The Effect of the Lateral Collateral Ligament on Coronoid Process Loading in Dogs: An Ex Vivo Study

By
Linda M. Yang

A PROJECT

Submitted to
Oregon State University
University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Zoology
(Honors Scholar)

Presented February 22, 2016
Commencement June 2016
AN ABSTRACT OF THE THESIS OF

Linda M. Yang for the degree of Honors Baccalaureate of Science in Zoology presented on February 22, 2016. Title: The Effect of the Lateral Collateral Ligament on Coronoid Process Loading in Dogs: An Ex Vivo Study.

Abstract approved:

________________________________________
Wendy Baltzer

Large canine breeds are commonly diagnosed with a type of elbow disease called fragmented medial coronoid process (FMCP). FMCP occurs when the cartilage and bone of the coronoid process, located on the ulna, is fractured. Etiologies include mechanical overload of the ulna and incongruences of the radius and ulna with the humerus. 18 canine cadaver forelimbs were subjected to a vertical load of 200N in seven different conditions: intact, humeral radial ligament cut, humeral ulnar ligament cut, no ligaments, prosthetic humeral radial ligament, prosthetic humeral ulnar ligament, and both prosthetic ligaments. Pressure sensors in the elbow joint were used to record the contact area, contact pressure, and peak contact pressure. Results indicated a significant difference between whether lateral collateral ligaments were kept intact and when ligaments were removed, demonstrating their importance in stability of the elbow joint. Subsequent replacement of the LCL ligament with a prosthetic one consisting of suture and bone screws resulted in significant changes in the peak contact pressure and contact area of the ulna. The use of prosthetic ligaments was effective in restoring stability in the elbow and may be used as an alternative treatment option for young and adult dogs vulnerable to FMCP.

Keywords: fragmented medial coronoid process, lateral collateral ligament, canine, orthopaedics
Corresponding e-mail address: yanglin@oregonstate.edu
The Effect of the Lateral Collateral Ligament on Coronoid Process Loading in Dogs: An Ex Vivo Study

By
Linda M. Yang

A PROJECT

Submitted to
Oregon State University
University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Zoology
(Honors Scholar)

Presented February 22, 2016
Commencement June 2016
Honors Baccalaureate of Science in Zoology project of Linda M. Yang presented on February 22, 2016.

APPROVED:

Wendy Baltzer, Mentor, representing Clinical Sciences

Luiz Bermudez, Committee Member, representing Biomedical Sciences

Jennifer Warnock, Committee Member, representing Clinical Sciences

Toni Doolen, Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Linda M. Yang, Author
Acknowledgements

I would like to personally thank the following people for their involvement during my honors thesis process:

To my mentor, Dr. Wendy Baltzer, for allowing me to use this project for my honors thesis and your mentorship throughout the thesis project. I appreciate the valuable experience you’ve given me by giving me the opportunity to work with you. The valuable skills I have learned during this adventure will be useful for the years to come in my future career.

To Dr. Jennifer Warnock and Dr. Luiz Bermudez for their time and their involvement in the project as committee members.

To my parents, Jane and Ken Yang, for their support during the many years of my education and their continuing support for the years to come.

To my sisters, Jessica and Jamie Yang, for lending a sympathetic ear when times got rough and for dealing with my overwhelmed self for all this time. The advice and support you two have provided for me helped me persevere through those challenges.

To my academic advisor in the Integrated Biology Department, Jen Olarra, and the academic advisors of the University Honors College, for their guidance during my undergraduate career.

Finally, I’d like to thank the members and mentors of the Pre-Veterinary Scholars in also providing support during my thesis process as my friends and colleagues. I am especially grateful for the Pre-Veterinary Scholars program that made opportunities like this possible for undergraduates pursing a career in veterinary medicine.
Table of Contents

Introduction ....................................................................................................................... 1

Materials and Methods .................................................................................................... 5
  Biomechanical Testing ..................................................................................................... 6
  Statistical Analysis .......................................................................................................... 7

Results .............................................................................................................................. 8

Discussion ......................................................................................................................... 12

Literature Cited .................................................................................................................. 19
**Introduction:**

Canine elbow dysplasia is an osteopathic developmental disease commonly found in large or giant canine breeds like the Bernese Mountain Dog, the Golden Retriever, or the Bull Mastiff. The three bones that make up the elbow joint are the radius, ulna, and humerus. Three joints comprise the elbow joint called the humeral radial, humeral ulnar, and radioulnar joints. The humeral radial joint, made up of the humeral condyle and the head of the radius, supports 57% of the weight that transverses through the elbow with the humeral ulnar joint supporting about 43%, indicating that the ulnar has a significant supporting role in the integrity of the joint (1,2). The size and surface features of the contact area between the three bones determine the magnitude and direction of the proximate articular forces that occur within the joint, which includes the compression and shear forces on the cartilage. The ground reaction force that occurs when the dog is running or walking is a major contributor to the forces that transmits through the elbow joint (2).

Canine elbow dysplasia manifests in one or more of the following abnormalities of the elbow joint: ununited anconeal process (UAP), fractured medial coronoid process (FMCP), or osteochondrosis. The medial coronoid process is located on the trochlear notch of the ulnar, where it interacts with the radius and articulates with the humeral condyle (1). Because of the dog’s large size, the asynchronous growth of the radius and ulna may subject the elbow joint to abnormal pressures and lead to elbow dysplasia and osteoarthritis. Lameness and pain develop in most dogs with elbow dysplasia, before one year of age. FMCP occurs when the cartilage and subchondral bone of the axial portion of the medial coronoid process, located on the ulna, is fractured (3).

The direct cause of FMCP is poorly understood, but multiple etiologies have been linked to FMCP that includes mechanical overload, genetics, and nutrition (4,5). Regardless, fragmentation is most likely to occur where the articular surface is exposed to high loads such as the medial coronoid process through which a substantial amount of loading occurs during weight-bearing stances (6). Applied loads that transverse through the elbow have a linear relationship to the transarticular forces that occur within the joint, and excessive force due to overloading has been correlated with the failure of the coronoid process in the elbow (2). Because of the dog’s large size, the weigh bearing
positions or tension from the annular ligaments may increase the load on the medial humeral condyle on the radius and ulna, causing the coronoid process to fragment or fracture (6). Another possible etiology for FMCP is related to incongruity in the joint between the three bones. Examples of elbow incongruity include unequal growth of the radius and ulna, an elliptical formation of the trochlear notch of the ulna (rather than circular), and a mismatch between the soft tissue, bone, and cartilage of the joint. Improper development of these bones can change the weight-bearing load within the coronoid or cause micro damage during movement that eventually leads to a fracture (1,6).

The diagnosis of FMCP is formed by a physical examination and imaging of the elbow joint. An evaluation for lameness identifies forelimb abnormalities in the dog’s walking and trotting. Abnormalities that may be observed are short strides and abduction of the elbow and carpus while standing. Other clinical signs include difficulty rising and lying down and increasing lameness after exercise or trauma (3,7). Radiographic signs of FMCP include a loss of detail in the region of the coronoid process, secondary osteoarthritic changes in the elbow, sclerosis of the trochlear notch, and periosteal proliferation of the upper aspects of the radius and ulna (7,8). Conformation of the diagnosis of FMCP is difficult with radiographs of the elbow since a clear view of the medial coronoid is often not possible. Computed tomography (CT) scan is the gold standard for diagnosis of FMCP, because it has the highest accuracy, sensitivity and negative-predictive value of diagnosing the disease compared to radiograph films, xeroradiography, linear tomography and arthrography (9). In comparison of radiographic, CT, necropsy, and micro-computed tomography findings on Labrador retrievers, results indicated that CT scans were able to detect lesions as early as 14 weeks and that a CT was about 30% more sensitive to detecting early medial coronoid disease compared to radiographs. The findings in this study concluded that a CT should be used when investigating early stages of medial coronoid disease (10).

Once FMCP has been diagnosed, FMCP can be treated with medical therapy or surgery. Medical therapy may include weight management, activity restriction, and treatment of both pain and osteoarthritis for the rest of the dog’s life (3,5). Arthroscopy and arthrotomy are two surgical procedures used to treat FMCP. Arthroscopy is a
minimally invasive procedure to assess the medial coronoid process and remove any bone fragments or large osteophytes from the joint to temporarily relieve lameness. Medical therapy is recommended postoperatively for surgical patients for long-term management of the disease, because surgery does not cure FMCP and elbow dysplasia (3,7). Canines who have FMCP over a long period of time develop secondary arthritis that eventually cripples the dog (8).

Multiple studies have been conducted to explore possible etiologies of FMCP and other elbow abnormalities found in elbow dysplasia. Hulse et. al. studied the relationship between the contraction of the biceps muscle and the medial coronoid process. They concluded that the force exerted by the bicep stabilized the elbow joint and compressed the medial coronoid process against the radial head, making it susceptible to microdamage (11). Danielson et. al. also looked into the relationship of FMCP and microfractures in its pathogenesis. Their findings suggested that fatigue from microdamage correlated with progression of the disease and there was a decrease in osteocyte density and a greater percentage of porosity than bone from normal dogs (8). Age was also a factor that was explored in its correlation with medial coronoid disease. The study found that medial compartment erosions were found exclusively in the “old” dogs (six years of age or older) while erosions were found in limited areas of the medial canal in “young” dogs (7). The hereditability of fragmented coronoid process has been investigated in Dutch Labradors, Golden Retrievers and Bernese Mountain Dogs. The heritability index was high enough to suggest removal of dogs with FMCP might lead to reduced incidence of the disease in the population, but that the disease has multiple environmental factors that influence the phenotype and thus make removal of subclinically affected dogs difficult (12). These studies support the hypothesis that FMCP is a multifactorial disease associated with age and mechanical overloading, and that the supporting structures of the joint may contribute significantly to the stability of the joint.

We hypothesized that the collateral ligaments are important stabilizing structures in the elbow joint and may play a role in prevention of overloading the ulna that leads to FMCP. The lateral collateral ligament (LCL) is an important stabilizer in rotation of the elbow joint and a change in the stability of the collateral ligaments significantly affects the stability of the elbow joint (13,14). In the standing position, one study determined that
the LCL was the primary stabilizer in supination of the elbow joint. Removal of the LCL decreases the amount of resistance to torque in the elbow that may lead to force redistribution within the joint (13). Because of the role of the collateral ligaments in elbow stability, studies have also been conducted to demonstrate the affects of prosthetic ligaments and compare them to intact ligaments. In humans, studies show that suture reconstruction of both collateral ligaments restores elbow stability in patients with a coronoid fracture and elbow displacement (15). Single strand suture reconstruction of the LCL in humans even restores elbow stability to resemble an intact state (16). The collateral ligaments, primarily the lateral collateral ligament, are essential to the stability of the elbow and the repair of a disrupted ligament can restore stability to prevent future elbow disease.

The objective of this study was to evaluate the lateral collateral ligament and observe its role in the elbow joint during simulated weight bearing and to compare the loads sustained by the radius and ulna with the collateral ligaments intact or with prosthetic ligament reconstruction. The lateral collateral ligament serves as one of the support structures in the elbow joint that prevents abduction and internal rotation (1). Laxity of these support structures may cause the increased pressure on the ulnar portion of the elbow joint, subjecting it to excessive mechanical load that leads to fracture. We hypothesized that the removal of the collateral ligaments will increase the load on the coronoid process, by allowing the humerus to rotate and shift medially. By replacing the LCL with prosthetic ligaments, we hypothesized that the load placed on the medial coronoid process of the ulna would be reduced when the limb is in a weight-bearing stance with 200N of pressure.
Materials and Methods

A total of eighteen canine cadaver forelimbs (33kg +/- 7kg) three right and fourteen left front forelimbs were used in this study from a variety of large dog breeds who died or were euthanized for reasons unrelated to this study. The forelimbs were harvested, wrapped in saline (0.9% NaCl) soaked sponges in plastic bags and stored in a freezer at -20 °C until thawed at room temperature the day of testing. After thawing, the forelimb was patted dry and the soft tissue structures as well as the scapula were removed to the distal metaphysis of the humerus. The soft tissues around the elbow, origins of the antebrachial muscles, and the medial and lateral collateral ligaments were left intact. In order to place the load sensors within the joint, the extensor carpi radialis and common digital extensors were removed as well as the anconeus olecranon ligament and caudal joint capsule in the caudomedial and caudolateral aspects of the joint.

A 2.5 mm hole was drilled into the humeral epicondyle from medial to lateral and tapped using a 3.5 mm bone tap. Using an oscillating bone saw, a medial epicondylar osteotomy was performed and the joint inspected for any grossly detectible abnormalities. Any limbs with articular cartilage abnormalities or evidence of pathology were excluded from the study. The I-scan sensors (custom made, Model 4041, Tekscan Inc., Boston, MA) were placed with each sensor centered over the medial ulnar coronoid and the radial head respectively. The medial epicondyle was anatomically aligned to its original position and a 3.5mm screw (SYNTHES® Vet, Monument, CO) used to secure it in place (while another researcher held the sensors in place). An 8.0 mm hole was drilled into the proximal diaphysis of the humerus in a caudal to cranial direction, then a 7.0 mm hook (EVERBILT, Homer TLC Inc., Willmington, DE) was passed through the hole and the hook secured caudally with a hex nut on the cranial aspect of the bone. A 5.5 mm drill bit was used to drill a hole through the olecranon from proximal to distal and an eye-hook 3/8 in size (EVERBILT, Homer TLC Inc., Willmington, DE) passed through the hole from proximal to distal, then secured with a hex nut. A turnbuckle (EVERBILT, Homer TLC Inc., Willmington, DE) was attached to the two pieces of hardware to connect the proximal humerus to the olecranon. The turnbuckle was tightened or loosened to place the elbow at 135 +/- 5 degrees to mimic the action of the triceps muscle to maintain the
limb in a position corresponding to the mean flexion angle of the limb in the stance phase of trotting and walking mixed breed dogs (13). 

**Biomechanical Testing**

During testing, the cadaver limbs were kept moist using a 0.9% saline solution. Tekscan sensors must be calibrated by procedures listed by the manufacturer before testing. Limbs were loaded onto the materials testing machine (Instron Compression Testing Device model 4444, Instron®, Canton, MA) by placing the head of the humerus into a plastic cup proximally and by placing the paw on the loading platform distally. The loading platform was covered in coarse sandpaper (Diablo Tools, High Point, NC) to prevent slipping. A static axial load was applied of 200N to imitate the peak vertical ground reaction force exerted during walking (17). Following maintenance of this force for 5 seconds the contact area and pressure mapping data was recorded, and this measurement was repeated two times. Each specimen was tested for six different conditions: intact ligaments, lateral humeral radial crus or humeral ulnar crus ligament intact, no LCL, prosthetic lateral humeral radial ligament, prosthetic lateral humeral ulnar ligament, and complete LCL prosthetic ligament. Following loading the limb with the LCL intact, either the radial crus or ulnar crus was transected (randomly assigned) with the limb remaining on the materials testing machine, but with only a load of <5 N placed upon the limb. Following measurement, the other crus was cut and the limb loaded again. To place a prosthetic ligament, holes were drilled at the origin of the LCL on the humerus and insertion of each crus on the proximal radius and ulna using a 2.0mm drill bit. Each hole was tapped with a 2.7 mm tap, then one 2x7mm 20mm screw and 7.0mm washer (SYNTHES® Vet, Monument, CO) screwed into each of the three holes. A #2 braided nylon suture (Ethibond Excel, Ethicon Inc., Sommerville, NJ) was used in a figure 8 pattern to create each prosthetic crus of the ligament. Either the humeral ulnar or humeral radial crus prosthetic was placed first and the limb loaded, then both crus were placed and the limb tested, finally the first crus that was placed was removed and the limb loaded again.

A Tekscan iscan program (Tekscan Inc., Boston, MA) was used to map the pressures within the elbow joint detected by the sensors and record the instantaneous
contact pressure, contact area, and peak contact pressure for each trial. The custom two-armed sensor consisted of plastic laminated film 0.1 mm in thickness with each sensing pad 31 Å~ 12 mm in size and capable of 0.01 MPa sensitivity and a measurement range of 0.5–30 MPa. The electronic sensors were connected to a sensor handle and a computer with data acquisition and analysis software. Calibration and conditioning was performed on each new sensor prior to use in any specimen.

**Statistical Analysis**

Statistics for our results used Prism software to perform a one-way ANOVA analysis and Friedman test of the contact area, contact pressure, and peak contact pressure of both the radius and the ulna. A Dunn’s multiple comparison test was applied to the data to compare contact area, contact pressure, and peak contact pressure in the ulna and the radius for intact, radial or humeral crus transected, prosthetic conditions, and no ligament condition with one another. Statistical significance of the analysis was determined of tests or comparisons with a p value of ≤ 0.05.
Results

A total of 18 canine forelimbs were used in this study for data analysis. Forelimbs were excluded from the data analysis due to over saturation of the sensors during one or more of the testing conditions, or there was a presence of elbow disease that was detected while preparing the specimen for experimentation. The intact condition of the specimen was used as a control for comparison with the other testing conditions used in the experiment.

Significant difference was found in the mean contact area in the ulna ($p < 0.0001$), but not in the radius ($p = 0.11$). Table 1 and figure 1 reflects this by showing the increase in contact area for the ulna between intact condition and removal of one or both of the ligaments while the radial component had little to no change. Peak contact pressure of the ulna and radius were also significant with $p$-values of 0.0077 and 0.0001 respectively (fig. 1). In the Dunn’s multiple comparison test of the peak contact pressure of the radius, intact versus no ligament, intact versus prosthetic humeral ulnar ligament, and intact versus prosthetic humeral radial conditions were significant. In the same test with the peak contact pressure of the ulna, no ligament versus both prosthetic ligament conditions were significant. This comparison was also significant for contact area in the ulna. Intact versus prosthetic humeral ulna ligament, intact versus both prosthetic ligaments, no ligaments versus prosthetic humeral ulna ligament were all significant in the Dunn’s multiple comparison test for contact area in the ulna.

Little change was observed when the condition of the ligaments were intact, when either ligament was cut, when no ligaments were intact, and when prosthetics were used for the contact pressure in either the ulna or the radius (fig. 2). The values of the contact pressure in all conditions stayed in the same range of 2.50 to 2.80 mPa (table 1). In peak contact pressure, figure 3 demonstrates the change in peak contact pressure as it increases in the ulna and decreases in the radius when ligaments are cut and how the pressure returns to similar values of the intact condition when prosthetic ligaments in place. The peak contact pressure increases more on the ulna portion of the elbow joint, while the radial portion decreases, leading to the peak contact pressure of a 200N load approximately equal to the radius and ulna when no ligaments were present in the elbow joint whereas in the intact state the radius had a higher peak contact pressure compared to
the ulna. Peak contact pressures in the joint when both ligaments are intact and when the humeral radial, and humeral ulnar ligaments were cut return to approximately similar values with the use of prosthetic ligaments (table 1, fig. 3).

<table>
<thead>
<tr>
<th>Contact Area (sq. mm)</th>
<th>Radial</th>
<th>Ulnar</th>
<th>Radial</th>
<th>Ulnar</th>
<th>Radial</th>
<th>Ulnar</th>
<th>Radial</th>
<th>Ulnar</th>
<th>Radial</th>
<th>Ulnar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intact</td>
<td>HU</td>
<td>HR</td>
<td>Both</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ligament</td>
<td>Ligament</td>
<td>Prosthetic</td>
<td>Prosthetic</td>
<td>Prosthetic</td>
<td>Prosthetic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact Area (sq. mm)</td>
<td></td>
<td>Intact</td>
<td>Intact</td>
<td>No Ligaments</td>
<td>Prosthetic Ligament</td>
<td>Prosthetic Ligament</td>
<td>Both Prosthetic Ligaments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ulnar</td>
<td>91.674 ± 37.47</td>
<td>92.080 ± 37.753</td>
<td>98.474 ± 26.875</td>
<td>97.068 ± 35.630</td>
<td>85.186 ± 37.622</td>
<td>90.659 ± 36.842</td>
<td>85.250 ± 37.948</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: The mean +/- standard deviation (n= 18) of contact area, contact pressure, and peak contact pressure in each of the loading conditions. The asterisk indicates the changes throughout the different loading conditions with statistical significance for the measured component of the joint condition.
Figure 1: The mean +/- standard deviation (n= 18) of radial and ulnar contact area in each loading condition. Statistical significance is indicated in the ulna by the asterisk where an increase in contact area occurred as the ligaments were removed, then decreased when prosthetic ligaments were used.

Figure 2: The mean +/- standard deviation (n = 18) of radial and ulnar contact pressure in each loading condition. None of the parameters were statistically significant in any of the tests as contact pressure was relatively constant as loading conditions changed.
**Figure 3:** The mean +/- standard deviation (n = 18) of radial and ulnar peak contact pressure. The asterisk indicates statistical significance in both the radius and the ulna where a lateral shift produced a decrease in the peak contact area in the radius and an increase in the ulna as ligaments were removed and was restored by prosthetic ligaments.
Discussion

Our results demonstrate the significant lateral shift of the vertical load towards the ulna when one or both crus of the lateral collateral ligament of the elbow joint are removed compared to the intact condition, and that the use of prosthetic ligaments is effective in restoring elbow joint loading but can even alter it and increase load on the radius. In both figure 3 and table 1, the significant difference found in the peak contact pressure in the radius and the ulna (p-value of 0.0077 and 0.0001) indicates that there is a difference between intact, prosthetic ligaments, and the absence of LCL in the elbow joint. The increase in peak pressure on the ulna may be a cause of medial coronoid fragmentation and failure.

The mechanism by which fragmentation and bone failure occurs may be due, in some cases at least, to overloading of the medial compartment of the elbow (6). The LCL crus are important structures that contribute to the stability of the elbow and results of this ex vivo study indicates that they may also protect the medial compartment of the elbow from excessive forces or chronically increased loads (14). A shift in loading from the radius to the ulna by incongruency, increases the mechanical loading of the medial compartment of the elbow and decreases the axial compression strength of the medial coronoid process by four-fold (18). Under normal loading conditions, the ulna is subjected to a vertical load proportional to the radius and distributed evenly over the medial compartment in a ratio of 51 to 49 laterally to medially (17). Chronic overloading and subchondral fatigue microdamage are reported in dogs suffering FMCP disease (8). If the weight-bearing axis is shifted medially in the elbow of dogs affected with FMCP, even mildly over time, the result may be chronic abnormal wear, subchondral microfracture, and eventual failure of the medial coronoid process. As dogs age, increasing bone density develops at the medial coronoid process and central axis of the humeral trochlea indicating the corresponding joint surfaces are under continuous load and, over time, the bone responds to the load with increasing density (19). In young dogs less than one year of age treated with fragmented coronoid removal with or without ulnar osteotomy or ostectomy, an increase in subchondral bone density and a decrease in joint space width (presumably articular cartilage thickness) in the medial compartment occurs in the first 6 months following surgery (20). Coronoid fragment removal and ulnar
ostectomy have been recommended as treatment modalities to reduce joint incongruency and restore normal joint loading biomechanics, however some studies have not shown these methods to be successful and long term osteoarthritis and subchondral bone sclerosis with medial compartment articular cartilage loss continues to occur resulting in end stage elbow disease (20-22). Recent investigations investigating incongruity of the elbow joint have shown that with greater than 2 mm incongruity between the radial head and ulna, an ulnar osteotomy can reduce the load placed upon the medial coronoid and that, in dogs with an increased incongruity (>2mm) at least, there is advanced and more severe osteoarthritis. Labrador retriever puppies with FMCP lesions had no evidence of incongruency at 15 weeks of age; however, one puppy with no coronoid lesion had a 1.5mm step (10). This study and other reports suggest that there may be more than one etiology for elbow dysplasia, indeed 40% of joints with FMCP in one study were found to be congruent (23).

Contact area may also be a factor in increasing forces on the ulna. Without the LCL, there was a significant change in contact area for the ulna, indicating that the increase in contact area depicted in table 1 and figure 1 may correlate with an increase in peak contact pressure when the LCL ligament is cut. A decrease in radial contact and an increase in ulnar contact can create incongruity in the elbow that may lead to medial compartment overloading (24). Narrowing of the joint space in the lateral portion of the elbow also may also suggest chronic overloading and reduced cartilage thickness has been identified in the medial compartment of dogs with FMCP (20). As the contact area shifts more towards the ulna during loading as in the study reported here, overloading of the medial coronoid process may result in fracture in clinical cases of FMCP because a majority of the loading pressure will be on the medial coronoid process rather than more equally between the radius and ulna (2,19). Since there was no significant change in contact area in the radius, the LCL may have less of a role in providing support for the radius than for the ulna. Previously, the LCL has been found to prevent dislocation of the elbow joint, as poor condition of the collateral ligaments could increase the amount of relaxations during pronation and supination of the limb (13,14).

Incongruence as a cause of FMCP is supported by the findings in this study and may be another cause of FMCP clinically in dogs. Incongruity of the elbow has been
suggested as a possible cause of FMCP due to altered loading through the joint and subsequent cartilage degeneration. Studies comparing the joint dynamics of both dysplastic dogs and normal dogs investigated incongruency as a cause of elbow dysplasia (17,23,25,26). The 3D in vivo kinematic pattern of elbow motion and loading in dogs with and without FMCP was similar to the results of this study in that there is a medial shift in contact with excessive lateral joint widening (reduction in contact) and increased internal rotational motion in the dysplastic elbow (25). Increased internal rotation and increasing the contact pressure towards the medial compartment of the elbow is likely, although the ex vivo study reported here and previous studies have not specifically documented rotational instability as a component of medial compartment disease (17). In a previous ex vivo study, 15 degrees of internal rotation also produced a lateral shift in contact mechanics (27). Limb alignment affects the weight-bearing load through the joint and specifically through the radius and ulna. A lateral shift of the mechanical axis may occur in some dogs with clinical signs of FMCP in order to try to unload the medial compartment of the elbow when weight bearing. Some dogs with lameness due to FMCP will laterally shift their paw and rotate the elbow joint internally to relieve the mechanical load on the medial coronoid process (28).

Not all reports suggest that incongruence is the major cause of FMCP. Incongruence was only found in 40% of the elbows with FMCP in one study and the authors suggested that a small amount of incongruence in the elbow may advance the disease later in the dog’s life (23). Another possibility is that some dogs have incongruency as the cause of FMCP while others have ligament laxity as a cause. In a significant amount of dogs with FMCP, incongruence was not present at the time of diagnosis of the disease (29). Incongruency between the radius and ulna may not be the only cause of elbow pathology and the findings reported here support the idea that elbow dysplasia may be multifactorial. Transient incongruence may also occur with the initial presence of unbalanced growth and length discrepancy in the ulna and radius, however, later during development, the radius and ulna may grow to reduce incongruence, leaving signs of joint surface articulation incongruence but not bone length discrepancy (30). Surface incongruence between the radius, ulna, and humerus suggests dynamic incongruence may be the cause of cartilage degeneration of the elbow because
incongruence may occur at certain positions of the elbow (29). Surface incongruence of
the joint contributes to load distribution in the elbow joint. Our study may indicate that
the lateral collateral ligaments may also affect how the surfaces of each bone interact
with one another and that laxity of the LCL may result in dynamic incongruence that over
time results in medial coronoid pathology.

The feline elbow has a similar origin of the lateral collateral ligament from the
condyle of the humerus as the dog. The lateral collateral ligament, in the cat, reduces
lateral movement of the ulna in the olecranon fossa during extension by the anconeal
process and holds the radius abducted to the ulna during supination. Tension of lateral
collateral ligament, along with the medial collateral ligament that prevents excessive
rotation of the ulna, providing stability of the elbow joint and preventing excessive
movement (31). The collateral ligaments prevent drift of the radius and the ulna so that
the distribution of vertical loads on the radius and the ulna are very nearly equal (19). Our
results support these findings, as we observed a lateral shift in the contact pressure and a
decrease in contact area when the ligaments were removed, allowing more movement of
the radius and ulna when the leg was loaded. This may support explain why a lateral shift
was observed in the forelimbs in this study with loading after the LCL was cut, because
when the ligament was removed, the constraint which kept the radius and ulna from
moving apart was not present. Our results were also similar to findings in a human study
of restoration of elbow stability when both collateral ligaments were repaired with Type 1
sutures (15). Laxity of the ligament may not allow the ligament to sustain enough tension
and that leads to a lateral shift in loading (17). Since the lateral collateral ligament serves
as an important supporting mechanism in the elbow joint, a laxity of the ligament may
lead to excessive movement of the radius and ulna during supination, extension, and
flexion during the activity of the dog’s life that leads to dynamic incongruence of the
elbow and degeneration of the cartilage of the medial coronoid process.

The comparison between prosthetic ligaments versus intact ligaments was
significant between no ligaments and both prosthetic ligaments in peak contact pressure
and contact area, demonstrating that elbow integrity can be restored. Figure 1 and 3 show
the same pattern that the placement of prosthetic ligaments of one or both ligaments are
effective in reducing the load on the ulna where the peak contact pressure and contact
area resembled the peak contact pressure of the intact condition of the joint. A conclusion can be made that using prosthetic ligaments may be able to restore elbow stability that is similar to the intact ligaments. This finding can be applied to a clinical setting as an alternative treatment if lameness is diagnosed in a patient and the patient is suspected to be vulnerable to a fragmented coronoid process. The use of prosthetic ligaments may be effective in treating dogs by restoring some of the stability within the elbow joint with the use of prosthetic ligaments. Prosthetic ligaments may be effective in reducing the pressure on the ulna to prevent a fragmented coronoid process from occurring, or help in reducing the rate of progression of osteoarthritis as it decreases the amount of pressure placed on the ulna. The use of ligament prosthesis, especially the LCL, prevented relaxation of feline and canine elbows when the integrity of the collateral ligaments was compromised (14).

The clinical significance of our findings is that it supports of laxity of the lateral collateral ligaments. With prosthetic ligaments having a significant difference compared to intact conditions, the use of prosthetic ligaments will help in increasing the support of the elbow if laxity in the lateral collateral ligament is present or if the ligament is damaged. Most of the present research looks into incongruence of the radius and ulna, but our findings may give information on a secondary cause that leads to incongruence of the elbow joint. Dogs who are presented with a predisposition to elbow dysplasia and FMCP may benefit from the implementation of prosthetic ligaments to reinforce the stability of the elbow joint. Arthroscopy and CT scans have been the best method of determining congruency within the elbow joint as it creates an unobstructed image of the elbow, but does not give a real image of the condition of the joint (32). Ligament laxity may also be used as a method to determine the likelihood of developing incongruence of the elbow followed by FMCP.

From our study, extending the research into a clinical in vivo study would allow us to determine how prosthetic ligaments would perform in live patients and the durability of the prosthetic ligaments in this setting. Looking into the changes of contact area, and peak contact pressure before prosthetic ligaments were placed and after, would determine if prosthetic ligaments would perform similarly in a live dog to restore elbow stability. Another study of interest would be to determine the relationship between the
porosity of the coronoid with laxity of the lateral collateral ligament. Multiple studies suggest a correlation with medial compartment disease with bone density in the coronoid (18-20). Bone density was seen to increase with age in the subchondral bone highest in the anconeal and medial coronoid process in normal dogs. This increase in density of the medial coronoid process correlates to the ulna being subjected peak loads that may lead to fracturing due to cartilage degeneration (31). Although, this correlation contradicts other findings where a reduction of bone density of dogs with FMCP was significantly lower than normal dogs. The reduction of bone density would then lead to a decrease of compression strength of the coronoid process further leading to incongruence and fracture (18). This would determine how bone density affects FMCP and how laxity of the LCL may lead to an increase in incidence of fractures.

A limitation to this study was that the statistical analysis was performed on the radius and ulna separately. Using a comparison of the contact area, contact pressure, and peak contact pressure of the intact, no ligament, and prosthetic ligament conditions between the radius and ulna would provide an insight on how the pressure changes between the radius and ulna as ligaments are removed and how it responds with the addition of prosthetic ligaments. Although the statistics performed in this experiment did demonstrate significance between an intact state and no ligament state and other conditions and was sufficient evidence that the ligaments served as a supporting role in the elbow joint and that adding prosthetic elements improved elbow stability, a comparison between the radius and the ulna would provide a perspective on the interactions between the two bones in the joint. Other limitations were that only the effects of vertical forces were observed in this study. The changes in the elbow compartment and the effectiveness of prosthetic ligaments might be different if rotational movements were included. This would look into the durability of the prosthetic ligaments in all ranges of movement rather than just in the vertical direction. The use of more dynamic kinematics to study the changes in the peak pressure, contact area, and contact pressure of the radius and ulna experienced while dogs are walking, could indicate what range or give an overall picture of how removal of the ligaments affect the interactions between the radius and ulna. Elbow incongruence was not part of our analysis in this
study. Inclusion of elbow incongruity may give knowledge about how incongruence plays apart with or without laxation in the lateral collateral ligaments.

In conclusion, this study was successful in demonstrating the supporting role of the lateral collateral ligaments in elbow stability and the effectiveness of prosthetic ligaments in restoring this stability. The removal of one or both ligaments compared to the intact condition significantly increased in the contact area and peak contact area of the ulna, producing a lateral shift towards the ulna. Also, the comparison between prosthetic ligaments and no ligament conditions were significant in reducing the peak pressure and contact area of the ulna and simulating intact conditions. This supports that the use of prosthetic ligaments can be an effective form of treatment in young and adult large breed dogs where elbow disease is commonly diagnosed in.
**Literature Cited**


