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Effect of Medial Opening Wedge and External Rotational Humeral Osteotomies on Medial Elbow Compartment Pressure: An *Ex Vivo* Study

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Abstract

Objective The aim of this study was to assess if the level of osteotomy (50 or 75% the length of the humerus), osteotomy angle (5, 10, or 20 degrees), direction of bone alteration (external rotational or medial opening wedge osteotomies), or orientation of osteotomy (perpendicular to the humeral long axis or perpendicular to the weight-bearing axis of the limb) affect pressure through the medial compartment of the elbow.

Study Design Humeral osteotomies were performed at 50 and 75% the length of the humerus on 12 canine cadaver thoracic limbs and patient-specific three-dimensional (3D) printed plates applied to induce the desired alteration. Sensors were placed into the medial and lateral aspects of the elbow joint and the limb compressed to 90 N in a universal testing system.

Results Increasing the angle of the induced change had a significant effect on the decreased load through the medial compartment. Performing the osteotomy at 75% of humeral length from proximal was significantly more effective at reducing the medial elbow load than performing it at 50%. Opening wedge osteotomies were more effective than external rotational osteotomies, but both were effective. Changing the direction of the osteotomy (comparing transverse to oblique) did not significantly affect the load reduction through the medial compartment.

Conclusion Performing an osteotomy at a more distal location along the humerus and increasing the angle of the induced change increased the effectiveness of load-shifting humeral osteotomies.

Keywords
- elbow dysplasia
- medial compartment disease
- humeral osteotomy
- load-shifting
- canine

Introduction

Medial compartment disease of the elbow is a common cause of lameness in dogs encompassing subchondral bone sclerosis, fissure or fragmentation of the medial coronoid process, osteochondritis dissecans, and erosion of the cartilage of the proximal ulnar and apposing humeral trochlear.[1]

Humeral osteotomies, including medial opening wedge osteotomies, medial sliding osteotomies, and external rotational osteotomies, have been investigated to shift the weight-bearing axis of the thoracic limb laterally at the level of the elbow joint.[2,3] The aim of these procedures is to reduce

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the load through the medial aspect of the joint, thereby alleviating pain and ameliorating the progression of osteoarthritis. A similar principle is applied with clinical success in high tibial osteotomies in humans, which are used to treat medial osteoarthritis by reducing load through the medial compartment of the knee.[4,5]

Ex vivo biomechanical studies have demonstrated that humeral osteotomies can reduce the joint contact pressures in the medial compartment of the canine elbow[2,3,6] and that sliding humeral osteotomies significantly affect thoracic limb alignment in the frontal plane, shifting the mechanical axis from the medial to the lateral compartment of the elbow.[7]

Reported humeral osteotomies have been performed perpendicular to the humeral diaphysis.[8] Initial work by the authors using a three-dimensional (3D) computer model demonstrated that an osteotomy perpendicular to the weight-bearing axis of the limb (a line drawn directly from the shoulder to the center of the foot as shown in ►**Fig. 1**) produced significantly greater lateralization of the weight-bearing axis than one perpendicular to the long axis of the humerus. Greater lateralization was yielded when the osteotomy was performed closer to the elbow joint (as is performed with high tibial osteotomies in humans), and increasing the angle of change increased the degree of lateralization.[9,10] These results have not been confirmed by *ex vivo* testing.

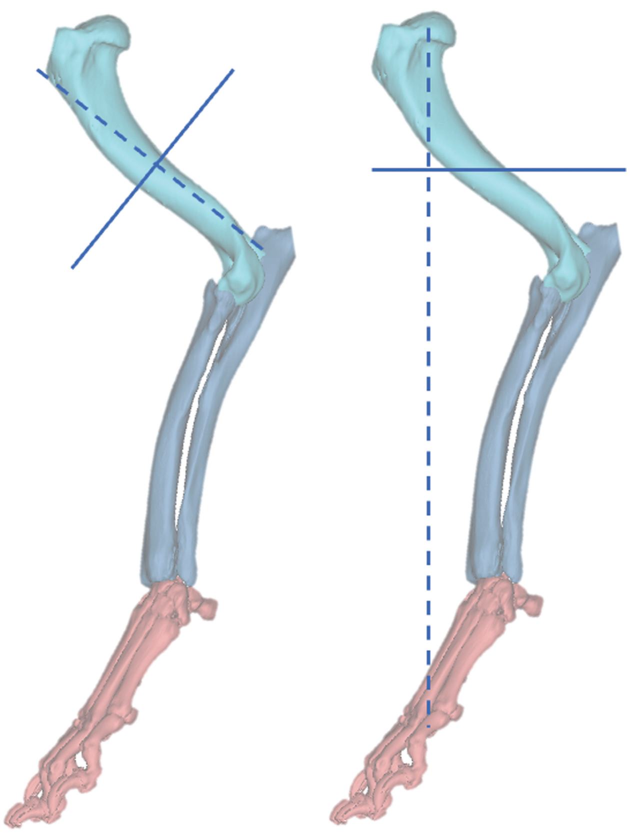

Fig. 1 Demonstration of the weight-bearing axis of the limb. The figure on the left demonstrates the long axis of the humerus (*dashed line*). "Transverse" osteotomies in this study were performed perpendicular to this axis (*solid line*). The axis of the humerus was determined using three-dimensional (3D) medical image processing software (Materialise Mimics), which places a line of best fit through the longitudinal axis. The image on the right illustrates the hypothetical "weight-bearing axis" (*dashed line*), which is a connecting line between the center of the shoulder joint and the estimated center of the weight-bearing surface of the paw with the joints at standard standing angles. The "oblique" osteotomies in this study are perpendicular to this *dashed line* (the *solid line* in the picture on the right).

The aim of this study was to assess the effect of various osteotomy parameters on the pressure in the medial and lateral compartments of the elbow joint using a cadaver-based *ex vivo* model, namely the following: the level of the osteotomy (50 or 75% the length of the humerus measured from proximal), the angular magnitude of the alteration (5, 10, or 20 degrees), the direction of bone alteration (external rotational or medial opening wedge osteotomies), and the orientation of the osteotomy (perpendicular to the humeral long axis or perpendicular to the weight-bearing axis of the limb). Our primary study aim was to identify the humeral osteotomy/alteration that most effectively reduced load in the medial compartment of the elbow. Our null hypotheses were that the load through the medial and lateral aspects of the elbow joint would not be affected by (1) the osteotomy location, (2) the angular magnitude of alteration, (3) the direction of bone alteration, and (4) the orientation of the osteotomy.

Material and Methods

Sample Acquisition

The University of Liverpool Veterinary Research and Ethics Committee granted ethical approval (VREC 780) for the study. Cadavers were acquired from medium to large (based on an ulnar length of 175–225 mm) adult dogs euthanized for reasons unrelated to the study; this size cadaver was chosen as breeds this size are commonly affected by medial compartment disease.[11] The limbs were frozen until time of computed tomography. Imaging was performed on the thawed limbs, which were then subsequently refrozen until the time of dissection and experiment.

The limbs were disarticulated at the glenohumeral joint, cutting through the musculature at this level. All humeral musculotendinous attachments, except those at the level of the medial and lateral aspects of the humeral condyle, were dissected from the humerus. The biceps brachii and brachialis muscles were cut near the elbow joint and the triceps brachii tendon was cut at its insertion at the olecranon tuber. Particular care was taken not to damage the collateral or annular ligaments.

Plate Design

Bone alterations were made using custom-designed bone plates, designed *in silico* and manufactured in titanium alloy (Ti6Al4V) via selective laser melting by an external manufacturer (Solo Additive, Suzhou, China). Prior to testing, the plates were sandblasted to remove any excess powder, and any remaining support material was removed using a file and rasp.

Computed tomography images of the thoracic limb from the mid-scapula to the manus were acquired using an 80-

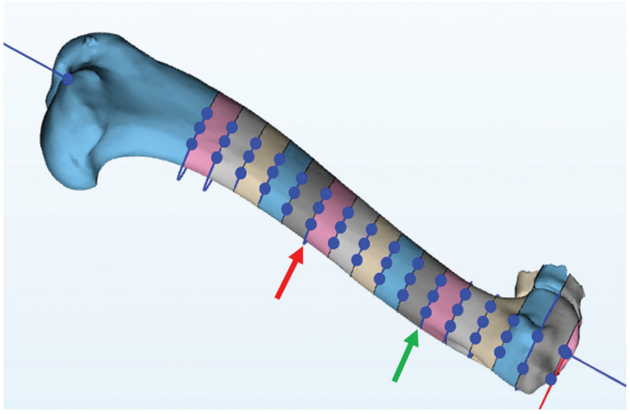

Fig. 2 Planned plate design on three-dimensional (3D) modeling software. This demonstrates a 3D *in silico* model of a humerus. The distal 75% of the humerus has been divided into 5% increments (*circumferential blue lines*), which have been block colored to demonstrate the divisions more clearly. The most medial aspect has been marked (*central blue dot*) 5.25 mm cranially and caudally to this (*blue dots* on either side). These *blue dots* map out the planned plate design. The *red arrow* indicates 50% the length of the humerus and the *green arrow* indicates 75% the length of the humerus, which are the locations of the two osteotomies.

slice Aquilion Prime scanner (TSX-303A/1C, Canon Medical Systems, CA, United States). Images were exported as DICOM files and imported into 3D medical image processing software (Materialise Mimics, Materialise NV, Belgium) where a 3D model was formed from the stack images.

The 3D model was imported into modeling software (Materialise 3-matic, Materialise NV, Belgium). The humerus was marked at 5% increments from distal to proximal. For the distal 75% of the humerus, the most medial aspect was marked, along with 5.25 mm cranially and 5.25 mm caudally, to generate planned plate designs 10.5 mm wide and 3.5 mm thick (►**Fig. 2**). These values were imported into a solid modeling computer program (SolidWorks, Dassault Systèmes, France) and the loft feature was used to create a solid structure between each layer.

One neutral plate (i.e., contoured to the natural bone shape) was created for each sample. The testing sample plates were created by performing *in silico* alterations, and generating plate designs to induce each of these states:

- Medial opening wedge plates (►**Fig. 3A**), designed for an osteotomy at either 50 or 75% the length of the humerus with 5-, 10-, or 20-degree adjustment angles. These plates incorporated a wedged disk at the level of the osteotomy designed to induce the desired angular alteration.
- External rotation plates (►**Fig. 3B**), designed for an osteotomy at either 50 or 75% the length of the humerus with 5-, 10-, or 20-degree adjustment angles. The whole orientation in these plates was such that insertion in the predrilled screw holes would induce the rotational alteration.

For each sample, there were a total of 12 testing plates: 6 opening wedge plates and 6 external rotation plates. Osteotomies perpendicular to the axis of the humerus (described as “transverse”) were performed in half of the samples, and osteotomies perpendicular to the weight-bearing axis of the

Fig. 3 Three-dimensional (3D) printed sample-specific implants showing an (**A**) opening wedge construct and (**B**) a rotational construct. The implants shown are 75% the length of the humerus straight osteotomy plates.

thoracic limb (line connecting the shoulder and the manus at standing angles and described as “oblique,” as they were oblique to the long axis of the humerus) were performed in the other half. All plates (neutral, opening wedge, and external rotational) were dynamic compression plates with nine screw holes that were numbered 1 to 9 from proximal to distal. The corresponding holes in the bone were numbered in the same fashion.

To add the opening wedge to the plate, the diameter of the humerus was measured at 50 and 75% the length of the humerus and a circle was drawn using the computer-assisted design software and extruded to create 5-, 10-, and 20-degree wedges (either perpendicular to the humerus or perpendicular to the weight-bearing axis), which were subsequently incorporated into the plate design. For the rotational alterations, the plate designs incorporated a rotational step at 50 or 75% of the humeral length.

Sample-specific cutting guides (►**Fig. 4**) contoured to the medial aspect of the bone were designed using the medical image processing and solid modeling software before being

Fig. 4 The sample-specific cutting guide. This guide would fit perfectly to the contour of the bone and was secured to the bone with three cortical screws placed in screw holes 4 and 6. The saw blade was lined up with the wings of the guide to ensure the osteotomy was performed at the current angle.

made in photopolymer resin using a 3D printer (Form 3, FormLabs, MA, United States).

Testing

Two limbs were used for preliminary testing to assess the best practice for the testing.

A custom-designed mount (►**Fig. 5**) was attached to the proximal humerus with three to four 4.5-mm cortical bone screws, depending on the size of the sample. The custom mount had a conical point, which articulated with a custom-made socket mounted on the biomechanical testing machine. A turnbuckle apparatus, anchored to the custom mount proximally and through a 2.5-mm hole in the olecranon distally, was used to simulate the triceps muscle.

Two ultra-thin load sensors (444-N FlexiForce sensors, Tekscan, MA, United States) were placed from cranial into the medial and lateral aspects of the elbow joint. These were secured in place by placing two short (~5 mm) screws into the cranial aspect of the humeral condyle, near to the joint, and fixing the sensors to the screws with a glue nondamaging to the sensors (No Nonsense, Siroflex, UK; ►**Fig. 6**). The same investigator placed the sensors into the joints for each test. Prior to placement, the sensors were calibrated by applying a load of 400 N at the rate of 10 N/s, holding each increment of 50 N for 10 seconds prior to placement into the joint. The sensors were connected to a microcontroller board (Arduino Uno, Arduino.cc), which gave live readings of the forces, in volts, applied to the sensors. The live readings were converted to a load in newton and transferred to a spreadsheet (Excel, Microsoft, WA, United States).

The sample was loaded into a universal testing system (Instron 3366, Instron, UK; ►**Fig. 7A** and **B**). The paw was placed directly under the humeral head and kept in place throughout testing using sandpaper glued to the machine; positioning of the paw was monitored using a plumbline. The turnbuckle was tensioned to bring the elbow joint to an angle of 135 degrees, which was assessed using a goniometer; one arm of the goniometer was aligned with the shaft of the humerus pointed toward the humeral head and the other with the antebrachial shaft pointed toward the styloid process of the ulna and the turnbuckle tensioned accordingly similar to previous studies.[2,12] The same person positioned the limb for each test and the angle was checked each time the limb was replaced in the testing system.

Initial testing was conducted on the native bone, prior to any hole drilled, osteotomy performed, or plate placed. The limb was loaded to 90 N at a rate of 5 N/s 20 times as a preconditioning cycle before each test. The load on the limb was then reduced to low (<10 N) before being loaded again to 90 N, where it was kept while three sensor readings were taken. This process was repeated five times, to collect 15 readings per sensor, per sample.

The sample was then removed from the testing system and the neutral plate was secured to the bone. The neutral

Fig. 5 Custom-designed mount with custom-designed socket for universal testing system. The mount was secured to the proximal humerus using three to four 4.5-mm cortical screws. The mount has a conical point that articulated with the custom-designed socket that was attached to the loading device. The turnbuckle apparatus mimicking the pull of the triceps is also appreciable; this was attached to the mount using a loop of stainless steel wire (all pictured).

Fig. 6 Cranial placement of the ultra-thin sensors in the lateral and medial compartments of the elbow joint. The photograph was taken from the cranial aspect of the joint; lateral is on the right (left limb). The sensors have been carefully threaded into the joint. Through the sensors very close to the joint two metal screws (one for each sensor) can be seen through the translucent plastic. The sensors were glued to these screws to prevent dislodgement during testing.

plate exactly matched the contour of the bone and had the same number of holes as the other plates, but did not induce any alteration to the bone. Holes were drilled with a 2.5-mm drill bit, tapped, and 3.5-mm cortical screws placed. Screws in holes nearest the osteotomies in the most proximal and distal fragments were placed in an eccentric position to allow compression. All screws were bicortical except the most distal screw, which was placed monocortical only to avoid inadvertent intra-articular placement. The screws were placed in the same order for each sample and by the same person to maintain consistency between samples. The limb was then remounted into the limb press, and preconditioned and then tested as above.

The limb was removed from the press and the plate was removed. The limb-specific osteotomy guide was then screwed to the limb using screw holes 4 and 6. Using the cutting guide, osteotomies were made at 50 and 75% the length of the humerus either perpendicular to the anatomical axis of the humerus (transverse) or perpendicular to the thoracic limb weight-bearing axis (oblique) using an oscillating saw. The neutral plate was placed again, using the saw blades as shims to fill the gaps in the bone created by removal of bone material caused by the osteotomies. The limb was then remounted into the testing jig, preconditioned, and tested as previously described. This process was then performed for each of the 12 testing plates. The order of the osteotomy plates tested was rotated between the samples.

Statistical Analysis

Student's *t*-tests were performed using statistical software (SPSS Statistics 27.0, IBM, New York, United States) comparing elbow joint forces before and after osteotomies performed and neutral plates applied to determine the effect of this process alone.

A mixed-design analysis of variance (ANOVA) was performed using the same aforementioned statistical software. The samples were split and analyzed in two groups depending on the osteotomy angle performed, either transverse or oblique. All the 12 test configurations were independent variables and the dependent variable was the difference in force through the medial compartment. The osteotomized sample with application of the neutral plate was used as the control group and significance was accepted if $p < 0.05$. The Pearson correlation coefficient was calculated using the same statistical software to assess the effect of the running order of the test samples.

Multilevel, multivariable regression was performed using programing language for statistical computing (R, R Foundation

Fig. 7 (A,B) Photographs of the testing setup for the 75% oblique 10-degree medial opening wedge construct. The plate is applied to the medial aspect of the bone with eight 3.5-mm bicortical screws and one 3.5-mm monocortical screw. At the location of the 50% osteotomy, an oscillating saw blade is left in place to fill the space left by the saw kerf and prevent limb shortening. The ultra-thin sensors can be seen along with their connections to the microcontroller board. The custom-designed mount is secured to the proximal humerus with three 4.5-mm bicortical screws and fits into a custom-designed socket to simulate the shoulder joint. The paw is positioned on sandpaper under which are four screws that aided repeatable paw positioning.

for Statistical Computing, Austria). Values analyzed included position of the osteotomy (50 or 75% length of humerus), magnitude of alteration induced by the applied plate (5, 10, or 20 degrees of humeral valgus OR external rotation), and the osteotomy axis (oblique or transverse).

Results

Twelve appropriate canine thoracic limbs were available. Performing osteotomies and applying the neutral plate reduced the mean force through the medial compartment by 21.1% ($p = 0.036$, Student's *t*-test) and reduced the force through the lateral compartment by 6.5% ($p = 0.099$).

Mixed-design ANOVA showed that the magnitude of alteration induced by the osteotomy (5, 10, or 20 degrees) and the location of osteotomy (50 or 75% the length of the humerus) had a significant effect on the force through the medial compartment. Oblique osteotomies reduced the load through the medial compartment more than transverse osteotomies, but not significantly so. The Pearson correlation coefficient was low ($R^2 = 0.0057$), meaning there was no correlation between order of sample testing and force through the medial compartment.

Multilevel, multivariable regression analysis revealed the variable with the greatest impact on the reduction of medial load was the osteotomy angle: it was estimated that for each 1 degree of angular alteration, the adjustment value for decreasing the load through the medial compartment was 1.08 ($p = 0.0002$). This means the adjustment value would be 21.6, 10.8, and 5.4 for 20, 10, and 5 degrees of angular change, respectively. Position of the osteotomy was the variable with the next greatest impact on reduction of medial load: osteotomies at 75% the length of the humerus were estimated to have an adjustment value for decreasing the load through the medial compartment of 8.06 compared to osteotomies performed at the humeral midpoint ($p = 0.026$). Type of osteotomy (wedged or external rotational) was the variable with the next greatest impact on reduction of medial load: wedged osteotomies were estimated to have an adjustment value for decreasing the load through the medial compartment of 7.26 compared to rotational osteotomies ($p = 0.045$). Osteotomies performed obliquely were estimated to have an adjustment value for decreasing the load through the medial compartment of 2.39 compared to osteotomies performed transversely, but this finding did not reach statistical significance ($p = 0.85$).

►**Fig. 8** illustrates the reduction of load through the medial compartment by each construct. As expected, in general, greater magnitudes of alteration led to greater reduction in medial elbow load. Osteotomies made more distally resulted in greater reduction in medial joint load than proximal osteotomies, and opening wedge osteotomies resulted in greater reduction in medial load than rotational osteotomies. ►**Fig. 9** illustrates the reduction in load through the medial compartment between oblique or transverse osteotomies for all positions, alteration types, and magnitude of alteration. The difference was not significantly different. ►**Fig. 10** illustrates the reduction in load through the medial compartment for each osteotomy position (mid-humeral or distal), including all orientations, alteration

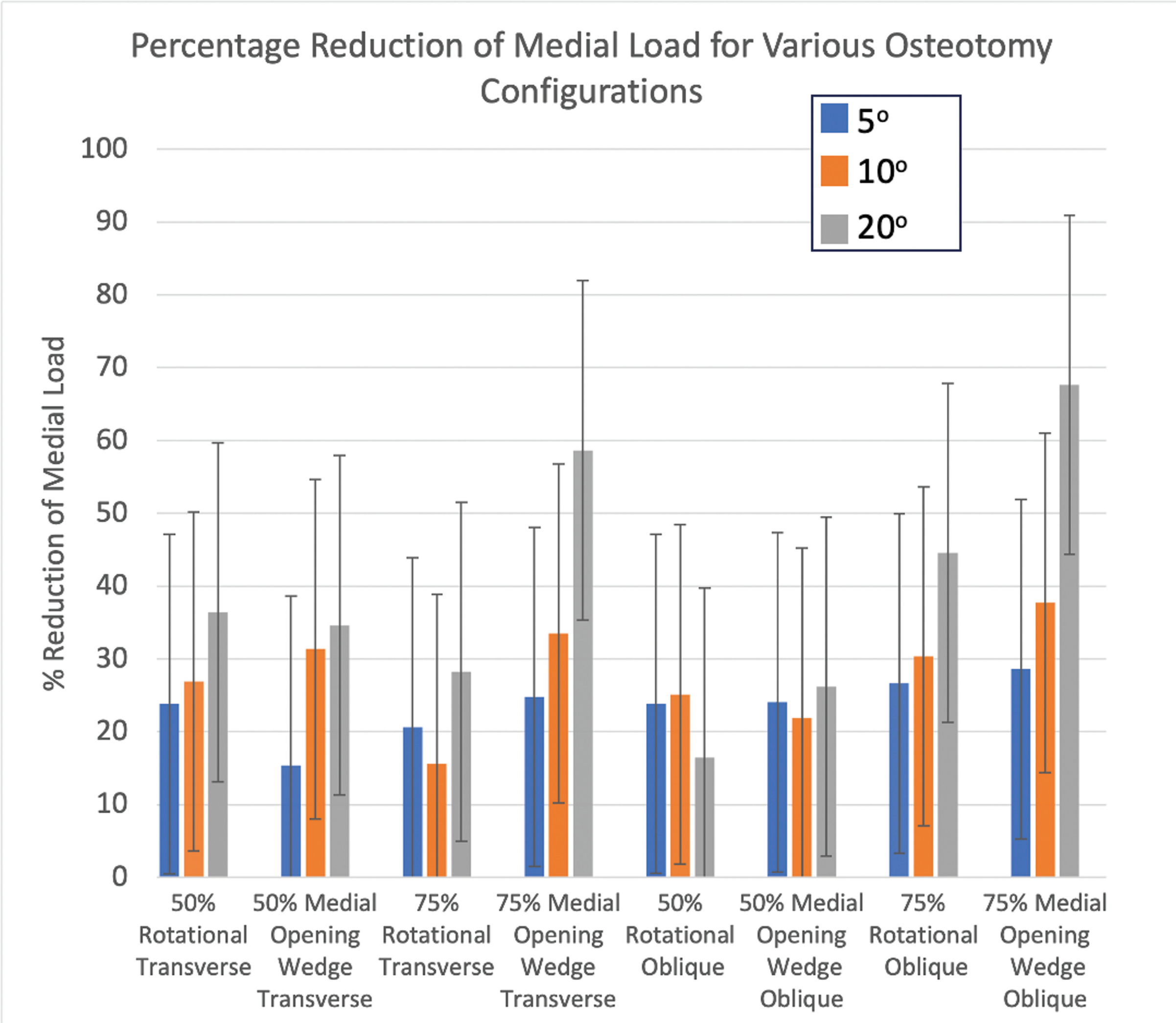

Fig. 8 Percentage reduction of load through the medial compartment for every test construct.

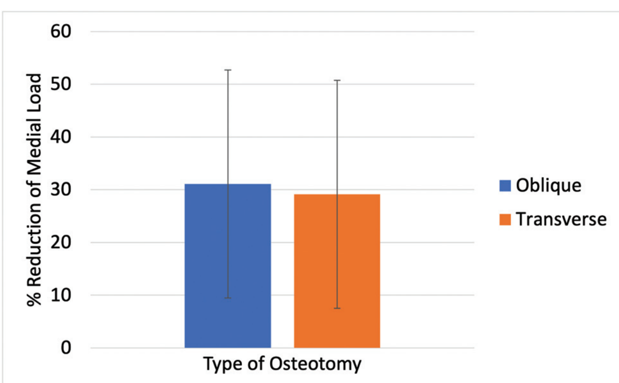

Fig. 9 Percentage reduction of load through the medial compartment for osteotomies either perpendicular to the thoracic limb alignment ("oblique") or perpendicular to the humerus ("transverse"). This graph demonstrates all "oblique" osteotomies compared to all "transverse" osteotomies (including all osteotomy levels, types, and angles). While the oblique osteotomies did demonstrate an increase in reduction of load through the medial compartment, statistical significance was not reached.

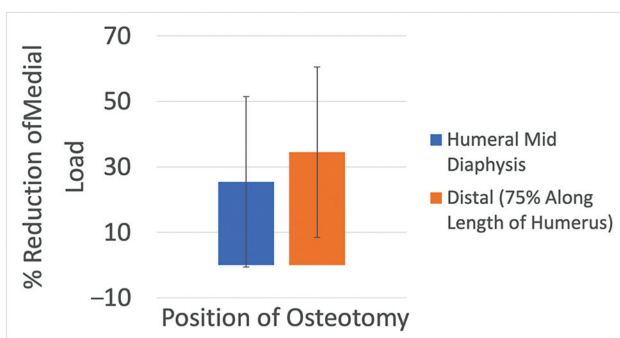

Fig. 10 Percentage reduction of load through the medial compartment of osteotomies through the mid-diaphysis (50% length of the humerus) or through the distal metaphysis (75% the length of the humerus). This graph demonstrates all mid-diaphyseal osteotomies compared to all distal osteotomies (including all osteotomy directions, types, and angles).

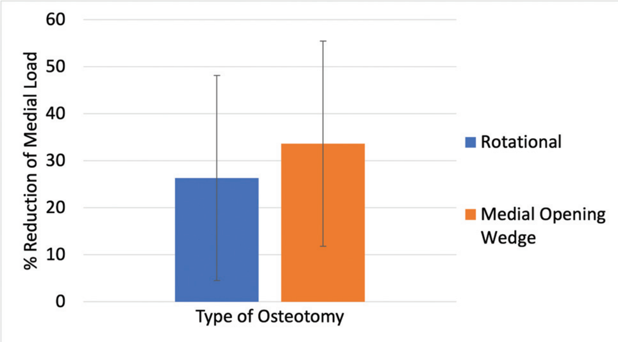

Fig. 11 Percentage reduction of load through the medial compartment for external rotational constructs compared to opening wedge constructs. This graph demonstrates all rotational constructs compared to all opening wedge constructs (including all osteotomy directions, levels, and angles).

types, and magnitude of alteration. Distal osteotomies significantly reduced load more than proximal osteotomies. ►**Fig. 11** illustrates the reduction of load through the medial compartment between rotational and medial opening humeral wedge osteotomies for all positions, orientations, and magnitudes of alteration. Medial opening wedge osteotomies significantly reduced load more than rotational osteotomies. ►**Fig. 12** illustrates the reduction in load through the medial compartment for 5, 10, and 20 degrees of alteration for osteotomies of all positions, orientations, and types. A magnitude of 20-degree alteration significantly decreased the load through the medial compartment compared to 10- and 5-degree alterations and a magnitude of 10-degree alteration significantly reduced the load through the medial compartment compared to a 5-degree alteration.

Statistical testing showed no trends for the lateral compartment (testing neither increased nor decreased load); therefore, figures illustrating this are not included.

Discussion

This study demonstrated that a more distal osteotomy reduced the load through the medial compartment more

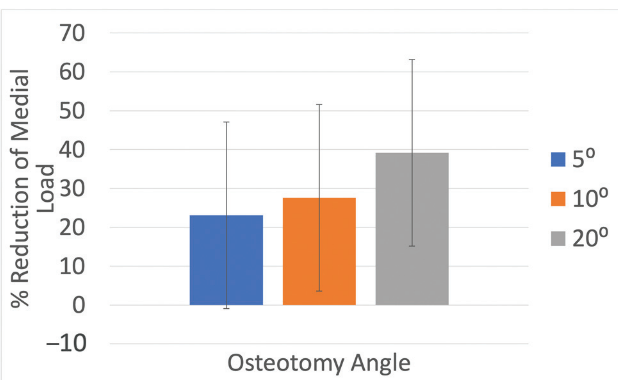

Fig. 12 Percentage reduction of load through the medial compartment depending on angle of change induced by the construct. This graph compares all 5-degree constructs with all 10-degree constructs and all 20-degree constructs, including all osteotomy directions, levels, and types.

effectively than a mid-humeral osteotomy. It also showed that increasing the angle resulted in greater reduction of load through the medial compartment. Both rotational and opening wedge osteotomies were found to be effective at reducing the load through the medial compartment. However, the angle of the osteotomy (transverse to the humerus compared to transverse to the thoracic limb weight-bearing axis) did not appear to have a significant effect. Therefore, our first three null hypotheses were rejected, and our fourth null hypothesis was accepted.

Osteoarthritis in human knees often progresses asymmetrically, predominating in the medial compartment, as seen in canine elbow medial compartment disease. Articular cartilage degrades primarily in the medial compartment, leading to collapse of the medial aspect of the joint, with the resulting varus deformity further increasing the load through this already diseased area.[13] High tibial osteotomies have been developed to reduce the contact pressures and contact area of the medial compartment.[4] Both medial opening and lateral closing wedge osteotomies have been described and compared, with both procedures having potential benefits. Opening wedge high tibial osteotomies have been reported to be more accurate, lead to improved range of motion, better preserve the tibiofibular joint, and have fewer early conversions to total knee replacement.[14–19]

Opening wedge high tibial osteotomies improve function and range of motion to the same degree as unicompartmental knee arthroplasty, although the complication rate might be higher.[5,20] High tibial osteotomies have been recommended for younger, more active patients, and a high rate of patients return to sport and work.[21,22] Canine patients with medial compartment disease are often young and active, which might make them suitable candidates for similar load-shifting osteotomies. There is some evidence that high tibial osteotomies may lead to medial knee compartment articular cartilage recovery,[23,24] and this might, therefore, be a realistic goal of load-shifting osteotomies for canine medial compartment disease.

Fujita and colleagues showed that a 10-degree medial opening wedge reduced humeroulnar contact and Mason and colleagues demonstrated a wedge osteotomy reduced the humeroulnar force, although statistical significance was not reached.[2,6] In these studies, the osteotomies were performed at the mid-diaphysis, for two reasons: it allowed for sliding and wedge osteotomies to be tested on the same samples and the authors argued it would make a more practicable surgery (adequate space for stabilization, avoiding neurovascular or joint stabilizing structures). However, performing the osteotomy closer to the joint will lead to greater lateralization effect at the level of the elbow, as shown previously.[9] Since these publications, locking plate technology has become more widespread and 3D-printed custom surgical guides have become relatively accessible, advances that may make osteotomies closer to the joint safer than they were before. Furthermore, it has been postulated that the metaphysis, rich in cancellous bone with abundant numbers of stem cells, may have improved healing properties compared to diaphyseal bone[25] and this may be another benefit to performing the osteotomy distally, although this cannot be proven at this stage.

The sliding humeral osteotomy has been reported clinically to improve subjective lameness scores and ground reaction forces, decrease clinician-assessed elbow pain, and improve owner-assessed mobility following surgery.[8,26,27] However, possibly due to fear of severe complications and the lack of comparator groups, clinical application has been limited. The apparent steep learning curve associated with the procedure[8,27] is also likely to be a deterrent for unfamiliar surgeons. It has been suggested that the sliding humeral osteotomy might be effective, at least in part, because of the valgus that is induced by the procedure.[8]

The proximal abducting ulnar osteotomy (PAUL; KYON, Switzerland) reduced contact pressure in the medial compartment of experimentally induced incongruent elbows but did not reduce contact pressure of congruent elbows, and translated the thoracic limb mechanical axis laterally at the level of the elbow joint in *ex vivo* studies.[28,29] Coghill and colleagues, however, reported no difference in canine brief pain index scores or long-term nonsteroidal anti-inflammatory drug use between dogs treated with arthroscopy alone, compared to dogs treated with arthroscopy and PAUL, and the major and total complication rates for the PAUL procedure have recently been reported to be 18 and 26%, respectively, raising concern regarding the safety of this technique.[30,31] Furthermore, the antebrachium is a two-bone segment, and the impact PAUL has on radioulnar congruency is not clear. A humeral osteotomy has the benefit that the brachium is a one-bone segment, and therefore the effect on limb geometry is more predictable.

While opening wedge constructs were more effective than external rotational osteotomies in the current study, external rotational osteotomies were also effective at reducing medial compartment load (►**Fig. 11**), corroborating previous findings that this procedure can shift the peak pressure location through the elbow laterally.[3] External rotational constructs offer some benefits compared to opening wedge osteotomies: the lack of induced humeral valgus may reduce compressive forces at the lateral aspect of the bone and bone fragments remain in compressed contact following plate application, allowing load sharing and primary bone healing.

Despite an oblique osteotomy proving beneficial in an *in silico* model,[10] the angle of the osteotomy did not have a significant effect in this study. In the *in silico* model, only limb alignment is assessed, excluding effects of soft tissues, particularly the pull of the triceps mechanism, which may negate the effects of the oblique osteotomy in the *ex vivo* experiment. It may also be that the degree of change is too small or the number of samples too few to reach significance or that the sensors were not sensitive enough to detect a difference.

Our study did not show a significant increase in the force through the lateral compartment, in line with other studies on humeral osteotomies.[2,6] It appears that redistribution of load is more complicated than a simple medial to lateral shift. The aim of this study was to assess which bone alterations would lead to a reduction in medial load as this is the ultimate therapeutic goal for treating dogs with medial compartment disease.

Prior to testing, all samples were tested with a “neutral” plate, a plate that did not induce an alteration on the bone. This was performed to investigate if application alone of the plate would affect the load through the medial compartment, which, surprisingly, it did and the reasoning for this is unclear. The test condition samples were compared to the sample with the neutral plate to remove this factor from the final analysis.

In this study, thin pressure sensors were used directly in the joint, similar to a previous report.[32] These sensors allow for assessment of load reduction at precisely the level of the elbow. Our primary objective was to evaluate loading change in the humeroulnar joint, specifically the craniodistal area that is most often clinically affected in medial compartment disease. Similar to other studies, a compressive load of 90 N was used,[3] which equates to the force through a thoracic limb of a 30-kg dog when standing. The use of 12 cadavers was comparable to the number of samples used in previous similar studies.[2,12,28]

The findings from this study support the statement that humeral osteotomies could be used to reduce the load through the medial compartment of the elbow, especially if the osteotomy is performed distally, and that the reduction of this load is proportional to the angle of induced change.

These findings should not be considered clinical recommendations. Aspects such as adverse effects on limb alignment, soft-tissue loading, and bone healing need to be carefully considered prior to clinical use. Once appropriate surgical systems and implants have been designed, ethically approved clinical trials should be performed, initially with a small group to assess safety, then a larger group to assess efficacy, ideally against an appropriate control group.

Authors’ Contribution

E.C. contributed to the study design, acquisition of data, data analysis and interpretation, and writing of the initial manuscript. A.B. contributed to conception of the study, study design, acquisition of data, and data analysis and interpretation. T.W.M. contributed to data analysis and interpretation. D.J. contributed to conception of the study, study design, and data analysis and interpretation. M.B.W. contributed to conception of the study, study design, and data analysis and interpretation. All the authors revised and approved the manuscript before submitting.

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Conflict of Interest

None declared.

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References

1 Fitzpatrick N, Yeadon R. Working algorithm for treatment decision making for developmental disease of the medial compartment of the elbow in dogs. Vet Surg 2009;38(02):285–300

2 Mason DR, Schulz KS, Fujita Y, Kass PH, Stover SM. Measurement of humeroradial and humeroulnar transarticular joint forces in the canine elbow joint after humeral wedge and humeral slide osteotomies. Vet Surg 2008;37(01):63–70

3 Gutbrod A, Guerrero TG. Effect of external rotational humeral osteotomy on the contact mechanics of the canine elbow joint. Vet Surg 2012;41(07):845–852

4 Mina C, Garrett WE Jr, Pietrobon R, Glisson R, Higgins L. High tibial osteotomy for unloading osteochondral defects in the medial compartment of the knee. Am J Sports Med 2008;36(05):949–955

5 Cao Z, Mai X, Wang J, Feng E, Huang Y. Unicompartmental knee arthroplasty vs high tibial osteotomy for knee osteoarthritis: a systematic review and meta-analysis. J Arthroplasty 2018;33(03):952–959

6 Fujita Y, Schulz KS, Mason DR, Kass PH, Stover SM. Effect of humeral osteotomy on joint surface contact in canine elbow joints. Am J Vet Res 2003;64(04):506–511

7 Breiteneicher AH, Norby B, Schulz KS, et al. The effect of sliding humeral osteotomy (SHO) on frontal plane thoracic limb alignment: an *ex vivo* canine cadaveric study. Vet Surg 2016;45(08):1095–1107

8 Fitzpatrick N, Yeadon R, Smith T, Schulz K. Techniques of application and initial clinical experience with sliding humeral osteotomy for treatment of medial compartment disease of the canine elbow. Vet Surg 2009;38(02):261–278

9 Brettle A, Garcia-Tunon E, Bates K, et al. Load-Shifting Osteotomies for Medial Compartment Disease of the Canine Elbow: Establishing a Geometric Model. Paper presented at: BVOA Spring Meeting; April 4, 2018; Birmingham, UK

10 Brettle A, Crystal E, Geraghty B, et al. Biomechanical Testing of Load Shifting Osteotomies for the Treatment of Medial Compartment Disease. Paper presented at: BVOA Spring Meeting; March 23; 2022; Manchester, UK

11 LaFond E, Breur GJ, Austin CC. Breed susceptibility for developmental orthopedic diseases in dogs. J Am Anim Hosp Assoc 2002;38(05):467–477

12 Cuddy LC, Lewis DD, Kim SE, et al. *Ex vivo* contact mechanics and three-dimensional alignment of normal dog elbows after proximal ulnar rotational osteotomy. Vet Surg 2012;41(08):905–914

13 Sutton PM, Holloway ES. The young osteoarthritic knee: dilemmas in management. BMC Med 2013;11:14

14 Sun H, Zhou L, Li F, Duan J. Comparison between closing-wedge and opening-wedge high tibial osteotomy in patients with medial knee osteoarthritis: a systematic review and meta-analysis. J Knee Surg 2017;30(02):158–165

15 Agarwala S, Sobti A, Naik S, Chaudhari S. Comparison of closing-wedge and opening-wedge high tibial osteotomies for medial compartment osteoarthritis of knee in Asian population: mid-term follow-up. J Clin Orthop Trauma 2016;7(04):272–275

16 Duivenvoorden T, Brouwer RW, Baan A, et al. Comparison of closing-wedge and opening-wedge high tibial osteotomy for medial compartment osteoarthritis of the knee: a randomized controlled trial with a six-year follow-up. J Bone Joint Surg Am 2014;96(17):1425–1432

17 Duivenvoorden T, van Diggele P, Reijman M, et al. Adverse events and survival after closing- and opening-wedge high tibial osteotomy: a comparative study of 412 patients. Knee Surg Sports Traumatol Arthrosc 2017;25(03):895–901

18 Wu L, Lin J, Jin Z, Cai X, Gao W. Comparison of clinical and radiological outcomes between opening-wedge and closing-wedge high tibial osteotomy: a comprehensive meta-analysis. PLoS One 2017;12(02):e0171700

19 Kim JH, Kim HJ, Lee DH. Survival of opening versus closing wedge high tibial osteotomy: A meta-analysis. Sci Rep 2017;7(01):7296

20 Takeuchi R, Umemoto Y, Aratake M, et al. A mid term comparison of open wedge high tibial osteotomy vs unicompartmental knee arthroplasty for medial compartment osteoarthritis of the knee. J Orthop Surg Res 2010;5(01):65

21 Dettoni F, Bonasia DE, Castoldi F, Bruzzone M, Blonna D, Rossi R. High tibial osteotomy versus unicompartmental knee arthroplasty for medial compartment arthrosis of the knee: a review of the literature. Iowa Orthop J 2010;30:131–140

22 Hoorntje A, Witjes S, Kuijer PPFM, et al. High rates of return to sports activities and work after osteotomies around the knee: a systematic review and meta-analysis. Sports Med 2017;47(11):2219–2244

23 Parker DA, Beatty KT, Giuffre B, Scholes CJ, Coolican MR. Articular cartilage changes in patients with osteoarthritis after osteotomy. Am J Sports Med 2011;39(05):1039–1045

24 van der Woude JAD, Wiegant K, van Heerwaarden RJ, et al. Knee joint distraction compared with high tibial osteotomy: a randomized controlled trial. Knee Surg Sports Traumatol Arthrosc 2017;25(03):876–886

25 Inoue S, Otsuka H, Takito J, Nakamura M. Decisive differences in the bone repair processes of the metaphysis and diaphysis in young mice. Bone Rep 2017;8:1–8

26 Wendelburg KM, Beale BS. Medium and long term evaluation of sliding humeral osteotomy in dogs. Vet Surg 2014;43(07):804–813

27 Fitzpatrick N, Bertran J, Solano MA. Sliding humeral osteotomy: medium-term objective outcome measures and reduction of complications with a modified technique. Vet Surg 2015;44(02):137–149

28 McConkey MJ, Valenzano DM, Wei A, et al. Effect of the proximal abducting ulnar osteotomy on intra-articular pressure distribution and contact mechanics of congruent and incongruent canine elbows *ex vivo*. Vet Surg 2016;45(03):347–355

29 Amadio A, Corriveau KM, Norby B, Stephenson TR, Saunders WB. Effect of proximal abducting ulnar osteotomy (PAUL) on frontal plane thoracic limb alignment: an *ex vivo* canine study. Vet Surg 2020;49(07):1437–1448

30 Coghill FJ, Ho-Eckart LK, Baltzer WI. Mid- to long-term outcome after arthroscopy and proximal abducting ulnar osteotomy versus arthroscopy alone in dogs with medial compartment disease: thirty cases. Vet Comp Orthop Traumatol 2021;34(02):85–90

31 Danielski A, Krekis A, Yeadon R, et al. Complications after proximal abducting ulnar osteotomy and prognostic factors in 66 dogs. Vet Surg 2022;51(01):136–147

32 Garofolo SQ, Conzemius MG. Articulated joint distraction in a cadaveric model of the canine elbow. Vet Comp Orthop Traumatol 2019;32(05):362–368

