Effects of anatomic conformation on three-dimensional motion of the caudal lumbar and lumbosacral portions of the vertebral column of dogs

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Objective—To determine the association between the 3-dimensional (3-D) motion pattern of the caudal lumbar and lumbosacral portions of the canine vertebral column and the morphology of vertebrae, facet joints, and intervertebral disks.

Sample Population—Vertebral columns of 9 German Shepherd Dogs and 16 dogs of other breeds with similar body weights and body conditions.

Procedure—Different morphometric parameters of the vertebral column were assessed by computed tomography (CT) and magnetic resonance imaging. Anatomic conformation and the 3-D motion pattern were compared, and correlation coefficients were calculated.

Results—Total range of motion for flexion and extension was mainly associated with the facet joint angle, the facet joint angle difference between levels of the vertebral column in the transverse plane on CT images, disk height, and lever arm length.

Conclusions and Clinical Relevance—Motion is a complex process that is influenced by the entire 3-D conformation of the lumbar portion of the vertebral column. In vivo dynamic measurements of the 3-D motion pattern of the lumbar and lumbosacral portions of the vertebral column will be necessary to further assess biomechanics that could lead to disk degeneration in dogs. (Am J Vet Res 2006;67:43–50)

Low back pain is a frequent complaint in human medicine. Among the currently discussed causes for low back pain, disk degeneration is most often mentioned. However, to date, a specific cause could not be determined. Similar diseases associated with intervertebral disk degeneration exist in dogs. As in humans, the cause of frequently occurring lumbosacral disk degeneration leading to cauda equina compression in large-breed dogs is still unclear. Despite differences in posture and gait, aging and degeneration of lumbar disks, including the respective clinical syndromes associated with disk degeneration, are similar in humans and dogs without chondrodystrophy. Degenerated intervertebral disks become more fibrotic, and the nucleus pulposus converts to a collagenous tissue.

A possible cause for the high prevalence of lumbosacral disk degeneration, as currently discussed in veterinary medicine, is an increased or altered mechanical load on the intervertebral disk. Motion is a complex 3-D process and has been described in dogs. Differences in the motion pattern between GSDs, which are predisposed to lumbosacral disk degeneration, and dogs of other breeds with similar body weights and body conditions have been detected.

Shape and orientation of the articular facets were found to be different in GSDs than in dogs of other breeds. Therefore, a specific anatomic conformation of the lumbar portion of the vertebral column is proposed to be associated with the motion pattern and probably an abnormal mechanical load on the intervertebral disk. However, analysis of morphology and 3-D motion pattern is missing. A few studies have been performed to assess the influence of single anatomic structures on the motion pattern of the lumbar portion of the vertebral column in the 2-dimensional sagittal plane in dogs, but no clear correlations were found.

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<td>GSD</td>
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Received March 16, 2005.
Accepted May 19, 2005.
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Supported in part by the Gesellschaft zur Förderung Kynologischer Forschung.
Presented at the 9th Annual Conference of the European Association of Veterinary Diagnostic Imaging in Archena (Murcia), Spain, July 2002 and at the 10th Annual Conference of the European Association of Veterinary Diagnostic Imaging in Ghent, Belgium, September 2004.
The authors thank Thomas Beutler, Franziska Theiler, and Elke Spielvogel for technical assistance.
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AJVR, Vol 67, No. 1, January 2006 43
The purpose of the study reported here was to determine the correlation between the 3-D motion pattern of the caudal lumbar and lumbosacral portions of the vertebral column and the morphology of the vertebrae, facet joints, and intervertebral disks of dogs. Ultimately, the purpose of the motion analysis of the lumbar and lumbosacral portions of the vertebral column of cadaver dogs will be to assess motion of the lumbar portion of the vertebral column by dynamic noninvasive measurements in vivo. In this respect, and by use of these methods, information from studies on dogs may also further the study of the pathogenesis of degeneration of the discovertebral junction in humans.

Materials and Methods

Specimens—Twenty-five vertebral columns (L4 through the sacrum) of dogs euthanatized for nonskeletal diseases were obtained. Specimens of 9 GSDs and 16 dogs of other breeds with similar body weights were used. Dogs were between 1 and 14.2 years of age; 8 were females, and 17 were males. Only vertebral columns without any radiographic evidence of degeneration were used.

Procedures—Helical multislice CT was performed to assess the morphology of the vertebrae immediately before testing. Technique settings were 80 kV and 80 mA. Contiguous 1.25-mm-thick transverse slices were obtained from the midsbody of L4 through the sacrum. Specimens were evaluated for degenerative lesions (ie, spondylosis, osteophytes at the facet joints, or subchondral sclerosis). By use of modified surgical planning software, the CT image data set could be viewed along any arbitrary cutting plane. In the transverse plane, slices parallel to the corresponding endplate were used to assess the facet joint angles. In the dorsal plane, slices perpendicular to the midsagittal line were used. With the viewing plane aligned, points were digitized along the facet joint faces and the midsagittal line. These 3-D point coordinates were exported to a software program for the subsequent calculation of facet joint angles. The angle was measured between the midsagittal line and the line connecting the dorsal and ventral edges of the cranial articular processes in the transverse plane and between the midsagittal line and the line connecting the cranial and caudal edges of the cranial articular processes in the dorsal plane (Figure 1). All measurements were performed 3 times. The shape of each facet joint was assessed subjectively at every level.

Ventral and lateral diameters of intervertebral disks were assessed at the motion segments L4-5, L5-6, L6-7, and L7-S1. The ventrodorsal-to-lateral diameter ratio was calculated for every intervertebral disk. Disk height was calculated as a mean value of the heights of the dorsal and ventral part of the intervertebral disk in the midsagittal plane. The disk wedge coefficient was calculated as a ratio for every intervertebral disk. The disk wedge coefficient was calculated as ventral disk height divided by dorsal disk height. The cross-sectional area of the intervertebral disk was calculated at the mid-disk height of every level by use of the ellipse approximation. The distance between the center of the right and left facet joints and the dorsal rim of the intervertebral disk was measured at all 4 motion segments and called lever arm (Figure 2). The cross-sectional area-to-height ratio was evaluated. All measurements were performed 3 times.

At the end of all procedures, the intervertebral disks were assessed by use of high-field magnetic resonance imaging (1.5 T) with a dedicated, circular, polarized human extremity coil. In the sagittal plane, T2-weighted 3-D free induction steady-state precession gradient recalled echo (fat saturation; TE, 10 milliseconds; TR, 30 milliseconds; flip angle, 40°; 1 mm), T2-weighted TSE (TE, 98 milliseconds; TR, 3,000 milliseconds; 2 mm), and T1-weighted TSE (TE, 17 milliseconds; TR, 526 milliseconds; 2 mm) sequences, and in the transverse plane, T1-weighted TSE (TE, 18 milliseconds; TR, 533 milliseconds; 2 mm) sequences were obtained. Intervertebral disks were assessed for degeneration according to a recently published classification system. Criteria for evaluation of disk degeneration were signal intensity of the nucleus pulposus on T2-weighted images and integrity of the annulus fibrosus on T1-weighted images.

Vertebral columns were dissected free of all nonligamentous soft tissue. Specimens were frozen at –20°C and thawed for approximately 16 hours at 22°C before testing. The cranial portion of the L4 vertebral body and the sacrum were embedded in PMMA, with the horizontal plane set level with the middle of the intervertebral disks. Screws drilled into the sacrum and the vertebral body and spinous process of L4 ensured a strong connection between the PMMA and the bony tissue.

Each specimen was mounted in a testing apparatus that permitted the precise application of specified pure moments to the vertebral column. The caudal PMMA block with the embedded sacrum was fixed and remained stationary during testing. On the cranial PMMA block, a torque wheel was mounted that had steel cables that permitted the application of pure moments without constraining the movement of L4.
Moments of flexion, extension, lateral bending to the right and left, and axial rotation to the right and left were applied stepwise to a maximum of 3 Nm (4 steps of 0.75 Nm). Testing was performed during 3 cycles in each direction to precondition the specimens and minimize the viscoelastic effects of the specimens. The third cycle was used for analysis. At each load, the torque was held for 30 seconds to permit equilibration of the specimen. Specimens were wrapped in wet towels during the entire procedure to prevent dehydration of the ligaments.

The motion of each vertebra in relation to the caudal vertebra was measured by use of an optoelectronic camera system. The system monitored the position of marker carriers fixed on every vertebral body. Each marker carrier comprised noncolinearly arranged infrared light-emitting diodes. For each applied moment, the complete motion of the cranial vertebra in relation to the caudal vertebra consisted of 6 degrees of freedom (3 rotations and 3 translations). Motion was described in biomechanics in relation to a coordinate system placed into the body (Figure 3). In our specimens, the origin was located at the cranial border of the sacrum. The positive y-axis points cranially, the positive z-axis points ventrally, and the positive x-axis points toward the left side. The direction opposite to the arrows was negative. Looking in the positive direction of the axis from the origin, clockwise rotations were positive (+) and counterclockwise rotations were negative (–). Thus, +x was flexion, –x was extension, +y was axial rotation to the left, and –y was axial rotation to the right, +z was right lateral bending, and –z was left lateral bending. To get the range of motion, the maximum rotation in the positive and negative direction was added. Main motion was defined as motion in the direction of the applied moment. Coupled motion was associated motion about a second axis. Translation, where 2 vertebrae move parallel to each other along each of the 3 axes, can also be regarded as coupled motion. Translation of the cranial vertebra along the coordinate axes was calculated relative to the caudal vertebra. Translation along the x-axis described the movement of the vertebrae to the right (–x) and to the left (+x). Translation in the cranial direction was +y and in the caudal direction was –y; ventral translation (the cranial vertebra moves ventrally, compared with the caudal vertebra) was +z, and dorsal translation was –z.

This technique permits the vertebral column to move freely in its natural motion pattern and provides a noncontacting motion measurement of the specimen. In our study, the measurement error of the motion measurement system was determined as 0.3 mm for translation and 0.1° for rotation. Before starting the test, a lateral radiographic view of the specimen was obtained and digitized to provide information about the geometric association between the anatomic coordinate system and the corresponding markers. Relative vertebral motions were calculated in terms of Euler angles by use of the angle sequence ZYX. The motion pattern of all specimens was determined, and that of GSDs was compared with that of dogs of other breeds.

**Statistical analysis**—All measurements were initially analyzed with descriptive methods (means and frequencies) to obtain information on the distribution of these data. On the basis of this information, it was decided to use parametric procedures to evaluate the data. Multiple multivariate linear models were then developed to assess differences of shape of anatomic structures and facet joint angles across L4 through the sacrum. Results were interpreted as differences of least square means adjusted for effects of age, sex, and breed of dogs, and regression parameters were used as effect estimators for continuous variables such as age. Agreement between observed data and models was verified by use of residual analysis, and power analyses were performed to justify the results. Associations between morphometric parameters and main motion were analyzed by use of Pearson product-moment correlation coefficients (r). An r value > 0.4 suggested strong correlation; an r value < 0.4 suggested weak correlation. All statistical analyses were done by use of a software program, and the level of significance was set at a value of P < 0.05 for all results.

**Results**

Of 100 CT images, 6 (6%) had small osteophytes at the facet joints of intervertebral joints, 5 (5%) had a
slightly thickened subchondral bone plate, and 4 (4%) had spondylosis at an early stage. On magnetic resonance imaging of 100 disks, 76 were classified as normal (stage 1) and 18 had reduced signal intensity on T2-weighted images (stage 2). Vertebral columns of 4 dogs had a protrusion of the lumbosacral disk (stage 3). Two disks at the level L4-5 could not be assessed as a result of artifacts. Data from the kinematic analysis of the discovertebral junctions with a disk protrusion were excluded from analysis.

Four shapes of facet joints were observed on transverse CT scans as follows: straight (28%), angled (14%), arcuate (29%), and round (14%; Figure 4). A few facet joints had different shapes on each side (15%); asymmetric facet joints were not assigned to 1 of the 4 groups. Distribution of shape was different between breeds. In GSDs, 47% of the facet joints were straight, 19% angled, 6% round, and 11% arcuate, whereas in dogs of other breeds, 16% were straight, 11% angled, 20% round, and 39% arcuate. In GSDs, 42% of the facet joints were asymmetric, whereas only 31% were asymmetric in dogs of other breeds. For analysis, angled facet joints were regarded as a subgroup of straight facet joints and arcuate facet joints were a subgroup of round facet joints. All facet joints were classified as either symmetric or asymmetric in regard to shape and size (ie, height or length). Facet joint shape and symmetry had no significant effect on the 3-D motion pattern.

The facet joint angle in the transverse plane was significantly ($P < 0.001$) greater at L7-S1 ($41^\circ$) than at the more cranial levels ($19.8^\circ$ to $22.6^\circ$; Figure 5; Table 1). The angle in the transverse plane increased significantly ($P = 0.002$) with age. The respective
The mean ± SD angle of the facet joint in the dorsal plane was largest at levels L4-5 and L5-6 (9.8 ± 4.8° and 10.4 ± 4.6°, respectively) and significantly (P < 0.001) decreased toward L7-S1 (5.6 ± 3.4°; Table 1). The angle in the dorsal plane increased significantly (P < 0.001) with age. The regression parameter for age was 0.42 (ie, the outcome variable angle changes in the transverse plane by 0.42 for each year of age).

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The difference in the facet joint angle between adjacent motion segments was significantly (P < 0.001) larger from L6-7 to L7-S1 than between the more cranial segments. In GSDs, the difference in the facet joint angle from L6-7 to L7-S1 was significantly (P = 0.001) larger (21.9°) than in dogs of other breeds (15.8°). In the dorsal plane, the difference in the facet joint angle was significantly (P = 0.001) smaller from L4-5 to L5-6 than between the more caudal segments (Table 1).

Mean ± SD facet joint tropism, defined as asymmetry between the right and left facet joint angle,16 ranged between 3 ± 1.6° and 5 ± 3° and, in the transverse plane, was significantly (P = 0.027) smaller at L7-S1 than at other levels of the vertebral column (Table 1). German Shepherd Dogs had more facet joint tropism than dogs of other breeds. The difference was greatest at L5-6 (6.5° in GSDs vs 4.3° in dogs of other breeds) and smallest at L7-S1 (3.1° in GSDs vs 2.9° in dogs of other breeds).

Mean ± SD disk height significantly (P < 0.001) increased from 3.8 ± 0.6 mm at L4-5 and 3.9 ± 0.6 mm at L5-6 to 4.4 ± 0.4 mm at L6-7 and 6 ± 0.9 mm at L7-S1 (Figure 5; Table 1). Ventrodorsal and lateral diameters...
versus plane; facet joint angle difference in the dorsal amount of axial rotation: facet joint angle in the transverse plane. The greater the difference in the transverse plane, the more axial rotation was possible. Although GSDs, which are most commonly affected by degeneration of the lumbosacral disk, and dogs of other breeds had the same lumbar and lumbosacral portions of the vertebral column were equally distributed between GSDs and dogs of other breeds. These mild degenerative changes did not lead to different motion patterns; therefore, these specimens were included in the analysis.

In our study, 4 major factors with effects on the motion pattern were determined as follows: disk height, facet joint angle in the transverse plane, facet joint angle difference between levels in the transverse plane, and length of lever arm. The higher the intervertebral disk height, the more flexion and extension were possible. Although GSDs, which are most commonly affected by degeneration of the lumbosacral disk, and dogs of other breeds had the same lumbar disk thickness, vertebral columns of GSDs had less mobility at L7-S1 than in dogs of other breeds. Therefore, in addition to mechanical load, other factors have to be considered as causes of disk degeneration.

Discussion

The purpose of our study was to determine the association between the 3-D motion pattern of the caudal lumbar and lumbosacral portions of the vertebral column of dogs and the morphology of vertebrae, facet joints, and intervertebral disks. Findings in our study will serve as a basis for future dynamic measurements to finally assess the physiologic motion pattern in vivo. Aging and degeneration, including the respective diseases associated with disk degeneration affecting the lumbar intervertebral disks, are similar in dogs and humans.17-24 In regard to pathologic changes that develop in humans, the study of dogs is limited because of the absence of the iliolumbar ligament, which mainly restricts lateral bending in humans.25 In dogs, the quadratus lumbarum muscle is responsible for fixation of the lumbar portion of the vertebral column and could be compared with the iliolumbar ligament of humans.26 The testing procedure performed in our study is a standardized and accepted method of testing vertebral column specimens in biomechanics27 and is discussed in detail in a previous study.8 The entire 3-D motion pattern of the caudal lumbar and lumbosacral portions of the vertebral column in large-breed dogs has been described.8 The mild degenerative changes observed in the lumbar and lumbosacral portions of the vertebral column were equally distributed between GSDs and dogs of other breeds. These mild degenerative changes did not lead to different motion patterns; therefore, these specimens were included in the analysis.

In our study, 4 major factors with effects on the motion pattern were determined as follows: disk height, facet joint angle in the transverse plane, facet joint angle difference between levels in the transverse plane, and length of lever arm. The higher the intervertebral disk height, the more flexion and extension were possible. Although GSDs, which are most commonly affected by degeneration of the lumbosacral disk, and dogs of other breeds had the same lumbosacral disk thickness, vertebral columns of GSDs had less mobility at L7-S1 than in dogs of other breeds. Therefore, in addition to mechanical load, other factors have to be considered as causes of disk degeneration.
Nutrition of the intervertebral disk occurs by diffusion of solutes and may be reduced in disks with high heights. In other studies, genetic components have been suggested as factors leading to disk degeneration, but these authors could not explain why only the lumbosacral disk was affected.

The facet joint angle in the transverse plane is the second critical parameter for increased motion. The observation that the extent of main motion of flexion and extension increases with facet joint angle appears counterintuitive, considering the motion-guiding and -limiting function of the facet joint. However, increases in segment mobility may be the result of secondary degenerative changes to the soft tissue structures of the intervertebral segment (ie, disk and ligaments), which were not directly measured in this study, rather than a direct consequence of facet joint geometry. Seiler et al found that large facet joint angles were more commonly associated with disk degeneration. It has been proposed that disk degeneration could be a consequence of increased axial rotation as a result of large facet joint angles. Our investigation revealed larger, less sagittally oriented facet joint angles at L7-S1, associated with mainly increasing flexion and extension and only a low influence on axial rotation. Boden et al found that more sagittally oriented facet joints were highly associated with disk herniation at the level of L4-5. However, in other studies on human vertebral column specimens, it was concluded that the facet joint angle was not correlated with axial rotation and was not a critical factor for disk degeneration, which is in accordance with our results. Further investigation of the relationship between intervertebral tissue properties and facet joint geometry would be required to determine the true cause of increased segmental mobility with increased transverse facet angle.

In our study, a large facet joint angle difference in the transverse plane favored main motion in all directions (ie, flexion and extension, axial rotation, and lateral bending). Therefore, this parameter seemed to be a factor with constant influence on the 3-D motion pattern. The difference in the facet joint angle from 1 level to the next was previously observed and hypothesized to cause increased axial rotation leading to disk degeneration. In our study, the finding that axial rotation was mainly influenced by angle differences between levels seems to support this hypothesis. However, this observation should be interpreted with caution. As the angle difference is a mathematically derived parameter, the observed correlation reflects principally the previous relationship determined between facet joint angle and motion at the level of interest. The fact that GSDs had a greater angle difference between L6-7 and L7-S1 but a slightly decreased mobility, compared with dogs of other breeds, could be explained by the fourth major factor.

The fourth major factor favoring flexion and extension is a short lever arm (ie, a small distance between the center of the facet joint and the dorsal rim of the intervertebral disk). The length of a lever arm may affect the way in which the facet joints and disk interact to determine motion centers. Under the assumption of an identical range of motion in the facet joint, a short lever arm will allow a higher amount of flexion and extension. To the authors’ knowledge, this parameter has never been described and correlated with the motion pattern.

Different shapes of the facet joint have been described, and differences have been found between levels within an individual, within the same breed, and also between breeds. In GSDs, straighter facet joints were found, whereas those of dogs of other breeds were more commonly round. However, shape did not influence the motion pattern, which is in accordance with previous studies. It has been concluded that facet joint acts as a positive stop to axial rotation, whereas variations of facet geometry do not influence motion. Different shapes have to be regarded as polymorphism of the facets with no effect on the 3-D motion pattern.

Although all dogs in our study were adult, the orientation of the joint facets changed with age; in the transverse and dorsal planes, the angle increased significantly with age. Bone is a structure that remodels gradually during life. It is plausible that forces acting on the facet joints lead to increasing angles. It has been shown in limited studies that intervertebral position has an influence on force transmission through the facet joints in humans. However, to our knowledge, a thorough analysis of the relationship between complex spinal motion and facet joint loading has not yet been reported.

Facet joint tropism was significantly greater in GSDs than in dogs of other breeds in our study, and it was smallest at L7-S1. Therefore, facet joint tropism is definitively not a major cause of the frequently observed degeneration of the lumbosacral disk. This finding is in accordance with previous studies done in dogs and humans that did not reveal an association between facet joint tropism and disk degeneration.

In some animals, the vertebral endplates seem to change toward a laterally drawn out ellipse toward L7-S1. Although our results confirm this finding by a slightly decreasing ventrodorsal-to-lateral diameter ratio of the disk, it did not have any influence on motion.

The cross-sectional area-to-height ratio decreased toward L7-S1, whereas motion, particularly flexion and extension, increased. The determining factor was the increased disk height, as the cross-sectional area of the lumbosacral disk also increased. This result is in accordance with a study in which the effect of disk height and cross-sectional area on mechanical response in humans was analyzed. These results lead to the conclusion that a lumbosacral disk with a small cross-sectional area-to-height ratio is more prone to large motions. It was proposed that a large cross-sectional area acts to protect against disk degeneration because the mechanical load on the intervertebral disk may be distributed over a greater area, resulting in lower overall stresses. Natarajan and Andersson showed that the mechanical response to physiologic loads was more pronounced in disks with a small cross-sectional area. In our study, we could not confirm the protective effect of a large cross section, as the cross-sectional area of the lumbosacral disk was the largest of the analyzed disks, but it is known to be the disk most often affected by degeneration in the vertebral column of dogs without chondrodystrophy.

It was not possible to assign a certain motion pattern to a specific anatomic conformation. We could
identify 4 structures (ie, facet joint angle, facet joint angle difference in the transverse plane, disk height, and lever arm) that have a major influence on motion. However, motion is a complex process that is composed and influenced by the entire 3-D deformation of the lumbar portion of the vertebral column. Therefore, it is necessary to determine the 3-D motion pattern by dynamic in vivo measurements to finally assess the kinematics and biomechanics of normal and abnormal motion patterns in the lumbar and lumbosacral portions of the vertebral column.


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