# Evaluation of changes in vertical ground reaction forces as indicators of meniscal damage after transection of the cranial cruciate ligament in dogs

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**Objective**—To determine whether decreases in peak vertical force of the hind limb after transection of the cranial cruciate ligament (CrCL) would be indicative of medial meniscal damage in dogs.

**Animals**—39 purpose-bred adult male Walker Hounds.

**Procedure**—The right CrCL was transected arthroscopically. Force plate measurements of the right hind limb were made prior to and 2, 4, 10, and 18 weeks after transection of the CrCL. Only dogs with ≥ 10% decreases in peak vertical force after week 2 were considered to have potential meniscal damage. Dogs that did not have ≥ 10% decreases in peak vertical force at any time point after week 2 were assigned to group 1. Group 2 dogs had ≥ 10% decreases in peak vertical force from weeks 2 to 4 only. Group 3 and 4 dogs had ≥ 10% decreases in peak vertical force from weeks 4 to 10 only or from weeks 10 to 18 only, respectively. Damage to menisci and articular cartilage was graded at week 18, and grades for groups 2 to 4 were compared with those of group 1.

**Results**—The percentage change in peak vertical force and impulse area was significantly different in groups 2 (n = 4), 3 (4), and 4 (4) at the end of each measurement period (weeks 4, 10, and 18, respectively) than in group 1 (27). The meniscal grade for groups 2 to 4 was significantly higher than for group 1. A ≥ 10% decrease in peak vertical force had sensitivity of 52% and accuracy of 72% for identifying dogs with moderate to severe medial meniscal damage.

**Conclusions and Clinical Relevance**—In dogs with transected or ruptured CrCLs, force plate analysis can detect acute exacerbation of lameness, which may be the result of secondary meniscal damage, and provide an objective noninvasive technique that delineates the temporal pattern of medial meniscal injury. (*Am J Vet Res* 2005;66:156–163)

Force plate analysis is used as a research tool to objectively measure normal and abnormal forces applied to the limbs of dogs.[1-12] Force plate analysis allows for description of peak forces and impulses (total force applied over time) applied in vertical, craniocaudal (braking and propulsion), and mediolateral directions. Many orthopedic studies[1-6] in dogs have included analysis of ground reaction forces to objectively determine normal forces applied for different gait cycles at varying velocities. Force plate analysis has also been used to measure abnormal forces that result from insult to the appendicular skeleton and the response of the limb to various surgical techniques or medical treatments used to treat joint impairment.[7-12]

Transection of the **cranial cruciate ligament (CrCL)** in dogs is an accepted experimental model of osteoarthritis that results in changes typical of the early stages of osteoarthritis in humans and dogs.[13] Transection of the CrCL in dogs causes lameness because of joint instability and inflammation that develops and ultimately results in damage to the synovium, menisci, articular cartilage, and subchondral bone.[13-15] Force plate analysis has been used to detect changes in the ground reaction forces that occur as a result of rupture or transection of the CrCL.[7-11] These studies reveal that after rupture or transection of the CrCL, the mean peak vertical, braking, and propulsion forces and respective impulse areas decrease dramatically within the first few weeks after injury and then slowly improve over time. Certain surgical techniques are associated with improvements in these kinetic data in the early period after transection or rupture of the CrCL, suggesting that force plate analysis is a sensitive tool for detection of subtle differences that can develop over time.[11]

Medial meniscal damage is a common sequela of rupture or transection of the CrCL in dogs.[16,17] It is believed to develop secondary to the unrestrained cranial tibial thrust that creates cranial tibial translocation with respect to the femur.[18] The types and locations of meniscal injuries have been described in dogs[17,19]; however, the exact time of meniscal tearing after rupture or

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transection of the CrCL is not known. It has been suggested that meniscal damage occurs simultaneously with CrCL rupture, but more than likely, it is secondary to abnormal biomechanical loading as a result of CrCL insufficiency.[20] It is a common clinical impression that dogs with ruptured or transected CrCLs that have sustained meniscal damage will have a greater degree of lameness than dogs that have no meniscal damage.[16,18,20,21] A greater degree of lameness may be evident soon after CrCL rupture, especially if meniscal damage occurs at the same time; however, meniscal injury is usually suspected in dogs acutely lame in the first few weeks after rupture or transection of the CrCL that start to improve, only to relapse with lameness within the first 2 months. Presumably, the greater degree of lameness as a result of meniscal damage should be detectable by use of ground reaction forces measured via force plate analysis. To the authors' knowledge, objective analysis of lameness in dogs with meniscal damage after rupture or transection of the CrCL has not been reported.

The purposes of the study reported here were to evaluate ground reaction forces of the hind limb after transection of the CrCL in dogs and compare decreases in peak vertical force with the degree of meniscal damage determined at the end of the study. We hypothesized that dogs that sustained moderate (surface longitudinal or small transverse tears) and severe (penetrating longitudinal tears) medial meniscal fraying or tearing would have ≥ 10% decreases in peak vertical force between successive measurement periods from 2 to 18 weeks after transection of the CrCL.

## Materials and Methods

The study protocol was approved by the Colorado State University Animal Care and Use Committee. Dogs were obtained from approved sources by the Colorado State University Laboratory Animal Resources. The study developed as an adjunct to another study that examined the effects of a novel drug (matrix metalloproteinase inhibitor). Twenty dogs were treated with this drug, and 19 dogs were given a placebo. All 39 dogs underwent the same procedures that were of a nature that did not affect the results of the present study.

**Animals—**Thirty-nine purpose-bred adult male Walker Hounds with a mean ± SD (range) weight of 22.4 ± 2.7 (16.8 to 29.5) kg were used. Each dog underwent a complete physical examination, and a blood sample was collected for CBC and biochemical analyses. An orthopedic examination included separate lameness and physical examinations of both hind limbs and radiography of both stifle joints. In anticipation of future gait analyses, each dog was acclimated to the force platform analysis laboratory for several weeks and was led on a leash at a trot across the force plate prior to inclusion in the study. Selection and inclusion criteria required that dogs be free of preexisting orthopedic disease of the stifle joints on the basis of orthopedic examination and radiography. In addition, dogs had to adequately trot across the force plate with minimal effort or coaxing from the handler.

**Experimental protocol—**All dogs were anesthetized, and the right hind limb was prepared for aseptic surgery. A lateral parapatellar arthroscopic approach to the right stifle joint was used to examine the joint for pathologic changes of articular cartilage, cruciate ligaments, and menisci. The CrCL was transected arthroscopically by use of a meniscectomy blade.[a] Analgesia was provided by use of a 5-mg fentanyl patch (2.0 µg/kg/h) that had been applied the day before surgery and was maintained for 72 hours after surgery. Morphine (1 mg/kg, SC) was administered postoperatively as needed. Cefazolin (22 mg/kg) was administered IV during surgery, and treatment with cephalexin (10 mg/kg, PO, q 12 h) was continued for 3 days. Throughout the study, all dogs were housed in individual runs. Dogs were closely monitored during the first 48 hours after surgery for signs of pain, infection, anorexia, or gastrointestinal upset. To encourage development of osteoarthritis, dogs were subjected to an exercise routine of leash walking for 30 minutes daily for 5 d/wk starting the second day after surgery and continuing until euthanasia at 18 weeks after surgery. Dogs that were non-weight bearing on the right hind limb were walked on 3 legs, and the limb was not passively manipulated. All dogs were euthanatized by use of sodium pentobarbital (88 mg/kg, IV) 18 weeks after surgery, and both stifle joints were disarticulated and examined.

**Subjective clinical parameters—**Subjective assessments of the degrees of lameness and pain were performed immediately before each force plate evaluation, prior to CrCL transection (baseline, week 0), and at 2, 4, 10, and 18 weeks after surgery. All subjective scores were assigned by the same evaluator (TNT). Degree of lameness was graded on a scale from 1 to 4 (1 = no lameness, 2 = mild lameness at a walk or trot, 3 = moderate lameness at a walk or trot, and 4 = severe lameness at a walk or trot). The degree of weight bearing when the limb was at rest was assessed prior to force plate evaluation and graded on a scale from 1 to 3 (1 = normal weight bearing at rest, 2 = partial weight bearing at rest, and 3 = non-weight bearing at rest). For subjective assessment of pain, the stifle joint was hyperextended after force plate evaluation so as not to influence lameness. Response to hyperextension was graded on a scale from 1 to 4 (1 = no response, 2 = mild response [turns head toward affected limb], 3 = moderate response [withdraws affected limb], and 4 = severe response [vocalizes or becomes aggressive]). The degree of joint effusion was also subjectively assessed at 0, 2, 4, 10, and 18 weeks after surgery. The scale for the effusion score ranged from 0 to 3 (0 = no effusion, 1 = mild effusion, 2 = moderate effusion, and 3 = severe effusion).

**Gross pathologic scores—**Grading of the degree of damage to medial and lateral menisci and articular cartilage was performed by a board-certified pathologist (AMB) unaware of the dogs' group assignments. Meniscal damage was graded on a scale from 0 to 3 (0 = no lesion, 1 = mild fraying or incomplete tears with or without substantial fibrous replacement or repair, 2 = moderate fraying or tearing [longitudinal surface or small transverse tears] with or without substantial fibrous replacement or repair, and 3 = severe fraying or tearing [penetrating longitudinal tears or bucket-handle tears] without substantial effective fibrous replacement or repair; **Figure 1**). Cartilage damage was graded on a scale from 0 to 4 (0 = normal; 1 = minimal superficial fibrillation; 2 = mild to moderate fibrillation, presumably into the upper middle zone; 3 = mild to moderate fibrillation, loss of cartilage extending to the middle zone, or both; and 4 = severe cartilage loss extending to the deep zone or subchondral bone). A total subjective cartilage severity score was calculated by summing the cartilage damage scores on the medial and lateral tibial plateaus and on the medial and lateral femoral condyles (maximum score of 16).

**Force plate evaluation—**The force plate[b] was mounted in the center of, and level with, the surface of a 15-m runway. The signal from the force plate was processed and stored by use of computer software programs.[c,d] As each dog was trot-

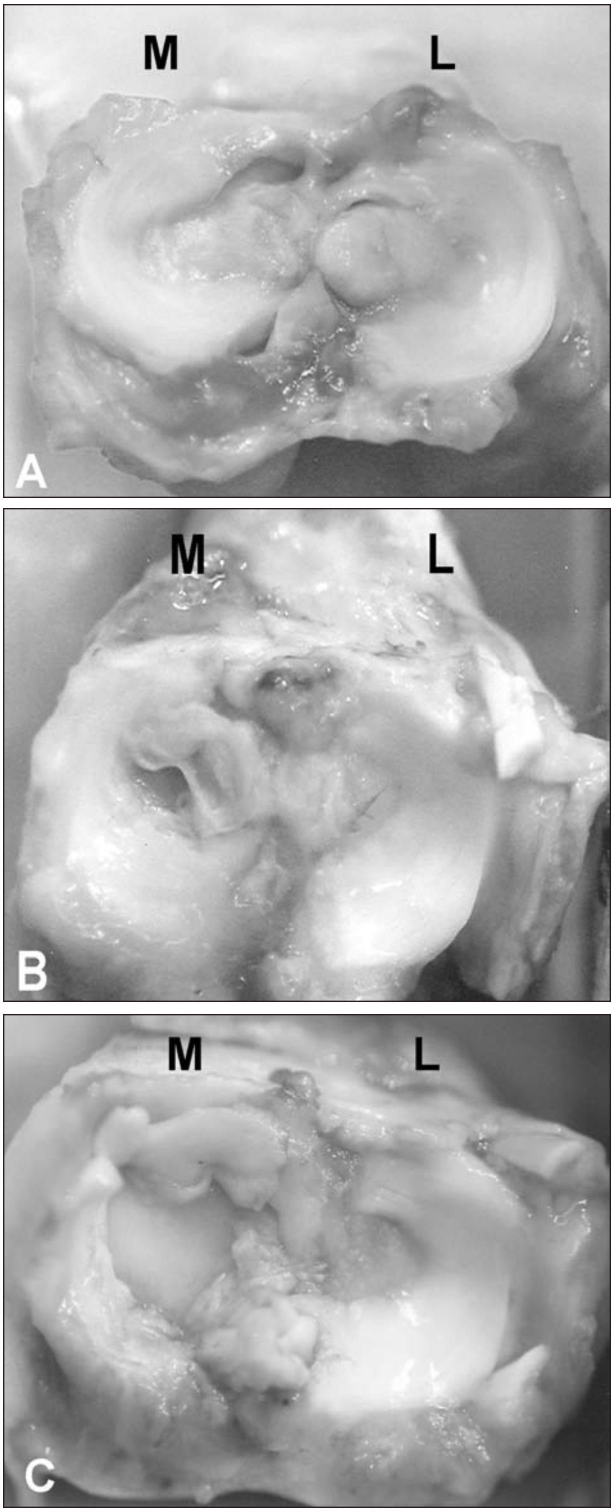


Figure 1—Photographs of representative menisci with grade 1 to 3 medial meniscal damage in a study that compared vertical ground reaction forces and meniscal pathologic changes in dogs after transection of the cranial cruciate ligament. A—Grade 1 medial meniscal damage (mild fraying or incomplete tears with or without substantial fibrous replacement or repair). B—Grade 2 medial meniscal damage (moderate fraying or tearing [longitudinal surface or small transverse tears] with or without substantial fibrous replacement or repair). C—Grade 3 medial meniscal damage (severe fraying or tearing [penetrating longitudinal tears or bucket-handle tears] without substantial effective fibrous replacement or repair). M = Medial. L = Lateral.

ted over the force plate, velocity was recorded by use of 2 photoelectric cells positioned 2 m apart and a start-interrupt timer system. Care was taken to ensure that the dog triggered the photoelectric cells and that a constant speed was maintained across the force plate during each trial. Dogs were trotted across the force plate by 1 handler prior to CrCL transection (baseline) and at 2, 4, 10, and 18 weeks after surgery. An evaluation was considered valid if the dog struck the force plate with its right forelimb followed by its right hind limb at a velocity from 1.45 to 2.05 m/s. If a dog was distracted during an evaluation or any other limb or combination of limbs struck the force plate, the data were considered invalid. Because of the severity of lameness in some dogs, dogs were trotted across the force plate up to 75 times during each trial session, and data for the first 5 acceptable trials were recorded for each dog. If the dog did not have 5 acceptable trials, data from the number of acceptable trials were used in the analysis. If the dog was completely non-weight bearing on the right hind limb, the value entered for each trial was zero. All trials were recorded and archived on digital video. Peak vertical force and impulse area were recorded at 1-millisecond intervals for 650 milliseconds after foot strike. All forces were normalized to the dog's body weight at each measurement period.

**Calculations and grouping—**Mean ground reaction force data from acceptable trials for each dog for all force plate sessions (baseline [week 0] and weeks 2, 4, 10, and 18) were calculated. To evaluate increases in lameness that may have been associated with meniscal damage, these values were used to calculate the percentage change in peak vertical force and impulse area from 1 force plate session to another (ie, baseline to week 2, weeks 2 to 4, weeks 4 to 10, and weeks 10 to 18). The percentage change was calculated by subtracting the value for the initial measurement period from the value for the subsequent measurement period, dividing the resulting value by the value for the initial measurement period, and multiplying by 100. To complete this calculation for dogs that were non-weight bearing, all dogs, both weight bearing and non-weight bearing, had a value of 1 added to the peak vertical force and impulse area to eliminate 0 from the calculations. A sample calculation for percentage change from weeks 2 to 4 used the formula [(week 4 value – week 2 value)/week 2 value] $\times$ 100, such that [($26.26 \times 10^{-2}$ N/kg – $31.78 \times 10^{-2}$ N/kg)/$31.78 \times 10^{-2}$ N/kg] $\times$ 100 = –17.4%, which indicated a decrease from weeks 2 to 4. A positive percentage change indicated that the dog was placing more weight on the affected limb, whereas a negative percentage change indicated an increase in the degree of lameness. All dogs had a large decrease in peak vertical force and impulse area from preoperative values (baseline) at week 2; this was attributed to joint instability after transection of the CrCL.[7-11] Meniscal injury has likely occurred when a period of greater lameness is detected in dogs with ruptured or transected CrCLs of chronic duration[16,18,20,21]; therefore, in our study, only dogs that had ≥ 10% decreases in peak vertical force from weeks 2 to 18 were considered to have sustained recent meniscal injuries. The percentage change was described with respect to the subsequent measurement time point because meniscal damage could have occurred at any time between the 2 measurement time points; therefore, for the example given previously, the percentage change from weeks 2 to 4 was tabulated under week 4 because this is when the decrease was measured.

For further analysis, peak vertical force was used to assign dogs to groups according to whether and when they had a ≥ 10% decrease in peak vertical force between 2 consecutive force plate sessions after week 2. Group 1 comprised dogs that had increases or < 10% decreases in peak vertical force from weeks 2 to 18. Group 2 comprised dogs that had

≥ 10% decreases in peak vertical force from weeks 2 to 4. Groups 3 and 4 comprised dogs that had ≥ 10% decreases in peak vertical force from weeks 4 to 10 and weeks 10 to 18, respectively. All dogs in groups 2 to 4 had ≥ 10% decreases for only 1 measurement period from weeks 2 to 18.

**Statistical analyses**—Ground reaction forces were determined to be normally distributed by use of the Kolmogrov-Smirnov test. The percentage changes in mean values for peak vertical force and impulse area were used as the dependent variables in a 2-way ANOVA with time as a repeated measure and treatment as the fixed effect to determine whether there were any differences between treatment (drug vs placebo) groups. A mixed-model ANOVA was performed by use of the same dependent variables with the 4 groups used as a fixed effect class variable over subsets of time, allowing examination of the differences in each ground reaction force among groups at each measurement time point (weeks 2, 4, 10, and 18). Tukey's pairwise comparison was also performed to determine differences between each group at each force plate measurement time point. Descriptive statistics were used to report meniscal grades and total subjective cartilage severity scores. Two-tail *t* tests were used to determine differences among groups for meniscal and cartilage scores, respectively, and a Spearman rank correlation was performed to compare the meniscal grade to cartilage severity scores. The sensitivity, specificity, and accuracy of the hypothesis that a ≥ 10% decrease in peak vertical force is indicative of medial meniscal damage were calculated by use of meniscal grades determined grossly 18 weeks after transection of the CrCL.

## Results

No significant differences in peak vertical force or impulse area between dogs that received drug treatment (n = 20) and those that received a placebo (19) were found; therefore, data from all 39 dogs were used in the study.

**Peak vertical force**—Mean peak vertical force for each group was calculated for each measurement time point (**Table 1**). Twenty-seven (69%) dogs were assigned to group 1. All dogs in group 1 had a decrease in peak vertical force at week 2, compared with preoperative values; values then increased at each subsequent measurement time point throughout the remainder of the study. Twelve (31%) dogs had ≥ 10% decreases in peak vertical force between 2 successive measurements at various time points after week 2. Groups 2 to 4 each comprised 4 dogs. Pair wise comparisons of the percentage change in ground reaction forces for groups 2, 3, and 4 versus group 1 for each measurement period were performed. No significant difference in percentage decrease in peak vertical force at week 2 was found between groups (**Table 2**); however, percentage change in peak vertical force in group 2 at week 4 was significantly ($P = 0.01$) different than that for group 1. At week 10, the percentage change in peak vertical force in group 3 was significantly different ($P = 0.002$) than that in group 1, and the percentage change in peak vertical force in group 4 at week 18 was significantly ($P = 0.001$) different than that in group 1.

**Vertical impulse area**—Vertical impulse area for all dogs in group 1 was decreased at week 2 and was increased at weeks 4, 10, and 18. No significant difference between groups in percentage decrease in vertical impulse area at week 2 was found (Table 2). Group 2 dogs had a mean percentage decrease in the vertical impulse area of 17% at week 4 that was significantly different than percentage change in group 1. Group 3 dogs also had a 17% decrease in vertical impulse area at week 10 that was significantly different than percentage change in group 1. Group 4 dogs had a 22% decrease in vertical impulse area at week 18 that was significantly different than percentage change in group 1.

**Clinical parameters**—Subjectively assessed degree of lameness, degree of weight bearing at rest, response to joint hyperextension, and degree of joint effusion were graded as normal for all dogs prior to transection of the CrCL (week 0). The grade (severity) of each parameter was greater than the preoperative grade 2 weeks after transection of the CrCL; however, most grades stayed the same or decreased throughout the remainder of the study. To determine whether the subjective grades of clinical parameters suggested acute exacerbation of pain in the stifle joint that may have coincided with medial meniscal damage, each time frame during which a ≥ 10% decrease in peak vertical force occurred was examined.

By use of the subjective lameness grading scale, 2 of 12 dogs had an increase in lameness grade and 10 had no change in lameness grade when a ≥ 10% decrease in peak vertical force was identified (**Table 3**). By use of the subjective grading scale for the degree of

Table 1—Mean ± SD peak vertical force (X $10^{-2}$ N/kg) in dogs in groups 1 to 4 at each measurement time point (0 [baseline] and 2, 4, 10, and 18 weeks after transection of the cranial cruciate ligament).

| | Time (wk) | | | | |
|---|---|---|---|---|---|
| Group | 0 | 2 | 4 | 10 | 18 |
| 1 (n = 27) | 65.0 ± 20.3 | **23.2** ± 12.7 | 30.8 ± 10.7 | 38.5 ± 12.0 | 46.4 ± 7.2 |
| 2 (4) | 57.2 ± 2.5 | **31.8** ± 7.0 | **26.3** ± 5.6 | 34.2 ± 7.4 | 41.5 ± 10.2 |
| 3 (4) | 56.1 ± 15.4 | **19.8** ± 13.5 | 35.1 ± 5.5 | **23.8** ± 17.0 | 39.8 ± 7.4 |
| 4 (4) | 56.8 ± 6.2 | **24.2** ± 5.0 | 30.9 ± 6.7 | 37.8 ± 3.1 | **27.7** ± 5.4 |

Group 1 = Dogs that had an increase or a < 10% decrease in peak vertical force from weeks 2 to 18. Group 2 = Dogs that had a ≥ 10% decrease in peak vertical force from weeks 2 to 4. Group 3 = Dogs that had a ≥ 10% decrease in peak vertical force from weeks 4 to 10. Group 4 = Dogs that had ≥ 10% decrease in peak vertical force from weeks 10 to 18.

Decreases in peak vertical force from 1 measurement period to the next are bolded. Notice that all dogs had a large decrease in peak vertical force at week 2.

Table 2—Mean ± SD percentage change in vertical ground reaction forces in dogs in groups 1 to 4 at each measurement time point (2, 4, 10, and 18 weeks after transection of the cranial cruciate ligament).

| | | Time (wk) | | | |
|---|---|---|---|---|---|
| Ground reaction | Group | 2 | 4 | 10 | 18 |
| Peak vertical force | 1 | –63 ± 18 | 32 ± 28 | 26 ± 20 | 21 ± 18 |
| | 2 | –43 ± 14 | –16 ± 8* | 29 ± 15 | 22 ± 19 |
| | 3 | –65 ± 15 | 77 ± 82 | –32 ± 18* | 66 ± 63 |
| | 4 | –57 ± 4 | 27 ± 20 | 25 ± 21 | –26 ± 9† |
| Vertical impulse area | 1 | –56 ± 11 | 24 ± 23 | 20 ± 20 | 12 ± 18 |
| | 2 | –44 ± 12 | –17 ± 10* | 38 ± 19 | 14 ± 18 |
| | 3 | –49 ± 8 | 19 ± 5 | –17 ± 12‡ | 41 ± 37 |
| | 4 | –50 ± 7 | 16 ± 21 | 17 ± 17 | –22 ± 8* |

*Significantly ($P \leq 0.01$) different than group 1 value. †Significantly ($P \leq 0.001$) different than group 1 value. ‡Significantly ($P < 0.05$) different than group 1 value.

Table 3—Clinical parameter grades determined at 0 (baseline) and 2, 4, 10, and 18 weeks after transection of the cranial cruciate ligament and meniscal grades determined at the end of the study (18 weeks) in 12 dogs that had a ≥ 10% decrease in peak vertical force (PVF) at various times.

| Dog | PVF decrease (%) | Time of PVF decrease (wk) | Med men grade | Lat men grade | Subjective lameness grade | | | | | Subjective weight bearing grade | | | | | Subjective joint hyperextension grade | | | | | Subjective effusion score | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Wk | | | | | | | | | | | | | | | | | | | |
| | | | | | 0 | 2 | 4 | 10 | 18 | 0 | 2 | 4 | 10 | 18 | 0 | 2 | 4 | 10 | 18 | 0 | 2 | 4 | 10 | 18 |
| 1 | 14 | 4 | 3 | 0 | 1 | **3** | **4** | 4 | 3 | 1 | **2** | **2** | 2 | 2 | 1 | **3** | **2** | 2 | 3 | 0 | **2** | **2** | 2 | 3 |
| 2 | 10 | 4 | 2 | 0 | 1 | **3** | **3** | 3 | 2 | 1 | **2** | **2** | 2 | 1 | 1 | **2** | **2** | 3 | 1 | 0 | **2** | **3** | 3 | 3 |
| 3 | 13 | 4 | 2 | 0 | 1 | **4** | **4** | 4 | 4 | 1 | **2** | **2** | 2 | 2 | 1 | **3** | **2** | 2 | 3 | 0 | **2** | **2** | 2 | 2 |
| 4 | 28 | 4 | 3 | 1 | 1 | **4** | **4** | 3 | 2 | 1 | **2** | **3** | 2 | 1 | 1 | **2** | **3** | 2 | 2 | 0 | **2** | **2** | 2 | 2 |
| 5 | 23 | 10 | 3 | 1 | 1 | 4 | **4** | **4** | 3 | 1 | 2 | **2** | **2** | 1 | 1 | 1 | **2** | **2** | 2 | 0 | 2 | **2** | **2** | 2 |
| 6 | 97 | 10 | 2 | 0 | 1 | 4 | **4** | **4** | 4 | 1 | 2 | **2** | **3** | 2 | 1 | 2 | **2** | **2** | 2 | 0 | 2 | **2** | **2** | 3 |
| 7 | 10 | 10 | 3 | 1 | 1 | 3 | **3** | **3** | 2 | 1 | 2 | **2** | **2** | 2 | 1 | 3 | **3** | **3** | 3 | 0 | 2 | **2** | **2** | 3 |
| 8 | 11 | 10 | 3 | 1 | 1 | 4 | **4** | **4** | 4 | 1 | 2 | **2** | **2** | 2 | 1 | 3 | **3** | **3** | 3 | 0 | 2 | **2** | **2** | 3 |
| 9 | 18 | 18 | 3 | 0 | 1 | 3 | 3 | **3** | **3** | 1 | 2 | 2 | **2** | **1** | 1 | 2 | 1 | **2** | **1** | 0 | 2 | 2 | **3** | **2** |
| 10 | 23 | 18 | 3 | 0 | 1 | 4 | 3 | **3** | **3** | 1 | 2 | 2 | **2** | **2** | 1 | 2 | 3 | **3** | **2** | 0 | 3 | 2 | **2** | **3** |
| 11 | 40 | 18 | 1 | 0 | 1 | 4 | 4 | **3** | **4** | 1 | 2 | 2 | **2** | **2** | 1 | 3 | 2 | **3** | **3** | 0 | 2 | 2 | **2** | **3** |
| 12 | 24 | 18 | 3 | 0 | 1 | 4 | 3 | **3** | **3** | 1 | 2 | 2 | **2** | **2** | 1 | 3 | 2 | **3** | **2** | 0 | 3 | 2 | **2** | **3** |

Successive grades during which a ≥ 10% decrease in PVF occurred are bolded. Medial meniscal grade (Med men grade) and lateral meniscal grade (Lat men grade) were defined as follows: 0 = no lesion, 1 = mild fraying or incomplete tears with or without substantial fibrous replacement or repair, 2 = moderate fraying or tearing [longitudinal surface or small transverse tears] with or without substantial fibrous replacement or repair, and 3 = severe fraying or tearing [penetrating longitudinal tears or bucket-handle tears] without substantial effective fibrous replacement or repair. Subjective lameness grades were defined as follows: 1 = no lameness, 2 = mild lameness at a walk or trot, 3 = moderate lameness at a walk or trot, and 4 = severe lameness at a walk or trot. Subjective weight-bearing grades when the limb was at rest were defined as: 1 = normal weight bearing, 2 = partial weight bearing, and 3 = non-weight bearing. Subjective joint hyperextension grades were defined as follows: 1 = no response, 2 = mild response (turns head toward affected limb), 3 = moderate response (withdraws affected limb), and 4 = severe response (vocalizes or becomes aggressive). Subjective effusion scores were defined as follows: 0 = no effusion, 1 = mild effusion, 2 = moderate effusion, and 3 = severe effusion.

Table 4—Mean ± SD meniscal grade (medial meniscus), corresponding total subjective cartilage severity score, and Spearman rank correlation between meniscal grade and total subjective cartilage severity score in dogs in groups 1 to 4.

| Group | Meniscal grade | Cartilage severity score | Spearman rank correlation |
|---|---|---|---|
| 1 | 1.6 ± 0.9 | 6.6 ± 2.6 | $r = 0.16$ ($P = 0.417$) |
| 2 | 2.5 ± 0.6 | 10.8 ± 3.3* | $r = 0.24$ ($P = 0.917$) |
| 3 | 2.8 ± 0.50 | 7.0 ± 3.7 | $r = 0.77$ ($P = 0.333$) |
| 4 | 2.5 ± 1.0 | 8.3 ± 2.2 | $r = 7.38 \times 10^{-20}$ ($P = 0.253$) |

*Significantly ($P \leq 0.01$) different than group 1 value.

Cartilage severity score was defined as follows: 0 = normal; 1 = minimal superficial fibrillation; 2 = mild to moderate fibrillation, presumably into the upper middle zone; 3 = mild to moderate fibrillation, loss of cartilage extending to the middle zone, or both; and 4 = severe cartilage loss extending to the deep zone or subchondral bone.

A total subjective cartilage severity score was calculated by summing the cartilage damage scores on the medial and lateral tibial plateaus and on the medial and lateral femoral condyles.

*See* Tables 1 and 3 for remainder of key.

weight bearing at rest, 2 of 12 dogs placed less weight on the limb (indicated by a higher grade), 9 had no change, and 1 placed more weight on the limb when a ≥ 10% decrease in peak vertical force was identified. By use of the grading scale for subjective response to joint extension, 1 of 12 dogs had a greater response, 6 had no change, and 5 had less response to joint extension when a ≥ 10% decrease in peak vertical force was identified. By use of the subjective effusion scoring scale, 4 of 12 dogs had greater effusion, 7 had no change, and 1 had less effusion when the ≥ 10% decrease in peak vertical force was identified. Overall, when all 4 clinical parameters examined were combined, 7 of 12 dogs had an increased grade in 1 or more parameters when a ≥ 10% decrease in peak vertical force was identified.

**Meniscal and cartilage damage**—Mean ± SD medial meniscal grade for 12 dogs in groups 2 to 4 was 2.6 ± 0.7 (**Table 4**), which was significantly ($P = 0.004$) higher than in 27 dogs in group 1 (1.6 ± 0.9). When medial meniscal grades of all dogs were considered, the 12 dogs in groups 2 to 4 comprised 8 of 14 grade 3, 3 of 7 grade 2, 1 of 17 grade 1, and 0 of 1 grade 0 lesions (Table 3). Four of these 12 dogs had grade 1 damage on the lateral meniscus, and all 4 of these dogs had grade 3 damage on the corresponding medial meniscus. Mean ± SD total subjective cartilage severity score in 4 dogs in group 2 was significantly ($P = 0.008$) higher than in 27 dogs in group 1. When the cartilage severity scores for the 12 dogs in groups 2 to 4 were combined, mean ± SD score was 8.7 ± 3.3, which was significantly ($P = 0.046$) higher than in group 1. No significant correlations between meniscal grades and total subjective cartilage severity scores for any of the groups or combination of groups were found.

**Sensitivity, specificity, and accuracy—**To test the usefulness of a ≥ 10% decrease in peak vertical force for determining medial meniscal damage, sensitivity, specificity, and accuracy were calculated. When a ≥ 10% decrease in peak vertical force was used to determine the presence of any medial meniscal damage (grades 1, 2, and 3), compared with no damage (grade 0), the sensitivity was 32%, specificity was 100%, and accuracy was 33%; however, when a ≥ 10% decrease in peak vertical force was used to determine the presence of grade 2 or 3 medial meniscal damage, compared with no damage (grade 0) or grade 1 damage, the sensitivity was 52%, specificity was 94%, and accuracy was 72%. When the ≥ 10% decrease in peak vertical force was used to determine the presence of grade 3 medial meniscal damage only, compared with no damage or grade 1 damage, the sensitivity was 57%, specificity was 94%, and accuracy was 78%.

## Discussion

In many studies[7-11] that used force plate analysis, the changes that occur in ground reaction forces of the hind limb after rupture or transection of the CrCL in dogs have been described. The most predictable changes occur in peak vertical force and impulse area (total force applied over time). For these ground reaction forces, there are large decreases from preoperative values in the first 2 to 4 weeks after transection or rupture of the CrCL; these decreases are presumed to be direct results of pain related to joint instability.[7-11] With time, most dogs start to use the affected limb more as inflammation subsides and the joint becomes more stable as a result of fibrosis of the joint capsule. This is demonstrated by continual improvement in the amount of force placed on the ground by the affected limb; a plateau is reached approximately 10 months after transection of the CrCL, and peak vertical force remains below original baseline values for up to 3 years.[8] In our study, peak vertical force measurements obtained in 27 dogs in group 1 fit this pattern. All dogs in group 1 had a large decrease in peak vertical force 2 weeks after transection of the CrCL and a gradual increase in the amount of weight placed on the affected limb afterwards; therefore, group 1 was used as the comparison group in our study. The response of group 1 dogs was considered as the typical response of most dogs after transection of the CrCL; if a dog had a change in peak vertical force that was different than dogs in group 1, meniscal damage was suspected.

Clinically, when there is acute exacerbation of lameness in dogs after transection or rupture of the CrCL, medial meniscal damage is frequently suspected.[16,18,20,21] Damage to the medial meniscus is believed to develop as a result of joint instability created by lack of an intact CrCL and not as a result of the initial injury.[20] The most common meniscal injury found during surgical repair of CrCL rupture is a longitudinal tear of the caudal horn of the medial meniscus; this damage likely occurs because the caudal horn acts as the main secondary stabilizer to cranial tibial thrust.[22,23] The location of the tear combined with cranial tibial thrust allows the torn portion of the meniscus to slide between the femur and tibia. This abnormal movement of meniscal tissue presumably causes acute exacerbation of lameness as a result of pain from inflammation and locking or giving way of the limb[18]; therefore, after CrCL rupture, any dog that remains very lame in the initial period or becomes acutely lame within the first few months after it has shown improvement is assumed to have sustained secondary meniscal damage.[16,18,20,21]

During force plate evaluation, some dogs (dogs 2, 3, 4, 5, 6, 7, 8, 9, 10, and 12 on Table 3) subjectively appeared to become more lame on the affected hind limb after the 2-week time point; however, our lameness grading scale of 1 to 4 did not adequately describe these dogs because subtle differences were difficult to describe. For example, a dog that was severely lame (grade 4) at 2 weeks but was still toe-touching (partial weight bearing) may have been non-weight bearing at 4 weeks but would still be categorized as having grade 4 lameness; therefore, the percentage changes in peak vertical force over successive measurement periods were examined to determine whether we could objectively differentiate between these particular dogs. These dogs all had ≥ 10% decreases in peak vertical force at some time point. Therefore, it appeared that a cutoff at 10% decrease in peak vertical force would best indicate acute exacerbation of lameness that could be suggestive of meniscal damage, although the subjective lameness grade did not differ in these dogs.

In a concurrent study performed in our laboratory, 3 additional dogs underwent force plate analysis and serial arthroscopic examinations at the same time points (weeks 0, 2, 4, 10, and 18).[e] Medial meniscal damage was evident as early as 2 weeks after CrCL transection, and 1 dog became very lame between weeks 4 and 10; this dog had a bucket-handle tear of the caudal pole of the medial meniscus. On the basis of these arthroscopic data and the typical clinical situation after CrCL rupture,[16,18,20,21] it was reasonable to hypothesize that the acute exacerbation of lameness observed in these dogs could be the result of recent meniscal injury. Mean medial meniscal grade for all 12 dogs in groups 2 to 4 was significantly higher than mean medial meniscal grade in group 1 dogs. On examination of all dogs with grade 3 meniscal damage, 8 of 14 had been assigned to groups 2 to 4. However, we made a presumption that exacerbation of lameness could be the result of meniscal damage on the basis of our arthroscopic findings in another study[e] and clinical impressions; menisci of dogs in our study were not examined or graded until the end of the study, 18 weeks after transection of the CrCL.

When the 10% cutoff was considered to be indicative of all meniscal damage (grades 1, 2, and 3), the sensitivity (32%) and accuracy (33%) were low; however, only 1 of 39 dogs had no damage (grade 0) of the medial meniscus. Also, acute exacerbation of lameness in dogs with only mild fraying or incomplete tears (grade 1) of the medial meniscus would not be expected; therefore, we determined whether this cutoff

(≥ 10% decrease in peak vertical force) could distinguish between grades 2 and 3 medial meniscal damage and grades 0 and 1 damage because grades 2 and 3 damage is more likely to be associated with clinical signs. With this categorization, sensitivity of the test increased to 52% and accuracy increased to 72%, indicating that more severe meniscal damage could result in an acute exacerbation of lameness that can be identified most of the time. The low sensitivity indicated that a ≥ 10% decrease in peak vertical force can identify some dogs with medial meniscal tears, but force plate analysis results should probably be combined with results of a thorough clinical examination to improve detection of meniscal damage.

When medial meniscal damage is suspected after rupture of the CrCL, a thorough clinical examination should be performed. This generally includes, but is not limited to, determination of the degree of lameness; pain response on hyperflexion, hyperextension, and palpation of the medial aspect of the stifle joint; presence of a meniscal click; and severity of effusion or periarticular fibrosis.[18,20] We focused on the degree of lameness in our study; however, we also determined the degree of weight bearing of the affected limb at rest, the response to hyperextension of the stifle joint, and the degree of joint effusion. Detection of subtle differences was a problem when subjective grades for these parameters were used, as it was for lameness grades; no clinical parameters on their own were good for identifying potential meniscal injury. However, when all clinical parameters were combined with the knowledge of exacerbation of lameness, a higher proportion of dogs with potential meniscal injury could be identified, suggesting that a thorough clinical examination is warranted.

Damage to articular cartilage could potentially contribute to exacerbation of lameness; however, rarely does cartilage damage develop at a sufficiently rapid rate to cause an acute exacerbation of lameness, unless a cartilage flap is present. Cartilage damage likely causes slowly progressive lameness that probably contributes to the inability of dogs with ruptured or transected CrCL to reach preoperative peak vertical forces.[8] Dogs in groups 2 to 4 of our study did have significantly higher total subjective cartilage severity scores, compared with dogs in group 1. The most likely explanation for this finding is that cartilage damage increases as meniscal damage increases; however, the results of a previous study[15] and the failure to detect significant correlations between meniscal and cartilage damage do not support this hypothesis. We cannot rule out that cartilage damage may have contributed to some of the changes in ground reaction forces found in our study.

The allocation of dogs to groups 2 to 4 on the basis of the time at which the ≥ 10% decrease in peak vertical force occurred allowed us to examine the relative time frame in which meniscal injury may develop. Presumed meniscal damage developed as early as 2 to 4 weeks and as late as 10 to 18 weeks after transection of the CrCL. Results of our previous study[e] in 3 dogs revealed that medial meniscal damage and cartilage fibrillation developed as early as 2 weeks after CrCL transection. Because there were 4 dogs in each of the groups in the present study, however, there did not appear to be a specific time at which dogs injured menisci. Dogs that had a decrease in peak vertical force at week 4 with respect to week 2 could simply have represented dogs with continuing pain response as a result of joint instability and not meniscal injury. In fact, this group of dogs had the most prominent cartilage changes of any of the groups, suggesting that longer-lasting effects of joint instability existed. Because cartilage and menisci were not examined until the end of our study, it is impossible to determine exactly what caused the decrease in peak vertical force in these 4 dogs.

In our study, force plate data were collected to minimize previously identified sources of variability on ground reaction forces[3-6]; however, variation among dogs and within each dog with regard to response to transection of the CrCL was difficult if not impossible to control for and could have affected results. Propulsion and braking forces were also measured but were not reported here because of lack of noteworthy findings. Twenty dogs used in our study were treated with a novel drug but were included in our study because there were no significant differences found in ground reaction forces between treated and placebo-control groups; therefore, the effect of drug treatment on the results of force plate analyses was likely minimal. An additional measurement that may have been useful to perform is measurement of the tibial plateau slope. Unfortunately, radiographs obtained during our study were not of sufficient uniformity to allow accurate measurement. Measurement of peak vertical force at various time points after rupture or transection of the CrCL may provide a potential noninvasive way to objectively delineate the temporal pattern of meniscal injury.

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d. Acquire, Version 6.3W, Sharon Software Inc, Dewitt, Mich.
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