Total elbow replacement in the dog: development and evaluation

Michael Gerard Conzemius

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Total elbow replacement in the dog: Development and evaluation

by

Michael Gerard Conzemius

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Biomedical Engineering

Major Professor: Thomas D. McGee

Iowa State University

Ames, Iowa

2000
This is to certify that the doctoral dissertation of

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For the Major Program

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LITERATURE REVIEW AND RESEARCH PLAN</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>MORPHOMETRIC ANALYSIS OF THE NORMAL CANINE ELBOW</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>INITIAL DESIGN</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>IN VIVO EVALUATION OF A SEMICONSTRAINED TOTAL ELBOW ARTHROPLASTY SYSTEM</td>
<td>37</td>
</tr>
<tr>
<td>5</td>
<td>EVALUATION OF A MODIFIED CANINE TOTAL ELBOW ARTHROPLASTY SYSTEM</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>LITERATURE CITED</td>
<td>100</td>
</tr>
</tbody>
</table>
The causes of osteoarthritis in the elbow of the dog

Elbow osteoarthritis (OA) secondary to fragmentation of the medial coronoid process (FCP), osteochondrosis (OCD), ununited anconeal process (UAP), intra-articular fracture, and elbow luxation is the most common cause of forelimb lameness in the dog.¹ Collectively, these conditions represent the cause of lameness for nearly 8% of all dogs that present to university hospitals for lameness.¹ The above conditions can be separated, based upon etiology, into either developmental (FCP, OCD, and UAP) or acquired (fracture and luxation) conditions. Regardless of the origin, OA develops because of incongruity, instability, or chronic inflammation in the joint. In addition, the developmental elbow abnormalities frequently occur bilaterally.

Treatment alternatives for these causes and their success rates

The goal of nonsurgical and/or surgical management of the developmental abnormalities is to slow the progression OA in the joint and reduce lameness in the patient. Nonsurgical management includes using nonsteroidal anti-inflammatory medications (NSAIDs), weight reduction (if the patient is overweight), and moderate daily exercise. Surgical management is dependent upon diagnosis. Fragmentation of the medial coronoid process is treated by removing the fragment via arthrotomy or arthroscopy. Osteochondrosis of the medial aspect of the humeral condyle is treated with curettage of the subchondral defect. An UAP is treated by removal of the process, internal stabilization of the process, or by proximal ulnar osteotomy.
Nonsurgical and surgical management of developmental conditions of the elbow joint frequently leads to unsatisfactory results. Huibregtse et al. studied 22 dogs with forelimb lameness caused by a FCP and provided evidence that elbow OA progressed radiographically in dogs following nonsurgical or surgical treatment. In addition, they performed force plate gait analysis on the dogs and found that there was no difference in limb function between groups. They also found that owners reported a recurrence of lameness in 78% of dogs treated without and 69% of dogs treated with surgery. Mean follow-up time was not reported in this retrospective study. Bouck et. al. studied 19 dogs diagnosed with FCP and/or OCD that were treated medically or surgically using physical, radiographic and force plate gait evaluations and found similar results. One distinct advantage of this study was that it was prospective with a one year follow-up time. They found that regardless of treatment, OA progressed radiographically and range of motion decreased over time. Using force plate gait evaluations they determined that dogs in both groups improved but there was no difference in the amount of improvement between treatment groups. The mean peak vertical force in the affected limb of dogs increased from 40 to 45% of body weight in both groups.

Read et al. studied the largest groups of dogs; reporting on 130 cases of FCP in 109 dogs. This retrospective study focused on the opinion of the dog's owner to report on the degree of lameness and activity before and after treatment. In this study 62 cases were managed nonsurgically and 68 were managed surgically. They found that the degree of lameness improved to some degree in 59% of dogs, regardless of treatment. Lameness, however, persisted in 75.9% of all dogs studied. They also attempted to correlate the degree of lameness at initial presentation to post-treatment outcome, reporting that dogs with mild lameness are less likely to benefit from surgery than dogs with moderate or severe lameness.
Tobias et al. performed a long-term evaluation of 35 dogs that had surgery for FCP. Their evaluation included an owner questionnaire, physical exam, and radiographic exam. They concluded that surgical approach and age of patient at the time of surgery did not affect prognosis. Perhaps more interesting, however, was the fact that nearly 65% of dogs still had lameness, 80% had joint pain, and over 95% had joint thickening and a reduced range of motion at follow-up examination. In addition, OA significantly increased in 100% of the cases.

Caplan et al. provided additional evidence that, regardless of treatment, OA progresses in dogs with developmental disorders of the elbow. They studied the progression of OA using radiographic examinations in 50 dogs that were treated for lameness because of a FCP. Twenty-four dogs were treated non-surgically, 26 were treated surgically. All dogs were had initial and follow-up radiographic examination performed at the Veterinary Teaching Hospital at Iowa State University. Radiographic views evaluated were a craniocaudal, lateral, and flexed lateral. All radiographs were covered such that the two radiologists would not know the signalment of the patient, or if the radiograph was an initial or follow-up radiograph. The radiographs were evaluated independently and scored for degree of OA based on the grading system developed by the International Elbow Working Group. They found that OA progressed in 100% of cases. In addition, they determined that the progression of OA was the same regardless of treatment. Currently, a treatment alternative for dogs with developmental diseases of the elbow that provides reliable, long-term relief does not exist. Additionally, no treatment alternative exists to manage cases that have had unsatisfactory outcomes following non-surgical or surgical management.
The goal of treatment of the acquired conditions is to restore normal anatomy. The conditions that can cause elbow OA include intra-articular fracture and luxation. In addition, fracture of the radius or ulna can lead to OA in the elbow by two mechanisms. First, fracture of the one of the growth plates of the radius or ulna can cause asynchronous growth between the two bones leading to incongruity in the elbow. Second, fracture and subsequent callus formation can cause synostosis between the radius and ulna which can also lead to incongruity in the elbow. Intra-articular fracture and traumatic luxation are treated surgically and can lead to a good prognosis with no long-term OA or lameness. Complications, however, are common. In one study, 45% of all cases that had surgery for traumatic luxation had an unacceptable clinical outcome. Although dogs with these injuries should still be treated with surgery upon presentation, clinicians and owners must be aware that lameness and OA in the future are possible and no surgical alternative is in the peer-reviewed literature.

**Current treatment alternatives for dogs with established OA**

Current treatment alternatives for dogs with moderate to severe elbow OA include nonsurgical management, removing loose bodies and osteophytes from the joint, and arthrodesis. In a clinical report, one dog with severe elbow OA had surgery to remove fragmented medial coronoid processes and a fractured anconeal process; this dog returned to near normal function after surgery. This case may be the exception, however, because the dog became acutely lame because of an intra-articular fracture and the case was complicated by the OA. There are no reports in the peer-reviewed literature addressing debridement arthroplasty for moderate to severe OA in the dog. deHann et al. retrospectively
investigated results after arthrodesis of the elbow and found that although pain in the joint was alleviated, function of the limb was limited. In a review article addressing the surgical treatment of OA, it was stated that debridement was the primary and arthrodesis the secondary option for OA in the elbow. They also stated that total elbow arthroplasty was likely the best future option.

**Total elbow arthroplasty as an option in the dog**

Improvements in implant design and surgical techniques have made total elbow arthroplasty a satisfactory treatment for arthritic disorders of the elbow in man since the mid-1970s. In two separate evaluations, 91% of total elbow arthroplasty cases had excellent long-term (∼4 years) outcomes. It is important to note that limb use in man after successful total elbow arthroplasty is far from normal. The level of limb function possible includes such activities as opening a door, using a fork, and bringing the hand to the back of the head. The success that veterinarians have had in total joint replacement has mirrored that of physicians when it comes to hip and knee. In the dog, 95% of patients will have a good or excellent outcome after total hip replacement. Current implant designs and surgical techniques for total knee replacement in man are commonly developed in canine models. The similarities in implant design and surgical success found in the hip and knee are likely because of similarities in anatomy and joint mechanics.

The anatomy and mechanics of the elbow joint, unfortunately, are dramatically different between man and dog. The first and most obvious difference is that the dog is a quadruped; thus, the elbow is a load bearing joint. In fact, the forelimbs have a peak vertical force that is approximately 75% greater than the rear limbs at a trot (velocity of 1.5 to 2.0 m/s).
Anatomically, the radius is the primary load bearing bone in the dog. In contrast, the ulna seems to be the primary load bearing bone in man. The difference is most likely explained by the fact that dogs almost exclusively load the elbow when in extension and man generally loads the elbow when in flexion. These differences in mechanical demands has led to differences in anatomy. The ulna of the dog is much smaller, relative to the human ulna. Likewise, the radial head of the dog is larger with respect to the human radius. This is reflected by the fact that radial head excision arthroplasty can be successfully performed in man. Given an understanding of canine anatomy and joint mechanics, it is easy to believe that radial head excision is not even reported in the dog. This point is further reflected in designs of total elbow components for humans. All currently used total elbow designs (Coonrad/Morrey elbow replacement prosthesis, GBS II design, Capitello-Condylar design, HSS-Osteonics Linked Semiconstrained Total Elbow Prosthesis, etc.) utilize a humeral and an ulnar component (Figure 1.1). The radial head is removed during the implantation of these components. These design concepts, although successful for the human elbow, seem inadequate for the dog elbow.

Total elbow arthroplasty has been reported in the dog. Lewis reported on his experiences with the use of a constrained (hinge-like) implant and although there were some successful outcomes he concluded that because of a high complication rate the system needed to be redesigned. Vasseur et al., at the University of California at Davis designed a nonconstrained system and tested it in three dogs with naturally occurring elbow OA. The dogs in that study had poor short-term and long-term results and the project was abandoned (Figure 1.2).
Figure 1.1. A photograph of a Conrad/Morrey elbow replacement prosthesis. Note that this design is hinge-like and has a stem for the humerus and ulna.
Figure 1.2. A photograph of the four component total elbow arthroplasty system used at the University of California at Davis, CA.
Conclusions

The dog is susceptible to several developmental and acquired conditions that cause lameness in the elbow. These conditions commonly occur. Current treatment alternatives frequently have unsatisfactory outcomes resulting in the progression of OA and lameness. Once OA develops in the elbow there are few treatment alternatives available, and all of those have been shown to be unreliable. When OA develops in the hip or knee joint of the dog, total joint arthroplasty successfully restores joint function. When OA develops in the elbow of man, total elbow arthroplasty has been successful in restoring joint function. Although currently available elbow arthroplasty designs cannot be used in the dog or have been shown to be ineffective, the concept of total elbow arthroplasty for the treatment of OA in the elbow of the dog seems prudent.

Description of research plan

The long-range goal was to develop a total elbow arthroplasty system that could be successfully and reliably used to restore joint function in dogs with OA in the elbow. The objective of the initial study was to design and test in vivo a total elbow arthroplasty system that reflects the normal anatomy of the canine elbow. The central hypothesis for the proposed objective is that the anatomical surface and the mechanics of the normal elbow are effective for a lifetime. Components that are similar in design to the normal elbow may also be effective for a lifetime. In the following studies I will investigate the normal anatomy of the elbow, design a total elbow replacement system with components that reflect normal anatomy, design cutting guides that allow for reproducible implantation of the components, describe a surgical technique to implant the components, test the effect of the components on
limb function in the normal dog, and perform post mortem investigations to determine the advantages and disadvantages of the initial design.
CHAPTER 2: MORPHOMETRIC ANALYSIS OF THE NORMAL CANINE ELBOW

Introduction

A review of the literature revealed that the anatomy and mechanics of the human elbow do not reflect the anatomy and mechanics of the canine elbow. Total elbow replacement designs used in man, therefore, should not be duplicated and tried in the dog. Intuitively, a total elbow replacement design for the dog should reflect the anatomy of the dog elbow with an emphasis placed on the fact that it is a load bearing joint during gait.

I hypothesized that the initial design should reflect the anatomy of the elbow of a dog breed that is not predisposed to elbow disease. The rationale for this is that dogs of some breeds rarely develop osteoarthritis (OA) in the elbow; therefore, if that anatomical configuration were reproduced in the design of components, the components would have a reasonable chance of mechanical success. The Greyhound is an athletic breed that rarely develops OA in the elbow joint and was chosen as the breed to be studied.

Prior to the start of the anatomical study several additional important points for the initial design were considered. These points are important to consider at this stage because they influence what anatomical measurements need to be taken. First, the design should be semiconstrained or nonconstrained. Constrained (hinge-like) designs do not share load with intact ligamentous structures. Lewis used a constrained design for total elbow replacement in the dog and have unsuccessful results. Load is absorbed by the implant and shifted to the implant-bone interface. This type of design has not withstood the test of time in load bearing joints; the best example being the human knee. Constrained total knee designs have an unacceptable rate of aseptic loosening and are reserved for use in revision surgeries of the
knee when no ligamentous structures remain intact.\textsuperscript{29} Semiconstrained and nonconstrained designs require a much shorter stem length relative to constrained designs. In fact, they are commonly referred to as pegs instead of stems. This reduces the information needed regarding the medullary canals of the bones about the dog elbow. Second, the design should be isometric, or left and right should be identical. The primary reason to do this is to reduce manufacturing cost and make the design potentially more appealing to manufacturers for licensing. A design that is impractical for licensing will not become available for use by veterinary surgeons around the country. If the design is to be isometric it is important that the left and right limbs of the dogs studied be similar enough that they will accept the implants of a design. Third, the design should have cement fixation. Cement fixation increases the margin of error for implant placement by the surgeon and implant sizing by the manufacturer. Press-fit and porous in-growth designs require a near perfect fit between existing bone anatomy and implant. Cement fixation allows the stems of the implant to be anywhere within the confines of the medullary canal as long as there is room remaining for a 2.0mm cement mantle.\textsuperscript{30} Finally, the design should have as few working pieces as possible. This limits manufacturing costs and makes it technically simpler for the surgeon. For example, the radial and ulnar components could be made as one component instead of two. If this were the case then the relationship between the two bones becomes much more important. Vasseur et al. followed all of the above criteria above with the exception of limiting the number of working parts.\textsuperscript{31} Their design used four implants and the technical challenge required to get all four parts to function as one joint contributed to failure.\textsuperscript{31}
Materials and Methods

Subjects: Morphometric data were collected on the elbows of ten adult, retired racing Greyhounds. Plane radiography was performed on all dogs. Four dogs were sacrificed for additional gross anatomical evaluation; the remaining six were used in the initial in vivo analysis.

Radiographic evaluation: Lateral, flexed lateral, and craniocaudal radiographic views were taken of the left elbow of all dogs. For all radiographs the elbow was placed directly on the radiographic film cassette so magnification would be limited. The radiographs were interpreted for the presence of OA, and measurements were taken. The measurements taken from the lateral radiograph included: (1) diameter of the proximal 4 cm of the radial medullary canal (2) diameter of the proximal 4 cm of the ulnar medullary canal starting at the level of the medial coronoid process, (3) distance between the proximal 4 cm of the centers of the radial and ulnar medullary canals, (4) radius of curvature of the humeral condyle, (5) distance between the center of rotation of the humeral condyle and the long-axis of the humeral medullary canal, and (6) diameter of distal 4 cm of the humeral medullary canal (Figure 2.1). The measurements taken from the craniocaudal radiograph included: (7) diameter of the radial medullary canal for the proximal four centimeters of the bone (8) diameter of the ulnar medullary canal for the proximal four centimeters of the bone starting at the level of the medial coronoid process, (9) distance between the centers of the radial and ulnar medullary canals for the proximal four centimeters of the bones, (10) width of the articulating surface of the humeral condyle, (11) diameter of distal four centimeters of the humeral medullary canal, (12) distance of trochlear notch from midline, (13) distance of supratrochlear foramen from midline (Figure 2.2).
Figure 2.1. A lateral radiograph of a Greyhound elbow. Measurements taken from the radiograph are marked on the radiograph and the numbers correlate with those described in the preceding paragraph.
Figure 2.2. A craniocaudal radiograph of a Greyhound elbow. Measurements taken from the radiograph are marked on the radiograph and the numbers correlate with those described in the preceding paragraph.
Gross anatomical evaluation: The forelimbs of four dogs were harvested. The limbs of two dogs were used to gather anatomical data; the remaining were used to develop a surgical technique for implantation of the newly designed components. The soft tissues were removed from the limbs collected for anatomical study. The articular surface of each bone was inspected for anatomical details that might have been over-looked by the radiographic evaluation. The bones were cut with a band saw either longitudinally or in cross-section and measurements were taken and compared to those collected in the radiographic evaluation (Figure 2.3).

Figure 2.3. A longitudinal cross-section of a Greyhound elbow.
Data Analysis: The mean and standard deviation of each measurement was calculated from the radiographic evaluation.

Results

The averaged data from the radiographic evaluation are presented in Table 2.1. It was determined that the diaphysis of the humerus was cylindrical and the radius and ulna had an oval shape.

Direct visualization of the bones detected that the radiographic evaluation did not adequately determine the anatomy of the articular surface. The length of the humeral condyle measurement accurately describes the width of the humeral articular surface in the cranial, weight-bearing portion of the bone. It, however, does not reflect the articular surface at the caudal, nonweight-bearing portion of the bone. At the caudal aspect of the humerus, the articulation wedges toward the center of the bone and creates the olecranon fossa. This fossa defines and separates the lateral and medial epicondylar crest of the humerus. The load bearing articular surfaces of the radius and ulna matched the humeral condyle. The nonload-bearing surface of the ulna, however, did not match the humerus. The ulnar trochlea appeared to be made up of two separate circles. The first is located on the load-bearing portion of the bone and has a smaller radius of curvature. The second is located on the ulnar trochlea and has a larger radius of curvature.

The left and right limbs were compared grossly and it was determined that they were mirror images of each other, not identical to each other. They, however, did not have large
Table 2.1. The mean and standard deviation values from the radiographic evaluation. The lateral (LAT) and craniocaudal (AP) radiographic views were evaluated. Refer to Figures 2 and 3 for examples of the measurements taken.

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<td>Distance between foramen and midline</td>
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curvatures in a medial or lateral direction near the elbow that would have limited the
possibility of an isometric design. This was in agreement with the radiographic evaluation
that found that the trochlear notch and supratrochlear foramen had only small deviations (≤
0.5mm) from midline.

Discussion

The importance of the information gathered in this exercise should not be
overshadowed by its simplicity. The physical act of looking closely at the radiographic and
gross anatomy of the elbow was an excellent learning tool. Of primary importance, however,
were the data collected and its significance for design shape and size.

The Greyhound was selected for this study because it rarely gets OA in its elbow
even after years of athletic function. The Greyhound is also readily available for study and
some investigation has already been published addressing its gait. The anatomy of the
Greyhound, however, may not reflect the anatomy of the dogs that are predisposed to elbow
OA. A design for total elbow replacement using Greyhound anatomy cannot be assumed to
be correct for other breeds of dogs; it is only the starting point.

The measurements addressing the width of the medullary canal of the bones can be
used to determine the shape and maximum size of the pegs used for implant design. These
measurements included the four centimeters most near the elbow for the radius, ulna, and
humerus and should be more than adequate for an implant peg or stem. Of importance is the
fact that the radius and ulna are not cylindrical bones. The diameter of the radius medullary
canal is greater in a medial-lateral plane and the diameter of the ulna medullary canal is
greater in a cranial-caudal plane. In contrast, the humerus is cylindrical; therefore a peg or stem could be designed as such.

One assumption made before the study was that the number of implants should be limited. With this in mind, the distance between the center of the radial and ulnar medullary canals was measured. It would be necessary to know this distance if one planned to use a radioulnar implant as opposed to separate radial and ulnar implants, as was the case with the Vasseur et al. design. An additional point to consider would be the angle of each medullary canal from midline. That was not measured in this study. If one planned to make implants isometric then all pegs need to be centered. In addition, if short pegs are used it dramatically reduces the likelihood of interference with the endosteal bone. This measurement, however, would be essential if one planned to use longer stems; they certainly would need to be located and angled in a fashion similar to the normal anatomy to avoid interference between the stem and cortical bone.

As expected the load bearing articular surfaces of the humerus, radius, and ulna formed almost a perfect circle. It would be difficult to conceive any other type of configuration that could accept load at multiple different angles without unacceptable wear. The ulna, however, changes its shape caudally in the area of its trochlea. This area forms a second, larger circle that articulates with the humerus and likely provides stability during extension and absorbs some reactant forces associated with the pull of the triceps muscles.

Using the cranial caudal radiographic view and the gross anatomical inspection of the bone it was determined that the differences between left and right were small enough that an isometric design would adequately fit in both limbs. The measured differences between left and right, in the Greyhound, were acceptably small.
CHAPTER 3: INITIAL DESIGN

Background

Total elbow replacement designs that have been used in the dog have led to unsatisfactory results. Lewis reported on his experiences with the use of a constrained (hinge-like) implant and although there were some successes he concluded that because of a high complication rate it needed to be redesigned. It is difficult to determine the specific cause of failure associated with this design because of limited information available for review. The design incorporated a metal-on-metal articulation using stainless steel. Metal-on-metal articulations can be successfully used in total joint arthroplasty. In fact, their wear rates are sometimes reported to be less than that of a more traditional metal on polyethylene articulation. The limiting factor, however, is the number of imperfections after the machining process. The greater the number of imperfections, the greater the initial wear rate. Increased wear leads to increased formation of particulate debris that ultimately increases the likelihood of aseptic loosening of the implant. Given that the time frame of loosening and failure in this group of dogs was generally less than one year, it is very unlikely that aseptic loosening from particulate wear debris contributed to failure. Lewis's design was very similar to many human elbow prostheses, in that he utilized a humeral and ulnar component. The ulna is not a primary load bearing bone of the elbow in the dog. The pathway of load, when using only an ulnar component, requires that load is directed through the ulna. The bone will remodel in response to this load. The remodeling process could lead to premature loosening of the implant. In addition, this type of dramatic change in the pathway of load up the limb could lead to a change in gait. Finally, Lewis's design was a hinge joint. Hinge
joints do not share load with pre-existing ligamentous structures. Hinge joints, by design, absorb all loads. This load is then transferred to the bone at the implant-bone or implant-cement interface. This type of design leads to premature loosening via micromotion.

A group led Dr. Phil Vasseur at the University of California at Davis designed and tested a nonconstrained system in three dogs. Dogs in that study had poor results and the project were abandoned. The design used was cemented and included a stainless steel Type 316L humeral component, an ultra-high molecular weight polyethylene (UHMWPE) ulna component, and a stainless steel Type 316L radial component with a UHMWPE insert. The suggested cause for failure with the use of this design was improper placement of the components. The design used four parts that had to articulate without instability or incongruency. This allowed for very little margin for error when bone cuts were made and implants were positioned. Apparently the precision demanded by this design was not achievable on a reliable basis; although, this type of design might work with increased surgical experience.

It was hypothesized that an initial design should reflect the anatomy of the elbow of a dog in a breed that is not predisposed to elbow disease. This hypothesis led to a morphometric analysis of the Greyhound elbow. The data gathered from that analysis were applied directly and indirectly to an initial design. In addition, several additional important points for the initial design were considered. First, the design should be semiconstrained or nonconstrained. Second, the design should be isometric, i.e. left and right are identical. Third, the design should have cement fixation. Finally, the design should have as few working pieces as possible.
Initial design

The initial design included a humeral and radioulnar component. The humeral component consisted of two parts, a body and a stem. As viewed from the side the body is circular (Figure 3.1). The widest part of the body was 0.5 mm smaller than the measured distance of the humeral condyle in order to preserve humeral bone stock. The width of the

Figure 3.1. Computer-aided design (in mm) of the humeral component (lateral view).
body decreases by almost 50% towards its caudal aspect in a manner similar to the normal humerus. This decrease gives the body a wedge shape (Figure 3.2). The body has a semicircular groove that is centered and remains unchanged in size throughout the entire circumference of the humeral body. This groove receives and articulates with a ridge on the radioulnar component. At the most caudal and proximal aspect of the body it blends into the stem (Figure 3.3). In this area a hole in the component is present similar to the supracondylar foramen. This hole receives and articulates, when in extension, with a protrusion on the radioulnar component. This aspect of the design is similar to the relationship between the

Figure 3.2. A computer-aided design print of the humeral component (ventral view).
Figure 3.3. A computer-aided design print of the humeral component (caudal view).

Olecranon fossa of the humerus and the anconeal process of the ulna. The stem is cylindrical and is nearly 3.0-cm in length to improve stability of the component. Semicircular grooves, 2.0-mm radius, are machined into the sides of the body and the stem to increase component-cement surface area. Finally, a 2.0-mm hole is present in the body. This will allow for
placement of 2.7-mm screws from the medial and lateral aspects of the condyle, providing compression between the component and the condyle, thus increasing component strength.

The radioulnar component consists of a body and three pegs. The body contains the articular surface that is a mirror image of the body of the humeral component. The two components have a contact area of 230°; this "snap-fit" was included to help prevent luxation. This type of design is considered a loose hinge or semiconstrained (Figure 3.4).

Figure 3.4. A computer-aided design print of the radioulnar component (cranial view).
All pegs are cylindrical and have a diameter of 4.5-mm. The cranial peg is designed to be inserted into the medullary canal of the radius, the middle peg into the metaphyseal area of the ulna, and the most proximal and caudal peg into the proximal ulna. Three pegs were used to reduce rotation of the component within the cement mantle (Figure 3.5). The components were hand machined out of medical-grade ultra high molecular weight polyethylene (UHMWPE). The design allowed for 160° of rotation (Figure 3.6).

Figure 3.5. A computer-aided design print of the radioulnar component (lateral view).
Prototype components were made and used in a cadaver study to investigate the size and shape of the components and to develop a surgical procedure. During the cadaver study, it was determined that the snap-fit between the components was too tight. In order to reduce the components the UHMWPE had to be plastically deformed. This essentially made the articulation constrained as opposed to the intended semiconstrained. The proximal protrusion of the radioulnar component was shortened so that the contact area between the two components was 200°. It was also determined that the components fit in the bones but very little bone stock was preserved. It was determined that the preservation of bone stock would be most critical at the medial and lateral aspects of the humeral condyle and the metaphyseal region of the proximal ulna. All measurements were reduced by 10% in order to preserve bone stock. Perhaps the most important result of the cadaver investigation were the development of a surgical approach and the production of bone cutting guides.
Initial surgical approach

A 10-cm incision is made through the skin and subcutaneous tissue beginning 5-cm proximal to the lateral epicondyle. The curvilinear incision extends in a caudodistal direction. The tissue is reflected and the anconeus muscle is longitudinally transected. The incision in the muscle is extended proximally along the cranial edge of the lateral head of the triceps brachii muscle and distally along the caudal edge of the supinator muscle. Using sharp dissection, the insertion lateral collateral ligament is taken off of the radius with the supinator muscle. The joint capsule is incised and the elbow is luxated medially.

Initial bone-cutting guides

In order to insert the components reproducibly bone-cutting guides were designed and machined from stainless steel Type 316L. In order to remove a bony wedge from the humeral condyle a cutting guide was developed that had three parts (Figure 3.7A and 3.7B).

Figure 3.7A. Photographs of the bone-cutting guides. From left to right are the humeral cutting guide, radioulnar cutting guide, and the humeral drill guide (top view).
The first part was the cutting plate. The plate was a solid piece of metal that had angled, slots cut in it for placement of a reciprocating blade. The slots were angled such that when the cutting blade was placed through them and was in contact with a cutting bar, the second part, the angle matched that of one of the edges of the humeral component. It was critical that the slots not only be at the correct angle but also remove the correct amount of bone at the correct location on the condyle. This was accomplished by mounting the cutting guide on the humerus via a 1/4-inch pin placed through a hole in the support plate in the cutting guide, the third part, and into the intramedullary canal of the humerus (Figure 3.8). The slots of the guide were based on the location of the bone after the pin was placed. A second pin was placed through the support plate and into the humeral condyle to prevent rotation between the cutting guide and the humerus. In effect, the humerus was not in contact with any part of the cutting guide but was fixed in a space between it parts (Figure 3.9).
Figure 3.8. A photograph of a 1/4-inch pin positioned in the medullary canal of a cadaver humerus.
Figure 3.9. A photograph of the humeral cutting guide mounted onto a cadaver humerus. The photograph on the left is a caudal view, on the right is a lateral view.

After the cutting guide was mounted a wedge-shaped piece of bone could be reliably removed from the humeral condyle (Figure 3.10). The widest part of the wedge is on the cranial aspect of the humeral condyle and it becomes narrower in the caudal and dorsal directions. After the initial bone cut, 2.7-mm holes needed to be pre-placed in the medial and lateral aspect of the condyle for later receipt of 2.7-mm bone screws. A drill guide that fit into the bony deficit created by the first cut was designed. This drill guide had three parts.
The first part, the body, fit into the humeral bony deficit in a manner similar to the way that the humeral component would sit. The second part, the drill guide arm, was positioned such that the drill guide allowed a hole to be drilled in the condyle that was in alignment with the 2.0-mm hole in the humeral component. The third part, a screw, attached the body to the arm. This screw could be removed, the arm flipped over, and the screw could be returned to its original position. This made the drill guide modular; allowing the medial and lateral aspects of the condyle to be drilled from the same guide (Figure 3.11). After all cuts and drill holes were completed, the humeral component could be positioned within the bony deficit of the humerus (Figure 3.12). The radioulnar bone-cutting guide was designed with two

Figure 3.10. A photograph of a cadaver humerus after a wedge-shaped piece of bone has been removed using the humeral cutting guide.
Figure 3.11. A photograph of the humeral drill guide mounted into the humeral deficit of a cadaver bone. On the left is a caudal view and on the right is a lateral view.

Figure 3.12. A photograph of the humeral component positioned within the bony deficit of the humerus. From left to right are cranial, caudal, and lateral views.
working parts. The cutting surface provided a guide for a saw, which would be used to remove the radial head, the coronoid processes of the ulna, the ulnar trochlea, and the anconeal process. In order to reproducibly position the cutting guide, a 1/8-inch pin was placed in the medullary canal of the ulna (Figure 3.13).

Figure 3.13. A photograph of a 1/8-inch pin placed in the medullary canal of a cadaver ulna.
The guide was then mounted onto this pin through one of three holes present in the body of
the guide. The remaining two holes allowed for small pins to be placed into the lateral aspect
of the ulnar and the cranial aspect of the radial diaphysis (Figure 3.14).

Figure 3.14. A photograph of the radioulnar cutting guide mounted on a cadaver radius and
ulna.

The surgical approach, prototype components, and bone-cutting guides developed allowed
for use of a semi-constrained total elbow arthroplasty system in the Greyhound, and perhaps
for use in other dog breeds as well. The system was used on four cadaver limbs to allow for
reasonable proficiency prior to in vivo testing.
CHAPTER 4: IN VIVO EVALUATION OF A SEMICONSTRAINED TOTAL ELBOW ARTHROPLASTY SYSTEM

Introduction

The data collected from a morphometric analysis of the normal Greyhound elbow joint were used to design a total elbow arthroplasty system. The system incorporated a humeral component, radioulnar component, humeral cutting guide, humeral drill guide, and radioulnar cutting guide. The components were hand machined from medical grade ultra-high molecular weight polyethylene, the guides from stainless steel Type 316L. The articulation between the components was semiconstrained (they had a "snap-fit" from 200° of contact at the articulation) and allowed for 160° of rotation about the horizontal axis of the body of the humeral component.

New surgical techniques and implants generally need to be tested in vivo prior to use in client-owned animals. This is especially true if the technique or implant deviates dramatically from previously described procedures. Any amount of mechanical or cadaver study cannot adequately predict the effect in a living animal. Such is the case with the previously described total elbow arthroplasty system for the dog. A pilot study was designed to test the effect of this total elbow arthroplasty system on limb function in the normal dog. The hypothesis was that limb function would be significantly altered initially but dogs would recover and lameness would resolve. In addition, it was hypothesized that success would not be 100%, but failure would occur in some dogs. The cause of failure could be determined and that information used for modifications to the existing system.
Materials and Methods

Animals

The experimental protocol was approved by the Animal Care and Use Committee at Iowa State University. Prior to inclusion in the study the Laboratory Animal Resource Veterinary Faculty evaluated dogs by physical examination, complete blood count, chemistry panel, urinalysis, and fecal floatation. Dogs were then vaccinated (Vanguard®, Pfizer Animal Health, Exton PA, 19341) and quarantined for two weeks. Six, healthy, adult Greyhounds were used in the study. Each candidate underwent an orthopedic, radiographic, and force plate gait evaluation before surgery and at 2 and 4 months after surgery for all surviving dogs. In addition, two dogs underwent computed-assisted tomography (CAT scan) before surgery and at 4 months after surgery. Four dogs were sacrificed at 2 months and two were sacrificed at 4 months after surgery. Treated limbs from the sacrificed animals were harvested and the components were examined.

Orthopedic Examination

Prior to inclusion in the study an orthopedic examination was performed on each animal to ensure that it was free of lameness and had no pain upon palpation of the joints, and to determine the pain-free range of motion in the left elbow joint.

Radiographic Examination

Plain radiographs (Picker GX1050 radiographic machine) of the left and right elbow of each dog were taken prior to inclusion in the study to ensure skeletal maturity and that no osteoarthritis was present in either joint. Standard lateral, craniocaudal, and flexed lateral radiographic views were taken.
Computer-assisted Tomography

Computer-assisted tomography (Picker International, PQ 6000 computed tomography unit) was performed on the left limb of two dogs prior to surgery. Two- and three-dimensional reconstruction of images was performed to improve visualization of the elbow using specialized software (Picker International, Voxel-Q software).

Force Plate Gait Examination

Computer-assisted force plate gait analysis was performed using a biomechanical platform (Biomechanics Platform OR6-5-1, Advanced Medical Technology, Inc., Watertown, MA, 02172) embedded in an 8 m walkway. Two sets of retroreflective photocell sensors, attached in series and connected to a timer were centered adjacent to the force platform 1-m apart and were used to determine velocity and acceleration over the measurement region. The dogs were walked across the platform at a comfortable speed (trial velocity between 0.90 to 1.10 m/s; acceleration variation +/- 0.5 m/s²) and ground reaction forces for the forelimb and hindlimb stance phases were recorded for each pass across the plate. Passes were repeated until 5 valid measurements were obtained for each limb. A trial was considered valid if a forelimb and ipsilateral hindlimb foot strike were isolated on the force plate and gait abnormalities were absent. The first 5 valid passes were used for analysis. The ground reaction forces in the vertical direction were normalized for the dog’s body weight and used for analysis of limb function.

Data Analysis

Pre- and post-surgical gait analysis data were compared for the normal and operated limb.
Surgical Procedure

Butorphanol tartrate (Torbugesic, Fort Dodge Animal Health, Fort Dodge, Iowa) (0.2 mg/kg) and acepromazine maleate (PromAce, Fort Dodge Animal Health, Fort Dodge, Iowa) (0.02 mg/kg) were injected intramuscularly 20 minutes before induction with sodium thiopental (Pentothal, Abbott Laboratories, North Chicago, IL) (2 to 4 mg/kg boluses to effect). Following intubation, anesthesia was maintained with isoflurane (AErrane, Anaquest, Inc, Liberty Corner, NJ) in oxygen. The dogs were placed in lateral recumbancy and standard aseptic preparation of the left forelimb was performed. Intravenous cefazolin sodium (Ancef, SmithKline Beecham Pharmaceuticals, Philadelphia, PA) (25 mg/kg), was administered following intubation and every 2 hours until anesthetic recovery was complete. A caudolateral approach to the elbow joint was modified by incision and retraction of the lateral digital extensor muscle and avulsion of the lateral collateral ligament from its radial insertion. The radius and ulna were luxated medially exposing the humeral condyle, the radial head, and the proximal ulna.

An ulnar ostectomy, 1-cm length, was performed 4-6 cm distal to the level of the medial coronoid process. A 1/4-inch pin was placed in retrograde fashion into the ulnar medullary canal until it exited at the olecranon. The radioulnar bone cutting guide was mounted onto the pin (Figure 4.1). The cranial aspect of the guide was placed approximately 0.5 cm distal to the level of the articulating surface of the radius and the guide was secured into place using small pins through the holes present on the guide. The articular surfaces of the ulna and radius were removed using a power driven saw along the cutting surface provided by the radioulnar guide. The cut ends of the radius and ulna were smoothed, using a flat bone file, in order to match the surface of the component. Care was taken to preserve
bone stock. Using a 4.5-mm drill bit, pilot holes, approximately 2-cm in depth, were drilled into the cancellous bone of the proximal ulna, the ulna metaphysis, and the radial metaphysis (Figure 4.2). The surgical field was irrigated, suctioned, and packed with saline soaked gauze for later bone cement and component placement.

Figure 4.1. An intraoperative photograph showing the radioulnar cutting guide mounted onto a pin placed in the ulna and fixed in place with a pin in the radius.
Figure 4.2. An intraoperative photograph showing the cut surface of the ulna and the pilot holes drilled in the ulna for later receipt of the radioulnar component pegs.
The humerus was prepared for implantation of the humeral component using custom designed bone-cutting guides. A 1/4-inch hole was drilled starting at the dorsal aspect of the trochlear notch and extending up the medullary canal for approximately 10-cm. A hole of the same size was drilled perpendicular to the long axis of the humeral shaft through the trochlear notch. A 1/4-inch pin was placed in the axial hole extending up the medullary canal of the humerus until it engaged cortical bone. The humeral cutting guide was mounted by sliding the guide onto the pin. The cutting slots were aligned evenly on either side of the condyle, and the guide was fixed in place by tightening set screws onto the intramedullary pin and by nailing a 1/8-inch pin through a hole in the cutting guide into the humeral trochlea (Figure 4.3). The articulating surfaces of the distal humerus, including the entire trochlea, were removed in a wedge-shaped piece using a reciprocating saw inserted through the cutting slots. The removed bone was wrapped in a blood soaked gauze and saved for later use as autogenous bone graft. The cutting guide and pins were removed. The cut ends of the distal humerus were smoothed using a flat bone file, taking care to preserve bone stock. The humeral drill guide was positioned in the bony deficit and a 2.7-mm hole was drilled into the medial and lateral aspects of the humeral condyle. The bony deficit was packed with saline soaked gauze until insertion of bone cement and the humeral component (Figure 4.4). The gauze was removed from the humerus and the surgical field was flushed, suctioned, and packed with dry gauze. Polymethylmethacrylate (Palacos®R, Smith+Nephew Richards Inc., Memphis, TN 38116) was prepared by hand mixing in a bowl, and while it was still in a liquid phase it was injected into the humeral shaft using an injection gun (Cement Injection System, BioMedtrix, Inc., Allendale, NJ), along the cut edges of the humeral condyle, and into the grooves present in the humeral component. The humeral component was manually
positioned and aligned so that the shoulder of the component was against the distal humeral shaft and the curved articulating portion of the implant was 1-2 mm distal to the remaining medial and lateral aspects of the humeral condyle. The component was held in place until the PMMA hardened (Figure 4.5).

Figure 4.3. An intraoperative photograph showing the humeral cutting guide mounted onto the humerus.
Figure 4.4. An intraoperative photograph showing the distal aspect of the humerus after preparation for implantation of the humeral component.

Figure 4.5. An intraoperative photograph showing the humeral component cemented in its position within the humerus.
Preparation for placement of the radioulnar component was similar. Bone cement, in the liquid phase, was injected into the holes drilled into the radius and ulna. The radioulnar component was positioned in the radius and ulna by placing the pegs of the component into the predrilled holes in the bones. The component was aligned by positioning the component edges with the cut edges of the bones and held in place manually until the cement hardened. (Figure 4.6). After the PMMA in the radius and ulna had hardened, the joint was reduced. The joint was then placed through a full range of motion to ensure that the components articulated at all times. A 2.0-mm hole, located 3-cm distal to the cut surface of the radius, was drilled through the diaphysis of the radius and ulna. The hole in the radius was overdrilled using a 2.7-mm drill bit. The hole in the ulna was tapped using a 2.7-mm bone tap and a 2.7-mm screw was positioned in the hole from the radius to the ulna. The joint was flushed and an autogenous, cancellous bone graft was placed between the proximal radius and ulna to encourage rapid synostosis (Figure 4.7). The joint was closed in a routine fashion taking care to reattach the lateral collateral ligament to its insertion. Post-operative radiographs were taken, a soft bandage was applied to the limb, and an intravenous analgesic (Morphine, Elkins-Sinn, Inc., Cherry Hill, NJ, 08003-4099) was given before the animal recovered from anesthesia (Figure 4.8).

Postoperative analgesics were given every 6 hours for 36 hours after surgery. The bandage was removed 5 days and skin staples 14 days after surgery. Exercise was limited to kennel rest in all dogs for the first four weeks of the treatment period. Surviving dogs were then taken on 15-minute leash walks twice a day for the duration of the study period.
Figure 4.6. An intraoperative photograph showing the radioulnar component cemented in its position within the radius and ulna.
Figure 4.7. An intraoperative photograph showing the components reduced prior to closure.
Figure 4.8. Lateral and craniocaudal radiographs of Dog 2 immediately after surgery.

Results

Orthopedic Exam Results

Post-operative complications occurred in 4 of 6 dogs. All 6 dogs began to toe-touch on the operated limb within 2 weeks after the surgery. At two months after surgery only 2 dogs were using the operated limb. When the operated limb in these dogs was palpated it
was stable in a medial and lateral direction, had 90° range of motion, and caused mild discomfort. The remaining 4 dogs were nonweight bearing two months after surgery and were sacrificed, in compliance with the study’s animal use protocol. When the joint was palpated in two of these dogs is caused severe pain. They had a varus deformity at the elbow in the operated limb, and the elbow was unstable laterally. The remaining two dogs seemed to experience moderate pain upon palpation of the operated limb and although the limb was stable, it had only 30° to 40° range of motion.

At 4 months after surgery, 2 of 6 dogs remained for evaluation. Lameness in these dogs had decreased since the previous evaluation. Circumduction, swinging the limb from a medial position during toe off to a lateral position and then returning the limb to a medial position for heel strike, of the operated limb was present during the swing phase of gait. The range of motion had not changed from the 2-month exam, and the limb was less painful during palpation.

*Radiographic Examination Results*

Radiographs taken immediately after surgery revealed that no gap was present in the interface between the components and the bone cement. Similarly, no radiolucent line was present at the cement-bone interface. The articulation between the components could not be evaluated since both were radiolucent. The humerus appeared to be correctly aligned with the radius and ulna by evaluation of the craniocaudal radiographic view. The tip of the humeral component was in contact with the humerus in all dogs. Radiographs of the two surviving dogs were performed two and four months after surgery and no significant changes were noted with the exception of a small amount of periosteal new bone formation on the cortical surfaces adjacent to cement.
**Computer-assisted Tomography**

Cross-sections through the cement-bone interface demonstrated that a gap was present at the interface. The gap was small (1 to 2-mm) but was present in all planes viewed of the radius and ulna. The gap was present only occasionally in the humerus (Figure 4.9). Three-dimensional reconstruction of the CAT scans was useful in visualization of the amount and location of new bone formation. A moderate amount of new periosteal bone had formed around all bones. In addition, it was determined that radioulnar synostosis was complete in only 1 of 2 dogs evaluated (Figure 4.10).

**Force Plate Gait Examination Results**

Before surgery, no obvious difference was found between the front limbs when vertical forces (peak vertical force and vertical impulse) were compared. Force plate gait examination was performed after surgery in the two surviving dogs. Peak vertical force was decreased in the operated limb at both two and four months after surgery when compared to pre-surgical values (Table 4.1). The PVF of the normal front limb was greater than its pre-surgical values at all time periods after surgery. The PVF of the operated front limb was less than that of the normal limb at all time periods after surgery but increased from 71% at two months to 82% at four months after surgery (Figure 4.11).

**Necropsy Results**

By 2 months after surgery, 4 of 6 dogs had been sacrificed and their prosthetic joints examined grossly. The prosthetic joints of the remaining two dogs were examined 4 months after surgery. The humeral component was stable by manual palpation in all 6 dogs. The condylar screws were loose and had backed out 3 of 4 dogs that did not use the operated limb.
Figure 4.9. A cross-section through the articulation (closed arrow) between the humeral and radioulnar components four months after total elbow arthroplasty. Note the gap (open arrow) between the cement mantle and the radius.
Figure 4.10. Three-dimensional reconstruction of a CAT scan 4 months after total elbow arthroplasty. Note the small amount of new bone formation (arrow) between the radius and ulna.
Table 4.1. Peak vertical forces of the limbs of dogs studied before and after surgery. The results from six dogs are included in the pre-surgical values and two dogs in the post-surgical values.

<table>
<thead>
<tr>
<th>Peak Vertical Forces (%BW)</th>
<th>Pre-operative</th>
<th>2 mo.</th>
<th>Post-operative</th>
<th>4 mo.</th>
<th>Post-operative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Forelimb</td>
<td>54.84</td>
<td>64.35</td>
<td>63.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Hindlimb</td>
<td>50.97</td>
<td>66.72</td>
<td>65.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Forelimb</td>
<td>57.01</td>
<td>40.40</td>
<td>46.61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left Hindlimb</td>
<td>51.38</td>
<td>51.96</td>
<td>53.47</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

and in neither of the dogs that used the limb. When the screws were removed from the two dogs that used the limb the humeral component remained stable.

The radioulnar component was loose in all dogs that did not use the limb. In contrast it was stable in the two dogs that did use the limb. The source of the instability was at the component-cement and/or cement-bone interface. In fact, in the two dogs that had varus deformity, the radioulnar component was luxated from the cement mantle or the cement mantle had luxated from the radius and ulna (Figure 4.12). In the remaining two dogs with loose radioulnar components, the radioulnar component and cement mantle could be manually subluxated from the radius and ulna when the joint was reduced and lateral or medial stress was applied to the joint. In effect, the prosthetic joint would not subluxate at the articulation between the components, as expected, but at the implant-cement or cement-bone interface of the radius and ulna. The cement mantle in the radius and ulna was extremely small, measuring less than 2-mm in most locations. The radioulnar synostosis was incomplete in all dogs and the screw placed between the radius and ulna was loose in 5 of 6 dogs (Figure 4.13).
Figure 4.11. A graph of PVF of the operated limb as a per cent of body weight at all time periods. The shaded areas in the graph demonstrate limb use in normal Greyhounds after femoral head and neck excision and total hip implantation.
Figure 4.12. A photograph of the radioulnar component and cement mantle luxated from the radius of a dog. A gap is present between the cement mantle and the radius (arrow).
Figure 4.13. A photograph of the elbow of one of the dogs sacrificed four months after surgery. Note that the radioulnar synostosis is incomplete (arrow). The components and screws were stable in this case.

Discussion

The purpose of this study was to determine the in vivo effects of a canine total elbow arthroplasty system in normal Greyhounds. The design used in this study was developed from anatomical and cadaver studies. It was hypothesized that lameness present immediately after surgery would resolve over time. Limb function improved over the four-month study period in 2 of 6 dogs, but their lameness never resolved. It is possible that limb use in these
dogs would have continued to improve if the study period were longer. In an evaluation of limb use in normal Greyhounds after femoral head and neck excision and total hip replacement limb function improved for the first six months after surgery. The purpose of this study was not to see if dogs could achieve normal function, although that would have been an impressive finding, but to determine the positive and negative attributes of the initial design. It was also hypothesized that surgery would fail in some dogs and that much could be learned by the mode of failure. This proved to be true.

The primary mode of failure was loosening of the radioulnar component at the cement-bone interface. The loosening was so severe that the component luxated in 2 of 6 dogs and the component was grossly unstable in 2 of 6 dogs. Several factors likely contributed to this mode of failure. First, the semiconstrained design. When the articulation between the components was flexed and extended it appeared that very little stress was shifted to the component-cement or bone-cement interface. Rotational and bending forces at the articulation, however, created luxation or subluxation at the bone-cement interface of the radius and ulna. This was demonstrated in the post-mortem examination of the elbows after all soft tissues were removed. This was likely because of the "snap-fit" design constraining motion in these planes. A nonconstrained design would not provide these constraints. In fact, if all soft tissues were removed around a nonconstrained prosthetic joint the joint would fall open at the articulation. If the proximal protrusion of the radioulnar component were removed the articulation would become nonconstrained. Second, the cement mantle was inadequate. Stress is equal to force divided by area. Thus, if the surface area between the bone and the cement is increased the stress at this interface will be similarly decreased, given force remains unchanged. One could increase the potential space in the radius and ulna for
bone cement by drilling deeper holes into the medullary canals of the bones and by removing the cancellous bone in the metaphyseal area of these bones. Third, the pegs were too short. Again, if the surface area between the component and cement is increased the stress at the interface is decreased. Longer stems could be added to the radioulnar component instead of pegs. The use of long stems, however, would likely preclude the component from being isometric. Fourth, the radioulnar synostosis was incomplete. In the normal dog, motion between the radius and ulna allows for pronation and supination at the level of the carpus. If a design utilizes a component that incorporates both a radial and ulnar peg or stem, motion between the radius and ulna will lead to premature component loosening. An autogenous corticocancellous bone graft was placed between the proximal aspects of the radius and ulna in a hope that fusion would occur. It is reported that bone grafts used to create new bone near a total joint replacement have a high likelihood of success.\(^\text{36}\) In addition, a compression screw was positioned between the radius and ulna. The screw was placed in compression because it would decrease the gap and motion between the radius and ulna thus increasing the likelihood of healing. In fact, this screw may have reduced the likelihood of healing. First, a single screw cannot adequately prevent rotation. If rotational forces are present stress will be applied at the screw-bone interface, leading to resorption of bone. This can result in the release of inflammatory mediators that increase osteoclastic and reduce osteoblastic activity, thus impairing healing of the bone graft.\(^\text{37}\) Second, the screw adequately reduced the gap between the bones but inadequately reduced micromotion. This may have actually increased strain between the bones and at the graft site. Healthy bone tolerates about 2% strain before mechanical failure. The interfragmentary strain theory suggests that new bone, in this case new bone from the bone graft, cannot form unless the strain is less than 2%.\(^\text{38}\) A
larger gap with similar motion would have less strain and may have allowed the graft to heal. An increased amount of bone graft and no screw might increase the likelihood of radio-ulnar synostosis.

The screws placed in the medial and lateral aspects of the humeral condyle became loose in a majority of the cases. It was also determined that the humeral component was stable in all cases even after the screw was removed. That being the case, it is possible that the condylar screws did not improve stability. In fact, since the screws have a propensity to migrate they could result in decreased use of the operated limb.

In this study both components were made from medical grade UHMWPE. This reduced the cost of materials and manufacturing. The wear of polyethylene on polyethylene articulation is similar to that of polyethylene on metal articulation. It has been suggested that this type of articulation is adequate for low loading situation such as the metacarpophalangeal joint in man. If wear is the primary concern for not using this type of articulation than it is reasonable to assume that this design would not fail given that the duration of the study was only four months.

Elbow osteoarthritis is the most common cause of front limb lameness in the dog. Currently available surgical treatment alternatives have been shown to yield inconsistent results. If total elbow arthroplasty could consistently yield good results, it would likely be the treatment of choice in the majority of dogs with severe elbow OA and lameness. It was determined from this study that only moderate success could be achieved using the proposed semiconstrained design. In addition, failure occurred at an unacceptable rate. The primary cause of failure was because of component loosening secondary to design flaws (eg. stems of radioulnar component too short, snap-fit too constrained, inadequate cement mantle). The
information gained from this study, however, will be critical in modifying the existing design in an effort to achieve a reliable, successful outcome after total elbow arthroplasty in the dog.
CHAPTER 5: EVALUATION OF A MODIFIED CANINE TOTAL ELBOW ARTHROPLASTY SYSTEM

Introduction

Elbow osteoarthritis (OA) secondary to fragmentation of the medial coronoid process (FCP), osteochondrosis, asynchronous growth between the radius and ulna, ununited anconeal process, intra-articular fracture or luxation is the most common cause of forelimb lameness in the dog. In addition, OA is commonly bilaterally. Current treatment alternatives for dogs with moderate to severe elbow OA include nonsurgical management (anti-inflammatory medication and weight loss), removing loose bodies and osteophytes from the joint, and arthrodesis. In a clinical report, one dog with severe elbow OA had surgery to remove a FCP and a fractured anconeal process; this dog returned to near normal function after surgery. deHann et. al. retrospectively investigated results after arthrodesis of the elbow and found that although pain in the joint was alleviated, function of the limb was limited. In a review article addressing the surgical treatment of OA, it was stated that debridement was the primary and arthrodesis the secondary option for OA in the elbow. They also stated that total elbow arthroplasty was likely the best future option. Currently, no commercially available canine total elbow arthroplasty system exists.

Improvements in implant design and surgical techniques have made total elbow arthroplasty a satisfactory treatment for arthritic disorders of the elbow in man since the mid-1970's. In two separate evaluations, 91% of total elbow arthroplasty patients had excellent long-term (approximately 4 years) outcomes. Total elbow arthroplasty has been reported in the dog. Lewis reported on his experiences with the use of a constrained (hinge-like)
implant and although there were some successes he concluded that because of a high complication rate it needed to be redesigned. Our research group used morphometric data from normal canine elbow joints to design a two component, semiconstrained system and tested it in six greyhounds. It was determined from that study that moderate success could be achieved (mean peak vertical force of affected limb 24 weeks after surgery was 82% of preoperative normal) but that success was limited primarily because of component loosening secondary to design flaws (eg. stems of radioulnar component too short, snap-fit too constrained). The objective of this study was to evaluate (using physical, radiographic, and force plate gait examinations) the short-term, in vivo effects of a modified canine total elbow arthroplasty system in normal dogs.

MATERIALS AND METHODS

*Canine Total Elbow Arthroplasty System*

The total elbow arthroplasty system evaluated in this study was a nonconstrained system using two components, a humeral and a radioulnar component, which require cement fixation. The humeral component consisted of a stem and condylar portion. The stem was designed to be positioned in the medullary canal of the distal humerus. The design of the stem was modified with respect to the initial design by angling the stem 5° in a cranial direction (Figure 5.1). The condylar portion was designed to replace a bony deficit created between the remaining medial and lateral aspects of the humeral condyle after the articulating cartilage and its underlying bony wedge were resected. The grooves in the sides of the component were modified such that they were deeper, would not communicate with the load-bearing surface of the component, and they had a dove-tail shape (Figure 5.2).
Figure 5.1. A lateral view of the computer-aided design of the second-generation humeral component. Note the angulation of the stem with respect to the body of the component.
Figure 5.2. A caudal view of the computer-aided design of the second-generation humeral component. Note the location of the grooves in the condylar portion of the component.
The edges of the load-bearing surface of the humeral component were softened, or rounded off. The component was isometric and machined (BioMedtrix, Allendale, NJ, 07401) from 316L stainless steel. The articulating surfaces of the humeral component were polished whereas non-articulating surfaces were bead-blasted to provide better adherence at the implant-cement interface (Figure 5.3).

Figure 5.3. A ventral view of the computer-aided design of the second-generation humeral component. Note the dove-tail shape of the grooves and the softened edges of the articular surface.
The radioulnar component consisted of a stem portion (two stems) and a head portion. The stem portion was designed such that the cranial stem could be cemented in the medullary canal of the proximal radius and the caudal stem in the medullary canal of the proximal ulna. In addition, a small post on the caudal aspect of the implant was designed to be received by the metaphyseal region of the proximal ulna (Figure 5.4). The length of the stems is much...
longer than that of the pegs of the initial radioulnar component. In addition, the length of the stems required that they be attached to the head of the component at locations and angles that matched that of the normal anatomy of the radius and ulna of the dog. For example, the radial stem is offset from midline and heads in a medial direction (Figure 5.5). The stems

Figure 5.5. A cranial view of the computer-aided design of the second-generation radioulnar component. Note the location and angle of the radial stem with respect to midline.
also had to be rotated with respect to the head of the component so they would not interfere with the cortical bone of the radius and or ulna. Finally, since the stems would be seated deeply within the medullary canals of the bones the distance between the two stems had to be near that of the distance between the caudal aspect of the medullary canal of the radius and the cranial aspect of the medullary canal of the ulna (Figure 5.6). The head portion of the

Figure 5.6. A ventral view of the computer-aided design of the second-generation radioulnar component. Note the rotation of the ulnar stem with respect to the component head.
radioulnar component was designed to articulate with the condylar portion of the humeral component. The radioulnar component was designed for use in left limbs only and was machined (BioMedtrix, Allendale, NJ, 07401) from medical grade, ultrahigh molecular weight polyethylene. The potential functional range of motion between the two components is 155°; from 15° of flexion to 170° of extension.

**Animals**

The experimental protocol was approved by the Animal Care and Use Committee at Iowa State University. Prior to inclusion in the study the Laboratory Animal Resource Veterinary Faculty evaluated dogs by physical examination, complete blood count, chemistry panel, urinalysis, and fecal floatation. Dogs were then vaccinated (Vanguard®, Pfizer Animal Health, Exton PA, 19341) and quarantined for two weeks. Six, healthy, adult medium and large breed dogs ranging from 25 to 38 kg were used in the study. Each dog underwent an orthopedic, radiographic, and force plate gait evaluation before surgery and surviving dog were reevaluated at 8, 16, 24 and 52 weeks after surgery. Dogs were sacrificed 6, 10, and 20 weeks after surgery, leaving three dogs for long-term evaluation. The three dogs that were evaluated at 52 weeks after surgery were adopted to private homes. Treated limbs from the sacrificed animals were harvested and the components were examined.

**Orthopedic Examination**

Prior to inclusion in the study an orthopedic examination was performed on each animal to ensure that it was free of lameness had no pain upon palpation of the joints, and to determine the pain-free range of motion in the left elbow joint.
Radiographic Examination

Plain radiographs of the left and right elbow of each dog were taken prior to inclusion into the study to ensure skeletal maturity and that no osteoarthritis was present in either joint. Standard lateral, craniocaudal, and flexed lateral radiographic views were taken.

Force Plate Gait Examination

Computer-assisted force plate gait analysis was performed using a biomechanical platform (OR6-6-1000, Advanced Mechanical Technology, Inc., Watertown, MA, 02172) embedded in an 8 m walkway. Three sets of retroreflective photocell sensors, attached in series and positioned in the walkway, 1 m apart with the middle sensor positioned at the middle of the force plate, were used to determine velocity and acceleration over the 2 m measurement region (Mek 92-TPAD Retroreflective Photocell, Sircon Controls, Mississauga, Canada). The dogs were walked across the platform at a comfortable speed and ground reaction forces for the forelimb and hindlimb stance phases were recorded for each pass across the plate (Sharon Software, Inc., Dewitt, MI, 48820). Passes were repeated until 5 valid measurements were obtained for each limb (trial velocity between 1.20 and 1.40 m/s; acceleration variation +/- 0.5 m/s^2). A trial was considered valid if a forelimb and ipsilateral hindlimb foot strike were isolated on the force plate and gait abnormalities were absent. The first 5 valid passes were used for analysis. The ground reaction forces in the vertical direction were normalized for the dog’s body weight and used for analysis of limb function.

Data Analysis

An analysis of variance for repeated measures over time was performed to determine if differences existed between means for peak vertical force and vertical impulse of the surgical and nonsurgical front limbs. When differences existed between-group post hoc
comparisons were made, using a multiple comparisons Tukey's test. Statistical significance was set at $p < 0.05$.

**Surgical Procedure**

Butorphanol tartrate (Torbugesic, Fort Dodge Animal Health, Fort Dodge, Iowa) (0.2 mg/kg) and acepromazine maleate (PromAce, Fort Dodge Animal Health, Fort Dodge, Iowa) (0.02 mg/kg) were injected intramuscularly 20 minutes before induction with sodium thiopental (Pentothal, Abbott Laboratories, North Chicago, IL (2 to 4 mg/kg boluses to effect). Following intubation, anesthesia was maintained with isoflurane (AErrane, Anaquest, Inc, Liberty Corner, NJ) in oxygen. The dogs were placed in lateral recumbancy and standard aseptic preparation of the left forelimb was performed. Intravenous cefazolin sodium (Ancef, SmithKline Beecham Pharmaceuticals, Philadelphia, PA) (25 mg/kg), was administered following intubation and every 2 hours until anesthetic recovery was complete. A caudolateral approach to the elbow joint was modified by incision and retraction of the lateral digital extensor muscle and avulsion of the lateral collateral ligament from its radial insertion. The radius and ulna were luxatedmedially exposing the humeral condyle.

The humerus was prepared for implantation of the humeral component using custom designed bone-cutting guides. A hole (7 to 9 mm) was drilled approximately 10 cm proximally from the dorsal aspect of the trochlear notch up the medullary canal. A hole of the same size was drilled perpendicular to the long axis of the humeral shaft through the trochlear notch. A 6-mm pin was placed up the shaft of the humerus, for a minimum of 10-cm of its length, until it engaged cortical bone. The humeral cutting guide was mounted by sliding the guide onto the pin. The cutting slots were aligned evenly on either side of the condyle, and the guide was fixed in place by tightening set screws onto the intramedullary
pin and by nailing a 3-mm pin through a hole in the cutting guide into the humeral trochlea. The articulating surfaces of the distal humerus, including the entire trochlea, were removed in a wedge-shaped piece using a reciprocating saw inserted through the cutting slots. The removed bone was wrapped in a blood soaked gauze and saved for later use as autogenous bone graft. The cutting guide and pins were removed. The cut ends of the distal humerus were smoothed using a flat bone file, taking care to preserve bone stock. The bony deficit was packed with saline soaked gauze until insertion of bone cement and the humeral component (Figure 5.7).

Figure 5.7. A photograph of the humeral component used in this study. From left to right are lateral, cranial, and caudal views.
A 1-cm length ulnar ostectomy was performed 4-6 cm distal to the level of the radial head. A 3-mm pin was placed in a normograde fashion into the ulnar medullary canal until it exited at the olecranon. The radioulnar bone cutting guide was mounted onto the pin. The cranial aspect of the guide was placed approximately 0.5 cm distal to the level of the articulating surface of the radius and the guide was secured into place using small pins through the holes present on the guide. The articular surfaces of the ulna and radius were removed using a power driven saw along the cutting surface provided by the radioulnar guide. The cut ends of the radius and ulna were smoothed using a flat bone file, taking care to preserve bone stock. Using a 4.5-mm drill bit and a curette, cancellous bone was removed from the ulna and radius to a depth of approximately 3-cm. The surgical field was irrigated, suctioned, and packed with a saline soaked gauze until bone cement and component placement (Figure 5.8).

Figure 5.8. A photograph of the radioulnar component used in this study. From left to right are lateral, cranial, and caudal views.
The gauze was removed from the humerus and the surgical field was flushed, suctioned, and packed with a dry gauze. Polymethylmethacrylate (Palacos®R, Smith+Nephew Richards Inc., Memphis, TN 38116) was prepared by hand mixing in a bowl, and while still in a liquid phase it was injected into the humeral shaft using an injection gun (Cement Injection System, BioMedtrix, Inc., Allendale, NJ). The humeral component was manually positioned and aligned so that the shoulder of the component was against the distal humeral shaft and the curved articulating portion of the component was 2-3 mm distal to the remaining medial and lateral aspects of the humeral condyle. The component was held in place until the PMMA hardened (Figure 5.9). Preparation for placement of the radioulnar component was similar with the component being positioned manually by alignment of the implant edges with the cut edges of the bones. After the PMMA in the radius and ulna had hardened, the joint was reduced. The joint was then placed through a full range of motion to ensure that the components articulated at all times (Figure 5.10). The joint was flushed and an autogenous, cancellous bone graft was placed between the proximal radius and ulna to encourage rapid synostosis. The joint was closed in a routine fashion taking care to reattach the lateral collateral ligament to its insertion. Post-operative radiographs were taken, a soft bandage was applied to the limb, and an intravenous analgesic (Morphine, Elkins-Sinn, Inc., Cherry Hill, NJ, 08003-4099) was given before the animal recovered from anesthesia (Figure 5.11).

Postoperative analgesics were given every 6 hours for 36 hours after surgery. The bandage was removed 5 days and skin staples 14 days after surgery. Exercise was limited to kennel rest in all dogs for the first 4 weeks of the treatment period. The dogs were then taken on 15-minute leash walks twice a day.
Figure 5.9. An intra-operative photograph of the humeral (top) and radioulnar (bottom) components cemented in their positions in the humerus and radius and ulna, respectively.

Figure 5.10. An intra-operative photograph of the prosthetic joint prior to closure.
Figure 5.11. Lateral (left) and craniocaudal (right) radiographs taken immediately after total elbow arthroplasty.

RESULTS

Orthopedic Exam Results

Post-operative complications occurred in 3 of 6 dogs. Five of six dogs began to toe-touch with the treated limb within 2 weeks after the surgery. Dog 6 never used the limb post-operatively and was subsequently sacrificed 6 weeks after surgery, in compliance with the study’s animal use protocol. The joint was mildly painful, but stable, throughout its range of motion and no physical reason for the disuse of the leg was ascertained. One dog (Dog 5) that had been using the surgical leg became acutely non-weight bearing 9 weeks post-
operatively because of an ulnar fracture and, was sacrificed in compliance with the study’s animal use protocol. One dog (Dog 2) developed an infection at the surgical site post-operatively and was subsequently treated with antibiotics (Baytril, 10 mg/kg PO SID).

Although clinically more lame than the others, Dog 2 steadily improved until the animal was euthanized at 20 weeks post-operatively for reasons not related to the elbow implant. This dog, a Rottweiler, was diagnosed clinically and histopathologically with severe Parvoviral enteritis and was removed from the study and sacrificed in compliance with the animal use protocol.

At 8 weeks after surgery, 5 of 6 dogs remained for evaluation. All dogs were using the surgical limb when walking yet all were moderately lame. Circumduction of the treated limb was evident during the swing phase of the walking cycle in all dogs. Only Dog 2 was painful on palpation of the left elbow joint. The mean pain-free range of motion was approximately 90 degrees (flexion angle of 70 degrees; extension angle of 160 degrees).

At 16 weeks after surgery, 4 of 6 dogs remained for evaluation. Lameness in all dogs had decreased since the previous evaluation. Circumduction of the surgical leg was still present during the swing phase in all 4 dogs. The range of motion had not changed from the 8-week exam and the dogs had developed a distinct stopping-point when the elbow was placed into flexion. The limb was not painful at this stopping point.

At 24 weeks after surgery, 3 of 6 dogs remained for evaluation. All dogs had improved, but mild lameness remained in the left forelimb. Circumduction of the limb was less evident. As before, range of motion was restricted in flexion and all dogs were pain free.

At 52 weeks after surgery, 3 of 6 dogs remained for evaluation. At this time the dogs could walk and run without lameness. Range of motion had not changed.
Radiographic Examination Results

Post-operative standard craniocaudal radiographs of the left elbow joint revealed a 1-3 mm gap between the humeral and radioulnar component on the lateral side in 3 of 6 dogs (Figure 5.12). During follow-up exams the gap was present in only one dog. At 8 and 16 weeks after the surgery, an approximately 2-mm gap was present at the lateral aspect of the joint in Dog 2.

Figure 5.12. Lateral (left) and craniocaudal (right) radiographs taken immediately after total elbow arthroplasty. Note the angulation on the lateral side of the elbow joint (arrow).
Radiographs of Dog 6 were taken before the animal was sacrificed 6 weeks after surgery in an effort to determine the reason for disuse of the treated limb. Radiographically, the implant and surrounding soft tissue structures were normal in appearance and no differences were noted when compared to the other dogs.

Dog 5 was radiographed 9 weeks after surgery following an acute onset of non-weight bearing lameness in the surgical limb. A simple, transverse fracture of the olecranon was evident in the metaphyseal region of the left proximal ulna, approximately 5 mm proximal to the transverse cut that removed the radial head (Figure 5.13).

![Figure 5.13. A lateral radiograph of the ulna fracture diagnosed in Dog 5, 9 weeks after total elbow arthroplasty.](image-url)
Radiographic evidence of osteomyelitis was present in Dog 2 (the most lame of the remaining dogs) at 8 weeks. An increased amount of periosteal new bone formation was present on the medial and caudal aspects of the humerus. In addition, a radiolucent line was present at the cement-bone interface at the intercondylar region of the humerus and at the radius (Figure 5.14).

Figure 5.14. Lateral and craniocaudal radiographs of Dog 2, 8 weeks after total elbow arthroplasty. Note the exuberant periosteal new bone formation on the humerus (closed arrow), the radiolucent line at the intercondylar region of the humerus (circle), and the gap on the lateral aspect of the joint (open arrow).
Synostosis between the radius and ulna was radiographically complete by 8 weeks after surgery in all six dogs. On the lateral radiographic view a radiolucent line, approximately 1-mm wide, was evident in 5 of 6 dogs 8 weeks after surgery. The radiolucent line was located at the bone-cement interface between the proximal radius and the radioulnar component. The size of this radiolucent line did not change during subsequent radiographic evaluations (Figure 5.15).

Figure 5.15. A lateral radiograph of a dog 8 weeks after total elbow arthroplasty. Note that only a moderate amount of periosteal new bone is present on the humerus and ulna. A small, radiolucent line is present (arrows) at the cement-bone interface of the radius.
Force Plate Gait Examination Results

Before surgery no significant difference was found between the front limbs when vertical forces (peak vertical force and vertical impulse) were compared. Peak vertical force of the treated limb was significantly lower than pre-surgical values at all time periods except at the 52-week evaluation (Figure 5.16). The PVF of the normal limb was greater than pre-surgical values at all time periods except the 52-week evaluation. The PVF of the treated limb was significantly less than that of the normal limb at all time periods after surgery except for 52 weeks after surgery. The vertical impulses of the operated and normal limb were significantly different from the pre-surgical values at all time periods until 52-weeks after surgery; and they were significantly different from each other at all time periods except at 52-weeks after surgery (Table 5.1).

Necropsy Results

By 20 weeks post-surgery, 3 of 6 dogs had been sacrificed and their left elbow joints examined grossly. The radioulnar synostosis was complete in all dogs and there was no apparent implant loosening. The width of bone at the radioulnar synostosis site was greater than 1-cm in width in all dogs (Figure 5.17). A fibrous tissue band, extending from the cranio-proximal joint capsule through the fossa in the humeral component to the caudal joint capsule, was evident in the dogs and restricted flexion of the elbow. The tissue band was more prominent on the medial aspect of the fossa and was associated with heterotopic new bone in two dogs (Figure 5.18). The joint capsule of Dog 6, which never used the limb after surgery, appeared red and was thickened but no obvious reason for the clinical outcome was found. Histology of the joint capsule revealed chronic-active inflammation with no evidence of bacterial infection.
Figure 5.16. A graph of PVF, as a per cent of body weight, of all dogs in the study.

Table 5.1. Mean (+/- SD) vertical forces of all dogs studied. Significant change from week 0 is marked with an asterisk (*); change from normal limb is marked with a number sign (#).

<table>
<thead>
<tr>
<th>Weeks Post-Op</th>
<th>Operated Limb</th>
<th>Normal Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PVF</td>
<td>Impulse</td>
</tr>
<tr>
<td>0</td>
<td>64.22 ± 6.96</td>
<td>23.28 ± 2.77</td>
</tr>
<tr>
<td>8</td>
<td>44.37 ± 15.60*</td>
<td>14.90 ± 5.65*</td>
</tr>
<tr>
<td>16</td>
<td>47.82 ± 8.29*</td>
<td>17.90 ± 5.98*</td>
</tr>
<tr>
<td>24</td>
<td>58.91 ± 4.00*</td>
<td>18.93 ± 3.72*</td>
</tr>
<tr>
<td>52</td>
<td>64.19 ± 3.87</td>
<td>22.00 ± 4.55</td>
</tr>
</tbody>
</table>
The dog that had developed a perioperative wound infection, Dog 2, had nearly 1-cm of periosteal new bone formation on the distal humerus. This dog also had a small amount of fibrous tissue between the components on the lateral aspect of the articulation; and an abnormal amount of medial wear was evident on the polyethylene radioulnar component. The medial edge of the humeral component was in direct contact with the groove in the UHMWPE; the groove was 0.05 mm deep and extended for the entire length of the articulating surface (Figure 5.19).

Figure 5.17. A photograph of the radius and ulna of Dog 2 after all soft tissues had been removed. Note the radioulnar synostosis (circled region) located just distal to the radioulnar component.
Figure 5.18. A photograph of the tissue (arrow) that extended through the hole in the humeral component. The ulnar attachment of the tissue is held by tissue forceps.

Figure 5.19. The radioulnar component Dog 2, 20 weeks after total elbow arthroplasty. Note the excessive polyethylene wear (arrow) on the medial aspect of the component.
DISCUSSION

Elbow osteoarthritis is the most common cause of front limb lameness in the dog. Currently available surgical treatment alternatives have been shown to yield inconsistent results.\textsuperscript{14,15} If total elbow arthroplasty could consistently yield good results, it would likely be the treatment of choice in the majority of dogs with severe elbow OA and lameness. In human medicine, total elbow replacement has been recommended as the first choice in the surgical treatment of the elbow with rheumatoid arthritis and cartilage destruction.\textsuperscript{26} Total elbow arthroplasty has been successfully used in man in cases of inflammatory arthritis, osteoarthritis, humeral nonunion, and erosive arthritis.\textsuperscript{16-18}

Total elbow replacement systems are classified as fully constrained, semiconstrained, and unconstrained, depending on the degree(s) of motion allowed between the articulating components.\textsuperscript{27} In the fully constrained type of design, there is a mechanical linkage between the components that restricts motion to rotation about a single axis (i.e., hinge joint). The predominant long-term problem with this type of design is component loosening due to the large rotational forces transmitted through the hinge to the bone-cement interface.\textsuperscript{27} In the semiconstrained elbow prosthesis, there is a mechanical linkage between the components but it is a sloppy joint or snap fit joint that does allow some motion about a second axis. The surrounding soft tissues, therefore, can help to absorb some of the forces that would otherwise be transferred to the bone-bone cement interface.\textsuperscript{28} In unconstrained total joint arthroplasty systems, there is no mechanical linkage between the components and the surrounding soft tissue structures are relied upon to stabilize the joint. Less bone is generally removed with this type of design and proper alignment of the articulating surfaces of the two components is critical.\textsuperscript{27}
Our first generation canine total elbow arthroplasty system was tested in 6 normal greyhound dogs. This prototype was a semiconstrained system (i.e., snap fit joint) in which the humeral and radioulnar components were cemented into place. From that preliminary study we found (based on peak vertical force from computer assisted force plate gait analysis) that dogs could return to 82% of normal function 6 months after surgery. For comparison, normal dogs that receive femoral head and neck excision return to 76-84% of function 16 weeks after surgery, and normal dogs that receive total hip replacement (cemented or uncemented) return to 90-100% of normal function 3 months after surgery.

Based on this we felt total elbow arthroplasty had the potential to become a clinically useful surgical technique. From this initial in vivo analysis we also concluded that the bone cutting guides were reliable for positioning of the implants, initial stability (bone-cement; cement-implant; implant-implant) of the implants was adequate, and perioperative complications were minimal. The initial system tested, however, provided barely acceptable 24-week results and needed improvement. The limbs from the dogs included in the initial in vivo study were harvested and analyzed for method of failure. Loosening of the radioulnar component was found in 5 of 6 dogs. Modifications in design and surgical technique were made and evaluated in cadaver limbs. Design changes were made primarily to the radioulnar component and resulted in an unconstrained system. The present study evaluated the modified system in vivo prior to use in client-owned dogs.

In this study complications occurred in 3 of 6 dogs early in the post-operative time period. Dog 6 never used the treated limb after the surgery and no orthopedic, neurologic, radiographic, or post-mortem evidence was discovered to explain the non-use of the limb. Although no histologic evidence of bacteria was found in a biopsy of the joint capsule it is
possible that infection was present. Additional diagnostic tests that could have been performed but were not include: joint culture at postmortem, nuclear scintigraphy, mechanical testing to determine if the joint was unstable, and high-resolution faxitron radiography to analysis the integrity of the implant-cement-bone interfaces. Given the information we have we could only conclude that, whatever the cause, the discomfort was such that the animal was unwilling to use the leg.

Dog 5 had excellent function until he developed an acute non-weighting bearing lameness on the treated leg 9 weeks after surgery. Radiographs of the left elbow joint revealed a fractured olecranon. In 5% of humans undergoing total elbow replacement, fracture of the olecranon has been reported as a major complication. Bone cuts that are perpendicular to each other, creating a stress riser in the ulna, have been identified as a predisposing factor for an olecranon fracture. In one study, comparing different ulnar ostectomies, the ulna retained a higher strength if it was prepared with a rounded rather than a 90° cut. Dog 5 was the smallest dog included in the study. We had only one component size available for this study and the radioulnar component used did indeed require a 90° cut. This component’s design has since been modified to incorporate a rounded caudal surface to fit into a rounded ostectomy. A curvilinear oscillating blade can be used to provide a rounded cut when removing the articulating cartilage of the radius and ulna. The fracture in Dog 5 was not treated in this study. If this type complication were to occur in a clinical case, the fracture would likely need to be treated with open reduction and fixation using a bone plate.

Osteomyelitis was diagnosed radiographically in Dog 2 eight weeks after surgery. This may explain the fact that although his lameness improved over time it was still greater
than other surviving dogs at 8 and 16 weeks. Dog 2 was euthanized at 20 weeks due to severe vomiting and bloody diarrhea. Parvoviral enteritis was diagnosed clinically and histologically.

Nonweight-bearing radiographic examination of the prosthetic joints revealed a gap between the humeral and radioulnar component on the lateral side in 3 dogs immediately after surgery. By 8 weeks after surgery, only 1 of those 3 dogs (Dog 2) had a lateral gap between the components. Post-mortem examination of Dog 2 revealed a wedge-shaped piece of fibrous tissue between the humeral and radioulnar components on the lateral side and wear grossly evident on the medial side of the radioulnar component. Lateral instability could cause this lateral gap. During the orthopedic examination performed at 8 and 16 weeks after the surgery, there was no gross instability noted on palpation of the joint. We, however, did not mechanically test the elbow so it is possible that it was unstable. If the elbow is unstable laterally, the humeral component could be in a valgus position with respect to the radioulnar component during weight bearing. This would lead to uneven wear on the medial aspect of the radioulnar component. Improper positioning of the humeral component is the other likely cause of the radiographic gap between the lateral side of the components. The bone removed from the humerus, depending upon the cutting guide used, provides for about 2-3 mm of space between the cut bone and the humeral component; this space is filled with cement. The component should be positioned centrally, such that the amount of space present between the medial and lateral aspects of the humeral condyle and the component are equal and the articular surface of the component is in a plane perpendicular to the long axis of the humerus. This allows the humeral component to sit flat on the radioulnar component. If the humeral component is positioned incorrectly it will not sit flat, and it will lead to abnormal
wear on the UHMWPE surface of the radioulnar component. The edges of the humeral component can be softened (made more round) to minimize this effect. In Dog 2 the articular surface of the component appeared to be positioned in the correct position, thus lateral instability may have been the cause of the gap. The position of the radioulnar component is dependent upon the cuts made to the radial head and the ulna. The two-stem design and the fact that the stems fill the majority of the radial and ulnar medullary canals make the positioning of this component relatively straightforward once the bone cuts are made.

Synostosis of the radius and ulna was radiographically complete by 8 weeks after the surgery in all dogs at during post-mortem examination. As the radioulnar component bridges the radius and ulna, rapid synostosis between the two is imperative to prevent motion that would cause component loosening and result in failure. The ulnar ostectomy is necessary to reduce the transfer of forces through the ulna, thereby discouraging motion between the radius and ulna and encouraging synostosis. The level of the ulnar ostectomy was chosen because it was just distal to the interosseous ligament and the nutrient foramen. Radioulnar synostosis limits the dog’s ability to supinate and pronate the foot. We are unaware of data that suggests that this would lead to disability. Our one year force plate gait analysis data provides evidence that synostosis is tolerated quite well in the short term.

Force plate gait examinations indicated that the vertical forces (peak vertical force and vertical impulse) for the surgical limb continued to increase throughout the course of study, while the vertical forces for the non-surgical limb continued to decrease. At 52-weeks the vertical forces of both front limbs had returned to pre-surgical values. Several studies have indicated that paired comparisons between the operated and normal limbs are more
 descriptive of gait than comparisons with pre-operative values.\textsuperscript{35,44} Limb symmetry has been evaluated in the dog and variance attributable to right and left limb variation was found to be negligible.\textsuperscript{45} In this study, as lameness changed in the operated limb the contralateral front limb had a similar in magnitude, yet opposite change.

Post-mortem results revealed that in all elbow joints a fibrous tissue band passed through the hole in the humeral component and connected the cranial and caudal aspects of the joint capsule. As the joint was flexed, the band of tissue stretched and displaced the joint capsule until it became tight; this was the origin of the distinct stopping point. Orthopedic examination indicated that the range of motion was restricted in flexion in all dogs after the surgery. The hole in the humeral component is a non-articulating surface that is essentially a remnant from the original semiconstrained design. Since nothing articulates with this area of the humeral component, fibrous tissue can, without restriction, form around and through this hole. The design of the humeral component has since been modified to eliminate this hole. Total elbow arthroplasty can be successfully performed in the dog. Ground reaction force data indicates that dogs had normal function in the surgical limb 1-year after the surgery. Data has been presented that suggests that total elbow arthroplasty can be successfully performed in normal dogs. Identifiable unsatisfactory outcomes are from infection, fracture, periarticular fibrous tissue formation, and surgical technique. In addition, a number of implant design modifications would improve the system prior to use in clinical cases. Including, the hole in the body of the humeral component was removed. This hole was intended for lag screw placement from the medial and lateral aspects of the humeral condyle into the component. Since loosening of the humeral component was not reported as a problem it was thought that this hole could be removed. This would eliminate the step of lag
screw placement. The grooves in the lateral aspect of the body of the component were made larger (changing the configuration of the groove allowed for this change) and with the inside diameter wider than the outside diameter of the groove. This would increase the component-cement surface area (Figure 5.20). The hole at the transition between the body and stem of the humeral component was removed (Figure 5.21). It was reported that this hole filled with fibrous tissue that restricted range of motion. The radius of curvature at the articular surface of the humeral component was increased. This softened the existing corners and made the articulation less constrained and reduced the likelihood of the metal cutting into the polyethylene if malalignment were present (Figure 5.22). The radius of curvature of the articular surface of the radioulnar component was increased to match the changes made with the humeral component. Also, the caudal peg of the radioulnar component was angled to match that of the existing ulna (Figure 5.23). The radius of curvatures of the non-articular portions of the body of the radioulnar component was also changed. The most significant change was at the caudal portion of the component were the radius of curvature when from almost being non-existent to that of one that matched the articular surface. This change was made to reduce the amount of ulnar cortical bone that needed to be removed in order to receive the component (Figure 5.24). Finally, three sizes were made. The small size being 10% smaller than the medium size which is similarly 10% smaller than the large size (Figure 5.25). The humeral component for this system should be metal, preferably stainless steel Type 316L, titanium alloy, or a cobalt chromium alloy. The radioulnar component for this system should be made from medical grade UHMWPE. The proposed final TEA system needs to be tested in dogs with naturally-occurring OA to ultimately determine its strengths and weaknesses.
Figure 5.20. A lateral view of the computer-aided design of the humeral component.
Figure 5.21. A caudal view of the computer-aided design of the humeral component.
Figure 5.22. A ventral view of the computer-aided design of the humeral component.
Figure 5.23. A lateral view of the computer-aided design of the radioulnar component.
Figure 5.25. A cranial view of the computer-aided design of the radioulnar component. Note the angulation of the caudal ulnar peg (dashed lines) and the radius of curvature of the articular surface of the component.
Figure 5.25. A photograph of the components used in this study. From left to right are lateral, cranial, and caudal views.


