Kinematic Motion Patterns of the Cranial and Caudal Canine Cervical Spine

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Objective: To define the kinematic motion patterns of the canine cervical spine, with a particular emphasis on identifying differences between the cranial (C2–C4) and caudal (C5–C7) segments, and to determine the significance of coupled motions (CM) in the canine cervical spine.

Study Design: Cadaveric biomechanical study.

Sample Population: Cervical spines of 8 Foxhounds.

Methods: Spinal specimens were considered free of pathology based on radiographic, computed tomography, and magnetic resonance imaging examinations. All musculature was removed without damaging ligaments or joint capsules. Spines were mounted in a customized pure-moment spine testing jig, and data were collected using an optoelectronic motion capture system. Range of motion, neutral zone and CM in flexion/extension, left/right lateral bending and left/right axial rotation were established. Data were analyzed using mixed-effects maximum likelihood regression models.

Results: Total flexion/extension did not change across the 4 levels. There was no difference between flexion and extension, and no CM was identified. Lateral bending was not different across levels, but tended to be greater in the cranial spine. Axial rotation was ~2.6 times greater in the caudal segments. Lateral bending and axial rotation were coupled.

Conclusions: Kinematics of the cranial and caudal cervical spine differed markedly with greater mobility in the caudal cervical spine.

Although the diagnosis and treatment of many cervical spine disorders have been described, their pathogenesis is poorly understood. Biomechanical studies are fundamental to the understanding of the pathogenesis of many of these conditions, in particular cervical spondylomyelopathy (CSM), also known as Wobbler syndrome. CSM is the most common disease of the cervical spine of large and giant breed dogs, in particular Doberman Pinschers and Great Danes. This disease has some similarities to, and has been proposed as a natural model for, the human cervical spondylotic myelopathy. Cervical spondylotic myelopathy is the most common cause of acquired spinal cord dysfunction in people and, as in dogs, can cause severe pain and neurologic disability.

Intervertebral instability, has long been implicated in the pathogenesis of CSM; however, we are unaware of any study that has objectively examined this hypothesis. A magnetic resonance imaging (MRI) study comparing the degree of intervertebral disc distraction between Dobermans with, and without, clinical signs of CSM found that both groups had the same degree of intervertebral distraction. It appears that dynamic spinal cord compression, rather than instability, may actually be involved in the pathogenesis of CSM, but this hypothesis requires confirmation in dogs.

Dogs with CSM can be treated by medical management and/or surgical techniques (eg, dorsal or ventral decompression, distraction and/or fusion, and stabilization). However, the effects of these varied techniques on the biomechanics of the cervical spine are not fully understood. Ventral fenestration of C5–C6 in the canine spine has led to an increase in sagittal instability at the disc space. In people, decompressive surgery has been associated with postoperative recurrent stenosis and instability, whereas fusion complications included stenosis, fixation failure, and adjacent level degeneration (domino lesion). In people, the risk of these surgical complications has been a stimulus for research into alternatives to spinal fusion, including motion-preserving surgeries such as total disc replacement.

Various techniques have been used to measure kinematics of the human spine in vitro and in vivo, including radiography, computed tomography (CT), electrogoniometry, radiostereometric analysis, optical motion...
A detailed knowledge of the normal biomechanics of the canine cervical spine is essential to our understanding of both the pathophysiology and pathogenesis of cervical spinal disorders. We designed this study to address 2 specific aims. The first was to develop a methodology for testing multilevel spinal segments in the canine cervical spine. The second was to identify the ROM in flexion/extension, left/right lateral bending, and left/right axial rotation in the cranial and caudal canine cervical spine, and to quantify the nature and magnitude of any associated CM. Our hypothesis was that the kinematic parameters of the cranial and caudal cervical spine would be significantly different in their ranges of motion and that lateral bending and axial rotation would be coupled.

**MATERIALS AND METHODS**

**Specimen Collection**

The cervical spine (C1–T2) was harvested en bloc from 10 skeletally mature Foxhounds (1.5–2 years old), euthanized for reasons unrelated to this study. Body mass averaged 30.5 kg (29.2–33.0 kg) and sex distribution included 7 males and 1 female. All spines had dorsoventral and right lateral plain radiography, followed by CT and MRI to evaluate vertebral morphology and intervertebral disc hydration (Fig 1). Spines were then stripped of all musculature, leaving the spinal ligaments and articular facet joint capsules intact. Specimens were wrapped in saline (0.9% NaCl) solution-soaked towels and stored at $-20^\circ$ C, then thawed for 12 hours to room temperature before testing. The spines were sprayed regularly with sterile physiologic saline solution during mounting and kinematic testing to prevent desiccation.

**Specimen Preparation**

The atlas was removed from all specimens, which were then separated into cranial (C2–C4) and caudal (C5–T2) segments by disarticulating the spine at the C4–C5 disc. Screws were inserted into the caudal aspect of the vertebral bodies of C4 and C7 for additional support, and the specimens were embedded in fiberglass resin (Bondo, Bondo Corp., Atlanta, GA) so that C4 and C7 were fixed in place. For flexion/extension tests, a threaded rod (1/4"0 × 22") was inserted through the body of the uppermost vertebrae (C2...
or C4) in a dorsoventral direction, and secured in place with bolts. For lateral bending and axial rotation test, the rod was inserted through the vertebrae in a transverse direction (Fig 2). This method has been described previously in human spinal specimens.32

Load Application

Each spinal construct was loaded into a custom-designed testing apparatus (Fig 2) at ECORE, University of Toledo, OH. A pure moment was applied to the spine in 3 directions: flexion/extension (FE), left/right lateral bending (LB), and left/right axial rotation (AR). Pure-moment testing allowed equal distribution of the applied load across all the tested segments. Loading cables were attached to the appropriate rod in opposite directions and equidistant from the center of the vertebra. The cables were placed so that they were perpendicular to the rod and parallel to each other in order to achieve pure moments (Fig 2A). In each test, loading was applied in a stepwise manner described previously, in the sequence 0.0 (neutral/no load), 0.5, 1.0, 1.5, and 0.0 N m.33 Positional measurements of the spines were taken at each of the 5 steps. The repeated final measurement at 0.0 N m was taken for measurement of neutral zone (NZ).

Data Collection

Marker sets with 3 infrared light-emitting diodes (IR-LEDs) were rigidly attached to the ventral aspect of the bodies of the 2 most cranial vertebrae of each segment and to the rigidly fixed base containing the most caudal vertebrae (Fig 2B). The positions of the IR-LED markers were tracked using an optoelectronic camera (Optotrak, Northern Digital, Waterloo, ON, Canada) and recorded for 300 frames at a frequency of 100 Hz at each loading position. Raw data were imported into a custom software program that calculated the rotation angles using the tilt/twist method34 that models the 2 adjacent vertebrae as stacked overlappable cylinders and describes motion of the upper vertebra relative to the lower vertebra. The following calculations were made for each loading direction:

1. ROM – The ROM of each FSU, measured from neutral to maximal displacement. For flexion/extension, the total ROM was the additive ROMs from flexion and extension. For left/right lateral bending and left/right axial rotation, the total ROM was the additive ROMs from the left and right tests.
2. NZ – The NZ is the part of the ROM within which spinal motion is produced with minimal effort. Physically, when a spine is loaded repeatedly in a single direction and then that load removed, the spine does not return to its initial neutral position. The NZ was calculated as the difference between neutral and the residual displacement when all loads were removed.
3. Primary motion (PM) – The PM was the motion that occurred in the direction of the applied moment.
4. CM – The CM was a motion that occurred in a consistent direction other than that of the applied moment.

Statistical Analysis

A mixed-effects maximum likelihood regression model was used to test whether ROM changed over segment level for each type of motion pattern (AR, FE, LB) and to compare results according to cranial or caudal location. The slope of the ROM regression line was tested to see whether it was significantly different from zero over segment level. A mixed-effects regression was used because the observations are nested within animal. The same method was used to determine the relationship between NZ and ROM and to test differences between ROM of flexion and ROM of

Figure 2  (A) Schematic image depicting a C2–C4 segment mounted in the testing frame and configured for a left lateral bend test. The pulley cables are equidistant from the spine, perpendicular to the rod and parallel to each other, resulting in the application of a pure moment to the construct. Note that although the spine appears in a neutral position, the position of the weights is shown for illustrative purposes. (B) Close-up view illustrating the orientation of the rod for a left lateral bending test and placement of the IR-LED markers (arrows) for optical tracking of spinal motion. IR-LED, infrared light-emitting diode.
extension. To conserve the overall type I error at 0.05, P-values were adjusted using the Holm’s procedure for each regression. All analyses were performed with software (Stata 10.1, Stata Corporation, College Station, TX).

RESULTS

Ten spines were imaged and 2 excluded because of presence of intervertebral disc degeneration. Mean results for ROM, NZ and CM are provided in Table 1. Load–deformation curves demonstrated that load–displacement did not occur in a linear fashion (Figs 3–5).

**Flexion/Extension**

A mixed-effects regression model indicated a difference of $1.1^\circ$ between the ROM for flexion and extension after adjustment for segment level; however, this result was not statistically significant ($P = .267$). There was a tendency across all spines for a decreased ROM at C5–C6. NZ increased 0.1° (95% CI: −0.00 to 0.03) for every $1^\circ$ increase in ROM; however this result was not significantly different from zero ($P = .213$). Flexion/extension ROM was not significantly different across the 4 spinal levels ($P = .916$).

**Left/Right Lateral Bending**

Left/right lateral bending ROM was not significantly different across the segment levels ($P = .0112$). On average, lateral bending ROM in the cranial spine was 4.8° greater than that in the caudal spine ($P = .051$). Left/right lateral bending was coupled with left/right axial rotation, with both movements occurring in the same direction simultaneously (Figs 4 and 6). One degree of primary lateral bending was associated with 0.47° of CM in the cranial spine and with 1.22° of CM in the caudal spine; these were significantly different ($P < .001$). NZ increased 0.05° for every $1^\circ$ increase in ROM after adjustment for segment level ($P = .424$). There was no significant association between ROM in lateral bending and ROM in flexion/extension ($P = .732$).

**Left/Right Axial Rotation**

Left/right axial rotation was significantly different over segment level C2–C3 to C6–C7 ($P < .001$). ROM in the caudal segments was ~19.7° greater than the cranial segments ($P < .001$). One degree of primary axial rotation was associated with 1.54° of CM in the cranial spine and with 0.82° of CM in the caudal spine; these were significantly different ($P < .001$). Left/right axial rotation was coupled with left/right lateral bending in the same direction. NZ increased 0.2° for every $1^\circ$ increase in ROM ($P < .001$).

**DISCUSSION**

We are unaware of other veterinary studies that compare kinematics in the cranial and caudal cervical spinal segments in dogs. Our findings indicate that motion patterns differ significantly between the cranial and caudal cervical spine, that lateral bending is strongly coupled to ipsilateral

**Table 1** Summary Data (Mean ± SD) for Flexion/Extension, Lateral Bending, and Axial Rotation Motion Patterns

<table>
<thead>
<tr>
<th>Level</th>
<th>ROM</th>
<th>NZ</th>
<th>Flexion</th>
<th>Extension</th>
<th>ROM</th>
<th>NZ</th>
<th>CM</th>
<th>CM/PM</th>
<th>ROM</th>
<th>NZ</th>
<th>CM</th>
<th>CM/PM</th>
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<tr>
<td>C2–C3</td>
<td>24.0 ± 2.6</td>
<td>2.3 ± 1.7</td>
<td>13.8 ± 2.6</td>
<td>10.2 ± 2.7</td>
<td>22.8 ± 3.2</td>
<td>3.2 ± 1.4</td>
<td>10.2 ± 5.2</td>
<td>0.5 ± 0.3</td>
<td>7.9 ± 2.3</td>
<td>1.4 ± 2.1</td>
<td>11.0 ± 5.8</td>
<td>1.4 ± 0.6</td>
</tr>
<tr>
<td>C3–C4</td>
<td>25.6 ± 2.7</td>
<td>2.9 ± 2.7</td>
<td>14.5 ± 3.8</td>
<td>11.1 ± 2.3</td>
<td>28.0 ± 4.0</td>
<td>4.1 ± 1.2</td>
<td>12.8 ± 3.3</td>
<td>0.5 ± 0.2</td>
<td>8.0 ± 2.1</td>
<td>1.6 ± 1.7</td>
<td>13.2 ± 7.1</td>
<td>1.7 ± 0.9</td>
</tr>
<tr>
<td>C4–C5</td>
<td>19.6 ± 3.0</td>
<td>1.2 ± 0.5</td>
<td>9.5 ± 1.7</td>
<td>10.1 ± 1.8</td>
<td>23.8 ± 4.1</td>
<td>3.0 ± 1.3</td>
<td>20.5 ± 6.1</td>
<td>0.9 ± 0.2</td>
<td>23.0 ± 10.0</td>
<td>3.5 ± 2.2</td>
<td>20.7 ± 7.8</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>C5–C6</td>
<td>26.4 ± 7.0</td>
<td>1.9 ± 0.9</td>
<td>14.7 ± 6.7</td>
<td>11.7 ± 2.5</td>
<td>17.4 ± 6.1</td>
<td>2.7 ± 1.0</td>
<td>23.7 ± 9.2</td>
<td>1.6 ± 0.8</td>
<td>32.4 ± 10.0</td>
<td>6.4 ± 3.2</td>
<td>16.3 ± 6.8</td>
<td>0.5 ± 0.3</td>
</tr>
</tbody>
</table>

ROM, range of motion; NZ, neutral zone; CM, coupled motion; PM, primary motion.
axial rotation, and that axial rotation occurs to the largest amplitude in the caudal segments. We used dogs that had been confirmed (by 3 clinically validated imaging methodologies) to be free of spinal pathology. This was vital to establish baseline information on cervical motion, since spinal pathology such as intervertebral disc degeneration is known to significantly affect motion patterns.21,22

One of the earliest papers to describe motion in the canine neck concluded that the canine cervical spine had only a minimal amount of rotation.29 This conclusion was based on the absence of uncovertebral joints, an anatomic feature that is involved in rotation in the human cervical spine, in the canine cervical spine. The absence of rotation was also documented in radiographic studies23,25 but it should be noted that the failure to detect rotation in these studies may have been because of the relative insensitivity of radiography in determining out-of-plane rotations. More recent studies have contradicted these earlier observations. For example, a detailed morphometric study of the canine spine revealed curvature of the articular facets, a feature which is typically associated with axial rotation.30 This same report indicated that axial rotation was coupled with lateral bending, an observation that has also been made in the human cervical spine.35–39 Hofstetter et al have also identified CM in the C4–C5 vertebral segment of the canine spine using mechanical testing.31 We confirmed that left/right axial rotation and left/right lateral bending are coupled in both the cranial and caudal segments of the canine cervical spine. The direction of the CM occurs in the same direction as the PM, and the 2 motions occur simultaneously, supporting the findings from earlier reports.30,31 There was a positive correlation between the NZ and the PM ROM in the all 3 loading directions, similar to the findings in people.40 We were unable to find evidence of significant coupling between lateral bending and flexion/extension in the dog.

Our study has some potential limitations. The cranial and caudal spinal segments were tested separately, a decision that was made on the basis that it was impossible to maintain the highly flexible canine spine in a neutral position during testing of the intact specimen. In addition, the curvature of the intact spine made it impossible to see all of the IR markers necessary to track spinal motions. The flexion/extension ROM values reported may be slightly higher than those seen clinically in normal dogs, because spines were tested to a maximum of 1.5 N·m and a study using anesthetized dogs found that applied pure

Figure 4  Load–deformation curves for lateral bending in the upper (A) and lower (B) segments of the canine cervical spine. Data are mean ± SD for 8 specimens at each of 4 spinal levels. Solid lines indicate primary motions, dashed lines reflect coupled motions. Differences between motion patterns in the different levels are described in the text.

Figure 5  Load–deformation curves for axial rotation in the upper (A) and lower (B) segments of the canine cervical spine. Data are mean ± SD for 8 specimens at each of 4 spinal levels. Solid lines indicate primary motions, dashed lines reflect coupled motions. Differences between motion patterns in the different levels are described in the text.
moments > 1.1 N m compromised breathing. We also used stepwise, rather than continuous, loading. Stepwise loading protocol results are more subject to creep effects of the disc (changes in angulation occurring during continuous loading); however, continuous loading results in smaller ROM and NZ results.

We found that left/right axial rotation was 19.7° greater in the caudal spine than the cranial spine. These data are in general agreement with predictions from a morphometric study of articular facet geometry. The same study also concluded that, based on articular facet morphology, large breed dogs should have a greater degree of axial rotation than smaller breeds. Foxhounds are considered a large breed, and around the same height and weight as a Doberman Pinscher. It is well known that small breed dogs are more likely to develop cervical disc disease in the cranial segments, particularly C2–C3, whereas large breed dogs are more likely to develop pathology in the caudal cervical segments. Left/right axial rotation is strongly coupled to ipsilateral left/right lateral bending in the dog and intervertebral discs are exposed to multidirectional patterns of loading that likely result in increased shear forces. A study on the human lumbar spine found that torsional strains rather than compressive loads are likely to be responsible for intervertebral disc degeneration. The difference in both the pattern and the magnitude of loading between large and small breed dogs may in part explain why cervical complaints in large-breed dogs tend to occur in the caudal cervical spine. Whereas our study was not designed to address this question directly, further studies, possibly

Figure 6  A C2–C4 specimen (A, B) and C5–C7 specimen (C, D) shown during a left lateral bending test. (A, C) Specimens are in the neutral position (0.0 N m). (B, D) Specimens are loaded with 1.5 N m left lateral bending. The associated coupled rotation is visible in both (note the orientation of the rod and screw heads), but greater in the C5–C7 specimen.
involving a combination of finite element modeling and direct validation in cadaveric specimens, should be undertaken to more completely explore this potentially intriguing relationship.

We found that the ratio of CM/PM increased for the caudal cervical levels for left/right lateral bending and decreased for left/right axial rotation. This reflects the increased amount of rotation capable in the caudal cervical spine. In the cranial cervical spine, the extent of coupled axial rotation during applied lateral bending forces was greater than the ROM reached during applied axial rotation moments. The CM/PM ratios here were greater than that achieved in published human reports. This indicates that the canine cervical spine has a larger degree of CM than seen in humans, confirming the findings observed on the canine C₄–C₅ segment.

Interestingly, we found that the flexion/extension ROM of C₅–C₆ tended to be decreased in comparison with other levels, though this did not reach statistical significance. Similar results have been documented in spinal mechanics studies using dog models, and these findings are at odds with an anatomic study that suggested that the range flexion/extension increases when descending the spinal column. The C₅–C₆ ROM found was lower than pre-operative values reported in a study on disc fenestration, This may be because this earlier study did not use pure moment testing, or it may reflect breed and/or body size differences in the groups of dogs used in the 2 studies.

Breed-associated differences in vertebral anatomy can have a significant effect on motion. We used 8 Foxhounds with similar body weights (29–33 kg). Whether our findings apply to giant canine breeds, such as Great Danes, requires further investigation. Our test method will form the basis of future studies that will explore the influence of breed-related differences in spinal morphometry on spinal kinematics and compare spinal kinematics in normal dogs and those with CSM or other spinal pathology. Ultimately, the results from these in vitro studies will allow us to better define normal and abnormal motions in the canine cervical spine, opening up new possibilities for the diagnosis and surgical management of dogs with cervical spinal disease.

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