Three-Dimensional Joint Kinematics in a Canine Elbow Joint with Medial Coronoid Disease before and after Bi-Oblique Dynamic Proximal Ulnar Osteotomy

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Introduction

Developmental elbow disease is a common cause of forelimb lameness especially in young dogs, being bilateral in 25 to 80% of cases.¹⁻⁵ A permanent developmental mismatch in the radioulnar joint surface, called static axial radioulnar incongruence (sRUI), has been shown to increase load at the medial coronoid process (MCP).⁶⁻⁷ Being related to the severity of joint pathology at the medial joint compartment,⁸ sRUI is commonly cited as one factor for the development of medial coronoid process disease (MCPD).³⁻⁹ Other factors, which have been cited as a potential biomechanical cause of MCPD, are dynamic RUI (dRUI) and humeroulnar rotational instability.¹⁰⁻¹⁶ Dynamic RUI is defined as an increased motion between the radius and ulna, leading to a temporary incongruence of the radioulnar joint surface during locomotion. Among those, sRUI as well as dRUI have recently been excluded as primary causes of MCPD.¹⁰,¹⁷,¹⁸

Dynamic proximal ulnar osteotomy (DPUO) was introduced in the 1990s to correct sRUI and to overall improve joint congruence.¹⁹,²⁰ Correction of positive sRUI leads to

Abstract

Objective The aim of this study was to report the humeroulnar joint kinematics in a dog with medial coronoid process disease (MCPD) before and after dynamic proximal ulnar osteotomy (DPUO).

Study Design A 15-month-old female Labrador Retriever with advanced MCPD was treated by DPUO and fragment removal. Bi-planar fluoroscopic kinematography of the affected joint was performed before and 12 weeks after DPUO along with computed tomography. Static axial radioulnar incongruence (sRUI), dynamic relative proximal-distal radioulnar motion (dynamic RUI), axial humeroulnar rotation, as well as humeroulnar joint contact at the medial coronoid process (MCP) were calculated.

Results Static axial radioulnar incongruence was reduced from 2.3 to 1.5 mm after DPUO but dynamic RUI remained unchanged (0.2 vs. 0.3 mm). Mean humeroulnar rotational amplitude increased from 2.6° (standard deviation 0.4) to 4.5° (standard deviation 2.0). Joint contact area at the MCP became substantially increased as well as broadly distributed among the MCP following DPUO (52.5 vs. 63.0%; p = 0.0012).

Conclusion Dynamic proximal ulnar osteotomy failed to restore the radioulnar congruence and increased the humeroulnar rotational instability. No effect was observed on dynamic RUI. Nevertheless, joint contact area at the MCP was increased and became more homogeneously distributed, which might explain the beneficial effect of clinical outcome in this case.
more physiologically balanced joint loads at the medial joint compartment. However, DPUO fails to re-establish radioulnar joint congruence in vivo, while at the same time DPUO ameliorates focal humeroulnar joint contact at the MCP.

We had the unique opportunity to follow a dog with MCPD, with positive sRUI and humeroulnar instability until bony union of a DPUO, using in vivo fluoroscopic kinematography. Our working hypothesis was that DPUO would reduce humeroulnar rotational instability, improve sRUI and would re-establish a homogenously distributed contact pattern at the MCP.

**Case Description**

A 15-month-old female Labrador Retriever with a body weight of 27 kg was presented to the Department of Small Animal Medicine, University of Leipzig, because of unilateral, left sided, grade 2/5, forelimb lameness. Both forelimbs were held in slight supination and abduction. Pain was elicited on palpation of the left elbow. Otherwise, the dog showed no other clinical abnormalities. Orthogonal radiographs of both elbow joints revealed subtrochlear sclerosis and signs of secondary osteoarthritis at the left elbow joint. Osteoarthritic changes were classified as grade 2 according to the International Elbow Working Group. Based on these findings, the tentative diagnosis of MCPD was made and confirmed by computed tomography (CT) and arthroscopy.

**Advanced Imaging Findings and Surgical Treatment**

Transverse CT with a slice thickness of 1 mm and an overlapping increment of 0.5 mm (Philips Brilliance; Philips, the Netherlands) of both elbow joints was performed under general anaesthesia with the dog in dorsal recumbence. Computed tomography showed fragmentation of the MCP at the left side, while the right elbow showed no signs of MCPD. Quantification of sRUI using the sphere fitting technique on three-dimensional (3D) renderings of the radioulnar joint cup provided evidence of a 2.3 mm positive sRUI in the left elbow.

Findings of standard medial arthroscopy of the left elbow using a 1.9 mm 30° fore-oblique scope (Storz Endoskope, Tuttingen, Germany) matched up with the results of the CT scan, showing a positive radioulnar incongruence, a non-displaced fragment at the radial incisure of the MCP as well as Modified Outerbridge grade 2 to 3 cartilage lesions at the MCP and grade 3 to 4 lesions on the opposing humeral trochlea. Arthroscopic evaluation of radioulnar incongruence was performed, using a scaled hook probe (Arthrex VetSystems, Munich, Germany). The fragment was removed via arthroscopy and the joint lavaged. Further surgical treatment, such as DPUO, was declined by the owners at that time. The right joint was not approached due to lack of clinical signs.

Five weeks later bi-oblique DPUO, as described by Fitzpatrick, was performed at the request of the owners, due to ongoing lameness of the left forelimb. A second transverse CT scan of the affected elbow joint was acquired 12 weeks following DPUO when the dog underwent laparoscopic ovarioectomy. Quantification of sRUI using the sphere fitting technique on these CT-based 3D bone models showed a radioulnar step of 1.5 mm. Comparing the preoperative 3D renderings to the images following DPUO,
the proximal ulna segment showed the typical rotation in multiple planes as described previously, with cranial tipping of the segment and lowering of the MCP being the most prominent geometric changes (Fig. 5).

**Fluoroscopic Kinematography**

With owner’s consent, three 0.8 mm tantalum beads (Tantalum Beads, X-Medics Scandinavia, Frederiksberg, Denmark) were implanted into ulna, radius and ulna each on the left side, immediately following arthroscopy. Transverse CT was performed after implantation using the same parameters as for the preoperative CT. Bead implantation was part of an unrelated clinical study comparing 3D elbow kinematics between sound and dysplastic elbow joints. The study was approved by the local governmental ethical committee for animal welfare (Reg. Nr.: 15-105/08).

Three weeks after implantation, fluoroscopic kinematic gait analysis of the left elbow joint was performed. While the dog was walking on a canine treadmill (Jog A Dog, LLC, Michigan, United States), synchronized biplanar X-ray movies of the elbow joint were taken at a frame rate of 500 fps with a shutter of 0.5 milliseconds. A third synchronized high-speed video camera was used to capture a life video stream of the dog on the treadmill. A second fluoroscopic kinematography was performed, using the identical setup 12 weeks after DPUO. By that time radiographic healing of the osteotomy had been documented and the dog showed no signs of lameness at walk and trot. To allow quantitative analysis of joint motion, it was necessary to transform the gained 2D image sequences to a 3D animation of the elbow joint. First, 3D bone models of the left humerus, ulna and radius were calculated, based on the transverse CT data acquired after bead implantation and following healing of the DPUO, respectively, using dedicated software (MeVisLab 2.0, MeVisMedical Solutions AG, Bremen, Germany). On these models, the 3D position of the implanted tantalum beads in respect to the local bone embedded coordinate system was digitized and stored for later use. Using special software (XrayProject; Providence, Rhode Island, United States), the image coordinates of each tantalum marker were determined.
manually in the synchronized X-ray movies. Tracking of bead trajectories started 30 frames before ground contact and ended 120 frames afterwards, using the life video to determine ground contact. These 120 frames represent about one-third of the whole stance phase. Restriction of the gait analysis to the first third of stance phase was due to technical reasons; during the later stance phase superimposition of the elbow joint with the thoracic body wall and/or the contra lateral limb occurred and made bead tracking unreliable. Using direct linear transformation, the 2D coordinates of the markers in the X-ray movies were converted to the respective 3D room coordinates and transferred onto the markers in the 3D models. This allowed animation of the 3D models in virtual space replicating exactly the kinematics of the elbow joint during the walk. Accuracy of this approach has been reported to be less than 0.1 mm and 0.1 degree. For measurement of relative humeroulunar motion, a 3D joint coordinate system was defined, with the z-axis orientated along a transcondylar axis of the humeral condyle, the y-axis parallel to the long axis of the ulna and the x-axis perpendicular to the first two. The medial and lateral epicondyle were used as landmarks for the transcondylar axis. Relative axial radioulnar translation was measured along a joint coordinate system with the z-axis along a transcondylar axis of the humeral condyle were used as landmarks for the transcondylar axis. Relative axial radioulnar translation was measured along a joint coordinate system with the z-axis and through the tip of the anconeal process and the z-axis and through the tip of the anconeal process and the y-axis perpendicular to these two. Dynamic RUJ was defined as any radial motion along the y-axis in relation to the ulna. For kinematic calculations, data of three steps of the left forelimb were averaged each. Relative bone motion was expressed as maximal amplitude, measured between beginning of ground contact (30th frame) and the 150th frame. Data from three gait cycles were averaged and expressed as mean values and respective standard deviation (SD). Pairwise comparison of calculated measurements was done using a paired t-test.

Mean amplitude of relative axial humeroulunar rotation was 2.6 degrees (SD: 0.4) before and 4.5 degrees (SD: 2.0) 12 weeks after DPUO, being not significantly different (p = 0.1819). Therefore, rotational moment of the humerus was even increased after DPUO, with the trochlea sliding towards cranio-lateral driving the trochlea against the lateral aspect of the MCP. Relative axial translation between radius and ulna, representing dRUI, was 0.2 mm (SD: 0.03) before DPUO and 0.3 mm (SD: 0.08) afterwards (not significantly different; p = 0.1126).

Based on the 3D animations, distance between the subchondral bone surface of humerus and ulna was calculated in every 10th frame and mapped onto the ulnar joint surface model, as described by Krotschek et al. For quantitative evaluation of joint contact at the medial coronoid, the MCP was divided into nine equally sized areas using dedicated software (3-matic Research 13.0; Materialise Mimics Innovation Suite, Materialise GmbH Munich, Germany). First, the MCP was separated from the remaining ulnar bone model. A line was drawn along the medial aspect of the MCP; separation of the MCP was than performed along a line perpendicular to that first line transecting the lateral coronoid process (Fig. 6A). Afterwards the joint surface of the MCP was segmented from the remaining ulnar bone (Fig. 6B). This joint surface model was divided into nine equal parts based on its maximal bone width and length. Starting at the coronoid base three rows were numbered A, B and C (from base towards tip) and three columns were numbered by 1, 2 and 3, starting at the medial aspect of the MCP (Fig. 6C). Joint contact patterns were evaluated for the whole mediocoronal joint surface and in each of the nine parts, using ParaView (ParaView 5.6.1; Kitware Inc., Clifton Park, NY, United States). Joint contact was measured and expressed as per cent; comparison between the preoperative and postoperative situation was performed using paired t-test. Before DPUO, 52.5% of the medial coronoid was in contact with the corresponding humerus and contact area was concentrated at the tip and the lateral aspect of the MCP. Following DPUO the contact area increased to 63.0% and was evenly distributed along the MCP (Fig. 7A, B, see additional Video 1). Difference was significant between the
that the humeroulnar joint contact area was increased (52.5 vs. 63.0%) and became more evenly distributed over the area of the MCP following DPUO. In particular, the coronoid base showed significantly increased contact (A1–A3 compartments), while the lateral aspect of the coronoid tip was unloaded following DPUO (C3: 95.9 preoperatively vs. 27.9% postoperatively). Compared with the preoperative concentration of a relatively small contact area at the lateral aspect of the MCP, which corresponds well with the typical topography of early MCPD lesions, we interpret this change in contact pattern to be a biomechanical improvement in overall humeroulnar joint mechanics, and we would expect a beneficial clinical effect. This assumption is strengthened by the observation during second-look arthroscopy following DPUO in joints with medial compartment disease, documenting fibrocartilage growth at the formerly denuded joint surfaces. Second-look arthroscopy was not available in the present case. Further, changes of the joint contact area within the humeroradial joint were not evaluated. Thus, we are not able to describe overall changes of the contact pattern within this canine elbow after DPUO.

After healing of the osteotomy, the dog showed no detectable lameness and was pain free on elbow palpation. Owners reported good function as well as no signs of lameness and pain. Sixteen months after DPUO, according to the owners, the dog still showed no signs of pain or lameness, even after intense exercise. However, because force plate analysis was not available at any point in time, it is impossible to objectivize the effect of DPUO on functional outcome.

The focal concentration of humeroulnar joint contact, seen before DPUO, is probably the result of humeral rotational instability present in elbow joints with MCPD. Comparing sound and dysplastic elbow joints revealed that in affected elbows the humeral condyle rotates externally, with the humeral trochlea being driven against the lateral part of the MCP. This motion pattern was also present in our case, and even markedly increased after DPUO. Although the anconeal process was pushed deeper into the olecranon fossa following DPUO, this did not constrain axial humeroulnar rotation. We speculate that the complex 3D deformity of the proximal ulna, induced by DPUO, allows more axial rotation, because the MCP rotates distally and therefore there is less rotational restraint for the trochlea. When comparing the deformity of the ulna in the present case to what has been reported previously following DPUO, it seems that malalignment was less severe than what typically occurs. This might be due to the very long bi-oblique cut in the ulna, which exceeded the recommendations made by Caron and Fitzpatrick, allowing less movement to the proximal ulna segment following the osteotomy.

Conclusion

To our knowledge this is the first report of in vivo joint kinematics and joint contact pattern following DPUO in a canine elbow joint with MCPD. Although DPUO did not restore normal radioulnar congruence while potentially increasing rotational humeroulnar instability, the...
humeroulunar joint contact became more homogenously distributed at the MCP following DPUO. We speculate that this biomechanical change corresponds with the functional improvement in this patient.

Author Contributions
All authors contributed to conception of study, study design, acquisition of data and data analysis and interpretation. All authors drafted, revised and approved the submitted manuscript.

Conflicts of interest
None declared.

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