). All amputees had pelvic limb removal (7 left; 5 right) because of various cancers (ie, osteosarcoma in 9 dogs, histiocytic sarcoma in 1, soft tissue sarcoma in 1, and anaplastic sarcoma in 1). The 24 control dogs were included as the control group in another study[8] conducted by our research group.

Age, height, and body weight did not differ significantly ($P \geq 0.017$; power ranged from 0.046 to 0.317) between groups (Table 1). All dogs, except for 2 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 induced during palpation, palpable periarticular fibrosis, palpable crepitus, or an altered range of motion. Neurologic abnormalities included mild ataxia or mild conscious proprioceptive deficits (1 amputee and 2 control 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 12 amputee dogs, 4 had joint abnormalities in all 3 limbs and 5 had joint abnormalities in 1 limb; the remaining 3 amputee dogs had no apparent joint abnormalities, but 1 had neurologic abnormalities. Bilateral joint abnormalities were common in a total of 15 control dogs and 4 amputee dogs. Abnormalities were detected in the hip joints (8 control dogs), stifle joints (7 control dogs), shoulder joints (3 control dogs), elbow joints (1 control dog and 3 amputee dogs), carpi (1 control dog and 1 amputee dog), and tarsal joints (1 control dog).

Table 2—Mean ± SD values for stance duration, axial foot displacement, and stride length for 24 control and 12 pelvic limb–amputee dogs during trotting.

Limb	Stance duration (s)	Axial foot displacement (m)	Stride length (m)
Thoracic			
Control*	0.234 ± 0.027	0.055 ± 0.028	1.155 ± 0.098
Amputee			
CTL	0.248 ± 0.081	0.061 ± 0.042	1.128 ± 0.098
ITL	0.238 ± 0.086	0.061 ± 0.016	1.253 ± 0.157
Pelvic			
Control*	0.197 ± 0.022	0.025 ± 0.028	1.125 ± 0.091
Amputee RPL	0.175 ± 0.037	0.004 ± 0.030	1.145 ± 0.133

Stride length is 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. For each variable, there were no significant ($P \geq 0.017$) differences between the amputee and control groups.

*Represents a pooled value for the left and right sides.

GRF kinetics—Eight amputee and 5 control dogs were unable to achieve or maintain velocity within the intended target 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 ± SD trotting velocity did not differ significantly ($P = 0.520$) between the amputee (2.25 ± 0.19 m/s) and control (2.29 ± 0.15 m/s) groups. There were no significant (all values were $P \geq 0.042$) differences between amputee and control dogs with regard to stance duration, stance width, or stride length for all limbs. Similarly, there were no significant (all values were $P \geq 0.647$) difference for CTLs and ITLs within the amputee group (**Table 2**). Mean ± SD axial foot displacement for the RPL in amputees (0.018 ± 0.038 m/m) was less than that of the control dogs (0.040 ± 0.045 m/m), which indicated a shifting of the RPL toward the midline; however, these values did not differ significantly ($P = 0.060$; power = 0.344). For variables that did not have significant differences, power ranged from 0.019 to 0.371.

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. All limbs of dogs in the amputee group bore significantly ($P < 0.001$) more weight than did limbs of the control dogs (**Table 3**). There was no significant ($P = 0.303$) difference in weight bearing between ITLs and CTLs within the amputee dogs. Peak vertical GRFs were significantly ($P = 0.004$) increased in the RPL of amputee dogs. Peak braking force was significantly ($P = 0.012$) increased in the CTL of amputee dogs, and peak propulsion forces and impulses were significantly ($P < 0.013$) increased in both the ITL and RPL, compared with values for the control dogs. Time to peak braking force was significantly

Table 3—Comparison of GRF kinetics for 24 control and 12 pelvic limb–amputee dogs.

	Thoracic limbs			Pelvic limbs	
		Amputee			
Variable	**Control***	**ITL**	**CTL**	**Control***	**Amputee**
Body weight support (% of total peak vertical GRF)	30.4 ± 2.1	37.1 ± 2.6†	35.8 ± 2.2†	19.7 ± 2.1	27.1 ± 3.1‡
Peak vertical GRF (N/% BW)	113.6 ± 16.4	126.3 ± 14.0	117.5 ± 16.7	74.1 ± 16.1	92.3 ± 13.9‡
Peak braking GRF (N/% BW)	–15.7 ± 2.8	–17.6 ± 4.3	–19.2 ± 4.8†	–5.5 ± 2.3	–8.5 ± 4.7
Peak propulsion GRF (N/% BW)	9.2 ± 3.4	12.3 ± 2.6†	10.6 ± 3.5	10.8 ± 3.8	16.8 ± 5.3‡
Time to peak vertical GRF (s)	0.11 ± 0.02	0.12 ± 0.04	0.13 ± 0.04	0.09 ± 0.01	0.09 ± 0.01
Time to peak braking GRF (s)	0.13 ± 0.04	0.08 ± 0.03†	0.08 ± 0.03†	0.08 ± 0.03	0.03 ± 0.03‡
Time to peak propulsion GRF (s)	0.11 ± 0.04	0.17 ± 0.07†	0.19 ± 0.08†	0.07 ± 0.03	0.11 ± 0.04‡
Vertical impulse (N•s/% BW)	15.5 ± 3.1	18.8 ± 5.7	19.4 ± 5.8†	8.8 ± 2.1	10.8 ± 1.7‡
Braking impulse (N•s/% BW)	–1.2 ± 0.2	–1.4 ± 0.7	–1.6 ± 0.9	–0.2 ± 0.09	–0.1 ± 0.1
Propulsion impulse (N•s/% BW)	0.5 ± 0.3	0.9 ± 0.4†	0.6 ± 0.5	0.9 ± 0.4	1.3 ± 0.5‡

Values reported are mean ± SD.

†Within a row, value differs significantly ($P < 0.017$) from the value for the thoracic limbs of the control dogs. ‡Within a row, value differs significantly ($P < 0.017$) from the value for the pelvic limbs of the control dogs.

% BW = Percentage of body weight.

See Table 2 for remainder of key.

Table 4—Mean ± SD joint angles (°) in the sagittal plane for limbs of 24 control dogs and 12 pelvic limb–amputee dogs.

Joint	Group	Limb	Mean	Maximum	Minimum	ROM
Shoulder	Control	Both*	135.0 ± 12.9	152.2 ± 13.1	126.2 ± 13.2	26.0 ± 7.0
	Amputee	CTL	143.3 ± 9.9	155.2 ± 11.9	132.8 ± 9.4	22.3 ± 9.4
	Amputee	ITL	131.6 ± 14.1	148.3 ± 13.1	122.1 ± 15.3	26.1 ± 11.2
Elbow	Control	Both*	138.7 ± 12.0	156.4 ± 12.3	123.0 ± 12.9	33.3 ± 8.6
	Amputee	CTL	138.7 ± 9.6	155.1 ± 10.6	124.1 ± 9.8	31.1 ± 9.5
	Amputee	ITL	140.1 ± 11.4	155.6 ± 8.9	124.5 ± 15.4	31.1 ± 9.1
Carpus	Control	Both*	148.4 ± 10.0	170.0 ± 7.7	133.1 ± 13.5	37.0 ± 10.7
	Amputee	CTL	143.4 ± 9.7	168.8 ± 7.1	127.4 ± 14.0	41.4 ± 16.4
	Amputee	ITL	140.4 ± 11.4	167.6 ± 5.7	120.6 ± 16.7	47.0 ± 14.7
Hip	Control	Both*	112.1 ± 10.3	124.5 ± 10.2	100.6 ± 9.6	23.9 ± 4.0
	Amputee	RPL	120.5 ± 11.4	133.5 ± 11.0	107.3 ± 14.2	26.2 ± 8.8
Stifle	Control	Both*	127.8 ± 10.9	144.5 ± 10.8	119.8 ± 11.9	24.8 ± 5.1
	Amputee	RPL	127.0 ± 12.9	145.8 ± 11.6	117.2 ± 14.9	28.7 ± 8.2
Hock	Control	Both*	131.2 ± 9.6	156.9 ± 8.2	112.9 ± 9.7	44.1 ± 5.9[a]
	Amputee	RPL	124.7 ± 12.0	157.5 ± 7.3	104.1 ± 17.0	53.3 ± 14.0[b]

[a,b]Values with different superscript letters differ significantly ($P < 0.013$).

See Table 2 for remainder of key.

Table 5—Mean ± SD angles (°) of vertebral regions in the sagittal plane during thoracic and pelvic limb stance phases for 24 control dogs and 12 pelvic limb–amputee dogs.

Vertebral region	Stance phase	Group	Limb	Mean	Maximum	Minimum	ROM
T1	Thoracic limb	Control	Both*	1.7 ± 5.5	6.0 ± 5.7	–1.78 ± 5.6	7.7 ± 2.6
		Amputee	ITL	2.2 ± 15.5	9.7 ± 15.9	–3.0 ± 14.4	12.7 ± 4.4†
		Amputee	CTL	8.1 ± 15.9‡	14.4 ± 15.3	2.1 ± 16.1	12.3 ± 5.8†
	Pelvic limb	Control	Both*	2.0 ± 5.3	5.8 ± 5.5	–1.0 ± 5.3	6.9 ± 1.8
		Amputee	RPL	2.7 ± 16.1	9.6 ± 17.0	–2.03 ± 15.6	11.6 ± 3.5†
T13	Thoracic limb	Control	Both	3.8 ± 5.3	6.8 ± 5.8	0.3 ± 5.2	6.5 ± 1.8
		Amputee	ITL	–6.5 ± 8.6†	–1.3 ± 9.9†	–12.3 ± 7.9†	11.0 ± 4.7†
		Amputee	CTL	–8.7 ± 8.8†	–3.8 ± 9.1†	–14.6 ± 8.7†,‡	10.8 ± 5.0†
	Pelvic limb	Control	Both*	4.3 ± 5.2	6.9 ± 5.5	1.0 ± 5.1	5.9 ± 1.4
		Amputee	RPL	–5.4 ± 8.9†	–1.1 ± 9.2†	–11.7 ± 7.8†	10.7 ± 4.1†
L7	Thoracic limb	Control	Both*	–15.4 ± 3.3	–11.5 ± 4.0	–20.1 ± 4.0	8.7 ± 4.0
		Amputee	ITL	–18.1 ± 6.3	–11.9 ± 9.4	–24.2 ± 6.8	12.3 ± 7.4
		Amputee	CTL	–22.07 ± 5.9†,‡	–15.8 ± 8.3†,‡	–27.4 ± 5.7‡	11.6 ± 7.1
	Pelvic limb	Control	Both	–14.7 ± 3.5	–11.0 ± 4.1	–19.0 ± 3.9	8.0 ± 0.4
		Amputee	RPL	–12.2 ± 15.9	–7.5 ± 17.2	–18.0 ± 15.4	10.5 ± 7.7

Negative values indicate vertebral flexion, and positive values indicate vertebral extension.

†Within a vertebral region and limb, the value differs significantly ($P < 0.013$) from the control value. ‡Within a vertebral region in amputee dogs, the value differs significantly ($P < 0.013$) from the value for the ITL.

ROM = Overall range of motion.

Table 6—Mean ± SD angles (°) of vertebral regions in the horizontal plane during thoracic and pelvic limb stance phases for 24 control dogs and 12 pelvic limb–amputee dogs.

Vertebral region	Stance phase	Group	Limb	Mean	Maximum	Minimum	ROM
T1	Thoracic limb	Control	Both*	–3.0 ± 10.5	4.3 ± 11.4	–10.1 ± 10.7	16.2 ± 9.1
		Amputee	ITL	–3.8 ± 18.0	5.8 ± 20.6	–16.1 ± 16.3	21.9 ± 11.6
		Amputee	CTL	–9.1 ± 22.6‡	4.3 ± 25.0	–19.3 ± 20.1	23.6 ± 12.0
	Pelvic limb	Control	Both*	–4.1 ± 11.2	2.2 ± 11.4	–10.5 ± 11.4	12.6 ± 5.8
		Amputee	RPL	–3.0 ± 19.0	4.5 ± 20.2	–13.0 ± 17.5	17.5 ± 8.9
T13	Thoracic limb	Control	Both*	0.8 ± 7.4	10.2 ± 6.9	–8.2 ± 8.7	18.4 ± 7.3
		Amputee	ITL	6.3 ± 9.5	17.2 ± 11.5	–3.5 ± 9.3	20.6 ± 7.8
		Amputee	CTL	6.4 ± 10.4	16.7 ± 9.4	–5.3 ± 11.2	21.9 ± 10.5
	Pelvic limb	Control	Both*	0.8 ± 7.01	9.3 ± 6.6	–7.5 ± 8.3	16.8 ± 6.4
		Amputee	RPL	4.9 ± 11.1	15.6 ± 11.0	–2.8 ± 10.5	18.4 ± 5.4
L7	Thoracic limb	Control	Both*	0.0 ± 7.6	5.3 ± 8.6	–5.6 ± 7.2	10.9 ± 4.9
		Amputee	ITL	–8.5 ± 13.3	–1.4 ± 13.1†	–15.9 ± 14.9	14.5 ± 8.9
		Amputee	CTL	–5.8 ± 12.9‡	0.4 ± 11.4	–13.3 ± 14.2‡	13.8 ± 5.9
	Pelvic limb	Control	Both	1.2 ± 10.7	6.3 ± 11.6	–4.0 ± 9.8	10.3 ± 5.1
		Amputee	RPL	–9.2 ± 15.2	–3.0 ± 13.2	–15.3 ± 16.3	12.3 ± 7.1

See Tables 2 and 5 for key.

(*P* = 0.002) decreased for all limbs within the amputee group, and time to peak propulsion was significantly (*P* = 0.012) increased for all limbs of amputee dogs. There were no significant (all values were *P* ≥ 0.153) differences in peak GRF or time to peak GRF between the CTLs and ITLs of amputee dogs. Vertical impulses of both the CTL and the RPL of amputees were significantly (*P* = 0.015) increased as a result of the combined effects of a prolonged stance duration and increased GRFs. Impulses of the CTLs and ITLs of amputee dogs did not differ significantly (all values were *P* ≥ 0.029). For variables that did not have significant differences, power ranged from 0.020 to 0.505.

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

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. The ITL and CTL joint angles of amputee dogs did not differ significantly (all values were *P* ≥ 0.043) from the values for the control dogs (**Table 4**). There also were no significant (*P* = 0.037) differences in joint angles between the CTL and ITL of amputees. In the RPL of amputees, the tarsal joint had a significantly (*P* = 0.012) increased overall joint range of motion, compared with that of the control dogs. For variables that did not have significant differences, power ranged from 0.013 to 0.508.

REGIONAL VERTEBRAL KINEMATICS

Within the sagittal plane, there was a significant increase in the range for vertebral angular motion in both the CTVR and TLVR during the stance phase for both the thoracic (*P* = 0.003) and pelvic (*P* < 0.001) limbs (**Table 5**). The increase in range for vertebral angular motion was attributable to a significantly (all values were *P* ≤ 0.004) greater maximum flexion and extension in both the CTVR and TLVR for all limbs of amputee dogs; however, maximum flexion and maximum extension in the CTVR did not differ significantly (*P* = 0.024) in any limbs of the control dogs. During the stance phase of the CTL, there was a gradual increase in flexion as the dogs started propulsion and ended the stance phase, whereas during the stance phase of the ITL, there was an initial increase in extension followed by a period of flexion as the dogs moved into propulsion and ended the stance phase. Also, the mean regional vertebral motion in the CTVR and LSVR in amputee dogs differed significantly (*P* = 0.005) between the stance phases of the ITL and CTL. There also was a significant (*P* < 0.001) increase in the maximum angle of the LSVR during the stance phase of the CTL in amputee dogs, which reflected an increase in extension. For variables that did not have significant differences, power ranged from 0.016 to 0.361.

For vertebral motion in the horizontal plane, there were no significant differences in regional angular motion in the CTVR or TLVR of the amputee dogs during the stance phase of the thoracic or pelvic limbs, compared with values for the control dogs (**Table 6**). In the LSVR, there was a significant (*P* = 0.010) increase in the maximum angle within the horizontal plane during the stance phase of the ITL. Within the amputee dogs, mean ± SD regional angular motion in the LSVR within the horizontal plane differed significantly (*P* = 0.009) between the stance phases of the ITL (–8.5 ± 13.3°) and CTL (–5.8 ± 12.9°). For variables that did not have significant differences, power ranged from 0.013 to 0.460.

Discussion

The purpose of the present study was to examine, through detailed examination of limb joint and vertebral kinematics and GRFs, compensatory mechanisms adopted by dogs after pelvic limb amputation. Pelvic limb–amputee dogs had compensation mechanisms, which included increased range of motion of the tarsal joint within the RPL, altered vertebral kinematics within the sagittal plane, increased peak GRFs (including weight redistribution), and increased propulsion impulses in both the ITL and the RPL, that allowed the amputees to ambulate on 3 limbs. Compensation for the missing pelvic limb appeared to be placed on the RPL and vertebrae because amputees laterally bent the vertebral column in an effort to place the pelvic limb in closer proximity to the ITL to adopt a unique laterally deviated gait when the pelvic limb was in propulsion, with reversion to a regular cranially oriented gait when either thoracic limb was in propulsion. A laterally deviated gait describes a gait pattern in which the long axis of the thoracolumbar vertebrae not parallel to the forward motion of a dog, and a cranially oriented gait describes a gait pattern in which the long axis of the vertebral column is parallel to the forward motion of a dog.

The trotting results for the present study are similar to those of walking amputee dogs in another study[2] in which there was an increase in weight bearing (ie, approx increase of 6%/limb) equally distributed among all remaining limbs. The amount of body weight supported by the ITLs and CTLs were equal, which indicated that the GRFs of these limbs should have been similar.

Alterations in the gait of pelvic limb amputees during walking and trotting have some similarities and differences; however, velocity of the dogs as well as differences in data collection methods could account for most of these kinetic differences. An increase in velocity causes significant increases in peak vertical and braking GRFs and impulses and decreases in vertical and propulsion impulses.[9] In the present study, amputees had an increase in peak propulsion force and impulse in both the ITL and RPL. The increase in propulsion within these 2 limbs could have been a compensatory strategy for the increase in cadence as well as a method of getting the limbs off the ground more efficiently without the support of a fourth limb in each of the aforementioned support pairs. There was an increase in vertical impulse of the CTL and the RPL, which indicated that there was a greater amount of force over the same amount of time in these limbs, which leads to increased impact and potential wear to the joints. Increased peak braking force within the ITL could provide increased balance as a result of the lack of support that would typically be provided by the missing pelvic limb during trotting. Time to peak braking force was decreased and time to peak propulsion force was increased in all limbs of amputee dogs. Decreased time to peak braking force could support the concept of an increase in limb cadence without a corresponding increase in overall trotting velocity, which theoretically could increase articular and muscular strain within the 3 remaining limbs, whereas an increase in time to peak propulsion force could be a mechanism to help propel the limbs off the ground as a result of the increase in body weight support on each remaining limb after amputation.

Although there were several significant changes found in the GRFs, there was only 1 significant change in limb kinematics. Amputee dogs had an increase in the range of motion of the tarsal joint within the RPL. This most likely was a compensation mechanism to increase the compliance of the pelvic limb by maximizing elastic recoil within the calcaneal tendon and contributing muscles, such as the gastrocnemius muscle, to absorb the increased body weight supported by the RPL after amputation. In addition to an increase in the range of motion and increase in the cadence of the RPL, an increase in body weight support could result in an increase in joint impact and strain within the remaining limbs of amputee dogs. Limb kinematics were otherwise similar between pelvic limb amputee and control dogs, so it is likely that amputee dogs did not compensate for the loss of a limb by relying on altered joint angular kinematic mechanisms; instead, they compensated through other compensation mechanisms that involved changes in GRFs and vertebral kinematics.

Several significant changes in vertebral kinematics were detected within the sagittal plane. Increased regional angular motion in the CTVR and TLVR during the stance phase for all limbs could indicate both increased flexion and extension of the head and neck during trotting. Pelvic limb–amputee dogs cyclically move the head upward during propulsion of the CTL in an effort to elevate the body's center of mass and then move the head downward at the termination of the swing phase and beginning of the stance phase. In trotting horses, thoracic limb lameness causes horses to elevate their head and neck during the stance phase of the affected limb in an effort to shift the body's center of mass caudally and to unload the affected limb and reduce pain associated with weight bearing.[6] Similarly, pelvic limb–amputee dogs that had pain in the thoracic limbs during the stance phase may have increased the vertical displacement of the head and neck in an attempt to reduce weight bearing in the thoracic limbs (4 amputee dogs had abnormalities in 1 or both of their elbow joints). There was an increase in the extension of the LSVR of amputee dogs during the stance phase of both the CTL and ITL, but it was greater within the CTL. Because the RPL acts as a compliant strut, it must remain in a position farther under the trunk to maintain stability and aid in propulsion, both of which require increased flexion of the lumbosacral region during most of the gait cycle.

Increased lateral bending in the LSVR indicated that the loss of a pelvic limb may induce more motion toward the RPL in the hindquarters of dogs. Axial foot displacement for the RPL could have been one of the gait adaptations used by pelvic limb amputees, even though in the present study we did not identify increased lateral bending of the vertebral column caudal to L7 toward the limb to increase the angle in the LSVR and improve balance. Also, increased lateral bending in the LSVR could indicate that the epaxial muscles were more active on the side contralateral to the amputated pelvic limb and flexed the vertebral column laterally toward the contralateral side.

Physical examination revealed only 1 amputee with discomfort localized to the vertebral column, which suggested that the vertebral compensatory changes made by amputee dogs may be of limited clinical impact; however, the sample size was limited, and palpation of the vertebrae is a crude method for evaluating pathological changes of the vertebral column. The significant increase in range of motion for the tarsal joint measured during the stance phase in the RPL of the amputee dogs might have been related to clinical findings of abnormalities in the remaining stifle or hip joints in the pelvic limb as a mechanism to avoid discomfort.

The present study had several limitations. 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. Client-owned dogs with various physical conditions were used in the study as a reflection of typical clinical candidates for limb amputation. Use of client-owned dogs limited recruitment and sample size. Dogs also had to be of a specific size for paw strikes to readily register on the force platforms and could not have excessively long coats because the retroreflective markers could not be rigidly fixed to the skin and visible during data analysis. The sample size for this study was limited to the number of dogs that met the inclusion criteria during the time frame of the study. A larger sample size would have been needed to identify differences in some of the variables evaluated, as indicated by the low statistical power for these variables. Another limitation was variation in the use of medications, including analgesics and NSAIDs, in these dogs, which could have altered their natural gait.[10] Because the study included client-owned dogs, retroreflective markers were placed on the hair as close to the skin as possible without the benefit of clipping; this method of affixing the markers could have contributed to marker motion artifact.[11]

The objective for the present study was to provide data on the gait of pelvic limb–amputee dogs in a clinical population. Pelvic limb amputees have unique compensation mechanisms during trotting that allow for adaptation to a tripedal gait; pelvic limb amputees alternate between a laterally deviated gait when the pelvic limb is in propulsion and then revert to a regular cranially oriented gait when either forelimb is in propulsion with horizontal rotation of the LSVR. Additionally, increased propulsion of the remaining limbs allows the dogs to maintain forward velocity and a more rapid cadence. Results of this study will provide information as to the anatomic regions that may have greater change following pelvic limb amputation and may provide a foundation for further research into long-term outcome measures of the gait of pelvic limb amputees as well as the gait in dogs undergoing alternative pelvic limb salvage procedures.

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a. Roberts indoor/outdoor double-sided carpet tape, QEP, Boca Raton, Fla.
b. Model BP400600-1000 force platforms, AMTI Inc, Watertown, Mass.
c. Model OR6-5-1000 force platforms, AMTI Inc, Watertown, Mass.
d. Motus, version 9.0, Vicon Motion Systems Inc, Centennial, Colo.
e. Dinion, Bosch Security Systems Inc, Fairport, NY.
f. MEK-92-PAD, Mekontrol, Richardson, Tex.
g. G*Power 3, version 20, release 3.1.5, Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany. Available at: www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/. Accessed Jan 8, 2013.

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