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Intraosseous stress distribution and bone interaction during load application across the canine elbow joint: A preliminary finite element analysis for determination of condylar fracture pathogenesis in immature and mature dogs

Beatrice Böhme [a], Vinciane d'Otreppe [b], Jean-Philippe Ponthot [b], Marc Balligand [a,*]

[a] Department of Clinical Sciences, Small Animal Surgery Service, Faculty of Veterinary Medicine, University of Liège, Belgium
[b] Department of Aerospace and Mechanics, University of Liège, Belgium

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ABSTRACT

Distal humeral fractures are common fractures especially in immature small breed dogs. The pathogenesis is still unknown. For this study, a three- dimensional bone model of the canine elbow was created and finite element analysis performed in order to determine the relationship between fracture type and bone interactions. Fused and non-fused humeral condyles were considered. A failure criterion was implemented to simulate the pathogenesis until fracture. Our study results confirm the clinical observation that lateral condylar fracture is the most common fracture type, implying interaction with the radius. Medial and Y-fractures are less common and occur always in interaction with the ulna whereas the radius causes lateral condylar fracture. Additionally, the fracture type is sensitive to bone positioning during trauma. The pathogenesis of distal humeral fractures is more complex than generally reported in the literature.

1. Introduction

Distal humeral condylar fractures account for approximately 50% of all humeral fractures (Bardet et al., 1983; Brinker et al., 2006). They are classified as simple and comminuted supracondylar, lateral and medial condylar and intercondylar or bicondylar (T- and Y-) fractures. Lateral condylar fractures occur most often (56–67%), compared to 33–35% bicondylar and 4–16% medial condylar fractures (Bardet et al., 1983; Cockett et al., 1985; Denny 1983; Rorvik 1993; Vannini et al., 1988a, b, 2007). These types of fracture are reported in dogs of any age (Knight 1959; Rorvik 1993; Shuttleworth 1938), but predominantly in young dogs less than one year in age (Guille et al., 2004; Schebitz et al., 1976; Vannini et al., 1988a, b) with a peak incidence around four months old when ossification of the humeral condyle is not yet completed (Cockett et al., 1985; Denny 1983; Knight 1959). Lateral condylar fractures are often described as the result of minor, indirect trauma (Anderson et al., 1990; Guille et al., 2004; Rorvik 1993; Vannini et al., 1988a,b).

A breed predisposition seems to be present in Yorkshire Terriers (Cockett et al., 1985; Rorvik 1993), French and English Bulldogs (Rorvik 1993), Pinscher (Rorvik 1993), Springer Spaniels, Cocker Spaniels (Vannini et al., 1988a, b) and Cavalier King Charles Spaniels (Denny 1983), whereas the incidence of condylar fractures in giant breeds is low (Cockett et al., 1985; Denny 1983). Incomplete ossification of the humeral condyle is an important risk factor for condylar humeral fractures in adults and has been described in Cocker Spaniels (Kaderly 1994; Marcellin-Little et al., 1994; Meyer-Lindenberg et al., 2002), Labrador Retrievers (Robin 2001), Rottweilers (Rovesti et al., 1998) and English Pointer dogs (Gnudi et al., 2005).

Though a number of theories have been proposed concerning the condylar fracture pathogenesis, there is no evidence in the literature for the influence of the elbow position when fracture occurs. Various authors describe condylar humeral fractures as occurring during axial loading with proximal displacement of the radius towards the weight-bearing lateral humeral condyle (Walker & Hickman; Shuttleworth 1938; Knight 1959; Schebitz et al. 1976; Cockett et al., 1985). For bicondylar fractures, Shuttleworth proposed a mechanism where the medial condyle fractures first, followed by the lateral condyle (Shuttleworth 1938). Two different hypotheses have been drawn from our observations. Most elbow fractures occur after a fall from a height. Upon impact, ground forces travelling from distal to proximal through the front limb may possibly cause the elbow to flex until the caudal aspect of the ulna touches the ground, with the ulnar notch acting then as a shim in between the two condyles, pushing them apart. Another scenario would be the very sudden bracing of the elbow joint in full extension upon impact of the front paw on the ground due to a strong reflex

* Corresponding author.
E-mail address: marc.balligand@ulg.ac.be (M. Balligand).

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contraction of the triceps muscle, hence making the radial head impact the distal lateral humeral condyle until fracture. Both scenarios may be possible in different varus–valgus positions of the elbow that could influence the fracture type: lateral, medial or bicondylar.

The objective of the three-dimensional finite element analysis was to determine the intraosseous stress distribution in the distal humerus after ground contact of the limb according to bone positioning at the moment of fracture.

2. Materials and methods

2.1. Specimen

Two pairs of canine forelimbs were harvested from 4 month old Beagle dogs weighing 7–7.5 kg and euthanised for reasons unrelated to this study. Humeri were cut at the level of the humeral and radial mid-diaphysis. Soft tissues were removed, but collateral ligaments, articular capsule and muscles directly surrounding the elbow joint remained in place. Standard mediolateral and craniocaudal elbow radiographs were taken for each specimen to confirm skeletal immaturity and to exclude radiographic visible elbow diseases.

2.2. Computed tomography

High resolution computed tomographic scans (CT) were performed in 0.7 mm sections on the elbows, from the distal third of the humerus to the proximal third of the radius and ulna, while placed in a flexion angle of 150°, at −10°,0° and +10° of endo-/exorotation (Siemens Somatron 16-slice, Germany). Each section had a resolution of 0.115 mm × 0.115 mm and dimensions of 512 × 512 pixels.

2.3. Finite element analysis

Computed tomographic scans were segmented using Slicer 3D software (Pieper et al., 2004) to delineate radius, ulna, and humerus, cortical, trabecular bone and cartilage of the area of interest. Based on these structure identifications, a three-dimensional model of the canine elbow was constructed using an automatic procedure described in (D'Otreppe et al., 2010; D'Otreppe et al., 2012). Models of immature and mature elbows were derived from the same CT images to facilitate comparison between both scenarios. The model was simplified by considering the unit of radius and ulna as a rigid body, whereas the humerus was defined as a deformable structure.

2.3.1. Models 1 and 2 (mature dog)

The numerical canine elbow model was built using a mesh for the humerus including trabecular and cortical bone: In Model 1, the mesh of cortical bone was built using 26 841 nodes. The trabecular bone was not considered and the space normally filled by it was left empty for simplification. In Model 2, the humerus was meshed using 9440 nodes for cortical bone and 5177 nodes for the trabecular bone. For radius and ulna a surface mesh of 1336 (radius) and 1657 nodes (ulna) was created using the external physical boundaries of the bone.

Table 2
Results of Simulation 1: tested conditions with different FEA, AbAdA and RA combinations: interaction of bones and stress–strain dependent resultant expected fracture type by von Mises stress field interpretation.

Flexion angle (°)	Abduction (+) Adduction (−)	Endorotation(+) Exorotation (−)	Bone contact to	Fracture type
60	0	0	Ulna	Lateral
60	−20	0	Ulna	Lateral
60	20	0	Ulna	Medial
60	0	+10	Ulna	Y
60	−20	+10	Ulna	Y or Lateral
60	20	+10	Ulna	Medial
60	0	−10	Ulna	Lateral
60	−20	−10	Ulna	Lateral
60	20	−10	Ulna	Lateral
130	0	0	Ulna	Medial
130	−20	0	Radius + Ulna	Lateral
130	20	0	Ulna	Medial or Y
130	0	+10	Radius	Lateral
130	−20	+10	Radius	Lateral
130	20	+10	Radius + Ulna	Y or Medial
130	0	−10	Radius	Lateral
130	−20	−10	Radius	Lateral
130	20	−10	Radius	Lateral
150	0	0	Radius + Ulna	Lateral
150	−20	0	Ulna	Lateral
150	20	0	Ulna	Medial
150	0	+10	Ulna	Lateral
150	−20	+10	Ulna	Lateral
150	20	+10	Ulna	Y
150	0	−10	Radius	Lateral
150	−20	−10	Radius	Lateral
150	20	−10	Radius	Lateral

Mechanical properties applied are listed in Table 2 (Kaneps et al., 1997). Trabecular and cortical bones were considered isotropic and homogenous linear elastic materials (Polikeit et al., 2007) (See Table 1).

In Model 1 no failure criterion was applied. As bone is weaker in tension than in compression, the modified Mohr–Coulomb failure criterion (Keyak et al., 2000; Shigley et al., 1989) was chosen to mimic fracture behaviour in Model 2.

2.3.2. Model 3 (immature dog)

To evaluate immature conditions with non-fused condyles or incomplete ossification of the condyles, the segmentation of the humerus was further refined: cortical bone, trabecular (diaphyseal and epiphyseal) bone within the medullary cavity and the cartilaginous growth plate were all given consideration (see Figs. 1 and 2). The numerical mesh was built using 9440 nodes for the cortical bone, 12,626 nodes for trabecular bone and 297 nodes for cartilage. Similar to Model 2, the modified Mohr–Coulomb failure criterion (Keyak et al., 2000; Shigley et al., 1989) was applied to model fracture behaviour.

Table 1
Material properties of bone used for the finite element analysis (Kaneps et al., 1997).

	Young's modulus (MPa)	Poisson's ratio	Failure stress (MPa)
Cortical bone	Long.: 2660 Trans.: 1596 Shear: 570	Long.: 0.3 Trans.: 0.3	Compression: 186 Tension: 93
Epiphyseal trabecular bone	2110	0.3	Compression: 21 Tension: 10.5
Diaphyseal trabecular bone	1055	0.3	Compression: 10.5 Tension: 5.2
Cartilage	1	0.45	0.015