Use of pressure mapping for quantitative analysis of pressure points induced by external coaptation of the distal portion of the pelvic limb of dogs

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OBJECTIVE
To quantitatively measure the amount of pressure induced at the calcaneus and cranial tibial surface of dogs by use of 2 cast configurations.

ANIMALS
13 client- or student-owned dogs.

PROCEDURES
Pressure sensors were placed over the calcaneus and cranial tibial surface. Dogs then were fitted with a fiberglass cast on a pelvic limb extending from the digits to the stifle joint (tall cast). Pressure induced over the calcaneus and proximal edge of the cast at the level of the cranial tibial surface was simultaneously recorded during ambulation. Subsequently, the cast was shortened to end immediately proximal to the calcaneus (short cast), and data acquisition was repeated. Pressure at the level of the calcaneus and cranial tibial surface for both cast configurations was compared by use of paired *t* tests.

RESULTS
The short cast created significantly greater peak pressure at the level of the calcaneus (mean ± SD, 0.2 ± 0.07 MPa), compared with peak pressure created by the tall cast (0.1 ± 0.06 MPa). Mean pressure at the proximal cranial edge of the cast was significantly greater for the short cast (0.2 ± 0.06 MPa) than for the tall cast (0.04 ± 0.03 MPa).

CONCLUSIONS AND CLINICAL RELEVANCE
A cast extended to the level of the proximal portion of the tibia caused less pressure at the level of the calcaneus and the proximal cranial edge of the cast. Reducing the amount of pressure at these locations may minimize the potential for pressure sores and other soft tissue injuries. (*Am J Vet Res* 2018;79:317–323)

Casts and splints are frequently used for stabilization of musculoskeletal injuries, including fractures and postsurgical support of sites distal to the elbow joint or stifle joint.[1–3] However, casts may be associated with soft tissue complications such as pressure sores, edema, and dermatitis.[3–5] In a retrospective study,[4] it was found that 63% of patients fitted with a cast developed a soft tissue injury.[4] Of the injuries that developed as a result of casting, 40% required continued veterinary intervention. These complications usually are minor; however, the cost of managing a cast-related injury can exceed the cost of treatment for the primary injury.[4] In some cases, injuries caused by a cast can be severe, which could result in necrosis of the limb and amputation.[1,6] Therefore, prevention of these secondary injuries is desirable.

ABBREVIATIONS

CF	Counter force
CRF	Corrective reaction force
MF	Mean force
MP	Mean pressure
PF	Peak force
PP	Peak pressure

Dermal sores or lesions usually develop at areas of high pressure. These high-pressure areas generally are located over bony prominences such as the calcanei, styloids, or malleoli or at the proximal and distal edges of a cast.[7] The reduced compressibility and thinner nature of the tissue over bony prominences can result in nonuniform distribution of pressure over the aforementioned points, which make them extremely susceptible to the adverse effects of pressure.[7,8]

To achieve adequate stabilization of fractures, it is commonly recommended that a cast should extend to the joints proximal and distal to the fracture site.[1,6,9,10] Surprisingly, extremely little information has been provided regarding the location (ie, proximal to the joint that is proximal to the fracture site) at which the rigid material of a cast or splint should terminate. Some authors describe application of cast padding to the level just distal to the nonimmobilized joint.[6,9] However, others state that a short cast that does not extend to the elbow joint or stifle joint may be appropriate for treatment of injuries to the distal portions of a limb.[11,12] More information is available regarding the forces created when applying external coaptation to humans. A biomechanical concept referred to as a 3-point corrective system theorizes that the rigid material of a cast should always extend as far proximal and distal as possible to minimize the overall forces acting on the limb **(Figure 1)**.[7,13] By minimizing these forces, it is expected that pressure points within a cast will be minimized, which will reduce the incidence of pressure sores and other soft tissue injuries. The 3-point corrective system is based on the concept that application of a rigid cast prevents normal joint motion and thereby couples the unaffected skeletal structures proximal and distal to the site of injury.[14] During weight bearing, the forces are expected to be largest at bony prominences and termination sites of the cast in locations at which the rigid cast material prevents normal motion (pressure points). The force opposing joint motion during weight bearing has been defined as the CRF. For the tarsus, these forces would occur during flexion and be located caudally at the level of the calcaneus and on the cranial surface proximally and distally at the points where the cast terminates. Two opposing forces (proximal and distal to the CRF) have been defined as CFs. In the example of a 3-point corrective system, 2 CFs oppose 1 CRF and are located opposite each other (ie, if the CRF is acting on the caudal aspect of a limb, the CFs act on the cranial aspect). The forces of both CFs are expected to equate to the force applied at the CRF location.[14] Thus, reducing 1 of the CF forces should result in a decrease in the CRF. On the basis of this concept, it has been suggested that by

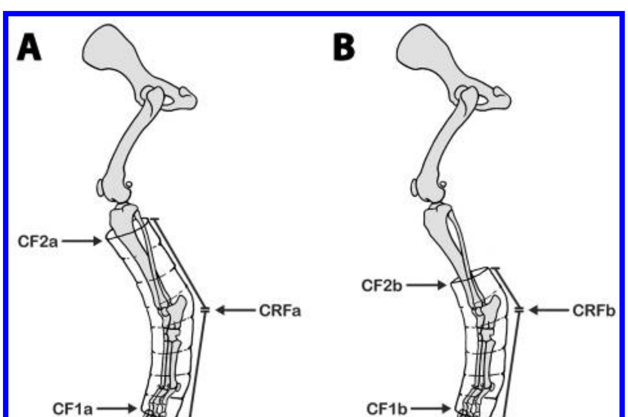

Figure 1—Schematic diagram that depicts the concept of the 3-point corrective system for a tall cast (A) and short cast (B) applied to a pelvic limb of a dog. The force acting at the calcaneus is the CRF for the tall (CRFa) and short (CRFb) casts. For the tall cast, the 2 opposing CFs are acting at the points where the cast terminates on the cranial surface of the proximal portion of the tibia (CF2a) and digits (CF1a). For the short cast, the 2 opposing CFs are acting at the points where the cast terminates on the cranial surface of the distal portion of the tibia (CF2b) and digits (CF1b). For both cast configurations, the forces of both CFs are expected to equal the force applied at the CRF location. The extended lever arm associated with the tall cast configuration results in lower pressures at CF2a and CRFa, compared with the pressures at the corresponding locations (CF2b and CRFb) with the short cast configuration.

extending the lever arm (ie, extending a cast proximally), the CF will be reduced, thereby reducing the CRF and reducing the incidence of pressure points and sores over the calcaneus.[7,14]

The introduction of veterinary orthoses and prostheses has resulted in the clinical application of this concept to veterinary patients[14]; however, to our knowledge, this concept has not been scientifically evaluated for use in small animals.

The purpose of the study reported here was to evaluate the effect of 2 cast configurations on the amount of pressure at various points on the canine pelvic limb. We hypothesized that a cast extending approximately 2.5 cm proximal to the tarsus would create greater pressures at the calcaneus, compared with pressures created by a cast that extended just distal to the tibial tuberosity. A second hypothesis was that pressure over the cranial surface of the tibia at the level of the proximal edge of the cast would be greater for a short cast configuration than for a tall cast configuration.

Materials and Methods

Animals

Client- or student-owned dogs were enrolled in the study. Dogs were included in the study if they weighed between 13.6 and 36.2 kg, had no history of major systemic or orthopedic disease, and did not have a condition that required application of a cast. Informed owner consent was obtained for each dog. The study was approved by the Institutional Animal Care and Use Committee of Colorado State University (No. 16-6399A).

Cast application and acclimation

A full-limb fiberglass cast was applied to the left pelvic limb of each dog. The left limb was chosen to accommodate the cords for the pressure sensing system so that the dogs would not step on the cords during data acquisition. Standard 1-inch white tape[a] stirrups were applied medially and laterally and a tubular stockinette[b] was placed over the limb. Three layers of cast padding[c] were applied to the pes and then continued proximally on the limb (approx 50% overlap in layers); the padding terminated just proximal to the tibial tuberosity. Roll gauze[d] was applied in a single layer with minimal overlap to compress the cast padding, and the limb then was wrapped with self-adherent bandaging tape.[e] This layer of bandaging tape was applied to prevent adhesion of the fiberglass casting tape[f] to the gauze. Approximately 3 layers of fiberglass casting tape were applied to the limb; the tape terminated approximately 2.5 cm distal to the tibial tuberosity (tall cast configuration). Once the cast had fully dried and hardened, it was transected longitudinally on the lateral and medial aspects of the limb by use of a battery-operated oscillating saw.[g] The 2 halves of the cast were left in place and secured circumferentially with white tape[a] to ensure full compression of the cast. Each dog then was allowed to acclimate to use of the limb and cast by walking on a leash over a hard flat floor until it could consistently bear weight on the casted limb.

Placement of pressure mapping sensors

Before data were collected, single-point calibration of each pressure mapping sensor was performed by placing the sensor between 2 flat foam boards and loading the sensor with 13.6 kg in the form of metal weights, as described elsewhere.[15] Sensor-specific calibration data were saved and used across all trials for all dogs.

Once dogs were deemed to be consistently bearing weight on the casted limb during ambulation, the cast, underlying bandaging tape, roll gauze, and cast padding were removed, but the stockinette and tape stirrups were left in place. Pressure mapping sensors[h] consisted of 6 columns of sensors to accommodate curvature of a limb. Three sensor columns were fixed over the most cranial aspect of the tibia, with the most proximal sensor located 2.5 cm distal to the insertion of the patellar tendon **(Figure 2)**. One sensor column was fixed over the calcaneus. The other 2 sensor columns were not used for data collection and were positioned outside the field of interest for pressure mapping (ie, not over bony prominences or in areas of expected pressure points). Sensors were fixed to the stockinette with white tape[a] in a manner that did not induce an artificial pressure point but that ensured correct placement over areas of interest.

Pressure point areas for evaluation were confirmed by applying direct manual pressure to the areas while simultaneously monitoring the real-time output of the pressure mapping sensor,[i] which displayed the entire area of the sensor. The locations were recorded on a transparent screen overlay to enhance subsequent identification of the pressure point areas. Subsequently, the cast padding, roll gauze, and cast were reapplied. The 2 halves of the cast were aligned, fully compressed, and taped together circumferentially with white tape. The pressure sensor cuff then was taped to the rigid cast. Each pressure mapping sensor was used to record data for 2 dogs.

Objective gait analysis

Objective gait analysis was performed with a previously validated walkway[j] to evaluate weight bearing and velocity during acquisition of pressure mapping data.[16,17] The walkway was located in an isolated gait analysis area. Dogs were always walked in the same direction across the walkway. A trial was considered valid for inclusion in data analyses when the dog walked without stopping and maintained a constant velocity (velocity range of ± 0.2 m/s across trials with respect to all other dogs),[16,17] the dog walked down the middle of the walkway without stepping outside the gait analysis runway, the casted limb bore weight and was in contact with the walkway at least twice during each gait trial, and the handler did not subjectively consider the dog to be pulling at the leash.

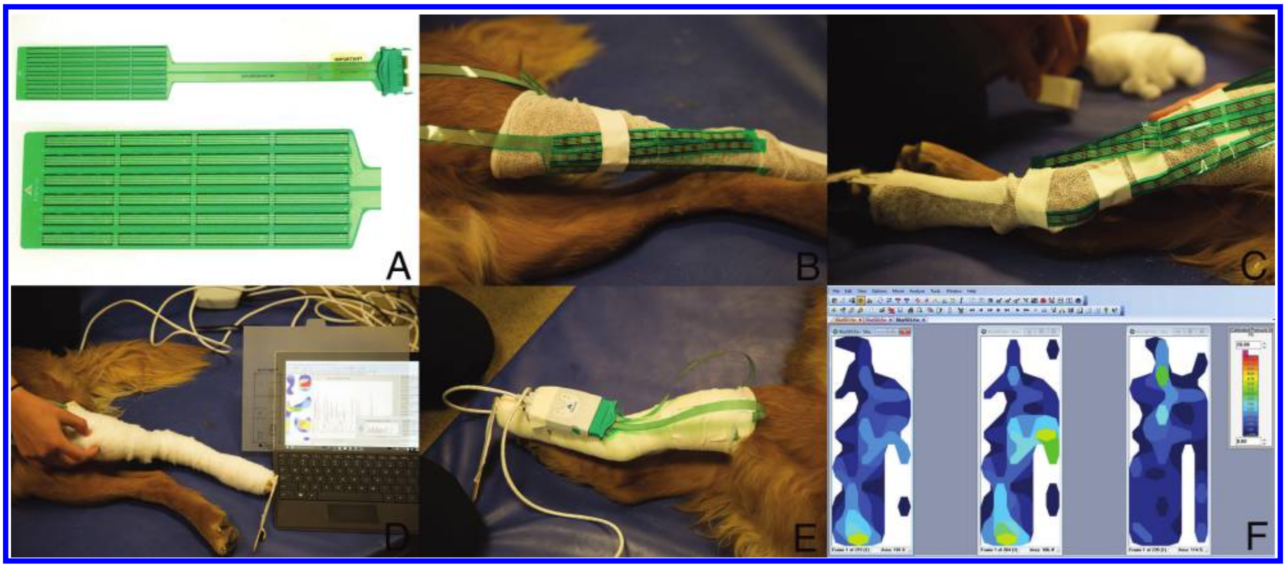

Figure 2—Photographs of a pressure sensor, application of the pressure sensors to a pelvic limb of a dog, and outputs for the sensor. A—Photographs of the pressure sensor (top) and a magnified view of the 6 sensor columns (bottom). B—Photograph of 3 sensor columns positioned (starting proximally at the tibial tuberosity) over the cranial aspect of the pelvic limb of a dog. C—Photograph of 1 sensor column positioned over the calcaneus. Notice that the 2 other sensor columns in the photograph are positioned outside the area to be evaluated (ie, outside the calcaneus). D—Photograph of the screen overlay for the pressure mapping software. Notice that the investigator is applying direct pressure to the area to be evaluated to record its location on the screen overlay for subsequent use in data analysis. E—Photograph of the final positioning of the sensors, cast padding, and fiberglass cast on a pelvic limb. The sensor cuff is affixed to the exterior of the cast over the tarsus. The sensor wires attach directly to the pressure mapping system. F—Photographs of the screen overlays of 3 recorded pressure measurements. Notice that areas of lower pressure appear dark blue, whereas areas of higher pressure appear yellow or green.

Figure 3—Photographs of procedures for the application of a short cast configuration. A—Photograph of the longitudinal transection of a short cast on the lateral and medial aspects of the limb by use of a battery-operated oscillating saw. B—Photograph of a short cast on the pelvic limb. Notice that the 2 halves of the cast have been aligned, fully compressed, and taped together circumferentially. C—Photograph of the final positioning of a short cast with the sensors, cast padding, and short cast in place. The sensors and padding were not removed to ensure there was no change in sensor placement. The sensor cuff is affixed to the exterior of the cast over the tarsus. The sensor wires attach directly to the pressure mapping system.

Collection of pressure data

Dogs were tethered to the pressure mapping system by use of a 3.6-m-long cord that allowed for concurrent recording of pressure data and objective gait analysis. Dogs were handled by the same investigator during each trial. Pressure mapping data were recorded only during the period that the dogs were walking over the walkway; data were collected by manually starting and stopping the recording.

A minimum of 3 valid trials/dog were required, which was a method used by another research group.[18] When > 5 attempts were performed without attaining a minimum of 3 valid trials, the dog was excluded from the study.

After trial completion with the tall cast, a short cast configuration was applied. The most proximal end of the cast was terminated approximately 2.5 cm proximal to the calcaneus by removing the proximal section of white tape without completely removing the entire cast **(Figure 3)**. The cast halves were then realigned, fully compressed, and secured circumferentially with white tape. The sensors and padding were not removed to ensure there was no change in sensor placement. The dogs were then walked across the walkway as previously described. Once 3 valid trials with the short cast were obtained, the cast was partially removed and the location of the sensors over the pressure point areas was reconfirmed by use of the screen overlay to ensure there were no changes in sensor placement.

Measurements of PP, MP, PF, and MF at the level of the proximal portion of the tibia, distal portion of the tibia, and calcaneus for each trial were recorded by use of software.[i] Pressure mapping data sets were evaluated in their entirety and included all frames recorded throughout the testing period. The previously identified areas recorded on the screen overlay were used to calculate data specifically for the areas of interest (calcaneus, distal portion of the tibia, and proximal portion of the tibia). Sensor data outside the areas of interest were not included in the analyses. Gait velocity and maximum PP from the objective gait analysis were recorded for each trial. All data were recorded at 100 Hz. Raw data for each area of interest were transferred to a commercially available spreadsheet program[k] for analysis.

Statistical analysis

Statistical analysis was performed with commercially available software.[l] Data were first examined for consistency of movement of a dog across the walkway among trials by use of a repeated-measures ANOVA. To ensure there was no difference in the trial variables between treatments (tall cast vs short cast), the mean gait velocity and mean maximum walkway pressure for the objective gait analysis of all trials were compared by use of paired *t* tests. When no significant differences were identified in the trials on the basis of dog or treatment, mean output values for each dog were used for subsequent analysis.

Outputs for the pressure mapping software[m] (MP, PP, MF, and PF) were analyzed by use of paired *t* tests to determine the difference in pressures between the tall cast and short cast configurations for each defined location (proximal portion of the tibia, distal portion of the tibia, and calcaneus). The same comparisons were made for measurements obtained at the proximal portion of the tibia for the tall cast configuration and the distal portion of the tibia for the short cast configuration. Values of $P \leq 0.05$ were considered significant.

Results

Animals

Thirteen dogs met the inclusion criteria for the study. Breeds represented included Labrador Retriever (n = 3), Border Collie (2), Boxer (1), Brittany Spaniel (1), German Shorthaired Pointer (1), and Portuguese Water Dog (1); there were also 4 mixed-breed dogs. There were 8 spayed females and 5 castrated males with a mean ± SD age of 6.2 ± 3.0 years (range, 2.0 to 13.0 years) and a mean body weight of 23.6 ± 6.1 kg (range, 14.4 to 35.2 kg). Median acclimation time until dogs consistently bore weight on the cast-

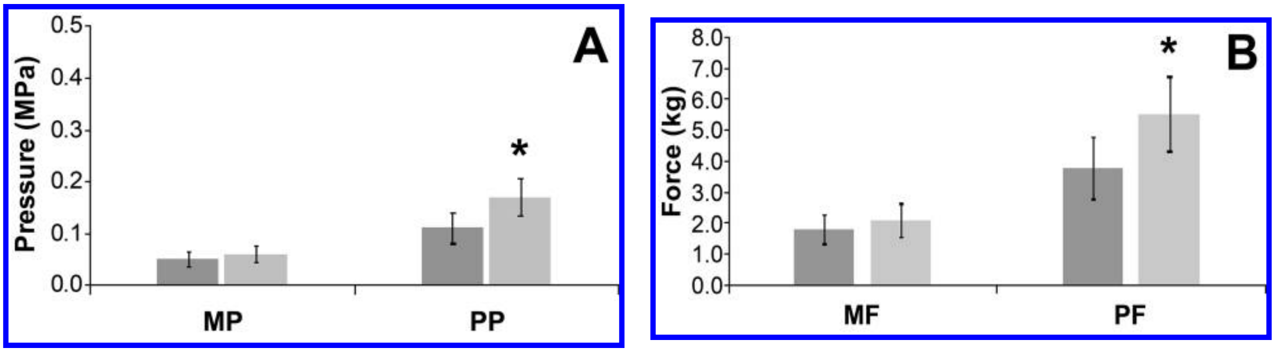

Figure 4—Mean and 95% confidence intervals for the MP and PP (A) and MF and PF (B) of a tall cast configuration (dark gray bars) and a short cast configuration (light gray bars) at the level of the calcaneus for 13 dogs. *Within a variable, the value for the short cast configuration differs significantly ($P \leq 0.05$) from the value for the tall cast configuration.

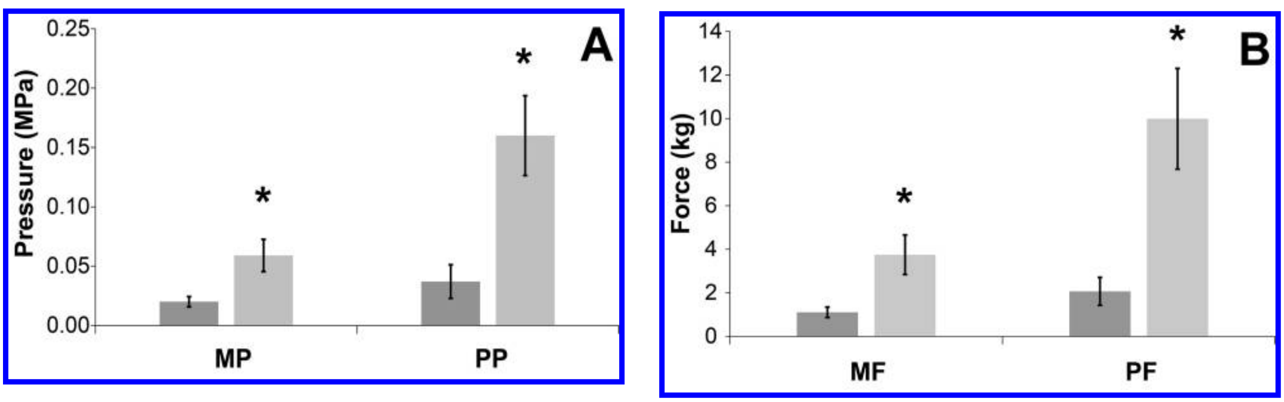

Figure 5—Mean and 95% confidence intervals for the MP and PP (A) and MF and PF (B) of a tall cast configuration (dark gray bars) and a short cast configuration (light gray bars) at the level of the proximal edge of each cast configuration for 13 dogs. ***See*** Figure 4 for remainder of key.

ed limb was 2 minutes (range, 0.5 to 4 minutes). None of the dogs required sedation for cast placement or changes. Use of the screen overlay to verify sensor locations before and after data acquisition subjectively confirmed that there was no substantial shifting of the sensors during the trials. Three trials for each dog and cast configuration were included in the data analyses; thus, there was a total of 78 trials (39 trials with the tall cast and 39 trials with the short cast).

Objective gait analysis

Gait velocity and maximum walkway pressure did not differ significantly among trials. Mean ± SD gait velocity (0.9 ± 0.2 m/s) was consistent and did not differ significantly ($P = 0.45$) between trials with short and tall cast configurations. Mean maximum walkway pressure across all trials was 0.2 ± 0.06 MPa and did not differ significantly ($P = 0.66$) between trials with a tall cast (0.2 ± 0.06 MPa) and trials with a short cast (0.2 ± 0.05 MPa). On the basis of these results, mean values of outputs for each dog were calculated across trials for each cast size and location of interest (proximal portion of the tibia, distal portion of the tibia, and calcaneus).

Pressure mapping

Results of pressure mapping for all pressure point locations of both cast lengths were analyzed. At the calcaneus **(Figure 4)**, PP and PF were both significantly ($P = 0.003$) greater with the short cast (mean ± SD, 0.2 ± 0.07 MPa) than the tall cast (0.1 ± 0.06 MPa). The MP and MF were also greater with the short cast than the tall cast; however, these values did not differ significantly ($P = 0.23$). At the level of the proximal portion of the tibia, PP ($P = 0.03$), MP ($P = 0.01$), PF ($P = 0.005$), and MF ($P = 0.001$) were significantly greater with the tall cast than the short cast (for which no part of the cast was covering the proximal portion of the tibia). Mean pressure at the proximal cranial edge of the cast was significantly greater with the short cast (mean ± SD, 0.2 ± 0.06 MPa) than the tall cast (0.04 ± 0.03 MPa).

Values for PP ($P = 0.01$), MP ($P = 0.003$), PF ($P = 0.01$), and MF ($P = 0.002$) at the distal portion of the tibia (a cast-covered area) were significantly lower for the tall cast than the short cast. Values for the PP, MP, PF, and MF at the proximal edges of each cast configuration (ie, proximal portion of the cranial tibial surface of the tall cast and distal portion of the cranial tibial surface of the short cast) were all significantly ($P < 0.001$) lower for the tall cast than the short cast **(Figure 5)**.

Discussion

In the study reported here, PP and PF at the calcaneus were significantly greater when the short cast configuration was used. This pattern was paralleled by MP and MF, but the results for these variables did not differ significantly. Mean values may not be as sensitive as peak values because the calcaneus is expected to be subjected to greater pressure while in a weight-bearing stance but to much less pressure during the swing phase of the gait. Therefore, calculating mean values for the entire gait cycle likely resulted in a lower overall difference in peak values. Because results obtained throughout the entire gait cycle were analyzed, the lack of significant differences for mean values at the level of the calcaneus was not surprising. It also appears more likely that PP would be responsible for the development of dermal sores, rather than the MP, which makes peak pressure the more important outcome measure. In contrast, mean values were significantly different when comparing the proximal and distal portions of the tibia, which may be explained by 2 factors. First, the comparison for the proximal portion of the tibia between rigid material (ie, proximal edge of the cast) or no rigid material (ie, short cast) likely created a greater overall difference even when mean values were evaluated throughout the gait cycle. Second, both pressure points on the tibia were located on the flexor surface of the joint and therefore may have been more likely to be subjected to constant pressure during the gait cycle.

Comparing the proximal edges of the tall and short casts (ie, proximal portion of the tibia for the tall cast and distal portion of the tibia for the short cast) revealed that pressures and forces created for the short cast configuration were significantly higher than those created for the tall cast configuration. Our data provided support that the concept of the 3-point corrective system can be applied to the canine pelvic limb. It is likely this concept would also apply to the thoracic limb and should be considered to reduce pressure points induced by external coaptation. Future studies should include measurement of both the proximal and distal CF simultaneously to further corroborate findings that are in support of the 3-point corrective system.

In addition to use of a tall or short cast, many other factors (eg, amount of cast padding) should be considered when attempting to reduce the incidence of pressure sores.[8] We recommend that all pertinent factors be taken into account to reduce the risk of pressure sores when choosing an external coaptation. Currently, early detection and intervention is the only definitive way to prevent pressure sores and other soft tissue injuries. This is accomplished by completely removing the cast and padding to enable direct examination of the limb.[4]

Each pressure mapping sensor was used to record data for only 2 dogs. This was in accordance with manufacturer recommendations to ensure the most accurate pressure mapping data were collected and to minimize the potential for loss of sensitivity over time. Different custom calibration algorithms and methods, as applied to these sensors, have been investigated, and it was found that correct calibration is important for obtaining accurate and reliable data.[19] For the purposes of the study reported here, we chose the point calibration method, as described by the manufacturer.[20] This method was chosen because of its simplicity; the study was focused on the comparison among data points, rather than the absolute values of the data points.

The use of live animals in a prospective clinical trial is associated with inherent variability. Medium-sized to large dogs were chosen to participate in the present study because it was observed during preliminary trials that smaller dogs (< 13.6 kg) ambulated poorly or not at all when a rigid cast was applied, which rendered the data acquisition trials invalid. This study did not include any chondrodystrophic, small, or toy-breed dogs because the body size or conformation was not conducive to the execution of the study protocol. Breed or body conformation certainly could have an impact on the relative pressure distribution within a cast. This was not assessed in the present study and is a limitation for the findings. Future studies should include a range of breeds, sizes, and body conformations to further elucidate how these factors impact forces inside a rigid cast.

We limited the total number of trials to a maximum of 5 to avoid fatiguing the dogs and to allow for more consistency among walks for the tall and short cast configurations. Starting and stopping the pressure recording manually as the dogs entered and left the walkway was another limitation and could have led to a timing discrepancy between the pressure walkway versus the pressure mapping sensors.

Another limitation of the present study was the lack of randomization of the treatment groups (order of tall cast vs short cast). However, evaluating the short cast configuration before evaluating the tall cast configuration would have required application of a completely new cast. The authors believed that reapplying the cast and the potential of sensor movement during such cast reapplication would have introduced a large number of variables because the application of a new cast may have changed the pressure points of the fiberglass. Evaluation of the tall cast before evaluation of the short cast allowed us to eliminate variation in cast design and minimize sensor movement (ie, the only modification was the height of the cast, and the underlying padding and sensors were not moved or altered between trials for the tall cast and short cast).

Finally, the sample size of the present study was small; however, significant and biologically relevant differences were detected. These findings were consistent with results reported for humans[21] and with the authors' clinical observations for dogs.

For the study reported here, a tall cast configuration created less pressure at the calcaneus than did a short cast configuration. In addition, a tall cast configuration created less pressure at the proximal cranial edge of the cast than did a short cast configuration. These findings suggested that application of a tall cast would be superior to application of a short cast in terms of reducing the amount of pressure at pressure points on the pelvic limbs of dogs. Results of the study provided new information on cast-related soft tissue injuries and may be useful to clinicians for the application of casts and splints.

Acknowledgments

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Footnotes

a. Zonas porous tape, 1-in, Johnson & Johnson, New Brunswick, NJ.
b. Tubegauz seamless tubular gauze, size No. 34, The Scholl Manufacturing Co Inc, Chicago, Ill.
c. Cast padding, 2 or 3 in, BSN Medical, Charlotte, NC.
d. Dermacea gauze roll, 2, 3, or 4 in, Covidien LLC, Mansfield, Mass.
e. Vetrap bandaging tape, 2 or 4 in, 3M, Maplewood, Minn.
f. Vetcast casting tape, 2 or 3 in, 3M, Maplewood, Minn.
g. JobMax 18-volt console multi-tool, Ridgid Inc, Newark, Del.
h. F-Socket medical sensor 9811E, TekScan Inc, South Boston, Mass.
i. F-Scan pressure measurement system, version 6.85-29, TekScan Inc, South Boston, Mass.
j. HRV walkway 6 VersaTek system, 23 in × 130 in, Tekscan Inc, South Boston, Mass.
k. Excel 2016, Microsoft Corp, Redmond, Wash.
l. IBM SPSS, IBM Corp, Armonk, NY.
m. Walkway research Beta, version 7.66-03, TekScan Inc, South Boston, Mass.

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