Injuries of the calcaneal tendon in dogs range from lacerations and acute ruptures to chronic strain injuries. Severe damage to the calcaneal muscle-tendon unit results in a plantigrade stance in the affected hind limb and mechanical lameness. Healing of tendon injuries is problematic because it can be difficult to achieve control of weight bearing and exercise restrictions. Injuries of the tendon are typically repaired by debridement and reattachment via various suture techniques.

Optimum tendon healing requires some degree of strain along the length of the tendon to stimulate proper recovery because the strength of collagenous tissue is positively affected by exercise and lessened with immobilization. Investigators in several studies have examined the effects of immobilization on tendon healing. In rabbits and mice, maturation of collagen tissue is faster in nonimmobilized groups and there is more rapid and continuous restoration of load to failure, compared with results for immobilized groups. Four months after sutured repair of calcaneal tenotomies, mice treated to allow immediate mobilization had regained their original tendon stiffness, whereas only half of the stiffness was regained in mice treated by use of immobilization. It is also important that a tendon anastomosis not be overstressed during the early postoperative period because this leads to gap formation or repair failure. Tendons with a gap > 3 mm during the repair process heal at a slower rate and have a decreased ultimate tensile resistance at 6 weeks after repair, compared with results for tendons healing with no gap or a gap < 3 mm. For this reason, the repair is typically protected for 6 to 12 weeks. Repaired tendon is extremely slow to regain breaking strength after sutured repairs, regaining only 56% by 6 weeks and 79% by 1 year after surgery. Various methods of tarsal joint immobilization and exercise restrictions have been used to attempt to limit calcaneal tendon strain; results have been mixed because every technique has potential complications.

Objective—To measure strain in the common calcaneal tendon during trotting in dogs and to compare strain before and after immobilization of the tarsal joint.

Animals—6 dogs.

Procedures—A microminiature strain gauge was surgically implanted on the tendinous portion of the gastrocnemius muscle. Surface electromyography (EMG) values, percentage strain, and ground reaction forces were measured before and after immobilization. Peak vertical force; vertical impulse; initial, maximum, and final strain; and peak-to-peak EMG amplitude were recorded. Data were analyzed by use of a repeated-measures ANOVA and paired t tests.

Results—Timing of strain data correlated closely with foot strike of the hind limb and EMG activity in all dogs. Maximum tendon strain was simultaneous with peak vertical force. Continued muscle contraction was evident after immobilization. There was no significant difference in maximum strain after immobilization, compared with maximum strain during normal motion. Minimum strain, both at the beginning and end of the strain curve, was significantly decreased for the immobilized state, compared with results for nonimmobilized joints.

Conclusions and Clinical Relevance—Immobilization of the tarsal joint did not eliminate calcaneal tendon strain during weight bearing in dogs. Decreased isometric muscle contraction during the swing phase of the gait could account for smaller minimum strain in immobilized joints. Immobilization is frequently applied after Achilles tendon rupture to alleviate strain and force on the sutured repair, with possible complications because of the immobilization method. Consideration of these findings could be important in adjusting current treatment recommendations. (Am J Vet Res 2009;70:134–140)
ing weight bearing, which can result in continued stress on the tendon despite the elimination of movement at the joint (isometric contraction). The value of immobilization can be determined by direct measurement of tendon strain.

In humans, injuries of the calcaneal tendon are treated after surgery by use of partial immobilization via hinged splints, which allows protected stress of the tendon unit and physical therapy throughout the healing period. Studies have revealed a faster return to normal function with less muscle disuse atrophy in these cases. In comparison with the upright stance of dogs, humans have a plantigrade stance, which leads to different stresses on the calcaneal tendon between these species. Also, postoperative activity can be more easily controlled in humans. For these reasons, use of partial immobilization is still not common in dogs.

Biomechanical studies for investigating tendon strain and forces have been performed in other species. Strain has been directly measured in vivo and can vary depending on the implanted tendon as well as the activity in which the animal is engaged. Calcaneal tendon force has been measured in vivo in horses, humans, cats, and rabbits. Peak forces in the common calcaneal tendons of cats increase with increasing intensity of movement as a result of increasing speed or external resistance. To our knowledge, measurements of in vivo common calcaneal tendon strain or force have not been reported in dogs.

In the study reported here, the hypotheses tested were that tendon strain in the common calcaneal tendon is partially but not completely eliminated by tarsal joint immobilization in animals with an upright stance and that active muscle contraction continues to contribute to tendon strain. The hypotheses were tested during ambulation before and after tarsal joint immobilization by direct measurement of in vivo tendon strain by use of an implanted strain gauge as well as surface EMG electrodes and measurement of ground reaction forces by use of a force plate.

Materials and Methods

Animals—Six purpose-bred female hounds were used in the study. Dogs ranged from 20.6 to 31.7 kg. The dogs were acclimated with daily training for 2 weeks prior to beginning the study to accustom them to walking on a leash while wearing a backpack. They also were acclimated to the force plate and to the associated EMG leads and cables. This project was approved by the Institutional Animal Care and Use Committee at Kansas State University.

Equipment—A force plate built into a 7.6-m walkway was used in the study. The force plate was operated with custom software, which allowed simultaneous integration of the EMG and strain gauge data with the ground reaction force data. An 8-channel analogue-digital laboratory acquisition system was used for additional data acquisition. Multiple-use surface EMG sensors with built-in preamplifiers were used to collect EMG data. Microminiature strain gauges and a signal conditioner were obtained and modified for operation with the 8-channel laboratory acquisition system.

The strain gauges and signal conditioner were calibrated at the factory to correlate voltage with displacement and calculate a slope and offset for each strain gauge, which established a linear range of the device. This process has been reported elsewhere. The strain gauges used in the study reported here had a functional stroke length of 3 mm, and voltage output depended on the core position within that stroke length. The midpoint of the voltage range could also be obtained with the core completely removed. To allow operation with the 8-channel laboratory acquisition system, the signal conditioner was modified (by the manufacturer) to bypass the internal voltage regulator and upgrade the electronics, which eliminated the output resistor-capacitor filter. Further modification was performed on-site by incorporation of a resistor network into the sensor. This attenuated the voltage signal by half, which resulted in an operating range of 0 to 2.3970 V within the range of the 8-channel laboratory acquisition system (ie, ±3 V).

The reference length to be used during calculation of strain was determined on the basis of 2 measurements. First, an initial reference length was determined prior to implantation of the strain gauge. The strain gauge core was fully inserted to obtain the maximal voltage, and the distance between the insertion barbs was measured with a digital caliper that was accurate to 0.01 mm (Figure 1). Voltage at that length was recorded, which provided the initial reference length. A second measurement was obtained after implantation of the strain gauge in each dog. The difference between the 2 voltages was used to calculate the actual reference length.

Preimplantation trials—Prior to surgical implantation of a strain gauge, an initial data set of ground reaction forces and surface EMG values was obtained for each dog. Trials were considered valid when the speed of a dog was within the range of 1.6 to 2.3 m/s and both the ipsilateral fore limb and hind limb struck the force plate. Acceleration was maintained between –0.5 and +0.5 m/s². Results of valid trials were used to calculate a mean value for each measurement time period.

Strain gauge implantation—Dogs were premedicated with acepromazine maleate (0.02 mg/kg, IM) and morphine (0.5 mg/kg, IM). Anesthesia was induced with thiopental (10 to 20 mg/kg, IV) and then maintained by administration of isoflurane. After standard surgical preparation, an approach to the lateral aspect of the common calcaneal tendon was performed. The tendon sheath was incised. The strain gauge was implanted onto the cranialateral aspect of the tendinous portion of the gastrocnemius muscle by use of the 2 barbed attachments (one was proximal on the sensor, and the other was distal on the core). The strain gauge was placed in the common calcaneal tendon in a zero-strain position in the anesthetized dogs; the tarsal joint was maximally extended, and the stifle joint was flexed. During implantation, voltage readings were obtained, and the barbs were fixed at a distance approximating the midpoint of the functional range of the strain gauge. The investigators were careful to ensure the strain gauge was securely affixed into the tendinous...
After implantation of the strain gauge, the superficial digital flexor tendon was not disturbed. The gauge cable was further affixed in position to the tendon with 2 cruciate sutures of 3-0 polypropylene (1 around each barbed attachment). The cable was tunneled proximally in the subcutaneous tissues and exited the skin immediately distal to the stifle joint; the external portion of the cable was secured in place by the use of friction sutures. The incision was closed in a routine manner in 2 layers. Smooth 3/32-inch intramedullary pins were placed in the distal portion of the tibia and tuber calcanei. Holes were drilled with a 2-mm drill bit, and pins were then placed with the drill at low speed. The tarsal joint was stabilized by placement of a type II fixator frame with 2 carbon fiber rods and 4 large clamps at an angle typical of a dog during a normal stance.

When not in use, the strain gauge cable and fixator were covered with a soft, padded bandage. After surgery, deracoxib (1 to 2 mg/kg, PO) was administered every 24 hours for 5 days, and acetaminophen with codeine (1 to 2 mg/kg, PO) was administered for 24 to 48 hours as needed on the basis of signs of pain. Dogs were evaluated via complete physical examination and pain scoring twice during the first 24 hours after placement (and again after removal) of the implants, then once daily thereafter for an additional 4 days. General attitude and degree of weight bearing were also evaluated 3 or 4 times daily for evidence of discomfort while the fixator and strain gauge were in place. All dogs appeared comfortable after surgery and would almost fully bear weight while standing or ambulating at a slow walk. Because of the physical impediment of the fixator, some of the dogs would initially lift the limb off the ground while at a fast walk or trot, yet when the fixator bars were removed, the dogs would almost fully bear weight.

After implantation of a strain gauge in each dog, voltage readings were obtained with the tarsal joint in a zero-strain position. A zero-strain position was defined as an anesthetized dog (which eliminated active muscle contraction) with the tarsal joint fully extended. Five voltage readings were obtained, and the mean value was calculated to obtain the zero-strain reference value. The difference between the zero-strain voltage and the pre-implantation voltage for each reference length allowed computer calculation of the actual implanted reference length for each dog by use of the following equation: percentage strain = (change in tendon length/reference tendon length) = ([L – L₀]/L₀) × 100, where L is the actual tendon length and L₀ is the initial or reference tendon length.

Collection of fixator-immobilized and nonimmobilized data—After implantation of the strain gauge, initial data sets were collected. Data sets included ground reaction forces, surface EMG, and strain gauge data. Two data sets were collected. The first data set was collected with the external fixator frame in place, which immobilized the tarsal joint at an angle typical of a dog during a normal stance. The second data set was obtained after removal of the fixator bars, which allowed free movement of the tarsal joint. Investigators were careful to ensure adequate weight bearing while a dog was trotting, as determined on the basis of comparison with preimplantation peak vertical force. When adequate weight bearing was not evident, repeated attempts were made twice daily until data could be obtained (range, 1 to 3 days). Nonimmobilized and fixator-immobilized data were collected on the same day to minimize the amount of variability related to possible dysfunction of the strain gauge or variation in the degree of weight bearing.

Three surface EMG sensors were used in collection of EMG data. Sensors were placed over the lateral and medial heads of the gastrocnemius muscle and the cranial tibial muscle. Placement sites were prepared by clipping the hair and cleaning with an alcohol pad to remove surface oils and keratin to decrease the surface impedance of the skin and ensure good adherence of the electrodes to the site. Investigators were careful to ensure that EMG sensors were placed over the midportion of the muscle belly and not in contact with the muscle fibers. A ground reference electrode was placed over the olecranon, which was prepared in a similar manner.

Fixator removal and cast-immobilized measurements—The dogs were sedated by administration of acepromazine (0.02 mg/kg, IV) and morphine (0.25 mg/kg, IV). The pins were removed, and a cast was placed from the midtibia to distal to the tarsus with the limb positioned at a similar angle as for the pre-
vously immobilized joint. Angles were measured with a goniometer to ensure consistency. Data collection, including ground reaction forces, strain data, and EMGs, was attempted 6 hours later; however, when adequate weight bearing during trotting was not evident because of physical impediment of the cast, additional attempts to obtain data were made on subsequent days (1 to 3 days after cast placement). The dogs were anesthetized for removal of the cast and strain gauge. After recovery from anesthesia, the dogs were eligible for adoption.

For each scenario (nonimmobilized, fixator immobilized, and cast immobilized), peak vertical force and impulse data were collected. After implantation of a strain gauge, EMG data and strain gauge data were evaluated in reference to the hind limb strike. Initial strain, maximum strain, and final tendon strain for each gait cycle were determined from evaluation of the strain curve. Peak-to-peak amplitude was collected from the EMG data. Timing of EMG impulses and tendon strain were evaluated in reference to the hind limb strike. Tendon strain and EMG data were used to make comparisons between the nonimmobilized state and each of the 2 methods of immobilization.

Statistical analysis—Mean peak vertical force and impulse were calculated for each hind limb before implantation of the strain gauge, after implantation of the strain gauge, after fixator immobilization, and after cast immobilization. Mean strain at start and finish as well as peak strain were calculated for each dog in the implanted limb at each time point. A repeated-measures ANOVA and Newman-Keuls multiple comparisons tests were used to detect significant differences in peak vertical force and impulse between the 4 data time points. Paired t tests were used to compare postimplantation and postimmobilization strain gauge data. Cast data could only be obtained from 2 dogs because of failure of the dogs to adequately bear weight during trotting. Because of this lack of adequate numbers, the cast data were not included in the statistical analysis. Differences were considered significant at values of P < 0.05.

Results

After triggering the initial light sensor, a cyclic or waveform pattern corresponding to foot strikes was obtained from the strain gauges in all dogs during the 4-second recording period (Figure 2). This waveform was symmetric, and it was consistent among trials. Occurrence of the waveform was closely correlated to the hind limb foot strike. In some dogs, an initial increase in strain was evident at the initiation of the foot strike, followed by a further increase in strain correlated to a burst of muscle activity from the surface EMGs placed over the gastrocnemius muscle. Peak strain was simultaneous with peak vertical force, then strain decreased toward the end of the foot strike. A wide variation was evident among dogs for measured percentage strain, but within each dog, values were consistent among all trials.

The EMG data were variable between trials among dogs. No valid quantitative comparisons could be made concerning peak-to-peak amplitude of muscle contractions during the immobilized and nonimmobilized state. Bursts of muscle electrical activity correlated well with the strain curve and hind limb foot strike, with contraction of the gastrocnemius muscle consistently

| Table 1—Mean ± SD values for the common calcaneal tendon in trotting dogs before implantation of a microminiature strain gauge, after implantation of the strain gauge, and after application of a fixator for immobilization of the tarsal joint. |
|---|---|---|---|---|---|
| Period | Peak vertical force (%) | Vertical impulse (%) | Initial strain (%) | Peak strain (%) | Final strain (%) |
| Before implantation | 67.88 ± 10.19* | 9.56 ± 1.98 | ND | ND | ND |
| After implantation | 58.18 ± 3.32 | 7.94 ± 0.31 | 4.57 ± 3.18* | 7.69 ± 4.61 | 4.59 ± 3.16* |
| Fixator immobilization | 52.95 ± 12.98* | 7.76 ± 3.11 | 3.34 ± 3.60* | 6.70 ± 4.37 | 3.31 ± 3.55* |

Results are reported as percentage strain, which represents the change in tendon length divided by the reference tendon length determined in anesthetized dogs by use of a zero-strain position (the tarsal joint was maximally extended, and the stiffe joint was flexed).

*Within a column, values with an asterisk differ significantly (P < 0.05).
ND = Not determined.
occurred at the initial moment of ground contact for the hind limb. A second burst was detected at the end of the foot strike.

No significant difference in peak vertical force was detected in preimplantation and postimplantation values or between postimplantation and fixator-immobilization values. A significant difference was detected between preimplantation data and fixator-immobilization data. No significant difference in vertical impulse was detected among the 3 time points (Table 1).

Mean maximum strain in the common calcaneal tendon ranged from 2.31% to 12.99%. After immobilization of the tarsal joint with an external fixator, mean maximum strain in the common calcaneal tendon ranged from 2.34% to 12.55%. Overall, there was no significant difference in mean maximum strain between nonimmobilized and fixator-immobilized states.

Mean minimum initial strain in the common calcaneal tendon ranged from 0.94% to 8.58%. Mean minimum final strain in the curve ranged from 0.92% to 8.62%. After immobilization of the tarsal joint with a fixator, mean minimum initial strain ranged from –1.17% to 6.97%. Mean minimum final strain ranged from –1.04% to 7.45%. Mean minimum initial (P = 0.009) and final (P = 0.010) strain were significantly less for the fixator state, compared with values for the nonimmobilized state.

**Discussion**

In the study reported here, no significant difference in maximum tendon strain was detected between fixator-immobilized and nonimmobilized tarsal joints. Contraction of the gastrocnemius muscle was still evident during trotting, as evidenced by the EMG activity. These findings supported the hypothesis that strain on the calcaneal tendon persists after tarsal joint immobilization as a result of the effects of isometric muscle contraction during weight bearing.

The tendons that comprise the Achilles tendon in dogs are the common calcaneal tendon, which inserts on the tuber calcani of the talus, and the superficial digital flexor tendon, which continues distally. The common calcaneal tendon is composed of the tendinous portion of the gastrocnemius muscle and the combined tendinous portions of the gracilis, semitendinosus, and biceps femoris muscles. The gastrocnemius muscle has paired heads, but it unites in the proximal portion of the limb to form a single tendinous structure that constitutes most of the common calcaneal tendon. In the study reported here, the strain gauge was placed on the tendinous portion of the gastrocnemius muscle. This may not be representative of calcaneal tendon strain as a whole because amounts of strain may vary among the various components. However, because the tendinous portion of the gastrocnemius muscle constitutes most of the common calcaneal tendon, this was considered the most important component for measuring strain on the common calcaneal tendon.

The percentage of weight bearing and type of activity would be expected to affect the forces and strain in a tendon. On the basis of measured ground reaction forces, dogs were substantially lame after implantation of the strain gauge. However, because no significant difference in ground reaction forces was detected between the immobilized and nonimmobilized scenarios, this should not affect the comparisons.

Although no difference in maximum strain was detected, minimum strain at the beginning and end of the curves was significantly lower in the fixator-immobilized tendons. These findings could be explained by a decreased need for muscle contraction to hold the tarsal joint in a fixed position during the swing phase of the gait because the fixator takes over this function. Decreased muscle contraction would lead to decreased magnitude of strain in the tendon during this period.

Wide variability in magnitude of surface EMG curves was evident in our study. This was likely related to difficulty in maintaining good adhesion of the EMG sensors between trials. Therefore, quantitative analysis of amplitude of EMGs was not possible. Visual examination of electromyographs was useful to determine the timing of muscle bursts in correlation with the hind limb foot strike and increase in tendon strain. In another study regarding timing of the EMG burst in the medial head of the gastrocnemius muscle in cats, it was reported that the primary burst of activity is before foot contact. During the stance phase, there is a second burst of activity that is responsible for the residual tension in the muscle. Similar timing of EMG activity was also evident in our study, with an initial burst of activity in the gastrocnemius muscle simultaneous with the initial foot strike and then a subsequent second burst. This indicated that muscle contraction persisted in the immobilized limbs.

The original objective of the study reported here was to obtain data sets after immobilization with a cast and with a fixator. We experienced difficulty in obtaining full data sets for the cast-immobilized tarsal joints. Many of the dogs would not adequately bear weight in a cast at the appropriate speed and gait for the force platform analysis. Use of a pressure platform for analysis may have allowed analysis of data obtained at a slower speed.

The microminiature strain gauge was selected because of its small size and biocompatibility and the fact that its use resulted in minimal morbidity. Investigators have used the strain gauge sensor for in vivo measurement of strain in the cranial cruciate ligament in humans. A zero-strain reference had to be established for each dog to allow accurate strain calculations. The optimal zero-strain reference would be based on the length of the ligament at the point when it begins to bear a load (slack-taut transition). However, it is difficult to determine the true neutral length without destructive sectioning. Therefore, we chose to establish our zero-strain reference with each dog anesthetized and the tarsal joint fully extended because this would simulate a zero-strain condition and was a reproducible position. Many other investigators have used arbitrary references based on a particular joint position. These references provide a value of relative strain or percentage elongation and are considered useful to compare peak strains of a ligament for different conditions in a particular study. Because the zero-strain reference was
reestablished for each dog and comparisons were made between the 2 scenarios on the basis of the same reference measurement, this was considered valid.

A wide range in measured tendon strain was obtained among the dogs in our study, with maximum measured tendon strain ranging from 2.31% to 12.99%. This variability among dogs can be explained by several factors. Dogs varied in size and degree of weight bearing, which could have resulted in tendon force and strain.\(^{16,17,19,20}\) Also, strain distribution within a ligament is not consistent along the length of the ligament because strain increases near the tendinous insertion.\(^{35}\) We were careful to place the strain gauge in the midpoint of the tendinous portion of the gastrocnemius muscle to limit this effect, but some variability attributable to position was likely.

When conducting research with live animals, exposed equipment is vulnerable to damage. A new strain gauge was not used for every dog, and 1 strain gauge was used several times before it was damaged prior to removal. Minor fatigue of the cable could have affected the voltage obtained prior to final destruction, which could have led to variability in maximum strain among dogs. To minimize this possible effect on our results, efforts were made to collect data for the immobilized and nonimmobilized state on the same day. Because trials for each dog were consistent in the amount of measured strain, and each dog acted as its own control animal, the variability among dogs was not considered important.

The main limitation of the study reported here was a lack of correlation of measured strain to force within the tendon. Tendon strain is directly related to the cross-sectional area of the tendon, tendon stiffness (modulus of elasticity), and the force applied. However, direct calculation of tendon force from strain is inaccurate. Because tendons are viscoelastic structures, the modulus of elasticity will be a strain-dependent phenomenon. As higher amounts of strain are applied, there is greater resistance to tension.\(^{36}\) Strain is calibrated to tendon force by use of postmortem methods in which measured strain is determined for known weights.\(^{17,31,32}\) Knowledge of the amount of force within the tendon during ambulation would allow direct correlation with force withheld by a sutured repair. Direct correlation of strain with tendon force would be an important factor before adjusting current treatment recommendations for immobilization after tendon repair.

Immobilization of the tarsal joint is frequently used after repair of tendons in a hind limb to alleviate strain and force on the sutured repair, with possible complications attributable to the immobilization method. As indicated in the study reported here, immobilization has no effect on maximum strain in a weight-bearing situation. Clinical benefits may result more from decreased weight bearing attributable to the method of immobilization as well as exercise restrictions. Direct correlation of strain with force within a tendon was not determined in this study. Future studies to investigate the corresponding forces in the common calcaneal tendon before and after immobilization as well as the degree of force and strain that can be withheld by a sutured repair would be important information before adjusting current treatment recommendations.

### References


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