Kinematic analysis of the hind limb during swimming and walking in healthy dogs and dogs with surgically corrected cranial cruciate ligament rupture

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Objective—To determine hip, stifle, and tarsal joint ranges of motion (ROM) and angular velocities during swimming and walking in healthy dogs and dogs with surgically corrected cranial cruciate ligament (CCL) rupture.

Design—Prospective clinical study.

Animals—13 healthy dogs and 7 dogs with CCL rupture.

Procedure—Dogs with CCL rupture were enrolled in a postoperative aquatic rehabilitation program and evaluated 21 to 35 days after surgery. Dogs were filmed while swimming in a pool and while walking at a fast (1.3 m/s) or slow (0.9 m/s) pace on a treadmill. Maximal angles of extension and flexion, ROM, and angular velocities were calculated.

Results—In healthy dogs, swimming resulted in a significantly greater ROM in the hip joint than did walking, but in dogs with CCL rupture, ROM of the hip joint did not vary with swimming versus walking. For dogs in both groups, swimming resulted in significantly greater ROM of the stifle and tarsal joints than did walking, primarily because of greater joint flexion. Stifle joint ROM was significantly lower in dogs with CCL rupture than in healthy dogs, regardless of whether dogs were swimming or walking.

Conclusions and Clinical Relevance—Results suggested that following surgical management of a ruptured CCL in dogs, swimming resulted in greater ROM of the stifle and tarsal joints than did walking. This suggests that if ROM is a factor in the rate or extent of return to function in these dogs, then aquatic rehabilitation would likely result in a better overall outcome than walking alone. (*J Am Vet Med Assoc* 2003;222:739–743)

Rupture of the **cranial cruciate ligament (CCL)** is the most commonly diagnosed stifle joint injury in dogs.[1] Although surgical management reportedly yields a satisfactory outcome in most dogs, a large number of dogs will have residual lameness.

In a recent study,[2] dogs that underwent postoperative aquatic rehabilitation following surgical management of a ruptured CCL had significantly higher peak vertical forces and vertical impulses 6 months after surgery than did dogs that underwent traditional postoperative exercise restriction. In dogs that underwent postoperative aquatic rehabilitation, peak vertical forces and vertical impulses in the treated limb were not significantly different from values for the contralateral unaffected limb. However, joint kinematic data were not collected in that study, limiting the authors' ability to characterize joint **range of motion (ROM)** and function.

Kinematic analysis has been previously used to objectively characterize joint motion in a variety of species[3-5] and to characterize the ROM of the stifle joint in healthy dogs and dogs with rupture of the CCL.[6-9] However, these studies have all involved evaluation of dogs during terrestrial motion, and to our knowledge, kinematic analyses of joint ROM and limb motion during swimming in dogs have not been published. The purpose of the study reported here, therefore, was to determine hip, stifle, and tarsal (hock) joint ROM and angular velocities during swimming and walking in healthy dogs and dogs that have undergone surgical treatment of a ruptured CCL. We hypothesized that dogs that had undergone surgical treatment of a ruptured CCL would have greater hip, stifle, and hock joint ROM during swimming than when walking.

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Materials and Methods

Dogs—Adult dogs undergoing postoperative rehabilitation at the Iowa State University Veterinary Teaching Hospital Canine Rehabilitation Facility between June 2000 and October 2001 were considered for inclusion in the study. Dogs were included in the study if they had undergone surgical treatment for rupture of a CCL, were undergoing postoperative aquatic rehabilitation, were between 1 and 10 years old, weighed between 25 and 45 kg (55 and 100 lb), and did not have any evidence of neurologic or additional orthopedic diseases.

Control dogs consisted of healthy dogs owned by students, faculty, and staff at the Iowa State University Veterinary Teaching Hospital. Control dogs were between 1 and 3 years old, weighed between 16 and 40 kg (35 and 88 lb), and did not have any signs of neurologic or orthopedic disease.

For all dogs, nonsteroidal anti-inflammatory medications were withheld for a minimum of 14 days prior to enrollment in the study. Owners of all dogs included in the study signed an informed consent form. For comparison of kinematic variables during swimming versus walking, each dog served as its own control. Investigators were not blinded to group assignment of dogs included in the study.

Rehabilitation group—Surgical treatment included débridement of the ruptured CCL, partial or complete medial meniscectomy, and extracapsular stabilization. After surgery, dogs were given morphine (0.5 mg/kg [0.23 mg/lb], IV, q 6 h) for analgesia for 24 hours and were hospitalized for 2 to 3 days. Dogs were permitted only short leash walks twice daily while hospitalized.

At the time of discharge, owners were not instructed to administer any analgesic or anti-inflammatory medications. Owners were instructed to limit their dogs' activity to short (0.5 miles) walks on a leash for urination and defecation only, twice daily, until suture removal. Dogs underwent postoperative aquatic rehabilitation during the third, fifth, and seventh weeks after surgery. Data for the present study were collected at the end of the third or fifth week after surgery.

Aquatic rehabilitation was performed on a Monday through Friday schedule at the Canine Rehabilitation Facility, with sessions twice daily. Each session began with 10 minutes of limb massage and passive ROM exercises, followed by 10 minutes of walking on a treadmill[a] and 10 to 20 minutes of pool time. Dogs were fitted with a personal flotation device for swimming[b] and allowed to walk into the pool. Aquatic rehabilitation began with alternating 1 minute of swimming with 1 minute of rest, for a total of 5 to 10 minutes of swimming. Nearly all dogs swam vigorously, with their limbs moving continuously, from the time they were suspended in the swimming pool with their limbs no longer touching the floor or stairs.

Aquatic rehabilitation was performed in a pool[c] that was 7-feet, 6-inches wide, 14-feet long, and 4-feet deep. Water was maintained according to standards set by the National Swimming Pool Foundation of America.[10] Water temperature was maintained between 32.2 and 33.3°C (90 and 92°F), total alkalinity was maintained between 80 and 120 ppm, total bromine concentration was maintained between 3 and 5 ppm, and pH was maintained between 7.2 and 7.6. Dogs were housed in stainless steel cages in the rehabilitation facility during each week of postoperative aquatic rehabilitation and were fed their typical diets as instructed by their owners. All dogs underwent a minimum of 4 rehabilitation sessions prior to collection of data for the present study.

Control group—Owners were instructed to allow their dogs normal activity in the days prior to data collection. Dogs were brought to the canine rehabilitation facility the morning of data collection and housed in stainless steel cages during the day. They were taken for a short walk to urinate and defecate prior to data collection. All dogs were allowed to acclimate to the treadmill and swimming pool prior to data collection.

Data collection—History, signalment (age, weight, breed, and sex), and body condition score (rated on a scale from 1 through 9 with 1 being gaunt and 9 being obese) of each dog were recorded. For collection of kinematic data, retroreflective markers[d] were unilaterally placed over the iliac crest, greater trochanter of the femur, femorotibial joint between the lateral femoral epicondyle and the fibular head, lateral malleolus of the tibia, and distolateral aspect of the fifth metatarsal bone. For all dogs that underwent surgery, the affected limb was chosen for placement of the markers, whereas for control dogs, the limb for marker placement was randomly assigned at the time of data collection. All markers were placed on each dog by a single individual (GSM). Three-dimensional volumes were calibrated in the pool and on the treadmill with two 60-Hz video cameras[e] and a surveyed 3-dimensional calibration object (12 points).[f] Dogs were then videotaped while walking and swimming. Dogs were walked at speeds of 0.9 m/s (slow walking) and 1.3 m/s (fast walking) on a treadmill and swum in a transparent pool that was 4-feet wide, 4-feet high, and 8-feet long and made from three-fourths-inch clear acrylic. Velocity of the treadmill was verified by using the known length of the treadmill and a reference point. From the digital time code on the collected data tapes, exact speed was determined.

Data analyses—Kinematic variables of interest included extension and flexion angles of the hip, stifle, and hock joints. Given that these data were planar (2-dimensional), use of 3-dimensional calibration was not strictly necessary for data collection while dogs walked on the treadmill. However, collection of data while dogs were swimming involved filming the dogs underwater, which distorted the image because of refraction through the water and acrylic pool. Therefore, a 3-dimensional direct linear transformation method of coordinate reconstruction was used to correct for distortion within the calibrated volume.[11,12] To ensure that the transformation method was effective in accounting for the effect of refraction, the calibration object was positioned in the center of the field of view of each camera, and trials were filmed with dogs swimming within the calibrated volume. Three-dimensional positions of the retroreflective markers were established by digitizing the videotapes with a motion analysis system.[g] Prior to any calculations, data were smoothed with a fourth-order, low-pass Butterworth filter with a cutoff frequency of 3 Hz to reduce digitizing error. Two-dimensional coordinates from each camera were used as input to a direct linear transformation algorithm that predicted the 3-dimensional coordinates of each marker. These data were then used to compute the respective kinematic measures.

Maximal extension and flexion angles of the stifle joint were determined for 3 consecutive cycles of motion, and joint ROM was computed. Trials were considered invalid if the dog appeared distracted or uncomfortable, the long axis of the dog was not parallel to the long axis of the pool or treadmill, or the dog moved forward or backward > 3 cm during the 3 consecutive cycles of motion. When dogs walked on the treadmill, a handler provided support to prevent forward and backward movement. When dogs swum in the pool, a handler restrained them by supporting the base of the tail to prevent forward and backward movement. Dogs readily acclimated to this support and were able to swim without distraction for a period sufficient to collect data.

A single cycle of motion was considered the period from toe off of the hind limb to the subsequent toe off. Data for the 3 cycles were averaged, and a mixed-model ANOVA (group × exercise) was used to compare maximal angles of flexion and extension, joint ROM, and angular limb velocities between exercise modalities and groups. A value of $P < 0.05$ was considered significant.

Results

Seven dogs that had undergone surgical management of a ruptured CCL and 13 healthy control dogs were included in the study. Significant differences were not detected between groups in regard to body weight, body condition score, or sex distribution. Mean ± SD body weight was 34.9 ± 8.3 kg (76.8 ± 16.3 lb) for dogs in the rehabilitation group and

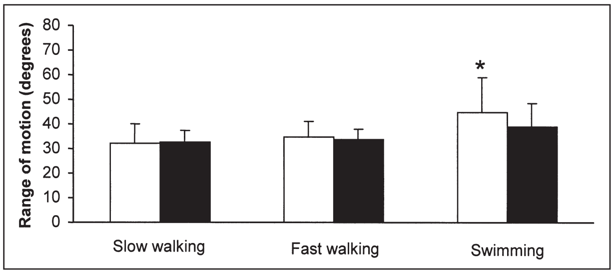

Figure 1—Range of motion of the hip joint during slow walking (0.9 m/s), fast walking (1.3 m/s), and swimming in healthy dogs (open bars; n = 13) and dogs that had undergone surgical management of a ruptured cranial cruciate ligament (CCL) and were enrolled in a postoperative aquatic rehabilitation program (closed bars; 7). Error bars represent SD. *Significantly ($P < 0.05$) different from value for slow walking or fast walking.

Table 1—Results of kinematic evaluation of the hip, stifle, and tarsal (hock) joints during swimming, fast walking (1.3 m/s), and slow walking (0.9 m/s) in healthy dogs (control; n = 13) and dogs (7) that had undergone surgical management of a ruptured cranial cruciate ligament and were enrolled in a postoperative aquatic rehabilitation program

		Swimming		Fast walking		Slow walking	
Joint	Variable	Control	Rehabilitation	Control	Rehabilitation	Control	Rehabilitation
Hip							
	Maximal flexion (°)	83.6 ± 15.1[a]	75.6 ± 7.9[d]	95.9 ± 11[a]	104.5 ± 12.5[e]	98.6 ± 11.4[a]	104.7 ± 13.8[e]
	Maximal extension (°)	128.2 ± 14.4[a]	114.9 ± 11.7[d,*]	130.5 ± 8.3[a]	138.4 ± 15.1[e]	130.7 ± 10.7[a]	137.1 ± 18.6[e]
	Angular velocity (°/s)	160.9 ± 68.1[a]	122.7 ± 47.0[d]	88.2 ± 15.0[b]	87.4 ± 21.8[e]	62.8 ± 15.3[c]	68.7 ± 11.3[f]
Stifle							
	Maximal flexion (°)	46 ± 10.7[a]	46 ± 6.3[d]	97.1 ± 8.7[b]	100.1 ± 7.1[e]	101.5 ± 8.0[b]	102 ± 9.3[e]
	Maximal extension (°)	112.9 ± 11.8[a]	94.4 ± 16.8[d,*]	133 ± 7.7[b]	130 ± 9.3[e]	135.1 ± 9.2[b]	129.4 ± 10.6[e]
	Angular velocity (°/s)	151.5 ± 39.3[a]	94.1 ± 19[d,*]	182.3 ± 50.9[a]	138.9 ± 48[d,*]	154 ± 38.2[a]	105 ± 47.6[d,*]
Hock							
	Maximal flexion (°)	52.9 ± 12.1[a]	74.7 ± 7.8[d,*]	107 ± 7.3[b]	120.2 ± 13.7[e]	111.9 ± 7.8[b]	124.8 ± 14.3[e]
	Maximal extension (°)	127.7 ± 10.8[a]	126.8 ± 12.6[d]	141.6 ± 8.7[b]	153.8 ± 12.4[e,*]	141.9 ± 8.7[b]	152.7 ± 11.3[e,*]
	Angular velocity (°/s)	216.9 ± 62.7[a]	134.1 ± 48.9[d,*]	80.9 ± 20.7[b]	70.5 ± 10.8[e]	55.8 ± 14.8[c]	48.6 ± 8[f]

Data are given as mean ± SD.
[a,b,c]For dogs in the control group, values in each row with different letter superscripts were significantly ($P < 0.05$) different. [d,e,f]For dogs in the rehabilitation group, values in each row with different letter superscripts were significantly ($P < 0.05$) different. *Significantly ($P < 0.05$) different from corresponding value for control group.

30.0 ± 7.1 kg (66.0 ± 15.5 lb) for dogs in the control group. Mean body condition score (rated on a scale from 1 through 9 with 1 being gaunt and 9 being obese) was 6.0 ± 0.64 for dogs in the rehabilitation group and 5.7 ± 0.75 for dogs in the control group. All control dogs were Labrador Retrievers or Labrador Retriever mixes; dogs in the rehabilitation group consisted of Rottweilers, Labrador Retrievers, and mixed-breed dogs. Mean age of dogs in the rehabilitation group (5.9 ± 2.3 years) was significantly greater than mean age of dogs in the control group (1.7 ± 1.2 years).

In the control dogs, swimming resulted in a greater ROM of the hip joint than did either slow or fast walking (**Fig 1**). However, in dogs that had undergone surgical management of a ruptured CCL, ROM of the hip joint during swimming did not differ significantly from ROM during walking. Range of motion of the hip joint was not significantly different between control dogs and dogs in the rehabilitation group. Within each group, swimming also resulted in a significantly greater angular velocity than did either slow or fast walking, but no differences were found between groups (**Table 1**).

For dogs in both groups, swimming resulted in a significantly greater ROM of the stifle joint than did either slow or fast walking (**Fig 2**) primarily because of significantly greater flexion of the joint (Table 1). Extension was significantly less for all dogs when swimming, compared with walking. During swimming, slow walking, and fast walking, ROM of the stifle joint for dogs in the rehabilitation group was significantly less than ROM of the stifle joint for control dogs. Similarly, during all 3 exercise conditions, mean angular velocities for control dogs were significantly greater than angular velocities for dogs in the rehabilitation group.

Also for both groups, swimming resulted in a significantly greater ROM of the hock joint than did either slow or fast walking (**Fig 3**), again primarily because of greater flexion of the joint (Table 1). Extension was significantly less for all dogs when swimming, compared with walking. During swimming, control dogs had a significantly greater ROM of the hock joint than dogs in the rehabilitation group; however, differences between groups were not detected during slow or fast walking. For both groups, swimming resulted in greater angular velocity of the hock joint than did slow or fast walking, and angular velocity of the hock joint during swimming was significantly greater for control dogs than for dogs in the rehabilitation group. For both groups, fast walking resulted in greater angular velocity of the hock joint than did slow walking, but no differences were detected between groups in regard to angular velocity of the hock joint during slow or fast walking.

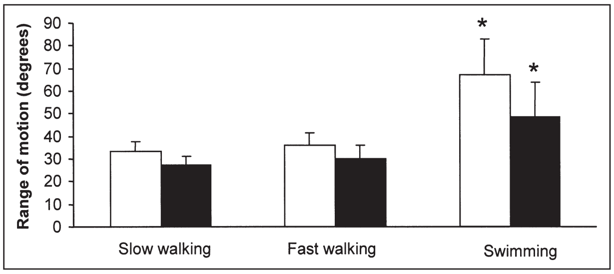

Figure 2—Range of motion of the stifle joint during slow walking (0.9 m/s), fast walking (1.3 m/s), and swimming in healthy dogs (open bars; n = 13) and dogs that had undergone surgical management of a ruptured CCL and were enrolled in a postoperative aquatic rehabilitation program (closed bars; 7). Error bars represent SD. *Significantly ($P < 0.05$) different from value for slow walking or fast walking. At each speed, values were significantly ($P < 0.05$) different between groups.

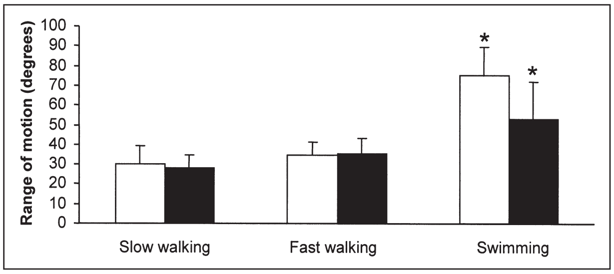

Figure 3—Range of motion of the tarsal joint during slow walking (0.9 m/s), fast walking (1.3 m/s), and swimming in healthy dogs (open bars; n = 13) and dogs that had undergone surgical management of a ruptured CCL and were enrolled in a postoperative aquatic rehabilitation program (closed bars; 7). Error bars represent SD. *Significantly ($P < 0.05$) different from value for slow walking or fast walking. During swimming, values were significantly ($P < 0.05$) different between groups.

Discussion

Results of the present study indicate that in healthy dogs, swimming resulted in greater ROM of the hip, stifle, and hock joints than did walking. Similarly, in dogs that underwent surgical management of a ruptured CCL, swimming resulted in greater ROM of the stifle and hock joints than did walking. In both groups of dogs, the greater ROM associated with swimming appeared to be a result of increased flexion of the involved joints.

These findings may be important in dogs undergoing surgery because of CCL rupture, as there is an emerging body of information in the human literature that supports the use of rehabilitation strategies that provide the greatest ROM. Early research[14,15] has shown that immobilization of the limbs was detrimental to tissues, and more recent research[16-18] demonstrated the beneficial effects of ROM on the health of tissues. In humans with anterior cruciate ligament rupture, early physical rehabilitation following joint surgery results in an earlier and more complete return to function, reduces the chances of reinjuring the joint, and does not increase the failure rate of intra-articular grafts.[19-22] In athletes recovering from anterior cruciate ligament surgery, physical rehabilitation reduces pain, joint effusion, capsular contraction, and periarticular fibrosis while increasing ROM, muscle mass, and limb strength.[23-26] Additionally, it has been suggested that early postoperative physical rehabilitation reduces the development of arthrofibrosis and osteoarthritis.[27,28]

In dogs with a rupture of the CCL, progressive osteoarthritis will develop unless the joint is stabilized,[29] and in human patients with osteoarthritis of the stifle joint, ROM and maximal angle of flexion are significantly reduced.[30] In dogs with chronic rupture of the CCL, motion of the hind limb joints changes over time, with stifle joint flexion being more pronounced throughout the stance and early swing phases and a failure of extension during the late stance phase.[31] A recent study[32] of human patients with osteoarthritis of the knee evaluated joint ROM and pain scores before and after terrestrial or aquatic rehabilitation. The authors found that ROM was similar between rehabilitation regimens but that patients who underwent aquatic rehabilitation had significantly lower pain scores, possibly because of decreased loading of the joint during aquatic exercise. These results cannot be directly compared with our findings, because limb positions in water vary substantially between dogs and people, and dogs in our study could not touch the ground; therefore, aquatic rehabilitation was purely swimming. Nevertheless, in a previous study[2] of dogs that underwent surgical management of CCL rupture, those that underwent postoperative aquatic rehabilitation had improved limb function, compared with those that underwent postoperative exercise restriction.

In this trial, we focused on comparing the ROM during walking and swimming. We did this to evaluate the potential benefits of an aquatic rehabilitation program for dogs undergoing surgical management of CCL rupture. During walking, joint reaction forces can reach several times body weight, placing stress on the joint and resulting in osteoarthritis, degeneration of articular cartilage, and formation of new bone at joint surface margins.[28,33,34] During swimming, the effects of gravity and axial loading are substantially diminished.[35,36]

Angular velocity is a measure of the speed at which a joint angle changes. In the present study, angular velocities of the hip and hock joints, but not the stifle joint, were significantly greater when dogs were swimming than when were walking. The effects of buoyancy and changes in body position for a dog in water are currently being elucidated; however, we postulate that buoyancy associated with swimming reduced the mass of the limb that had to be moved during each stride, resulting in greater angular velocities. Reduction of mass in motion may lead to diminished joint reaction forces.

Angular limb velocity measurement is important in characterizing the additional ROM seen in the stifle joint during swimming. One may have suggested that the additional ROM might be a function of the increased velocities seen between conditions. For example, a faster limb may naturally have a greater ROM. The opposite may be postulated in this case in which stifle velocities were similar between walking and swimming, and the increase in ROM was likely a function of the aquatic medium.

Evaluating limb function in dogs with naturally occurring CCL rupture is problematic because of the number of variables inherent to the condition that must be controlled for. In the present study, we only included medium- to large-breed dogs without any other orthopedic or neurologic diseases that underwent a standard postoperative rehabilitation regimen. We did not control for the surgical procedure performed, the surgeon, or the severity of osteoarthritis among dogs in the rehabilitation group or the home environment among dogs in the control group. In addition, dogs were not randomly assigned to a group, although they did serve as their own controls for comparisons within groups. All dogs were acclimated to the treadmill prior to data collection, but none of the dogs were acclimated to the acrylic pool prior to data collection. Dogs that would swim in the rehabilitation pool but not the acrylic pool were excluded from the study. Additionally, data were not analyzed if the cameras were moved at all during the taping segment, if the video field was unable to capture the entire swing and stance phases of each gait cycle, or if speeds on the treadmill were not discernible.

Another limiting aspect of this study related to placement of the retroreflective markers. Several studies[37-39] have suggested that skin surface markers cannot be used to adequately estimate joint centers. A previous study[6] overcame this limitation by using orthopedic implants, but this was impractical for a study investigating client-owned animals, and the orthopedic implants may themselves have interfered with the dogs' locomotion.

Finally, kinematic analyses in the present study were performed while dogs walked on a treadmill. It is possible that kinematic analyses at a trot, a more rigorous gait, would have provided different results; however, many dogs would use the affected limb at a walk but would not bear weight on it at a trot. Variations between treadmill and overground walking have been found in humans.[40] However, use of the treadmill was necessary in the present study to control walking velocity during data collection.

Rehabilitation of dogs following joint surgery has become an integral part of postoperative care at our institution, because we believe that preservation of joint ROM through rehabilitation allows dogs to return to a greater level of function, compared with exercise restriction and joint immobilization. Results of the present study document the effects of the method of rehabilitation on ROM in healthy dogs and dogs that have undergone surgical treatment of CCL rupture and suggest that if ROM is a factor in rate or extent of return to function in dogs with CCL rupture, then aquatic rehabilitation would provide a better opportunity for return to full function than walking alone.

[a]Widestride Duo48, ICON Health and Fitness Inc, Logan, Utah.
[b]SERF Leisure Products Inc, Mississauga, ON, Canada.
[c]Aquaswimjet swimpool, Rio Plastics, Port of Brownsville, Tex.
[d]3290 Scotchlite reflective sheeting, 3M, St Paul, Minn.
[e]WVD-5100 camera, Panasonic, Secaucus, NJ.
[f]Peak Performance Technologies, Englewood, Colo.
[g]Motion analysis system, Peak Performance Technologies, Englewood, Colo.

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