FINITE ELEMENT SIMULATION OF CANINE HUMERAL CONDYLAR FRACTURES

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SUMMARY
The goal of this work is to understand the effects of bone posture and skeletal development on canine humeral fractures by means of the finite element method. Main contributions are: (1) the building of patient-specific multi-material finite element meshes of the dog elbow, (2) the use of an anisotropic material law to model the behavior of cortical bone and (3) the implementation of the modified Mohr-Coulomb failure criterion to take account for bone strength asymmetry. Results are in good agreement with clinical observations.

INTRODUCTION
Humeral condylar fractures are common in dogs and are often associated with trauma such as fall. Lateral condylar fractures are the most common, while medial and bicondylar (Y- or T-shaped) fractures occur less frequently. Moreover, lateral fractures are most prevalent in young dogs, before the ossification of the humeral condyles. On the other hand, bicondylar fractures are typically seen in skeletally mature dogs. It is believed that lateral condylar fractures are due to an excessive force carried by the radius, which predominantly articulates with the lateral part of the humerus.

The objective of this study is to verify the pathogenesis of condylar fractures and to determine the influence of bone positioning as well as skeletal development on the fracture type, by means of the finite element method.

Even though it is focused on a particular application, this paper addresses the key challenges seen in subject-specific biomedical modeling. High quality multi-material meshes are extracted from the CT-data allowing us to apply distinct material properties to cortical bone, trabecular bone and cartilage. This is crucial because elastic and strength properties of these structures are extremely different [1]. In the proposed model, an anisotropic constitutive law is used for cortical bone while cancellous bone and cartilage are considered isotropic. The Mohr-Coulomb failure criterion is applied to take account for strength asymmetry.

METHODS
A computed tomographic scan of the right elbow in extension coming from a 4 months old beagle was taken. This three-dimensional image was segmented in order to delineate the three bones composing the elbow: humerus, radius and ulna. The humerus was further subdivided into cortical bone, trabecular bone, medullary cavity and cartilaginous growth plate. The latter was replaced by epiphyseal trabecular bone to create a skeletally mature humerus model. Finite element meshes were then generated from this multiple region 3D image using our home-made mesh generator [2]. The meshes obtained for the humerus contain three (adult) and four (young) material regions (Figure 1).

Four distinct finite element simulations were performed, corresponding to an immature and a mature dog elbow, respectively in extension 150° and flexion 60°.

In these simulations, radius and ulna were considered rigid, and their surface meshes, extracted from the CT images, were used to define their contact with the humerus. The articulation, as extracted from the CT-data, was in extension. For the two models in flexion, manual rotation of the ulna and radius around the humerus was performed.

The assumed material properties are reported in Table 1. The cortical bone was modeled as a transversely isotropic material, having a lower Young’s modulus in the transverse direction than along the longitudinal axis [1,3]. Trabecular bone and cartilage were modeled as elastic materials with isotropic hardening [3]. The medullary cavity was filled with a linear elasto-plastic material of lower Young’s modulus and yield strength than the epiphyseal cancellous bone. The Mohr-Coulomb failure criterion was used to take

Figure 1: Finite element mesh of a dog humerus condyle obtained from the CT-data. The humerus is subdivided into four components: cortical bone (semi-transparent), trabecular bone (blue), medullary cavity (red) and cartilage (green).
into account the difference between compression and tension failure properties [1]. Indeed, previous studies have shown that the Von Mises criterion was not able to reproduce the observed failure patterns.

Loading was applied by imposing a displacement to the radius and the ulna, in a direction parallel to the longitudinal axis of the humerus, at a speed of 140 mm/min (Figure 2, Left). Radiohumeral and humeroulnar frictionless contact are defined using the penalty method. An implicit Newmark time integration scheme is used. Finite element simulations are performed in Metafor [4].

Bone contact, stress-strain distribution within the distal humerus, failure type and failure load were reported in 60° and 150° of flexion-extension angle for both the mature and immature canine elbow.

RESULTS AND DISCUSSION

Lateral humeral fractures are observed for both the young and adult dog elbow in extension and flexion (Figure 2, Right).

![Figure 2: Finite element simulation of the failure of a skeletal immature canine elbow in extension.](image)

For the simulations in extension, the radius impacts the humerus first and is then followed by the ulna. For the simulations in flexion, the radius plays no role, and the ulna is the only bone interacting with the humerus. The initiation and propagation of the fracture is similar in all simulations. The fissure initiates on the articular surface, between the lateral and humeral condyle, and propagates towards the supracondylar fossa. A second crack then appears on the lateral part of the supratrochlear foramen and propagates through the lateral condyle. Some elements are also ruptured on the medial condyle when the elbow is in flexion.

Observed failure loads are higher for the simulations in flexion (2.57 kN for the immature dog and 2.6 kN for the mature dog) than for the simulation in extension (2.14 kN for the immature dog and 2.15 kN for the mature dog). The presence of the cartilaginous growth plate has little effect on the failure load. However, distinct elasticity and strength properties should be used in order to better model the difference between a young and an adult humerus. The effect of radioulnar exo/endo-rotation on the fracture type should also be studied in order to determine the conditions under which medial and bicondylar humeral fractures occur.

CONCLUSIONS

Finite element simulations of distal humeral fractures have been performed. The results obtained for a dog elbow in extension are in accordance with clinical observations in which lateral condylar fractures occur most frequently.

ACKNOWLEDGMENTS

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REFERENCES


Table 1: Mechanical properties used in the finite element simulations.

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<tr>
<th></th>
<th>Elastic modulus (MPa)</th>
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<th>Hardening (MPa)</th>
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