The role of negative intra-articular pressure in the maintenance of shoulder joint stability in dogs

B. K. Sidaway¹, R. M. McLaughlin², S. H. Elder³, C. R. Boyle³, E. B. Silverman²

¹Southwest Veterinary Surgery Service, Glendale, Arizona, USA
²Departments of Clinical Sciences and ³Basic Sciences, College of Veterinary Medicine; and the
³Department of Agricultural and Biological Engineering, College of Agriculture and Life Sciences, Mississippi State University, Mississippi State, MS, USA

Summary
The objective of this study was to evaluate the effect of negative intra-articular pressure on shoulder joint stability in canine cadavers. Cadaver forelimbs from 12 mature dogs were used. The forelimbs were placed in a testing frame and axially preloaded with 4 kg of weight. Shoulder joint stability was tested in flexion, extension, and neutral position before and after venting of the joint capsule. Humeral translation relative to the glenoid was induced by applying a 3 kg load in three different directions (cranial, lateral, and medial) and quantitatively measured by use of an electromagnetic motion tracking system. Peak translational data were compared in each joint position before and after venting of the joint capsule. After venting the shoulder joint capsule, a significant increase in translation was observed in the cranial direction with the joint in neutral position and in the medial direction with the joint in extension. The horizontal translations measured after venting of the joint capsule were likely not clinically relevant. Negative intra-articular pressure is not a major contributor to shoulder stability in dogs during weight-bearing.

Keywords
Shoulder joint, biomechanics, instability, intra-articular pressure, canine

Introduction
Shoulder stability in dogs is dependent on both active and passive stabilizing mechanisms. Primarily, the joint capsule and glenohumeral ligaments prevent excessive translation and rotation of the glenoid and humeral head (1, 2). In addition, the biceps tendon is an important passive stabilizer in several joint positions (1). Numerous other shoulder joint stabilizing mechanisms have been investigated by researchers in human orthopaedics, including the phenomenon of negative intra-articular pressure. In the normal shoulder joint, a slight negative intra-articular pressure is present and is created by the synovium as it removes free fluid via osmosis (3, 4). Several researchers have investigated the effects of this negative intra-articular pressure on the stability of the human shoulder joint (5–8). This negative pressure contributes to shoulder stability in all directions by adding a slight resistance to distraction when the humerus and scapula are separated. The amount of resistance is about 431 N/m² (3). Violation of the joint can negate this stabilizing effect because of the equilibration of the intra-articular pressure with atmospheric pressure. Venting of the joint capsule in human shoulders reduces the force necessary to displace the humeral head by an average of 50% (5). In veterinary literature, the authors know of only one study that has evaluated the role of negative intra-articular pressure as a stabilizer of the dog shoulder (9). In that study, negative intra-articular pressure did not appear to be a major contributor to shoulder stabilization. The goal of this study was to provide additional objective, biomechanical data regarding the effect of negative intra-articular pressure on shoulder stability in dogs.

Material and methods
Testing frame
The testing frame has been described and used in a previous biomechanical study of shoulder joint stability (1) (Figs. 1, 2). To summarize, the frame consisted of a foundation, a locking plate, a loading platform, and three horizontal loading bars. The locking plate anchors the antebrachium during mechanical testing. Four stainless steel vertical posts (height, 9.1 cm) were fixed to the corners of the foundation (25.4 cm apart). A 4 kg loading platform was positioned on the four posts and was used to axially load the shoulder joints once they were positioned in the frame. A braking device placed on one of the vertical posts prevented loading of the limbs during mounting of the specimens. A metal brace projected from the loading platform to rigidly fix the scapula during testing. The scapular brace allowed for easy angular adjustment of the shoulder joints. On three sides of the testing frame, adjustable loading bars were present that permitted loading of the proximal portion of the humerus in the cranial, lateral, and medial directions.

Data collection
An electromagnetic motion tracking system (Fastrak, Polhemus, Inc., Colchester, VT)
was used to measure three-dimensional movement (in centimeters) of the humeral head after application of a horizontal load to the proximal portion of the humerus. The source of the tracking system was permanently attached to the horizontal loading bar of the testing frame just cranial to the limb. The position of the transmitter was moved cranial to the limbs for this study). The 'set-up' of each limb in the testing frame was identical and has been described previously (1). Briefly, the scapula was secured to the scapular brace of the loading platform. The distal limb was secured to the locking plate and to the foundation which immobilized everything distal to the elbow. The sensor for the electromagnetic motion tracking system was then attached to the proximal portion of the humerus adjacent to the insertion of the supraspinatus tendon. A mediolateral hole (at the level of the midpoint of the deltoit tuberosity) was drilled through the proximal portion of the humerus. This hole allowed for horizontal loading of the humerus. A strand of 60 pound-test monofilament nylon leader material (Mason Hard Type Nylon, Mason Tackle Company, Otisville, MI) was threaded through the hole and 1 toggle rod (Toggle Rod, Securos, Inc., Charlton, MA) was tied to the nylon medial and lateral to the humerus. The toggle rods were tied two to three cm from the bone with approximately 10 to 15 cm of nylon remaining outside of the toggle rod. The free ends of the monofilament nylon on each side were tied, leaving a large loop that would accommodate the loading weights.

Before releasing the brake on the testing frame, the shoulder joints were positioned in the desired testing angle. The same observer (BKS) measured the shoulder joint angle twice with a goniometer to assure the correct joint position for each limb. The forelimbs were assigned to one of the following joint positions: extension (160°), flexion (70°), or neutral position (110°). With the limbs fully secured and correctly aligned, the shoulder joints were axially loaded by releasing the loading platform brake. After loading, the limbs were allowed to settle in position, for several moments, and were examined again to ensure normal limb alignment and joint angle prior to testing.

Specimen preparation and mounting

The right and left forelimbs of dogs without radiographic evidence of osteoarthritis were used for this study. The limbs were from dogs weighing between 15 and 26 kg. After procurement of the forelimbs, they were wrapped in saline (0.9% NaCl) soaked towels and stored at –10°C until the study date. The day prior to biomechanical testing, the limbs were thawed at room temperature (approx 21°C). All of the specimens were sprayed intermittently with physiologically normal saline solution during testing to maintain tissue hydration.

The three-dimensional starting point of each shoulder joint was first established on the basis of coordinates supplied by the electromagnetic motion tracking system. Three consecutive X, Y, Z coordinate readings were recorded with the electromagnetic motion tracking system and were averaged independently to establish the three-dimensional humeral head starting point (referred to as ‘starting coordinates’). All of the translational measurements were calculated from the starting point of each limb.

A 3 kg horizontal load was applied to the proximal portion of the humerus of each limb by the use of a ‘free weight’ to create translation of the humeral head in relation to the glenoid. This load is similar to that used to create horizontal translation of joints in previous studies (1, 10–12). The load was applied to each tested forelimb in the cranial, lateral, and medial directions in a randomized order. In order to create horizontal loading, weights were placed within the loop of nylon on the appropriate side of the

Biomechanical testing

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humerus, and the nylon was laid over the desired (cranial, lateral, or medial) loading bar on the testing frame. So as to ensure that loading occurred perpendicular to the anchor hole in the humerus, the loading bars on the frame were positioned at the level of the hole. During loading in the lateral and medial directions, engagement of the toggle rods with the cortex of the bone on the opposite side of the humerus created displacement of the humeral head. During loading in the cranial direction, both ends of the nylon were laid over the cranial loading bar and the nylon coursing through the humerus created displacement of the humeral head. The loading weights were gently hung over the loading bars and allowed to settle so that movement did not occur during collection of translational data.

Following horizontal loading, the humeral head was allowed to settle and a peak translation point, consisting of X, Y, Z coordinates, was recorded from the values generated by the electromagnetic motion tracking system and the system’s tracking software (Fastrak Graphical User Interface 1.0, Polhemus, Inc., Colchester, VT). Three consecutive loading trials were performed for each direction of loading. The humeral heads were unloaded between trials and allowed to return to a resting position. The peak translational data points were stored by use of commercial spreadsheet software (Microsoft Excel 2002, Microsoft Corporation, Bellevue, WA) for later analysis. The mean value of the three peak translational data points was used to determine the translation (in cm) of the humeral head following loading and compared with its starting position, as follows: 

\[
\text{vented peak coordinates (mean) – starting coordinates (mean)} = \text{translation after venting.}
\]

The translational (mean of three measurements for each direction) values in the cranial, lateral, and medial directions in the intact shoulder joints were then subtracted from those acquired from the shoulder joints following capsular venting (mean of three measurements for each direction) to calculate the difference in translation as follows: 

\[
\text{vented translation (mean) – intact translation (mean)} = \text{difference in translation between vented and intact joint.}
\]

Statistical analysis

Translation of the humerus in relation to the scapula was analyzed separately for each direction of loading (cranial, medial, and lateral) using mixed model analysis of variance (ANOVA) for a repeated measures design with one between-limb factor and one within-limb factor in a factorial arrangement. The between-limb factor was shoulder joint position (neutral, flexed, and extended); the within-limb factor was venting (before and after). The residuals from each ANOVA were examined using frequency histograms and normal probability plots; the normality assumption appeared to be adequately satisfied. ANOVA was performed using the SAS procedure MIXED (13). All statistical tests used the 0.05 level of significance. When significant effects were found, means were compared using the Least Significant Difference Test. The clinical importance of statistically significant differences was assessed using confidence intervals (14). All calculations were performed using SAS® Version 9.1 (SAS Version 9.1, SAS Institute, Inc., Cary, NC).

Results

Four limbs were tested in each limb position: neutral, flexion, and extension.

Neutral joint position

With the shoulder joints in neutral position and a 3 kg load applied in a cranial direction to the proximal portion of the humerus, mean translation of the humerus increased by 0.04 cm (CI, 0.002 to 0.078 cm) after venting of the joint (Table 1). This was statistically significant (P=0.04). When the proximal portion of the humerus was loaded in the lateral direction, mean translation increased by 0.01 cm (CI, −0.06 to 0.08 cm) after venting of the joint but this increase was not statistically significant (P=0.76). When the proximal portion of the humerus was loaded in the medial direction, mean translation increased by 0.03 cm (CI, −0.001 to 0.067 cm) after venting of the joint and this was not statistically significant (P=0.06).

Flexed joint position

With the shoulder joints in the flexed position and a 3 kg load applied in a cranial direction to the proximal portion of the humerus, mean translation of the humerus increased by 0.02 cm (CI, −0.02 to 0.05 cm) after venting of the joint. This increase was not statistically significant (P=0.40) (Table 1). When the proximal portion of the humerus was loaded in the lateral direction, there was no increase in translation (0.00 cm, CI, −0.07 to 0.08 cm) after venting of the joint (P=0.94). In addition, when the proximal portion of the humerus was loaded in the medial direction, there was also no increase in translation (0.00 cm, CI, −0.03 to 0.03 cm) after venting of the joint (P=1.0).
Extended joint position

With the shoulder joints in the extended position and a 3 kg load applied in a cranial direction to the proximal portion of the humerus, mean translation of the humerus increased by 0.03 cm (CI, –0.01 to 0.07 cm) after venting of the joint, which was not statistically significant (P=0.11) (Table 1). When the proximal portion of the humerus was loaded in the lateral direction, mean translation increased by 0.04 cm (CI, –0.03 to 0.11 cm) after venting of the joint, but this increase was not statistically significant (P=0.25). When the proximal portion of the humerus was loaded in the medial direction, mean translation increased by 0.04 cm (CI, 0.01 to 0.08 cm) after venting of the joint. This was statistically significant (P=0.02).

Discussion

In the normal shoulder joint, there is only a small amount of free fluid present (3). The synovium normally removes free fluid from the joint via osmosis, creating a slightly negative pressure within the joint (3). In human shoulders, this negative intra-articular pressure holds the joint together with a force proportional to the joint surface area and the magnitude of the negative intra-articular pressure (3). Progressive distraction of the joint surfaces in the sealed joint lowers the intra-articular pressure even more which increases resistance to distraction (3).

The results of this study indicate that the negative intra-articular pressure present in the shoulder joints of dogs does contribute slightly to stability of the joint. However, the stability afforded by this mechanism is likely to be clinically insignificant in the joint positions and directions that we tested. We found that venting the joint capsule lead to an increase in translation in the cranial direction with the joint in neutral position and the medial direction with the joint in extension. Although it is unknown as to what magnitude of translation of the humeral head is abnormal or harmful to the shoulder joint of a live dog, we feel that the translational differences seen in this study would not be detrimental. The translational differences that we witnessed were negligible and substantially smaller than those of a previous study (1). In most cases the differences identified between the intact and vented joints in this study were only tenths of millimeters and two of the loading scenarios did not increase at all after venting. We feel that the amount of micromotion seen in this study would easily be counteracted or stabilized by the active shoulder stabilizing mechanisms, such as proprioception and muscle contraction.

Although our testing model varied slightly from those used to evaluate negative intra-articular pressure in human shoulders, our results differed from those studies. In humans, negative intra-articular pressure is a considerable factor in the maintenance of shoulder stability. In particular, it helps to prevent inferior displacement and keep the humeral head positioned in the center of the glenoid. Kumar and Balasubramaniam identified marked inferior subluxation of the humeral head, after puncture of the joint capsule, irrespective of the puncture location and integrity of the overlying periarticular muscles (6). They concluded that the negative pressure was one of the main static stabilizers of the joint. Later, Gibb et al. evaluated the effect of venting the joint on shoulder laxity using a translational model similar to the one used in this study (5). The force necessary to displace the humeral head was decreased after venting of the capsule by an average of 55% in the anterior direction, 43% in the posterior direction, and 57% in the inferior direction (5). Itoi et al. conducted an investigation and had similar findings (8). This study showed that the position of the humeral head was significantly lowered in all loading directions after capsular venting (8).

The most obvious explanation for the discrepancy between our results and those in human research is the difference in function of the two species’ forelimbs. The distraction resistance provided by negative intra-articular pressure is more valuable in the human upperlimb because of its hanging position, whereas joint compression is probably more important in the dog’s forelimb. In fact, when negative intra-articular pressure has been evaluated in the human shoulder, researchers have used hanging limbs which lead to the aforementioned

### Table 1

<table>
<thead>
<tr>
<th>Position and translation</th>
<th>Before and after venting of shoulder joint</th>
<th>Difference</th>
<th>P value†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact</td>
<td>Vented</td>
<td></td>
</tr>
<tr>
<td>Neutral</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CT (cm)</td>
<td>0.12 ± 0.02</td>
<td>0.16 ± 0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>LT (cm)</td>
<td>0.26 ± 0.05</td>
<td>0.27 ± 0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>MT (cm)</td>
<td>0.22 ± 0.05</td>
<td>0.25 ± 0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Fluid</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CT (cm)</td>
<td>0.02 ± 0.02</td>
<td>0.04 ± 0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>LT (cm)</td>
<td>0.18 ± 0.05</td>
<td>0.18 ± 0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>MT (cm)</td>
<td>0.20 ± 0.05</td>
<td>0.20 ± 0.05</td>
<td>0.00</td>
</tr>
<tr>
<td>Extended</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CT (cm)</td>
<td>0.06 ± 0.02</td>
<td>0.09 ± 0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>LT (cm)</td>
<td>0.10 ± 0.05</td>
<td>0.14 ± 0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>MT (cm)</td>
<td>0.11 ± 0.05</td>
<td>0.15 ± 0.05</td>
<td>0.04</td>
</tr>
</tbody>
</table>

*Standard error of the least squares mean as determined on the basis of a pooled estimate of variation from an ANOVA. †Values of P < 0.05 were considered significant.

CT = Cranial translation, LT = Lateral translation, MT = Medial translation.
conclusions. In most cases, once the joint was penetrated with a hypodermic needle, the arm dropped inferiorly. In order to make our experimental model more appropriate and to mimic the normal weight-bearing nature of the canine forelimb, we axially loaded the limbs and created compression through the shoulder joints. In this situation, the effects of negative intra-articular pressure appear to be less important, whereas the effects of compression across the joint seem to be more significant. Therefore, we conclude that negative intra-articular pressure is merely an ancillary stabilizing mechanism in dogs, particularly during weight-bearing. However, this mechanism may be more important in other joint positions, loading directions, or at other points of the gait cycle.

One limitation of the study reported herein was that the intra-articular pressure was not quantified before and after venting. Intra-articular pressure was measured in some, but not all, of the human studies evaluating negative intra-articular pressure’s effect on shoulder stability. We relied upon the audible sound of air rushing into the joint to confirm the presence of negative intra-articular pressure and the cessation of the sound to tell us that the pressure had equalized. A second limitation was the uniform axial preload placed on all the limbs. A 4 kg axial preload was chosen to approximate the load that a 15 kg dog would place on one of its forelimbs (30% of the total body weight) (15). The preload was the same for all limbs, despite small variations in size and conformation. However, since the limb size variation and the translational measurements in the joints were small, the impact on the results was likely minimal.

The results of this study indicate that the negative intra-articular pressure present in canine shoulder contributes little to the stabilization of the axially loaded joint. The increases in linear distance, seen in this study, were very small and would likely not lead to negative effects within the joint. In addition, the contribution of the periarticular muscles and other soft tissues in a live dog would probably negate, or limit, the small translations that we witnessed in this experimental model. It seems apparent that the negative intra-articular pressure within the dog’s shoulder, has less effect on shoulder stability due to the significant compression across the joint from weight bearing. However, the phenomenon of negative intra-articular pressure may be important in joint scenarios not tested in this study.

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References

Correspondence to:
Brian K. Sidaway, DVM, MS, DACVS
Southwest Veterinary Surgery Service
6677 W. Thunderbird Road, Building L-188
Glendale, AZ, 85306, USA
Phone: +1 623 298 5354, Fax: +1 623 298 5363
E-mail: bsidaway@swvets.com

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