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Development of a finite element model of the ligamentous cervical vertebral column of a Great Dane

Marília de Albuquerque Bonelli[a,b], Anoli Shah[c], Vijay Goel[c], Fabiano Séllos Costa[b], Ronaldo Casimiro da Costa[a,*]

[a] Department of Veterinary Clinical Sciences, College of Veterinary Medicine, The Ohio State University, 601 Vernon Tharp St, Columbus, OH 43210, USA
[b] Department of Veterinary Medicine, Federal Rural University of Pernambuco, R. Dom Manoel de Medeiros s/n, Recife, PE 52171-900, Brazil
[c] Engineering Center for Orthopaedic Research Excellence (E-CORE), Departments of Bioengineering and Surgery, College of Engineering and Medicine, University of Toledo, 2801 West Bancroft St., Toledo, OH 43606, USA

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ABSTRACT

Cervical spondylomyelopathy (CSM), also known as wobbler syndrome, affects mainly large and giant-breed dogs, causing compression of the cervical spinal cord and/or nerve roots. Structural and dynamic components seem to play a role in the development of CSM; however, pathogenesis is not yet fully understood. Finite element models have been used for years in human medicine to study the dynamic behavior of structures, but it has been mostly overlooked in veterinary studies. To our knowledge, no specific ligamentous spine models have been developed to investigate naturally occurring canine myelopathies and possible surgical treatments. The goal of this study was to develop a finite element model (FEM) of the C_2-C_7 segment of the ligamentous cervical vertebral column of a neurologically normal Great Dane without imaging changes. The FEM of the intact C_2-C_7 cervical vertebral column had a total of 188,906 elements (175,715 tetra elements and 12,740 hexa elements). The range of motion (in degrees) for the FEM subjected to a moment of 2 Nm was approximately 27.94 in flexion, 25.86 in extension, 24.14 in left lateral bending, 25.27 in right lateral bending, 17.44 in left axial rotation, and 16.72 in right axial rotation. We constructed a ligamentous FEM of the C_2-C_7 vertebral column of a Great Dane dog, which can serve as a platform to be modified and adapted for studies related to biomechanics of the cervical vertebral column and to further improve studies on osseous-associated cervical spondylomyelopathy.

1. Introduction

Cervical spondylomyelopathy (CSM), also known as wobbler syndrome, usually affects the cervical vertebral column of large- and giant-breed dogs with compression of the spinal cord and/or nerve roots (da Costa et al. 2008; da Costa 2010; De Decker et al. 2012; Lipsitz et al. 2001). Among giant breeds, the most commonly affected is the Great Dane (da Costa 2010; da Costa et al. 2012; Faissler et al. 2001; Gasper et al. 2014; Lipsitz et al. 2001; Murthy et al. 2014).

The form of the disease that generally affects Great Danes and other giant breeds is osseous-associated CSM (OA-CSM), which usually results from osseous proliferation of the articular processes leading to spinal cord and/or nerve root compression (Gasper et al. 2014; Gutierrez-Quintana and Penderis 2012; Martin-Vaquero and da Costa 2014; Murthy et al. 2014). Aside from static compressions, lesions are also considered to be dynamic (da Costa 2010; De Decker et al. 2012), increasing or decreasing depending on flexion and extension of the neck (Ramos et al. 2015).

In human medicine, biomechanical studies have used computer models, specifically finite element models (FEMs), to analyze a wide range of surgical interventions and implants such as discectomy, corpectomy and cervical disc replacement (Faizan et al. 2012; Goel et al. 2012; Hong et al. 2014; Hussain et al. 2012); fractures, intervertebral disc degeneration (Jones and Wilcox 2008), and even the biomechanical contribution of specific anatomic components (Clausen et al. 1997; Teo and Ng, 2001).

There have been only two canine vertebral models created, one for L_6-L_7 (Lim et al. 1994), and one for the C_3 to C_6 segment (Villarraga et al. 1999), to test implants in those locations. Both these canine models used human material properties and represented only one half of the studied region (along the midline), thus assuming each half to be identical to the other.

Our objective was to create and validate a C_2-C_7 ligamentous FEM of a clinically normal Great Dane to be used in the future research of the

* Corresponding author.
E-mail addresses: anoli.shah@rockets.utoledo.edu (A. Shah), vijay.goel@utoledo.edu (V. Goel), dacosta.6@osu.edu (R.C. da Costa).

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pathogenesis and treatment options for OA-CSM. Our hypothesis was that by using high resolution magnetic resonance and computed tomographic images, we would be able to develop a high fidelity model of the canine cervical vertebral column.

2. Material and methods

2.1. Dog

A 2-year-old female Great Dane dog with no history of neurologic disease was selected. There were no abnormalities found on neurologic exam, computed tomography (CT), and magnetic resonance imaging (MRI), all evaluated by a board-certified veterinary neurologist (RC_DC).

2.2. Image acquisition

Transverse computed tomography images were obtained with an 8-slice CT scanner (GE LightSpeed Ultra 8-slice, GE Healthcare, Waukesha, WI) using bone and soft tissue filters, 120 kV, and auto mA. Slice thickness was 0.6 mm, and there was no interval between slices. The transverse slices were aligned perpendicular to the vertebral canal.

Transverse and sagittal T1- and T2-weighted images were also obtained at 2.7 mm thickness continuously throughout the entire cervical vertebral column with a 3 T MRI Scanner (Achieva 3.0 T, Philips Healthcare, Best, The Netherlands). Repetition time (TR) and echo time (TE) were TR = 594 ms and TE = 8 ms for T1; and TR = 3877 ms and TE = 120 ms for T2-weighted sequences. The dog was positioned in dorsal recumbency with the head and neck extended in neutral position. Image acquisition was made under general anesthesia using propofol and isoflurane.

2.3. Image processing and model construction

2.3.1. Segmentation (i.e.: Selection of structures of interest)

The transverse CT images acquired using bone filter were imported into Materialise mimics (Materialise NV). Using the CT bone threshold feature and manual selection, segmentation of the vertebrae C_2 to C_7 was performed. For the intervertebral discs, contrast and level were modified to allow better visualization of soft tissue structures. The intervertebral discs were then manually segmented from $C_{2–3}$ to $C_{6–7}$. After all structures were segmented separately (C_2, $C_{2–3}$, C_3, etc.), each mask was saved as an STL file.

2.3.2. Surface and polygon models

The files were then imported into Geomagic Wrap (3D Systems) where the segmented parts were transformed into tridimensional polygon meshes and edited to remove minor irregularities prior to being exported as a surface object (vertebrae - IGES file type) or STL file type (intervertebral discs).

2.3.3. Meshing of vertebrae

The IGES files were subsequently imported into HyperMesh (HyperWorks), where each part was meshed separately using first order tetrahedral elements. Each meshed part was then exported as an INP file.

2.3.4. Meshing of discs

The STL files were imported into IA-FEMesh (The University of Iowa), where each disc was meshed by using hexahedral elements and exported as INP files.

2.3.5. Model assembly

The parts were then imported into Abaqus FEA (Dassault Systèmes). The vertebrae were separated into sets for cortical and cancellous bone. The intervertebral discs were divided into annulus fibrosus and nucleus pulposus. After assembly of the model, dorsal longitudinal, ventral longitudinal, and flava ligaments were added. The articular capsule surrounding articulating intervertebral articular processes was represented as a series of “capsular ligaments” connecting the cranial articular process to the caudal articular process (DeVries Watson et al., 2014; Lim et al. 1994; Villarraga et al. 1999).

Material properties were adapted from previously published canine models, both of which used human material properties (Lim et al. 1994; Villarraga et al. 1999). The vertebrae and the adjacent discs were tied and the articular surfaces of the articular processes were simulated using surface to surface exponential contacts. The caudal edge of C_7 was fixed in all directions and a moment of 2 Nm (Lim et al. 1994) applied to the cranial aspect of C_2 to simulate flexion, extension, left and right lateral bending and axial rotation. Material properties for the FE model are displayed in Supplementary file 1.

A convergence test was performed for the model using the C_6-C_7 segment, the purpose of which was to determine the optimum number of elements necessary to compose the model (thus making it feasible in terms of computational time) without interfering in model quality.

2.3.6. Validation

For validation of the FEM, predicted range of motion (ROM) in flexion, extension, lateral bending and axial rotation under 2 Nm was compared with previously published biomechanical data for ROM of the canine cervical vertebral column under 1.5 Nm published by the senior author's research group (Johnson et al. 2011).

3. Results

The FEM of the intact C_2-C_7 cervical vertebral column (Fig. 1) had a total of 188,906 elements (175,715 tetra elements and 12,740 hexa elements). The ROM (in degrees) for the FEM subjected to a moment of 2 Nm was approximately 27.94 in flexion, 25.86 in extension (Fig. 2), 24.14 in left lateral bending, 25.27 in right lateral bending, 17.44 in left axial rotation, and 16.72 in right axial rotation. The ROM obtained for each vertebral segment is shown in Table 1. Please note that all ROM values in this paper have been rounded to the nearest 2 decimals.

Left and right axial rotation seemed to show an increase towards the caudal segments. The maximum difference was observed between C_2-C_3 with 5.02 degrees and C_6-C_7 with 9.96 degrees. Combined range of motion for flexion/extension and left and right lateral bending showed some variations between segments. For combined flexion/extension, the maximum difference was between C_2-C_3 with 11.98 degrees, and C_6-C_7 with 9.77 degrees. The maximum difference for combined left and right lateral bending was between C_3-C_4 with 8.8 degrees and C_5-C_6 with 11.15 degrees.

4. Discussion

In this study, we constructed an intact FEM of the C_2-C_7 segment of a Great Dane. To the authors' knowledge, this is the first geometrically accurate intact ligamentous FEM of the cervical vertebral column of a dog. Development of a ligamentous FEM representing the cervical vertebral column of a clinically normal Great Dane is the first step for

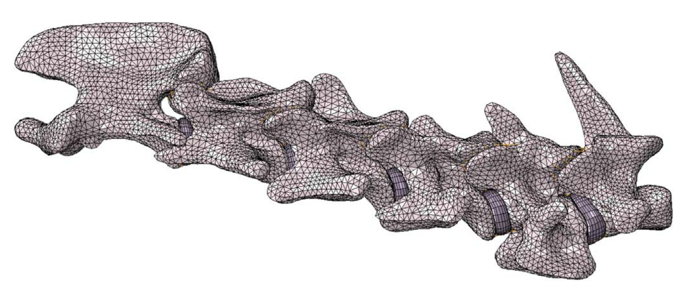

Fig. 1. Geometrically accurate ligamentous finite element model of the C2-C7 segment of a Great Dane without spondylomyelopathy.