MARÍLIA DE ALBUQUERQUE BONELLI

ELABORAÇÃO DE MODELOS DE ELEMENTOS FINITOS DA COLUNA VERTEBRAL CERVICAL DE DOGUE ALEMÃO

RECIFE

2017

UNIVERSIDADE FEDERAL RURAL DE PERNAMBUCO
PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM MEDICINA VETERINÁRIA

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Tese apresentada ao Programa de Pós-Graduação em Medicina Veterinária do Departamento de Medicina Veterinária da Universidade Federal Rural de Pernambuco como requisito final para obtenção do grau de Doutor em Medicina Veterinária.

Orientador:
Prof. Dr. Fabiano Séllos Costa

RECIFE - PE
2017

B712e Bonelli, Marília de Albuquerque.
Elaboração de modelos de elementos finitos da coluna vertebral cervical de Dogue alemão / Marília de Albuquerque Bonelli . – 2017.
76 f. : il.

Orientador: Fabiano Séllos Costa.
Tese (Doutorado) – Universidade Federal Rural de Pernambuco, Programa de Pós-Graduação em Ciência Veterinária, Recife, BR-PE, 2017.
Inclui apêndice(s) e referências.

1. Neurologia 2. Espondilomielopatia cervical 3.Wobbler 4. Biomecânica 5. In vitro I. Costa, Fabiano Séllos, orient. II. Título

CDD 636.089

UNIVERSIDADE FEDERAL RURAL DE PERNAMBUCO
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Tese de Doutorado elaborada por
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DEDICATÓRIA

Aos meus pais, por tudo.

AGRADECIMENTOS

Agradeço principalmente aos meus pais, pelo apoio e paciência durante esses longos anos;

Ao meu fantástico orientador, professor Dr. Fabiano Séllos Costa, pelo apoio e liberdade para traçar meu próprio caminho – desde que seja na imagem;

Ao meu orientador no exterior, professor Dr. Ronaldo Casimiro da Costa, pelas várias oportunidades e pelo imenso aprendizado;

À Cássia, pela contínua amizade à distância mesmo depois de nos ter abandonado;

À Simone, Juliana, Nadyne e Marcelo, por estarem sempre presentes quando alguém precisa de filme e chocolate;

À Camila, pelas conversas técnicas a cerca de 6000 Km de distância;

À equipe do E-CORE, da Universidade de Toledo, principalmente Anoli, pela ajuda durante a realização desse projeto;

Ao pessoal da neurologia da Ohio State University, pelo acolhimento e ajuda durante o período de sanduíche;

Às minhas *roommates* durante o sanduíche, Devinn e Kanyon, pela amizade;

E a todos que participaram comigo dessa jornada de uma forma ou de outra;

E também às criaturinhas que foram e são parte integral do meu lar, e que fazem tanta falta quando não presentes.

“If knowledge can create problems, it is not through ignorance that we can solve them”.

(Isaac Asimov)

RESUMO

Título: Elaboração de modelos de elementos finitos da coluna vertebral cervical de Dogue alemão

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Orientador: Prof. Dr. Fabiano Séllos Costa

Modelos de elementos finitos ajudam a entender processos dinâmicos no estudo de doenças e tratamentos. Espondilomielopatia cervical (EMC), também chamada de síndrome de wobbler, é uma doença que afeta principalmente cães de raças grandes e gigantes, e que parece ter um componente estático e dinâmico na sua fisiopatogenia. Objetivou-se criar um modelo de elementos finitos representando o segmento de C_2 a C_7 da coluna vertebral de um dogue alemão sem alterações, assim como adaptar esse modelo para representar uma laminectomia dorsal e hemilaminectomia em C_5-C_6. Espera-se com isso contribuir para a investigação do componente biomecânico da EMC, além de permitir a comparação dos diversos métodos cirúrgicos propostos para o tratamento dessa síndrome. Foi selecionado um cão de 2 anos de idade, da raça Dogue alemão, sem alterações neurológicas ou de imagem na região cervical da coluna vertebral. Imagens de tomografia computadorizada deste cão foram processadas para construir um modelo de elementos finitos representando as vértebras, discos intervertebrais e ligamentos. As propriedades materiais foram adaptadas da literatura. A amplitude de movimento do modelo sob 2Nm para flexão, extensão, rotação axial e flexão lateral foram comparadas com a literatura. Observou-se que a amplitude de movimento do modelo foi menor do que a citada para cadáveres de outra raça. Considera-se que essa diferença possa advir de diferenças entre raças e do uso de propriedades materiais adaptadas de humanos. Ao comparar o modelo intacto com os modificados com laminectomia e hemilaminectomia, observou-se que houve influência da hemilaminectomia na amplitude de movimento, principalmente na rotação axial contralateral ao procedimento simulado. A construção desses modelos seria o primeiro passo para aplicar o uso do método de elementos finitos para o estudo da espondilomielopatia cervical em Dogues alemães.

Palavras chave: neurologia, espondilomielopatia cervical, wobbler, biomecânica, *in vitro*.

ABSTRACT

Title: Construction of finite element models of the cervical vertebral column of a Great Dane

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Finite element models aid in understanding dynamic processes in the study of diseases and treatments. Cervical spondylomyelopathy (CSM), also called wobbler syndrome, is a disease that affects mainly large- and giant-breed dogs, and seems to have a static and dynamic component in its pathophysiology. The present objective was to create a finite element model representing the C_2-C_7 segment of the vertebral column of a Great Dane dog without abnormalities, as well as the adaptation of this model to represent a dorsal laminectomy and a hemilaminectomy at C_5-C_6. This is expected to contribute to the investigation of the biomechanical component of CSM, as well as allow a comparison of the various surgical methods proposed for treatment of this syndrome. A 2-year-old Great Dane dog without neurologic or imaging changes in the cervical region of the vertebral column was selected. Computed tomography images from this dog were processed to construct a finite element model representing vertebrae, intervertebral discs, and ligaments. Material properties were adapted from the literature. Range of motion of the model under 2Nm for flexion, extension, axial rotation, and lateral bending were compared with literature. Range of motion was observed to be lesser than cited for cadavers of a different breed. This difference could be considered as resulting from differences between breeds and the use of human material properties. When comparing the intact model with the modified laminectomy and hemilaminectomy models, an influence of the hemilaminectomy was observed in range of motion, especially in axial rotation to the side opposite the simulated procedure. Construction of these models would be the first step to applying finite element analysis to the study of CSM in Great Danes.

Key words: neurology, cervical spondylomyelopathy, wobbler, biomechanics, *in vitro*

LISTA DE FIGURAS

LISTA DE TABELAS

SUMÁRIO

1 INTRODUÇÃO

Modelos computadorizados fornecem um método ideal para o estudo biomecânico de diversas situações (HONG et al., 2010). Uma forma de análise seria o método de elementos finitos, onde estruturas geométricas complexas com diferentes propriedades são divididas em partes menores (os ditos elementos) para facilitar a avaliação (PHUNTSOK et al., 2016).

Na medicina humana, modelos de elementos finitos (MEFs) são utilizados na prevenção, diagnóstico e tratamento de várias condições que afetam a coluna vertebral (CLAUSEN et al., 1997; TEO e NG, 2001; JONES e WILCOX, 2008; ZAFARPARANDEH et al., 2014), assim como na análise de intervenções cirúrgicas e implantes (JONES e WILCOX, 2008; FAIZAN et al., 2012; GOEL et al., 2012; HUSSAIN et al., 2012; HONG et al., 2014).

Para a construção de um MEF, são obtidas imagens de uma determinada área utilizando tomografia computadorizada (TC) e ressonância magnética (RM), que são processadas utilizando programas específicos (JONES e WILCOX, 2008). O operador seleciona as regiões de interesse e escolhe quais elementos serão integrados ao modelo, atribuindo propriedades para cada material das estruturas a serem representadas. No caso dos modelos animais, essas propriedades podem ser adaptadas da literatura humana e modificadas durante a fase de testes para validação do modelo (DEVRIES, 2011).

Existem MEFs construídos para a coluna vertebral de cães, mas estes tiveram como objetivo estudar a interação entre implantes e vértebras, seja para correlação com dados em humanos (LIM et al., 1994; VILLARRAGA et al., 1999) ou para testar a viabilidade de um novo implante para ser usado em cães com espondilomielopatia cervical (MARINHO, 2015). No caso deste último, foi modelado somente a porção de osso esponjoso dos corpos vertebrais onde o implante estaria localizado.

A espondilomielopatia cervical (EMC), também conhecida como síndrome de wobbler, afeta principalmente a porção cervical da coluna vertebral de cães de raças grandes e gigantes, gerando uma compressão da medula espinal e/ou raízes nervosas (LIPSITZ et al., 2001; DA COSTA et al., 2008; DA COSTA et al., 2012; DE DECKER et al., 2012a; GASPER et al., 2014; MURTHY et al., 2014). As raças mais comumente afetadas são Doberman Pinscher e Dogue alemão (LIPSITZ et al., 2001; DA COSTA et al., 2008; DA COSTA, 2010; FAISSLER et al., 2011; DA COSTA et al., 2012; PLATT e DA COSTA, 2012; MURTHY et al., 2014).

Existem duas formas de EMC, as quais podem ocorrer separadas ou em conjunção (DA COSTA, 2010). Na forma de EMC associada à degeneração de discos intervertebrais, a compressão da medula espinal ocorre primariamente devido à protrusão dos discos intervertebrais. Essa é a forma encontrada mais comumente em cães de raças de grande porte, principalmente Doberman Pinschers (DA COSTA et al., 2006; PLATT e DA COSTA, 2012). Já a forma óssea é observada com maior frequência em Dogues alemães e outras raças gigantes, onde a compressão da medula espinal e/ou de raízes nervosas geralmente resulta da proliferação óssea dos processos articulares das vértebras (GUTIERREZ-QUINTANA e PENDERIS, 2012; MARTIN-VAQUERO e DA COSTA, 2014a; MARTIN-VAQUERO e DA COSTA, 2014b).

Considera-se que as lesões ocorridas devido à EMC resultam não somente de compressões estáticas, mas também de um componente dinâmico, onde a compressão das estruturas nervosas aumenta ou diminui dependendo da flexão ou extensão do pescoço (DA COSTA, 2010; DE DECKER et al., 2012a). Até o momento, existem 30 técnicas cirúrgicas descritas para tratamento da EMC, mas nenhuma é considerada ideal (PROVENCHER, 2016). No caso da forma óssea, pode-se realizar uma laminectomia, hemilaminectomia, ou estabilização com um *plug* de polimetilmetacrilato (DEWEY e DA COSTA, 2016).

Objetivou-se neste estudo criar um modelo ligamentoso de elementos finitos representando o segmento cervical de C_2 a C_7 da coluna vertebral de um cão da raça Dogue alemão, além de adaptar esse modelo para representar uma laminectomia dorsal e hemilaminectomia em C_5-C_6. Espera-se com isso contribuir para a investigação do componente biomecânico da EMC, além de permitir a comparação dos diversos métodos propostos para o tratamento dessa síndrome.

Esta tese é inicialmente composta de uma revisão de literatura sobre o assunto, seguida da parte experimental, que está redigida na forma de artigos científicos de acordo com as normas de publicação do periódico BMC Veterinary Research (http://bmcvetres.biomedcentral.com/submission-guidelines).

2 REVISÃO DE LITERATURA

2.1 Modelo de elementos finitos (MEF)

O uso de modelos computacionais é o método ideal para se realizar o estudo biomecânico de diversas situações. Após o desenvolvimento e validação de um modelo, um teste pode ser repetido infinitamente com somente uma variável sendo modificada (HONG et al., 2014).

2.1.1 Conceito

O método de elementos finitos é uma análise matemática onde é feita a divisão de um meio contínuo em elementos menores que mantêm as mesmas propriedades do meio original. Esses pequenos elementos são representados por equações diferenciais e resolvidos por modelos matemáticos, para que sejam obtidos os resultados desejados (LOTTI et al., 2006). Ou seja, estruturas geométricas complexas com diferentes propriedades materiais são divididas em partes menores para facilitar a avaliação do comportamento do todo (PHUNTSOK et al., 2016).

2.1.2 Uso na medicina humana

Na medicina humana, os MEFs são utilizados para auxiliar na prevenção, diagnóstico e tratamento de diversas condições da coluna vertebral (ZAFARPARANDEH et al., 2014), assim como para estudar uma variedade de intervenções cirúrgicas e implantes (JONES e WILCOX, 2008; FAIZAN et al., 2012; GOEL et al., 2012; HUSSAIN et al., 2012; HONG et al., 2014), fraturas, degeneração do disco intervertebral (JONES e WILCOX, 2008) e a contribuição biomecânica de componentes anatômicos específicos (CLAUSEN et al., 1997; TEO e NG, 2001).

Além de conseguir avaliar estresses internos das estruturas que não conseguem ser avaliados *in vivo* ou *ex vivo*, tem-se também como uma das principais vantagens do uso de MEF, a capacidade de realizar inúmeras modificações em um mesmo modelo e rodar infinitas simulações sem a necessidade de possuir uma quantidade infinita de espécimes (KUMARESAN et al., 2000; HONG et al., 2014; ZAFARPARANDEH et al., 2014).

Uma abordagem biomecânica parece ser ideal para estudar a origem de condições que possuem um componente dinâmico (SAIRYO et al., 2006), e MEFs têm sido o método mais popular para analisar a tensão na coluna vertebral (SCIFERT et al., 2002). Ao contrário de modelos *in vitro* e *in vivo*, os MEFs podem prever, por exemplo, a resposta interna da coluna vertebral cervical a forças que agem sobre ela (ZAFARPARANDEH et al., 2014).

Estudos biomecânicos com MEFs também podem ser usados quando não é prático ou fácil obter cadáveres para estudos científicos (SAIRYO et al., 2006), ou quando é inviável o estudo das contribuições individuais de uma estrutura anatômica (e.g.: uma articulação entre vértebras) para a amplitude de movimento da coluna como um todo através de testes com cadáveres ou *in vivo* (CLAUSEN et al., 1997).

Os modelos de coluna ditos intactos ou normais são elaborados para estudar o comportamento fisiológico das estruturas ou para servir como referência, ou ponto de partida, para estudar alterações posteriormente (CLAUSEN et al., 1997; WHEELDON et al., 2008; DREISCHARF et al., 2014).

2.1.3 Modelos animais

Apesar da grande quantidade de modelos e trabalhos existentes na área humana, existem poucos relatos do uso de MEFs em animais (LIM et al., 1994; VILLARRAGA et al., 1999; DEVRIES WATSON, 2014). Em relação à coluna vertebral, existe um modelo para a região cervical de ovelhas, cujo objetivo foi melhorar o entendimento das diferenças biomecânicas entre ovelhas e humanos para melhor usaressa espécie como modelo para estudos humanos (DEVRIES WATSON, 2014).

Seguindo uma linha de pensamento similar, existem também dois MEF para a coluna vertebral de cães, cujo propósito foi utilizar os resultados para melhorar o uso de cães como modelos animais para estudo de condições humanas. O primeiro focou na construção de um modelo de das vértebras L_6-L_7 representando somente um lado, dividido na linha sagital, das estruturas presentes. Foi feito o modelo intacto e com a aplicação de uma placa. Esse modelo utilizou propriedades materiais obtidas da literatura humana, e foi validado utilizando dados de amplitude de movimento publicados anteriormente (LIM et al., 1994). O segundo modelo foi da região cervical, incluindo as vértebras C_3 a C_6, com o objetivo de estudar a interação entre placa e vértebras, para analisaro uso desses implantes na medicina humana. Para construção do modelo, foram utilizadas imagens de TC e propriedades materiais também foram obtidas da literatura humana (VILLARRAGA et al., 1999).

Recentemente foi desenvolvido um MEF para testar a viabilidade de um novo implante a ser usado em cães com EMC cervical. Esse modelo foi composto por dois corpos vertebrais (C_5 e C_6, sem regiões superiores) construídos a partir de medidas de cadáveres. Nele, não foram modelados ligamentos; somente osso esponjoso, com propriedades materiais obtidas a partir de trabalhos humanos. Não houve alguma tentativa de validar o modelo (MARINHO, 2015).

2.1.4 Construção de modelos de elementos finitos

A construção de um MEF da coluna vertebral envolve as seguintes etapas: construção das vértebras, discos intervertebrais e ligamentos; atribuição de propriedades materiais e condições de contorno; e validação do modelo (ZAFARPARANDEH et al., 2014).

Para construção de um modelo geometricamente preciso, são obtidas imagens com uso de tomografia computadorizada (TC) e/ou ressonância magnética (RM), que são processadas utilizando programas específicos (JONES e WILCOX, 2008). O operador seleciona as regiões de interesse, determinando quais os componentes que serão reconstruídos no modelo, atribuindo propriedades para cada material da estrutura a ser representada. No caso dos modelos animais, essas propriedades podem ser adaptadas da literatura humana e corrigidas ao longo do experimento após testes realizados com cadáveres da espécie sendo estudada (DEVRIES, 2011).

2.1.5 Limitações

Uma das principais limitações dos MEFs geometricamente corretos é a sua confecção a partir de um só exemplar de uma população, já que são criados a partir das imagens de TC, por exemplo. Apesar disso, os modelos que seguem a anatomia das estruturas sendo representadas são considerados mais representativos da realidade. Foram desenvolvidos métodos estatísticos para tentar adequar os modelos para as variações encontradas em uma população, mas este método é extremamente complexo e difícil de ser aplicado (DREISCHARF et al., 2014). Outra limitação inerente aos MEF é que a simulação leva em conta somente as estruturas representadas, ou seja, não tem como levar em consideração a influência da musculatura em um animal vivo, mas essa é uma limitação também observada nos testes biomecânicos utilizando cadáveres (XIE et al., 2013).

2.2. Espondilomielopatia cervical

Espondilomielopatia cervical (EMC), comumente chamada de síndrome de wobbler, afeta a coluna vertebral cervical de cães, causando compressão da medula espinal e/ou raízes nervosas (DA COSTA, 2010; DE DECKER et al., 2012a). Esta condição atinge principalmente cães de raças grandes e gigantes (LIPSITZ et al., 2001; DA COSTA et al., 2008; DA COSTA et al., 2012; GASPER et al., 2014; MURTHY et al., 2014). Cães de raças pequenas podem também apresentar EMC, mas representam menos de 5% dos casos relatados (DE RISIO et al., 2002; DA COSTA et al., 2008; HARRIS et al., 2011). As raças mais afetadas são Doberman Pinscher e Dogue alemão (LIPSITZ et al., 2001; DA COSTA et al., 2008; DA COSTA, 2010; FAISSLER et al., 2011; DA COSTA et al., 2012; MURTHY et al., 2014; DEWEY e DA COSTA, 2016).

Existem duas formas reconhecidas de EMC, uma forma óssea e outra associada a protrusão de disco, e estas podem ocorrer separadamente ou em conjunto (DA COSTA, 2010). A forma associada à protrusão de disco leva à compressão da medula espinal secundária à protrusão de disco e, geralmente, ocorre nas raças grandes, principalmente Doberman Pinscher (DA COSTA et al., 2006; DE DECKER et al., 2012b). Já a forma óssea da EMC geralmente afeta raças gigantes, principalmente Dogue alemão, com compressão lateral ou dorsolateral resultante primariamente de proliferação óssea nos processos articulares (GUTIERREZ-QUINTANA e PENDERIS, 2012; MARTIN-VAQUERO e DA COSTA 2014b). A compressão da medula espinal por ligamentos, mais especificamente, pelo ligamento amarelo (ligamento flavo), pode ocorrer em ambas as formas da EMC, mas geralmente não ocorre como causa única da compressão medular (DA COSTA, 2010).

Os cães de raça grande geralmente desenvolvem a forma de EMC associada à protrusão de disco após os três anos de idade (DA COSTA et al., 2006), comumente apresentando sinais neurológicos por volta dos seis anos de idade. São vistos casos em cães mais jovens, embora não seja comum. Os cães de raça gigante, entretanto, desenvolvem a forma óssea da doença em média com 3 anos e 10 meses, podendo ser acometidos com somente alguns meses de idade (DEWEY e DA COSTA, 2016).

A forma de EMC associada à protrusão de disco ocorre devido a uma combinação de protrusão de disco intervertebral, com ou sem hipertrofia de ligamentos (seja o ligamento amarelo ou o longitudinal dorsal). Além disso, considera-se que a forma de EMC associada à protrusão de disco ocorra devido a uma associação de estenose do canal vertebral, torção da coluna vertebral cervical caudal levando a degeneração dos discos intervertebrais (PLATT e DA COSTA, 2012), e da possível protrusão de um volume maior de material discal nessa região. Dobermans com EMC parecem ter discos intervertebrais mais espessos (largos) na região cervical quando comparados com cães normais (DA COSTA et al., 2006), entretanto, não foi estabelecida uma relação entre esse achado e a manifestação de sinais clínicos (DE DECKER et al., 2012a).

Já a forma óssea da EMC decorrente da estenose do canal vertebral causada pela proliferação do arco vertebral, facetas articulares e pedículos, parece estar relacionada a más-formações, assim como alterações osteoartríticas das superfícies articulares dos processos articulares, podendo também haver protrusões de disco intervertebral ou cistos sinoviais associados com a proliferação óssea em alguns cães (DA COSTA, 2010;

GUTIERREZ-QUINTANA e PENDERIS, 2012; MARTIN-VAQUERO e DA COSTA, 2014a; MARTIN-VAQUERO e DA COSTA 2014b).

Ao longo dos anos, tem sido supostos etiologia genética e fatores de risco relacionados à conformação racial (em Dobermans), ou à nutrição (como suplementação com cálcio e excesso de alimentação em Dogues alemães), mas nenhuma dessas teorias foi comprovada (DA COSTA, 2010; DE DECKER et al., 2012a).

2.2.1 Fisiopatogenia

A fisiopatogenia da EMC não é completamente compreendida, mas parece ter componentes estáticos e dinâmicos (DA COSTA, 2010; DE DECKER et al., 2012a). O componente estático considerado mais importante seria a estenose do canal vertebral, que é considerada relativa em Doberman Pinschers (DA COSTA et al., 2006; DE DECKER et al., 2012b; PLATT e DA COSTA, 2012) e absoluta em Dogues alemães (MARTIN-VAQUERO et al., 2014). Na estenose relativa, existe uma redução do canal vertebral, mas não o suficiente para causar compressão das estruturas neurais e causar sinais clínicos por si só. Esta estenose relativa, entretanto, facilitaria a ocorrência de compressão na presença de condições que ocupem espaço dentro do canal vertebral. A estenose absoluta, por outro lado, é um estreitamento do canal vertebral que é diretamente responsável pela compressão da medula espinal (BAILEY e MORGAN, 1992).

Alterações estruturais da porção cervical da coluna vertebral, assim como componentes dinâmicos, parecem estar associadas com a ocorrência de EMC, entretanto, a contribuição de cada um desses fatores ainda não foi elucidada (DA COSTA, 2010; DE DECKER et al., 2012a). As lesões dinâmicas, onde a compressão da medula espinal aumentaria ou diminuiria de acordo com a flexão ou extensão do pescoço (DA COSTA, 2010), parecem ser, em parte, uma consequência da diminuição do diâmetro do canal vertebral e contato das estruturas adjacentes com a medula espinal durante a extensão fisiológica do pescoço (RAMOS et al., 2015).

Dobermans em geral, quer afetados por EMC ou não, tem um canal vertebral cervical afunilado, não sendo observadas diferenças entre cães com e sem sinais clínicos. Além disso, o diâmetro do canal vertebral parece ser menor em machos do que fêmeas e, apesar de não haver relatos de predileção por idade para essa síndrome, o diâmetro do canal diminui com o aumento da idade. Esta última observação poderia explicar porque sinais clínicos são geralmente vistos em adultos jovens (DA COSTA e JOHNSON, 2012).

Estenose do canal vertebral foi relatada em Dobermans independentemente da presença de EMC, entretanto, essa estenose parece ser mais pronunciada em cães com a doença (DA COSTA et al., 2006). Em cães afetados, este fato poderia predispor o desenvolvimento de sinais clínicos, já que facilita a compressão da medula espinal (DE DECKER et al., 2012a). É importante lembrar, entretanto, que cães com alterações vistas em TC ou RM podem não ter sinais clínicos de EMC apesar de ter estenose do canal vertebral ou forame intervertebral, protrusão do disco intervertebral e compressão da medula espinal (DA COSTA et al., 2006; MARTIN-VAQUERO et al., 2014).

Essa falta de concordância entre os achados de imagem e lesões neurológicas também é vista em humanos com mielopatia espondilótica cervical, doença análoga à EMC em cães. Para explicar essa discrepância, foi sugerida uma base biomecânica para um desenvolvimento dessas lesões que melhor explicaria os achados clínicos relacionados à lesão da medula espinal e mielopatia clínica em pacientes com um menor grau de estenose ou mínima evidência de compressão (HENDERSON et al., 2005).

Já foi sugerido que pode haver um componente de instabilidade (SHARP e WHEELER, 2005), ou seja, incapacidade da medula espinal de manter sua integridade sob cargas fisiológicas em cães com EMC. Embora não existam estudos biomecânicos que confirmem ou invalidem essa teoria, instabilidade não parece estar relacionada com a ocorrência de EMC. Na verdade, a compressão da medula espinal parece estar associada a um componente dinâmico, mencionado anteriormente, onde a compressão aumentaria ou diminuiria de acordo com a extensão ou flexão da coluna vertebral (DA COSTA, 2010).

Em humanos, o principal fator que parece influenciar a lesão da medula espinal é tensão resultante de flexão e extensão contínua. Em cães, existe aparentemente uma redução da mobilidade quando os discos intervertebrais estão muito degenerados com colapso do espaço intervertebral, embora pareça haver um aumento na mobilidade com graus menores de degeneração (PLATT e DA COSTA, 2012). Isso é consistente com achados de um estudo em humanos que determinou que o movimento de translação aumentou durante as fases menos severas de degeneração de disco, mas diminuiu quando a degeneração resultou em anquilose (MIYAZAKI et al., 2008).

Um estudo biomecânico em cadáveres utilizando a coluna vertebral cervical de cães da raça Foxhound encontrou uma diferença significante entre o movimento da porção cranial e caudal da coluna vertebral cervical. A flexão lateral foi associada com rotação axial ipsilateral, e o segmento caudal teve uma maior capacidade para rotação axial. Os discos intervertebrais, principalmente aqueles na região caudal da coluna vertebral cervical, estariam, portanto, expostos a maiores forças de cisalhamento

(JOHNSON et al., 2011), que parece contribuir para degeneração discal nessa região (PLATT e DA COSTA, 2012).

Nesse experimento supracitado, a coluna vertebral foi testada separada em dois segmentos (cranial e caudal) devido à curvatura natural e flexibilidade da coluna cervical dos cães, que dificultou a realização dos testes biomecânicos em todo o segmento (JOHNSON et al., 2011). Uma alternativa para obter dados sobre a biomecânica do segmento cervical da coluna vertebral seria utilizar MEFs (WHEELDON et al., 2008; DEVRIES WATSON et al., 2014).

2.2.2 Sinais clínicos

Os sinais clínicos descritos mais comumente são déficits neurológicos e dor (PLATT e DA COSTA, 2012). Hiperestesia cervical, embora vista regularmente, não é a principal queixa ao primeiro atendimento (DEWEY e DA COSTA, 2016). Os sinais vistos com EMC incluem ainda graus variáveis de ataxia (DA COSTA et al., 2012). Cerca de 10 a 15% dos cães com EMC chegam ao médico veterinário com tetraparesia não-ambulatória (DA COSTA, 2010, PLATT e COSTA, 2012). A progressão dos sinais pode ser relatada como aguda ou crônica, podendo ainda haver uma piora aguda de sinais crônicos (DA COSTA et al., 2012).

O principal local afetado é a região cervical caudal da coluna vertebral (DA COSTA et al., 2006; DA COSTA et al., 2008; MARTIN-VAQUERO et al., 2014); mas alterações são encontradas ao longo da coluna cervical e inclusive nas primeiras vértebras torácicas (HARRIS et al., 2011; DA COSTA et al., 2012; MARTIN-VAQUERO et al., 2014). Cães de raças gigantes geralmente possuem mais de um local de compressão (DEWEY e DA COSTA, 2016). A localização de lesões na porção cervical mais caudal da coluna vertebral comumente resulta em uma marcha com passos mais curtos nos membros torácicos e mais longos nos membros pélvicos (DA COSTA, 2010).

2.2.3 Diagnóstico

O diagnóstico deve ser feito através de exame neurológico e métodos avançados de imagem, idealmente, TC, mielotomografia ou RM (DA COSTA et al., 2006; DA COSTA et al., 2012; DE DECKER et al., 2012b; MARTIN-VAQUERO e DA COSTA, 2014b; MURTHY et al., 2014). Além de compressão da medula espinal e/ou raízes nervosas, pode-se observar compressão do espaço subaracnóide, degeneração e protrusão de disco intervertebral, alterações ósseas como osteoartrose dos processos articulares, má-formação de pedículos e lâmina, cistos sinoviais, espessamento do ligamento amarelo, e estenose do forame intervertebral (DA COSTA et al., 2012; MARTIN-VAQUERO e DA COSTA, 2014b). Nas imagens de RM, observa-se ainda hiperintensidade na medula espinal em imagens ponderadas em T2, e hipointensidade de sinal em T1 nos locais de compressão em cães com EMC, que parecem estar associados com compressão crônica, entretanto, esses achados já foram descritos em humanos sem sinais clínicos de mielopatia espondilótica cervical (MARTIN-VAQUERO e DA COSTA, 2014b).

É importante lembrar que em um mesmo cão, pode haver diversos locais de compressão, de tipo e magnitude variável, e que esses achados nem sempre estão correlacionados com os sinais neurológicos, existindo inclusive cães sem déficits neurológicos que apresentam locais de compressão de raízes nervosas e/ou medula espinal (DA COSTA et al., 2006; MARTIN-VAQUERO et al., 2014).

O uso de RM dinâmica parece fornecer informações adicionais nos casos de EMC associadas a protrusão de disco, com a flexão exacerbando a compressão e, portanto, facilitando a identificação do(s) local(is) afetado(s) (PROVENCHER et al., 2016).

2.2.4 Tratamento

O tratamento da EMC pode ser conservativo ou cirúrgico. O tratamento conservativo consiste em tentar aliviar os sinais clínicos através do uso de corticoides e restrição de exercícios (DEWEY e DA COSTA, 2016). Quanto às opções cirúrgicas, existem diversas técnicas cirúrgicas descritas, embora nenhuma seja considerada ideal. Deve-se levar em consideração o tipo de EMC, o tipo e grau de compressão ao se escolher o melhor tratamento para cada cão (DA COSTA, 2010; PLATT e DA COSTA, 2012). No caso da forma óssea de EMC, que afeta primariamente cães da raça Dogue alemão, as principais formas de descompressão são a laminectomia dorsal e a hemilaminectomia (DEWEY e DA COSTA, 2016).

Curiosamente, independentemente do tratamento ser cirúrgico ou conservativo, o tempo médio de sobrevivência é de aproximadamente 36 meses (DA COSTA et al., 2008; FAISSLER et al., 2011). A cirurgia parece resultar mais consistentemente em melhora clínica para cães com a forma de EMC associada à protrusão de disco (DA COSTA, 2010), mas pode também acelerar a progressão de alterações na medula espinal (DA COSTA e PARENT, 2007).

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4. Experimento

4.1. Artigo 1

Research article

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

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Abstract

Background

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 (FEMs) have been used for years in human medicine to study the dynamic behavior of structures, but there is still very little attention to its use in veterinary studies. To our knowledge, no specific vertebral models were ever developed to investigate naturally occurring canine myelopathies. The goal of this study was to develop a finite element model (FEM) of the C_2-C_7 segment of the cervical vertebral column of a neurologically normal Great Dane without imaging changes.

Results

The FEM of the intact C_2-C_7 cervical vertebral column had a total of 188906 elements (175715 tetra elements and 12740 hexa elements). The range of motion (in degrees) for the FEM subjected to a moment of 2Nm 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 lateral rotation. These results are in agreement with biomechanical testing in actual canine specimens.

Conclusions

We constructed a geometrically accurate 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.

Keywords: biomechanics; cervical spine; cervical spondylomyelopathy; finite element analysis; wobbler syndrome

Background

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 [1-4]. Among giant breeds, the most commonly affected is the Great Dane [1,3,5-8].

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 [7-10]. Aside from static compressions, lesions are also considered to be dynamic [3,4], increasing or decreasing depending on flexion and extension of the neck [11].

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 [12-15]; fractures, intervertebral disc degeneration [16], and even the biomechanical contribution of specific anatomic components [17,18].

There have been only two canine vertebral models created, one for L_6-L_7 [19], and one for the C_3 to C_6 segment [20], 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 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.

Methods

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).

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, 120kV, and auto mA. Slice thickness was 0.6mm, 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 2.7mm thickness continuously throughout the entire cervical vertebral column with a 3T MRI Scanner (Achieva 3.0 T, Philips Healthcare, Best, The Netherlands). Repetition time (TR) and echo time (TE) were TR = 594ms and TE = 8ms for T1; and TR = 3877ms and TE = 120ms 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.

Image processing and model construction

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.

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).

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.

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.

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 [19-21].

Material properties were adapted from previously published canine models, both of which used human material properties [19,20]. 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 2Nm 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 from in terms of computational time) without interfering in model quality.

Validation

For validation of the FEM, predicted range of motion (ROM) in flexion, extension, lateral bending and axial rotation under 2Nm was compared with previously published biomechanical data for ROM of the canine cervical vertebral column under 1.5Nm published by the senior author's research group [22].

Results

The FEM of the intact C_2-C_7 cervical vertebral column (Figure 1) had a total of 188906 elements (175715 tetra elements and 12740 hexa elements). The ROM (in degrees) for the FEM subjected to a moment of 2Nm 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. 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.

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 applying this technique to the study of canine OA-CSM.

The FEM underpredicted ROM for C_2 to C_4 and C_5 to C_7 when compared with biomechanical tests done in Foxhounds to evaluate motion of the C_2-C_4 and C_5-C_7 segments [22]. That study found maximum ROM (in degrees) under 1.5Nm (mean ±SD) of 26.4 ±7 at C_6-C_7 for flexion/extension, 28 ±4 at C_3-C_4 for lateral bending, and 32.4 ±10 for axial rotation. It is unknown, however, if those findings in ROM would apply to giant breeds, more specifically, Great Danes [22].

As with our model, biomechanical tests have shown that the capacity for axial rotation is considered higher in the caudal cervical vertebral segments, though the reported ROM increase (from 7.9 at C_2-C_3 to 32.4 at C_6-C_7) [22] is greater than what was observed in our model (from 5.02 at C_2-C_3 to 9.96 at C_6-C_7).

Generally, the model's predictions for axial rotation were within the maximum-minimum range for individual measurements obtained from Foxhound cadavers [23]. For the measurements falling outside that range, minimum difference was 1.5 degrees for extension at C_5-C_6 and maximum 12.14 degrees for C_6-C_7 axial rotation, and the mean difference between the model and the lowest ROM was 3.6 degrees for flexion, 3 degrees for extension, and 7.89 degrees for lateral bending.

One explanation for the discrepancies between the FEM ROM predictions and the available data in the literature would be that it stems from the difference between breeds and individuals. While individual differences are widely accepted in human literature as a concern during FE modelling and using a single model to represent a population, a study comparing eight models from different research centers found that they differed by a few degrees in predicted ROM [24]. The authors of that study suggested that pooling together results from various FEM would better improve their representation of an entire population. In dogs, however, there are also variations related to breed that would need to be considered. A morphologic study, for instance, found differences in vertebrae conformation, including in articular process characteristics between breeds [25].

There is a scarcity of biomechanical studies for the cervical column of dogs in the literature, and no study focusing specifically on giant breeds such as Great Danes.

Another factor that may be responsible for the discrepancy between FEM ROM predictions and biomechanical data available in the literature is the use of human material properties for the canine model. Although the only two other studies that modeled segments of the dog spine also used material properties from human literature and reported no significant issues [19,20], differences are expected and should further be explored to improve canine FE models [19]. The lack of dog-specific material properties is one of the limitations of this study. Further biomechanical cadaver tests in the cervical spine of dogs and, more specifically, of Great Danes, would be necessary to adapt the material properties used to those that better reflect the actual Great Dane cervical vertebral column. However, having a working FEM allows more specific canine material properties to be inserted into the model whenever they become available.

Conclusions

We constructed a geometrically accurate 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.

List of abbreviations

CSM: cervical spondylomyelopathy

OA-CSM: osseous-associated cervical spondylomyelopathy

CT: computed tomography

FE: finite element

FEM: finite element model

MRI: magnetic resonance imaging

ROM: range of motion

Declarations

Ethics approval and consent to participate

This study was performed in accordance with the guidelines and with approval of the Clinical Research Advisory Committee and the Institutional Animal Care and Use Committee of The Ohio State University.

Consent to publish

Not applicable.

Availability of data and materials

Range of motion predictions for the developed finite element model are available in Table 1. Material properties obtained from literature are available in Supplementary file 1.

Competing interests

There are no competing interests.

Authors' contributions

MAB, RC_DC, and VKG participated in conception and design of the study. MAB and AS constructed and tested the finite element model. MAB, AS, VKG, and FSC interpreted the results along with RC_DC. All authors contributed to, read, and approved the final version of the manuscript.

Acknowledgements

Dr. Bonelli received a scholarship grant from the Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil. CAPES was not involved in any stage of this study. This work was supported in part by an allocation of computing time from the Ohio Supercomputer Center. We would also like to thank Rodney Summers, Sushil Sudershan, and Amirhesam Amerinatanzi for their assistance with troubleshooting during the initial steps.

Funding

This project was funded by the Gray Lady Foundation. The Gray Lady Foundation was not involved in any stage of this study.

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Figure legends

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

Tables

Table 1. Predicted range of motion of the finite element model for extension, flexion, left and right lateral bending, and left and right axial rotation, in degrees.

Level	Extension	Flexion	L lateral bending	R lateral bending	L axial rotation	R axial rotation
$C_{2\text{-}3}$	5.427834	6.551987	4.308903	5.295008	2.795842	2.220618
$C_{3\text{-}4}$	4.914963	5.521693	4.264677	4.536102	3.065371	2.762369
$C_{4\text{-}5}$	5.525042	6.169835	4.963788	4.977083	3.445774	3.169803
$C_{5\text{-}6}$	4.804269	5.108233	5.681846	5.46553	3.235505	3.507232
$C_{6\text{-}7}$	5.193022	4.585705	4.924902	4.995118	4.897282	5.064728

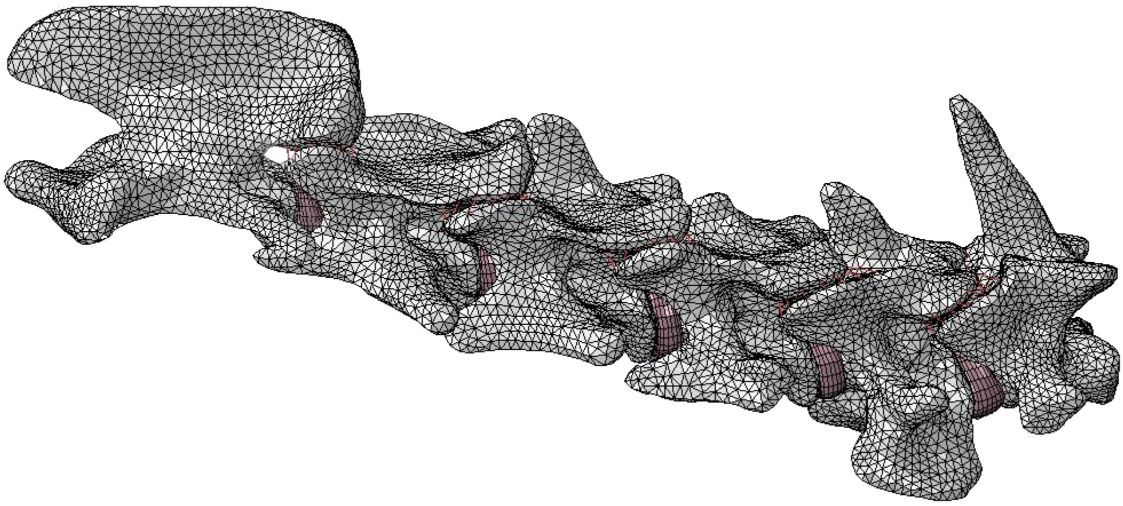
R, right; L, left.

Supplementary files

Supplementary Table 1. Material properties used in modelling bone and soft tissues.

Material	Young's Modulus (MPa)	Poisson's Ratio
Cancellous bone	100	0.2
Cortical bone	12000	0.3
Ligaments	Nonlinear (hypoelastic)	0.3
Nucleus pulposus	1	0.4999
Annulus fibrosus	Nonlinear (hyperelastic)	-

Figure 1



4.2 Artigo 2

Research article

Comparison of a C5-C6 laminectomy and hemilaminectomy using a canine C2-C7 finite element model

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Abstract

Background

Osseous-associated cervical spondylomyelopathy (OA-CSM) affects mostly Great Danes, with spinal cord and/or nerve root compression resulting mainly from osseous proliferation of the articular processes. The most common surgical treatments are laminectomy, hemilaminectomy, or stabilization with a polymethyl methacrylate plug. In humans, finite element models (FEM) have been used to study the effects of hemilaminectomy or laminectomy on the cervical vertebral column. Our objective was to compare the effects of a C_5-C_6 dorsal laminectomy (leaving the articular processes intact) and a C_5-C_6 hemilaminectomy using a geometrically accurate finite element model of the C_2-C_7 segment of the vertebral column of a Great Dane.

Results

Overall, there was no difference in range of motion between the laminectomy and the intact model. There were differences between the left hemilaminectomy and the intact model mainly at C_5-C_6, with the hemilaminectomy model displaying greater extension, left lateral bending, and right axial rotation. This suggests that the main role of the left C_5-C_6 articular joint comes into play during these motions, particularly as a restricting component during right axial rotation.

Conclusions

Articular process joints seem to participate in restricting the range of motion mainly during contralateral axial rotation.

Keywords: biomechanics; cervical spine; cervical spondylomyelopathy; dog; finite element analysis; wobbler syndrome

Background

The form of cervical spondylomyelopathy (CSM) that usually affects giant breeds, particularly Great Dane dogs, is osseous-associated cervical spondylomyelopathy (OA-CSM). In OA-CSM, spinal cord and/or nerve root compression results mainly from osseous proliferation of the articular processes with or without thickening of ligaments, mainly the ligamentum flavum [1,2]. There seems to be a dynamic component to injury in CSM as well [3,4], with compression increasing or decreasing depending on flexion and extension of the neck [5,6].

Currently, there are over 26 surgical procedures described for managing CSM, though none are considered ideal. For OA-CSM, the most commonly used procedures are laminectomy, hemilaminectomy, or stabilization with a polymethyl methacrylate plug [7].

In humans, finite element models (FEM) have been used, among other aspects, to study the effects of hemilaminectomy or laminectomy on the cervical vertebral column, alone or associated with other procedures [8-12]. One of the main advantages of FEM studies in these cases are the ability to perform any number of modifications to an initial model and run an infinite number of simulations without needing several specimens, as well as looking at internal stresses and strains that are not identifiable in other in vitro or ex vivo studies [13-15].

To date, there have been very few canine vertebral models created: one for L_6-L_7 [16], and one for the C_3 to C_6 segment [17], to test implants in those locations as a means of improving the use of dogs as models for human studies. Recently, our group has developed an intact ligamentous FEM of the C_2-C_7 segment of the vertebral column of a Great Dane [18].

The objective of this study was to compare the effects of a C_5-C_6 dorsal laminectomy and a C_5-C_6 hemilaminectomy using a geometrically accurate finite element model of the C_2-C_7 segment of the vertebral column of a Great Dane. Our hypothesis was that a laminectomy and hemilaminectomy would increase range of motion at C_5-C_6.

Methods

Intact C_2-C_7 model

A previously constructed geometrically accurate ligamentous finite element model of the C_2-C_7 segment of the vertebral column of a Great Dane was used [18]. The model had been constructed from CT a 2-year-old female Great Dane with no abnormalities found on neurologic exam, computed tomography (CT), and magnetic resonance imaging (MRI) evaluated by a board-certified veterinary neurologist (RC_DC). For construction of the model, segmentation of the vertebrae C_2 to C_7 and intervertebral discs from $C_{2\text{-}3}$ to $C_{6\text{-}7}$ had been done using threshold and manual selection. The vertebrae had been meshed separately using first order tetrahedral elements, while the intervertebral discs used hexahedral elements. The final model had 188906 elements (175715 tetra elements and 12740 hexa elements), with dorsal longitudinal, ventral longitudinal, flava ligaments, and articular capsule (represented as “capsular ligaments”) also modelled. The material properties were adapted from canine models using human material properties [16,17].

Simulation of a C_5-C_6 laminectomy

The laminectomy model was developed from the aforementioned C_2-C_7 intact model. Editing the intact model using Abaqus FEA (Dassault Systèmes), the elements within an area encompassing approximately the caudal half of the lamina of C_5 and the cranial half of the lamina of C_6 were deleted, including the ligamentum flavum at C_5-C_6 to simulate a laminectomy at C_5-C_6 (Figure 1). The "capsular ligaments" representing the articulation between the articular processes of C_5 and C_6 remained unaffected.

Simulation of a C_5-C_6 left hemilaminectomy

The previously constructed intact C_2-C_7 model was also edited to represent a hemilaminectomy at C_5-C_6. For this, the left caudal articular process of C_5 and the left cranial articular process of C_6 were removed along with the elements representing the articular process capsule (represented as "capsular ligaments"), as well as part of the lamina of C_5 and C_6 (Figure 2).

The size and extent of the laminectomy and hemilaminectomy were based on previously published guidelines [19].

Comparison between models

A 2Nm moment was applied to the cranial surface of C_2 in both models to simulate flexion, extension, left and right lateral bending, and left and right axial rotation. Results from the laminectomy and hemilaminectomy models were then compared to the ones for the intact model.

Results

The laminectomy model (Figure 1) had a total of 185989 elements (172803 tetra elements and 12740 hexa elements). The range of motion (ROM - in degrees) for the

FEM subjected to a moment of 2Nm was 27.94 in flexion, 25.90 in extension, 24.15 in left lateral bending, 25.27 in right lateral bending, 17.50 in left axial rotation, and 16.77 in right axial rotation. The ROM obtained for each vertebral segment is shown in Table 1. All ROM values in this paper have been rounded to the nearest 2 decimals.

The hemilaminectomy model (Figure 2) had a total of 185057 elements (171880 tetra elements and 12740 hexa elements). The ROM (in degrees) for the FEM subjected to a moment of 2Nm was 28.42 in flexion, 27.07 in extension, 24.98 in left lateral bending, 25.37 in right lateral bending, 17.82 in left axial rotation, and 25.37 in right axial rotation. The ROM obtained for each vertebral segment is shown in Table 2.

Overall, there was no difference in ROM between the laminectomy model and the intact model. There were, however, some differences in ROM between the hemilaminectomy model and the intact model. As expected, those differences were mainly at C_5-C_6, with the hemilaminectomy model displaying greater extension (6.0 compared to 4.8 degrees from the intact model), left lateral bending (6.46 compared to 5.68 degrees from the intact model), and right axial rotation (8.45 compared to 3.51 from the intact model).

Discussion

In this study, we evaluated the influence a laminectomy or hemilaminectomy at C_5-C_6 would have on range of motion and stress distribution using a geometrically accurate FE model of the C_2-C_7 segment of the vertebral column of a Great Dane. Our main hypothesis, that range of motion would increase for both the laminectomy and hemilaminectomy models was only partially confirmed. While there was some difference in ROM between the hemilaminectomy model and the intact model, there was no difference between the ROM obtained for the laminectomy model and the intact model. We also did not confirm our hypothesis that laminectomy would lead to higher range of motion compared to hemilaminectomy.

The increased ROM seen in the hemilaminectomy model when compared to the intact model in extension at C_5-C_6 (1.2 degrees greater), left lateral bending (0.8 degrees greater), and right axial rotation (4.93 degrees greater) suggests that the main role of the left C_5-C_6 articular joint comes into play during these motions, particularly as a restricting component during right axial rotation. That the articular facets participate in axial rotation has been previously evidenced [20], and coupled motion has been shown to exist between axial rotation and lateral bending in dogs [21]. In humans, facets are also considered to restrict extension in the cervical vertebral column [22].

The lack of a significant difference between the laminectomy model and the intact model could be due to the fact that during this laminectomy, the major component participating in range of motion that was removed was the ligamentum flavum (removed along with part of the dorsal lamina of C_5 and C_6). It is likely that removal of this component, under a moment of 2Nm, does not lead to significant changes to ROM. It is important, however, to remember that, in vivo, greater interference with muscles and their attachments occur during laminectomy, and this also affects stability and leads to motion changes [11].

There is a scarcity of studies focusing on the biomechanics of the cervical spine in dogs, whether related to surgical procedures or not. Only one study focuses on the biomechanical behavior of a large portion of the intact cervical vertebral column (analyzing C_2 to C_4 and C_5 to C_7) [21], and there are no studies using giant breeds. Comparison with long-term in vivo studies [22] is difficult at best since the FEM does not take into account muscle function, nuchal ligament, inflammation, pain, and healing.

In humans, FEM studies have shown that dorsal laminectomy in the cervical region increases motion, particularly flexion and extension [8,9,11], and a multilevel laminectomy has more noticeable effects than a multilevel hemilaminectomy [11]. Perhaps due to the anatomical differences, such as a shorter vertebrae in humans, in that species, a laminectomy entails the complete removal of the dorsal lamina of a single vertebra (and thus the removal of two ligamenta flava) [9] as opposed to what is usually performed in the dog during a single level laminectomy (without removal of the articular processes). These anatomical differences also hinder a direct comparison between canine and human findings.

Studies testing the biomechanical influence of multiple hemilaminectomies or laminectomies, sometimes associated with discectomies, are available in dogs in the lumbar or lumbosacral region [23-25]. Other than the inherent anatomical differences between these locations and the cervical vertebral column, the combination of different procedures impedes a trustworthy comparison with the present study.

A limitation of the present study was the use of an FEM with human material properties because of the lack of availability of canine-specific material properties [16-17]. However, when comparing a modified version with the intact model using the same material properties, any differences seen are due to the modifications performed, thus it is still possible to gather information from these tests. To improve these models, material properties specific to dogs, and ideally, Great Danes, can be inserted whenever they become available as the models are already constructed.

Another limitation – and this applies to any ligamentous finite element model – is that the model takes into account only the structures being represented, therefore, muscle forces are not taken into account and there would be differences in what is observed in the model and in vivo. However, this is also true of any cadaver study, and while care should always be taken when translating these findings to a living subject, any information gathered on specific components of a whole can better our understanding of that whole, in this case, the biomechanics of the cervical region. Towards that end, one of the advantages of a FEM is that it can be modified to study the participation of each component (by removing that component) in the motion of the cervical vertebral column.

Conclusions

We modified a geometrically accurate ligamentous FE model of the C_2-C_7 vertebral column of a Great Dane to represent a C_5-C_6 laminectomy, where the articular processes were left intact, and a C_5-C_6 left hemilaminectomy, with removal of these articular processes. Based on a comparison of these models with an intact C_2-C_7 model, we observed that the articular process joints seem to participate in restricting the range of motion mainly during contralateral axial rotation.

List of abbreviations

CSM: cervical spondylomyelopathy

OA-CSM: osseous-associated cervical spondylomyelopathy

FEM: finite element model

ROM: range of motion

Declarations

Ethics approval and consent to participate

This study did not involve recruitment of live animals, however, the images obtained for the construction of the initial intact model were obtained in accordance with the guidelines and with approval of the Clinical Research Advisory Committee and the Institutional Animal Care and Use Committee of The Ohio State University.

Consent to publish

Not applicable.

Availability of data and materials

Range of motion predictions for the models are available in tables 1 and 2.

Competing interests

There are no competing interests.

Authors' contributions

MAB, RC_DC, and VKG participated in conception and design of the study. MAB and AS constructed and tested the finite element models. MAB, AS, VKG, and FSC interpreted the results along with RC_DC. All authors contributed to, read, and approved the final version of the manuscript.

Acknowledgements

Dr. Bonelli received a scholarship grant from the Coordination for the Improvement of Higher Education Personnel (CAPES), Brazil. CAPES was not involved in any stage of this study. This work was supported in part by an allocation of computing time from the Ohio Supercomputer Center.

Funding

This project was funded by the Gray Lady Foundation. The Gray Lady Foundation was not involved in any stage of this study.

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Figure legends

Figure 1. Ligamentous finite element model of the C2-C7 segment of a Great Dane without spondylomyelopathy with a portion of the dorsal lamina of C5 and C6 removed to represent a laminectomy (shaded area); in dorsal (A) and lateral (B) view.

Figure 2. Ligamentous finite element model of the C2-C7 segment of a Great Dane without spondylomyelopathy with the articular processes of C5 and C6, as well as a part of the lamina and pedicles removed to represent a hemilaminectomy (shaded area); in dorsal (A) and lateral (B) view.

Tables

Table 1. Predicted range of motion of the intact and laminectomy finite element model for extension, flexion, left and right lateral bending, and left and right axial rotation, in degrees.

Level	Extension		Flexion		L lateral bending		R lateral bending		L axial rotation		R axial rotation	
	I	**L**	I	**L**	I	**L**	I	**L**	I	**L**	I	**L**
C_2-C_3	5.43	**5.43**	6.55	**6.55**	4.31	**4.31**	5.29	**5.29**	2.79	**2.8**	2.22	**2.22**
C_3-C_4	4.91	**4.91**	5.52	**5.52**	4.26	**4.26**	4.54	**4.54**	3.06	**3.06**	2.76	**2.76**
C_4-C_5	5.52	**5.52**	6.17	**6.17**	4.96	**4.96**	4.98	**4.98**	3.44	**3.45**	3.17	**3.18**
C_5-C_6	4.8	**4.84**	5.11	**5.11**	5.68	**5.68**	5.46	**5.65**	3.23	**3.28**	3.5	**3.54**
C_6-C_7	5.19	**4.58**	4.58	**4.58**	4.92	**4.92**	5.0	**4.99**	4.90	**4.90**	5.06	**5.07**

R, right; L, left; I, intact model; L, laminectomy model

Table 2. Predicted range of motion for the intact and hemilaminectomy finite element model for extension, flexion, left and right lateral bending, and left and right axial rotation, in degrees.

Level	Extension		Flexion		L lateral bending		R lateral bending		L axial rotation		R axial rotation	
	I	**H**	I	**H**	I	**H**	I	**H**	I	**H**	I	**H**
C_2-C_3	5.43	**5.42**	6.55	**6.55**	4.31	**4.32**	5.29	**5.29**	2.79	**2.8**	2.22	**2.24**
C_3-C_4	4.91	**4.91**	5.52	**5.52**	4.26	**4.27**	4.54	**4.53**	3.06	**3.06**	2.76	**2.81**
C_4-C_5	5.52	**5.53**	6.17	**6.17**	4.96	**5.0**	4.98	**4.97**	3.44	**3.44**	3.17	**3.20**
C_5-C_6	4.8	**6.0**	5.11	**5.58**	5.68	**6.46**	5.46	**5.58**	3.23	**3.63**	3.5	**8.45**
C_6-C_7	5.19	**5.20**	4.58	**4.59**	4.92	**4.92**	5.0	**4.99**	4.90	**4.90**	5.06	**5.06**

R, right; L, left; I, intact model; H, hemilaminectomy model

Figure 1

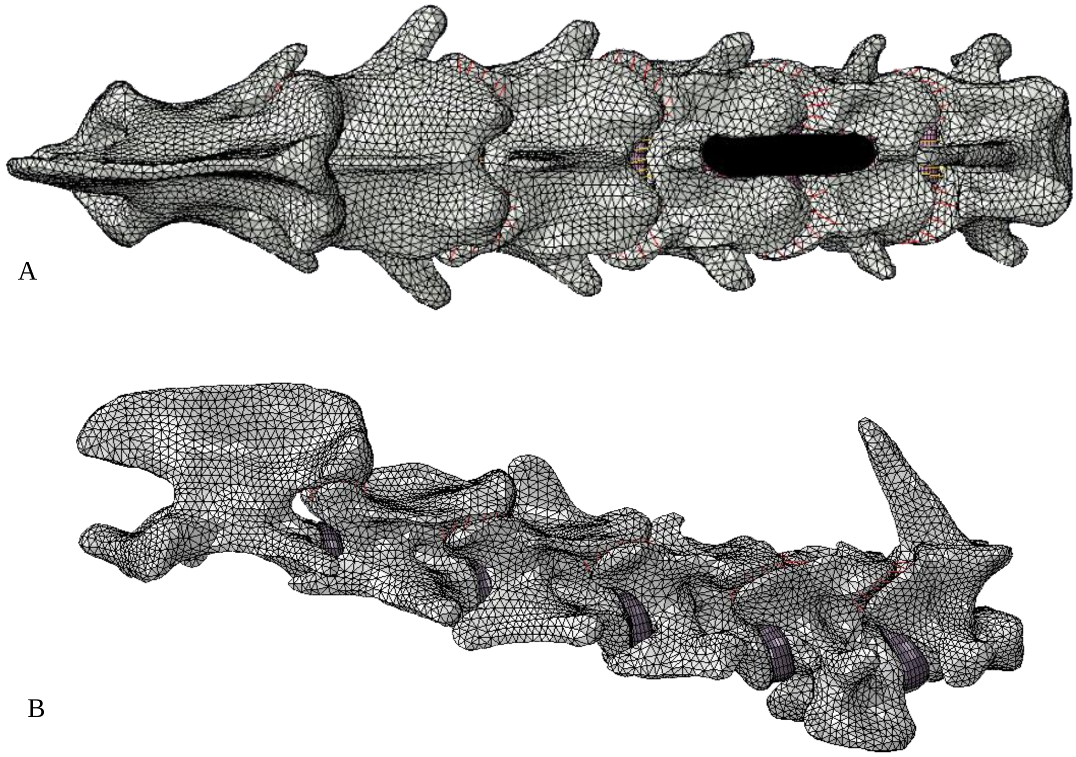
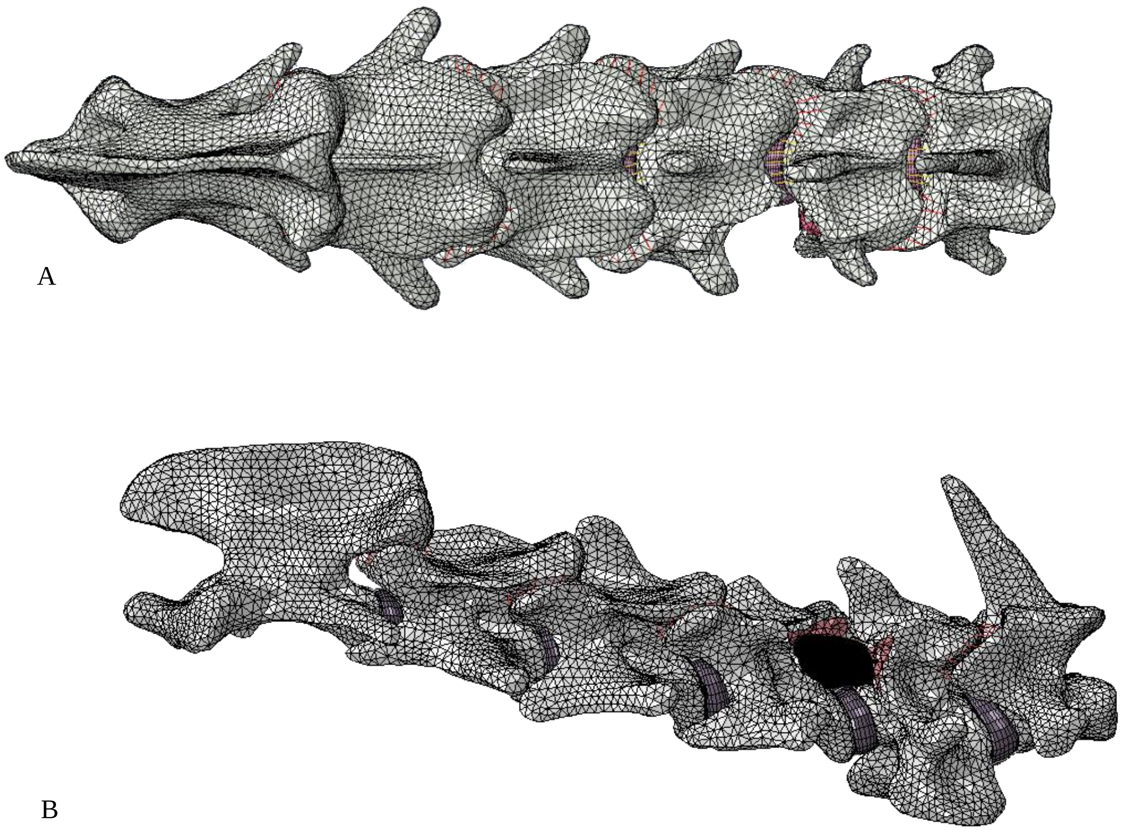


Figure 2



Apêndice

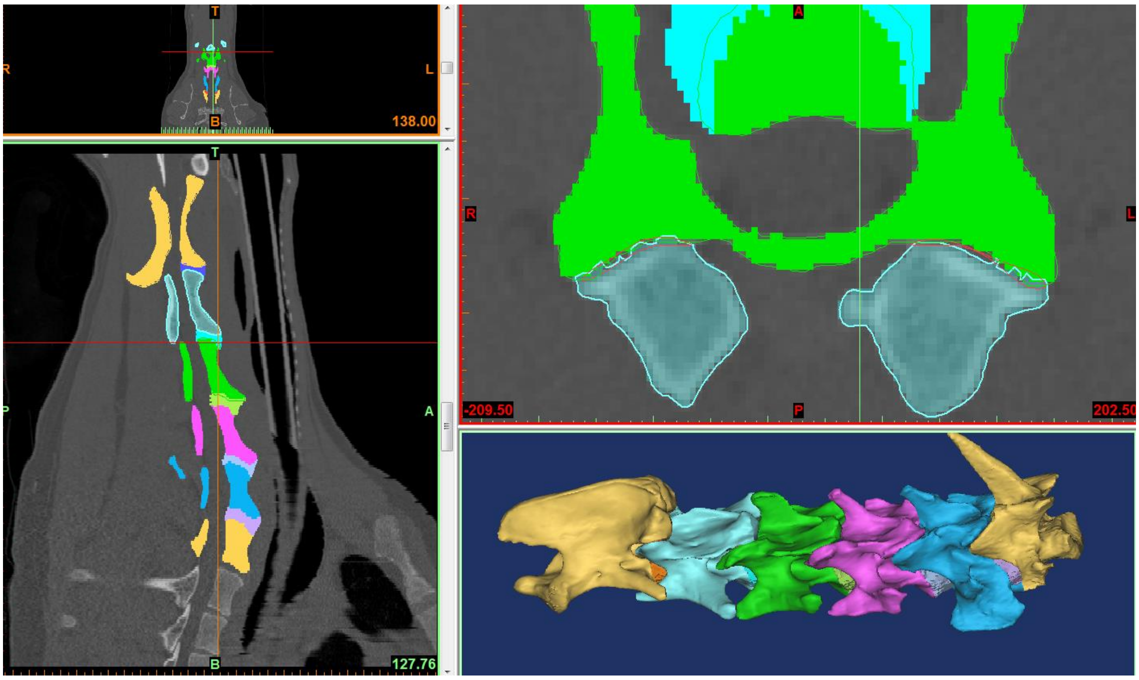


Figura 1. Segmentação das vértebras e discos intervertebrais de C_2 a C_7 de um Dogue Alemão sem alterações neurológicas ou de imagem.

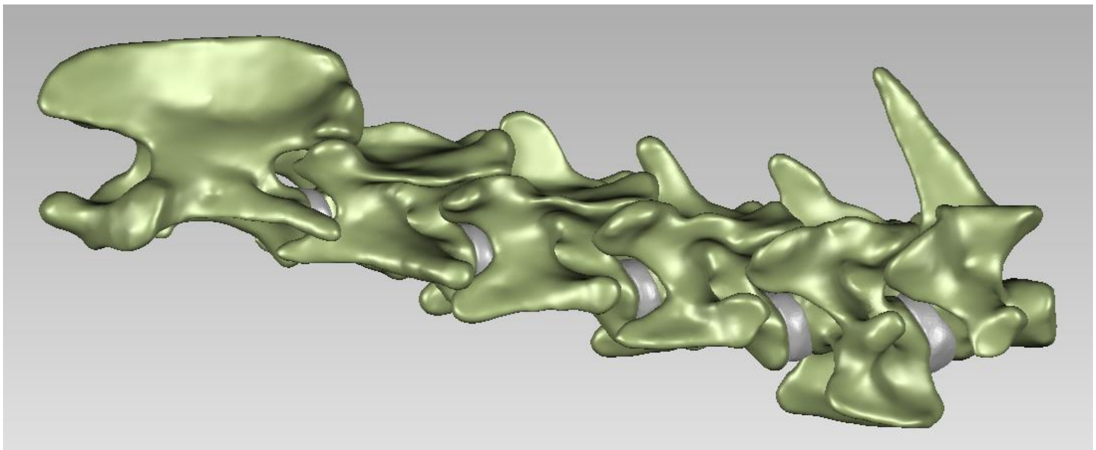


Figura 2. Representação dos modelos de superfície e de polígonos para as vértebras e discos intervertebrais de C_2 a C_7 de um Dogue Alemão sem alterações neurológicas ou de imagem.

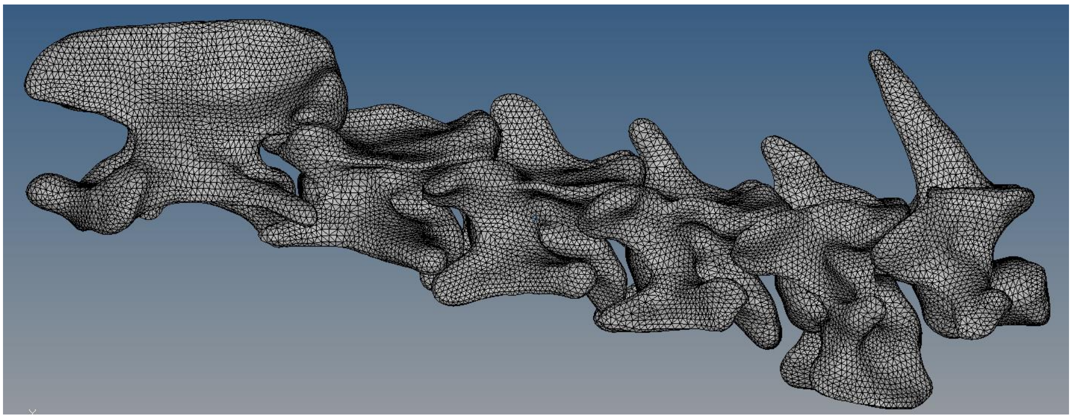


Figura 3. Malha de elementos finitos para as vértebras de C_2 a C_7 de um Dogue Alemão sem alterações neurológicas ou de imagem.

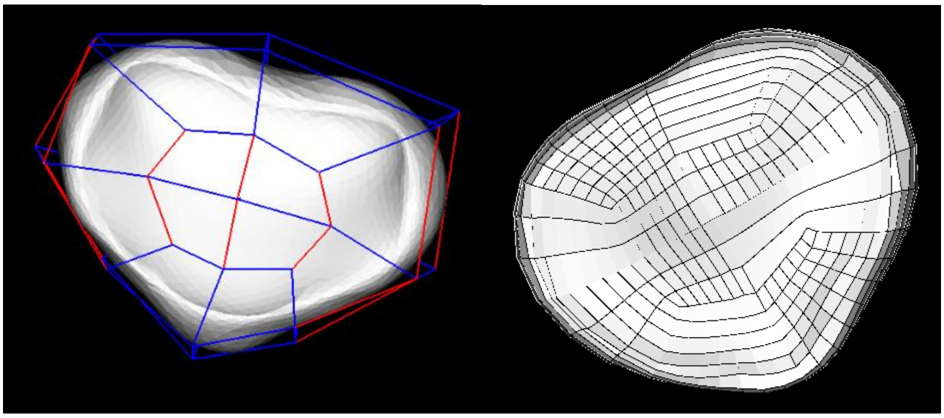


Figura 4. Malha de elementos finitos dos discos intervertebrais $C_{2\text{-}3}$ (imagem à esquerda) e $C_{3\text{-}4}$ (imagem à direita).

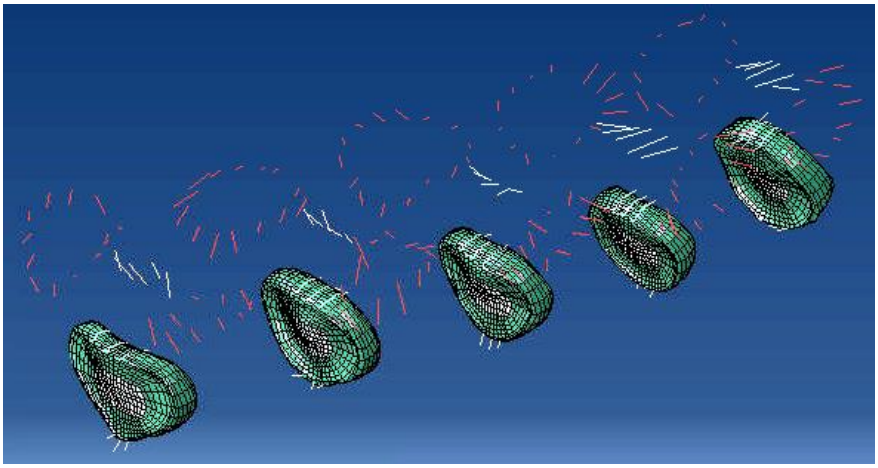


Figura 5. Discos intervertebrais e ligamentos como representados no modelo de elementos finitos de Dogue alemão sem alterações neurológicas ou de imagem. Note que a cápsula articular está representada por diversos “ligamentos capsulares”, em vermelho.

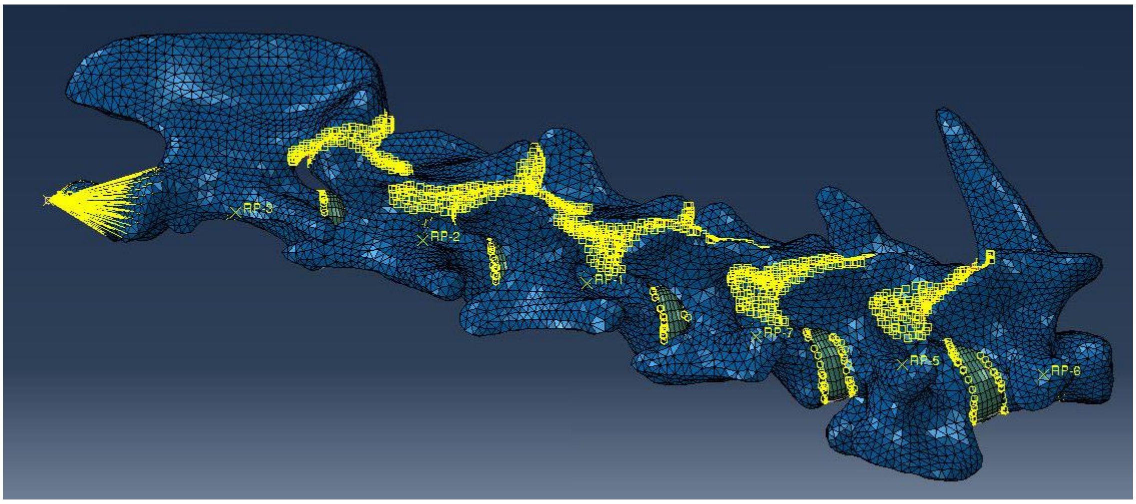


Figura 6. Modelo de elementos finitos de C_2 a C_7 de um Dogue alemão sem alterações neurológicas ou de imagem, com interações entre as estruturas representadas (regiões em amarelo), e o local onde é aplicada a força de 2 Nm em C_2.

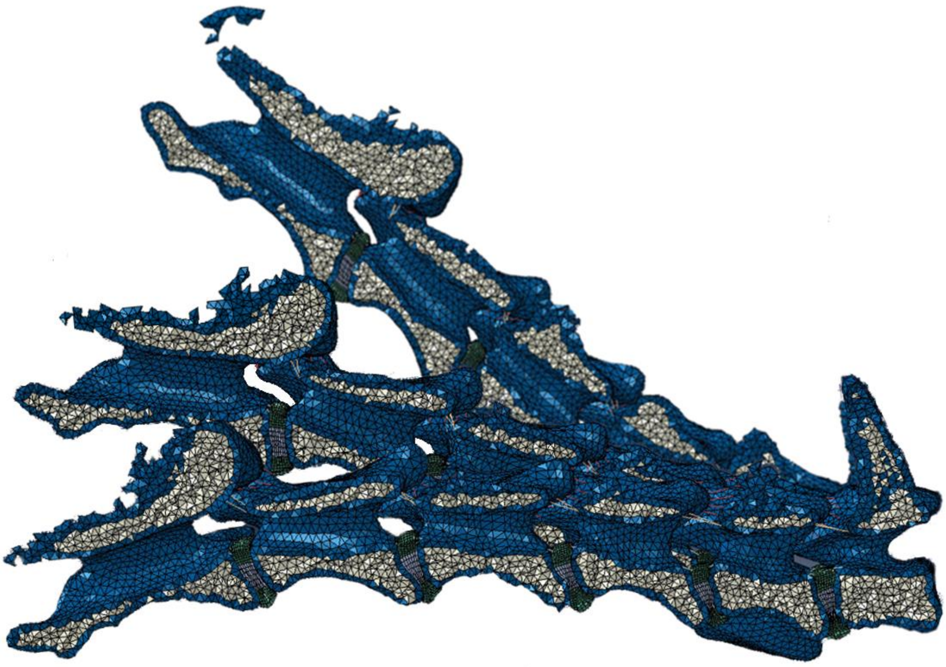


Figura 7. Corte sagital de modelo de elementos finitos de C_2 a C_7 de um Dogue alemão sem alterações neurológicas ou de imagem, em posição neutra, e flexão e extensão simuladas sob 2Nm.