

# In Vitro Biomechanical Comparison of Cervical Disk Arthroplasty, Ventral Slot Procedure, and Smooth Pins with Polymethylmethacrylate Fixation at Treated and Adjacent Canine Cervical Motion Units

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**Objective**—To compare the biomechanical properties of cervical arthroplasty to a ventral slot procedure and pin-polymethylmethacrylate (pin-PMMA) fixation.

**Sample Population**—Fresh cadaveric cervical (C2–T1) spines from 6 large dogs.

**Methods**—Four spinal conditions were studied in each spinal specimen: intact, disk arthroplasty, ventral slot, and fixation with smooth pin-PMMA at C5–C6 intervertebral space. Axial compression, torsion, flexion–extension, and lateral bending moments were sequentially tested on each specimen for the 4 spinal conditions. Data from the C3–C4, C4–C5, C5–C6, and C6–C7 vertebral motion units (VMUs) were compared among treatments.

**Results**—In axial compression and torsion, the ventral slot procedure allowed significantly less motion than intact, pin-PMMA, and arthroplasty groups at C5–C6. In lateral bending and flexion–extension, pin-PMMA had the least motion of C5–C6, followed by the arthroplasty group, intact spine, and ventral slot, all of which were significantly different from each other. Overall, the artificial disk was better able to mimic the behavior of the intact specimens compared with the ventral slot and pin-PMMA, producing similar displacements in axial compression and rotation in torsion, but more limited motion than intact in flexion–extension and in lateral bending.

**Conclusion**—Cervical spine specimens with an implanted prosthesis have biomechanical behaviors more similar to an intact spine compared with spinal specimens with ventral slot and pin-PMMA procedures. Cervical arthroplasty may then preserve some of the motion in the affected area after neural decompression while providing distraction.

**Clinical Relevance**—Cervical arthroplasty should be further investigated in vivo to determine if it is a viable alternative to the ventral slot or pin-PMMA procedures for surgical treatment of cervical diseases in dogs and in particular for treatment of disk-associated caudal cervical spondylomyelopathy.

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## INTRODUCTION

**C**AUDAL CERVICAL SPONDYLOMYELOPATHY (CCSM),<sup>1–5</sup> also known as wobbler syndrome,

predominantly affects large-breed dogs, particularly Doberman Pinschers.<sup>1–3,5–10</sup> In one study Doberman Pinscher accounted for as many as 68% of cases.<sup>10</sup> Canine CCSM is characterized by abnormalities of the cervical

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Supported by the Companion Animal Found Grant from the University of Wisconsin–Madison, School of Veterinary Medicine and by the Harlan and Anne Seaver donation.

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Submitted December 2006; Accepted July 2007

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0161-3499/07

doi:10.1111/j.1532-950X.2007.00327.x

column that result in neurologic deficits, cervical hypesthesia, or both.<sup>11</sup> Although the pathogenesis of canine disk associated CCSM is not well understood, it is thought to be multifactorial including primary developmental abnormalities and secondary degenerative changes that lead to vertebral canal stenosis and spinal cord compression.<sup>2</sup> In Doberman Pinscher, chronic degenerative disk disease seems to be an important factor that the term disk-associated wobbler syndrome has been suggested.<sup>11,12</sup> Spinal cord compression in disk-associated CCSM is often dynamic and secondary to a combination of degenerative disk diseases, hypertrophy of the dorsal aspect of the annulus fibrosus, and hypertrophy of the dorsal longitudinal ligament resulting in spinal cord compression at C5–C6 and/or C6–C7.<sup>1,5,9</sup> The extent of cord compression can vary with flexion, extension, and linear traction (distraction).<sup>1,9</sup> The incidence of disk-associated CCSM in dogs is not known. In a study assessing morbidity and mortality in Dobermans, cervical instability was responsible for the 3.5% morbidity and 2.5% mortality.<sup>13</sup>

Surgery is the treatment of choice, medical treatment is usually indicated in a normal dog with first episode of neurologic deficits following minor trauma or when CCSM develops before skeletal maturity.<sup>14</sup> There are many surgical techniques described to treat disk-associated CCSM, which can be broadly divided in 2 categories: direct access decompressive surgeries and distraction-stabilization surgeries.<sup>3,14</sup> Direct access decompressive surgeries involve removal of the hypertrophied annulus fibrosus and the dorsal longitudinal ligament. In contrast, distraction-stabilization techniques distract the vertebrae to stretch the hypertrophied tissue and relieve spinal cord compression. The vertebrae are then stabilized with an appropriate implant.<sup>14</sup> Many authors using these surgical techniques claim a 70–90% success rate.<sup>3,5–7,14,15</sup>

Recurrence of clinical signs secondary to a “domino” lesion may occur as late postoperative complication occurring with any of these techniques.<sup>3,14,16</sup> Recurrence can be caused by compression at the original site or by a domino lesion at an adjacent site.<sup>12</sup> Domino lesions or adjacent segment disease are believed to be the result, at least in part, of abnormal stresses imposed on 1 intervertebral space by fixation of an interspace adjacent to it.<sup>14</sup> These stresses can exacerbate any pre-existing subclinical instability and hence produce either disk extrusion or hypertrophy of annular or ligamentous structures.<sup>6,14</sup> Recurrence of paraparesis to tetraparesis occurs in up to one-third of dogs after either ventral decompression or metal implant and bone cement fixation.<sup>14</sup> It usually occurs between 6 months and 4 years after the original surgery, with a mean recurrence around 2 years.<sup>5–7,9,17</sup>

In people affected by cervical myelopathy and radiculopathy secondary to degenerative disk disease, anterior cervical discectomy and fusion is a reliable surgical treatment with satisfactory outcome in 90–95% of patients.<sup>18</sup> However, similar to dogs affected by CCSM, long-term reports document a significant incidence of domino effect at the adjacent sites with the recurrence of neurologic symptoms.<sup>18–20</sup> Within 10 years after the first surgery, about 25% of people require a 2nd surgery for the same problem at an adjacent intervertebral space, and within 5 years, 92% of the fusion-treated patients have radiographic evidence of adjacent segment degenerative disk disease.<sup>18,19</sup>

Biomechanical studies in a human cadaveric model demonstrated increased intradiscal pressure recordings in the adjacent disk segment after fusion.<sup>21–24</sup> Clinical studies, using dynamic radiography, showed increased motion at adjacent segments above and below the level of cervical fusion, and this has been incriminated as a factor associated with deterioration after anterior cervical fusion.<sup>25,26</sup> An interesting dilemma regarding domino lesion is whether the development of a 2nd lesion at the adjacent site after fusion represents the natural progress of an underlying similar process at the adjacent vertebral motion units (VMUs) or whether it is an accelerated degenerative process influenced by the biomechanical effect of fusion.<sup>27</sup> The influence of the latter is supported by documentation of adjacent-segment diseases in children where long-term follow-up review of pediatric patients who required anterior cervical fusion for fracture and dislocation revealed a high rate of adjacent-segment disease.<sup>27</sup> Furthermore, in case of Klippel–Feil syndrome, in which congenital cervical fusion is known to occur, magnetic resonance imaging studies revealed signal intensities consistent with degenerative disk disease in adjacent segments in all patients.<sup>28</sup> It is theorized that motion preservation at the surgery site may reduce the rate of adjacent-level cervical disk disease after anterior cervical discectomy and fusion.<sup>29–33</sup> This still remains to be fully demonstrated in long-term clinical studies.

In recent years several designs of cervical arthroplasty have been developed; however, very few have reached the stage of animal studies and fewer have progressed to human clinical trial.<sup>29,34</sup> The goals of cervical arthroplasty is to preserve motion after neural decompression while providing distraction and stability.<sup>29–33,35–38</sup> This is an area of controversy and the beneficial effects of cervical prosthesis over interbody fusion has been recently questioned.<sup>39</sup>

To our knowledge, no studies have been conducted to test cervical prosthesis in dogs. Ventral slot followed by the implantation of cervical disk prosthesis in dogs with disk-associated CCSM has the potential to achieve the optimal goal of spinal decompression, restoration of the

biomechanics at the surgical-treated sites with sparing the adjacent VMUs from the alterations in loading associated with the surgical procedures, which may eventually prevent the occurrence of domino lesion. An additional advantage of cervical arthroplasty over pin-PMMA fixation may be the elimination of the potential complication associated with pin impingement on neurovascular structures.<sup>16</sup>

Our aim was to test whether or not cervical arthroplasty preserves or is most similar to the normal motion of the canine spine compared with usual treatments for CCSM such as ventral slot or pin-PMMA distraction stabilization. A prototype of a canine cervical artificial prosthesis was tested *in vitro*, and the biomechanical behavior of the implanted spines was compared with intact cervical spines, and spines treated by a ventral slot or by distraction stabilization with pin-PMMA procedures.

## MATERIALS AND METHODS

### Study Design

A canine cervical disk prosthesis was designed and manufactured at the University of Wisconsin, Madison. The prosthesis consisted of 2 stainless-steel end plates (Ultra Corrosion-Resistant Stainless Steel [Nitronic 60], and 304 SS, Mc Masterr-Carr, Chicago, IL, Catalog No. 112, Mc Master Carr Supply Co, 2006) with a metal-on-metal bearing surface, with a range of movement of 30° in all directions (Fig 1). The back surface of each endplate was convex to avoid implant migration and had concentric grooves to allow bone ingrowth into the implant. Two stainless-steel L-shaped fins were attached to the ventral part of the prosthesis to facilitate the handling of the prosthesis during implantation. The short end of the L arm of the fin was attached to each half of the prosthesis by one point of fusion. After implantation the fins were easily detachable from the implant by the repetitive twisting of each fin along the long axis of the prosthesis.

The prosthesis was made in 2 different sizes based on the cross-sectional cervical spine area measured on MR images from 2 Dobermans affected by disk-associated CCSM and

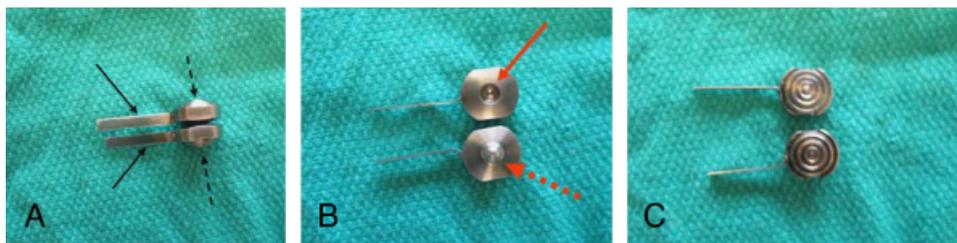
from 2 cervical cadaveric specimens of medium-sized dogs weighing between 25 and 30 kg. Respective sizes of the large and small prostheses were as follows: width (lateral-to-lateral) 8.5 and 7.4 mm, height (dorsal-to-ventral) 11.3, and 10.5 mm, thickness (cranial-to-caudal with the shells assembled) 10.7 and 10.5 mm.

Six fresh cadaveric cervical (C2–T1) spines from large dogs were biomechanically tested sequentially in 4 different conditions: (1) intact specimens, (2) specimens with an artificial disk implanted at C5–C6 intervertebral space, (3) specimens with ventral slot, and (4) specimens with distraction and fixation with smooth pin-PMMA. Peak segmental displacements or rotations from C3–C4, C4–C5, C5–C6, and C6–C7 VMUs for axial compression, torsion, flexion, extension, and lateral bending were compared among treatments.

### Specimen Collection and Preparation

Cervical spines specimens (C2–T1) were collected from mature canine cadavers (25–30 kg) that were euthanatized for conditions unrelated to this study. Each spine was harvested with the surrounding musculature and screened with dorso-ventral and lateral radiographs to exclude any specimens with gross anatomic abnormality or orthopedic disease. Each spine was then double-wrapped in plastic bags and stored at  $-20^{\circ}\text{C}$ . The day before the testing, all specimens were moved into a refrigerator at  $+4^{\circ}\text{C}$  to thaw. On the day of the testing each specimen was warmed to room temperature and kept moist by application of saline (0.9% NaCl) solution and wrapped in saline solution-moistened towels during preparation and testing procedures.

Before preparation and testing, the bone surface of the C2 and T1 vertebral bodies were cleaned, the dens and the cranial edge of C2 and the spinous process of T1 were trimmed to accommodate the specimens in the grips that attach to the biomechanical testing apparatus. Excessive surrounding paravertebral soft tissue was further dissected leaving the surrounding epaxial spinal musculature (spinalis cervicis millimeter dorsally, intertrasversarii dorsales and ventrales cervicis laterally, and longus colli ventrally), ligaments, and joint capsules intact. Two holes using a 3.2-mm-diameter drill-bit were drilled at  $\sim 90^{\circ}$  to each other at the cranial and



**Fig 1.** Canine cervical artificial disk prototype. (A) Lateral view. The two breakable fins (black arrows) are attached to the dorsal portion of each end plate of the prosthesis. The breaking point of the fins is at the attachment to each end plate. Once the disk is implanted the fins can be detached from the prosthesis by twisting each fin along its long axis. The external surface of each end plate (dotted black arrows) is convex to prevent implant migration. (B) The inside area of the 2 end plates is visible. The concavity (red arrow) and convexity (dotted red arrow) in the center area of each surface acts like a ball and the socket. (C) Dorsal view of the external surface of both end plates. Each surface has concentric grooves to allow bone in growth into the implant.

caudal thirds of both the C2 and T1 vertebral bodies in each specimen. A 3.2-mm-diameter steel rod was placed in each hole and was left protruded at  $\sim 2$  cm from each hole's end. C2 and T1 vertebrae with the rods inserted were fixed in the pots with a low-melting point polyester resin (LiteWeight; Fiber Glass Evercoat, Cincinnati, OH). A further gentle dissection of the epaxial musculature from the underlying bone was completed to allow attachment of extensometers used to measure relative displacement between adjacent vertebrae. After pre-drilling with a 1.7-mm-diameter bit, 18 g needles were secured in place dorsally on the mid-portion of the dorsal lamina, ventrally on the vertebral body, and bilaterally on the pedicles of C3, C4, C5, C6, and C7, respectively, where extensometers were attached (Fig 2).

### Biomechanical Testing Apparatus

Biomechanical testing was conducted on multi-degree of freedom servo testing system (MTS Bionix 858, MTS Corporation, Minneapolis, MN). This system loaded the cervical spines with axial, torsional, and pure bending (i.e. rotational) deformations applied the grips at C1 and T1.<sup>40</sup> The apparatus used servomotor load actuators for bending loads connected to the axial and torsional actuators in the load frame. All load information were directly measured by load cells and recorded by a computer. Spinal deformations between adjacent vertebrae were measured with custom built linear extensometers and used to calculate segmental relative motion and rotation at C3–C4, C4–C5, C5–C6, and C6–C7 during application of axial compression, flexion–extension, and lateral bending, except for torsion motion. A rotational extensometer was utilized for the study of torsion motion.

### Mechanical Testing Protocol and Sequence

Each specimen was tested sequentially in the intact spine, after the insertion of the artificial disk, in the ventral slot condition, and after fixation with pin-PMMA at the C6–C7

intervertebral space, respectively. The size of prosthesis that would best fit in the intervertebral space was chosen based on overlapping the implant to the 2 radiographic projections of the cervical specimen (Fig 3).

**Cervical Arthroplasty.** A fenestration with an 11-scalpel blade was created across the C5–C6 intervertebral space, the space was then distracted using the self-retaining Gasper retractor (Life instruments, Braintree, MA; Fig 4A and B). With a high-speed air drill and a  $5 \times 5$  mm spherical burr, a ventral slot was created preserving as much as possible of the caudal edge of C5. The slot extended in the cranial and caudal direction by removing the mid-portion of both endplates of C5 and C6 to the cancellous bone and followed the oblique angle of the intervertebral space. The length of the slot extended no more than 25% of the length of the C5 and C6 vertebral bodies, the width of the slot extended no more than 50% of the width of the vertebral body and never exceeds 8.5 mm (Fig 4C). The slot was extended to the depth of the dorsal longitudinal ligament, which was also removed to allow visual inspection of the spinal canal. Additional cancellous bone was removed as needed from both ends of the slot to fit the convexity of the external surface of the prosthesis.

During implantation the 2 shells of prosthesis were held together by their ventral fins using a large needle holder, which was also used to force (via gentle manual pressure) the prosthesis into the slot (Fig 4D). For biomechanical testing for the ventral slot, the implant was removed by grasping and pulling each shell with a mosquito forceps while the intervertebral space was maintained in distraction with the Gasper retractor.

**Pin-PMMA Distraction-Fixation Procedure.** Two 3.17-mm-diameter smooth pins were placed through the vertebral bodies cranial and caudal to the slot at an approximately  $30^\circ$  angle from the sagittal plane in a transverse plane (Fig 5A). All pins were inserted to a depth at which the tip of the pin was visibly protruding from the dorsal lamina and they were cut at  $\sim 5$  cm from the point of insertion. A preformed paper mold was placed around the pins to create a 2 cm tall oval area to hold the PMMA plug. Specimens were linearly distracted axially with a small non-standardized tensile force manually

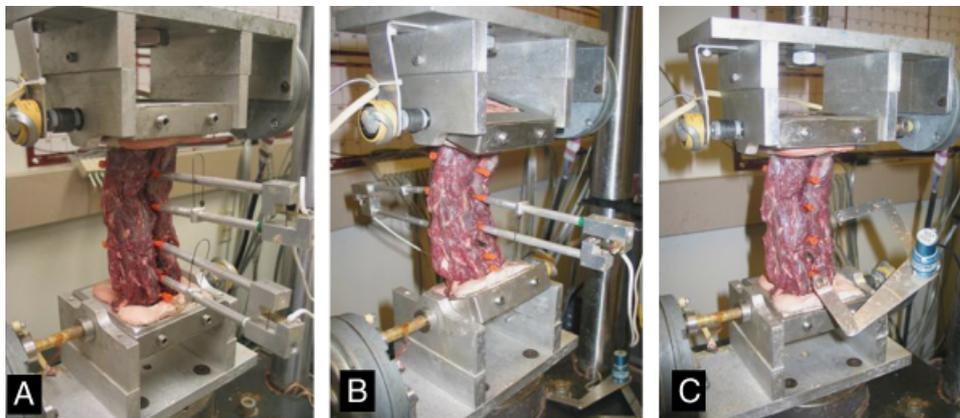
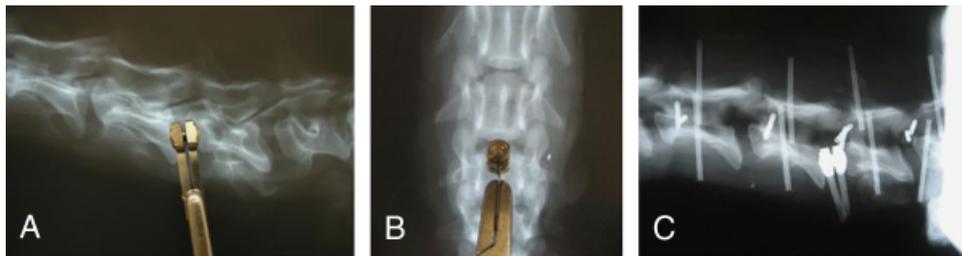


Fig 2. Mounted spine in the testing apparatus during biomechanical testing. The hubs of the 18 gauges needles where the extensometers were applied are visible in orange. The photograph is showing the spine during the testing for axial compression (A), flexion–extension and lateral bending (B), and torsion (C). For lateral bending the spine was rotated  $90^\circ$  in the mounting fixture.



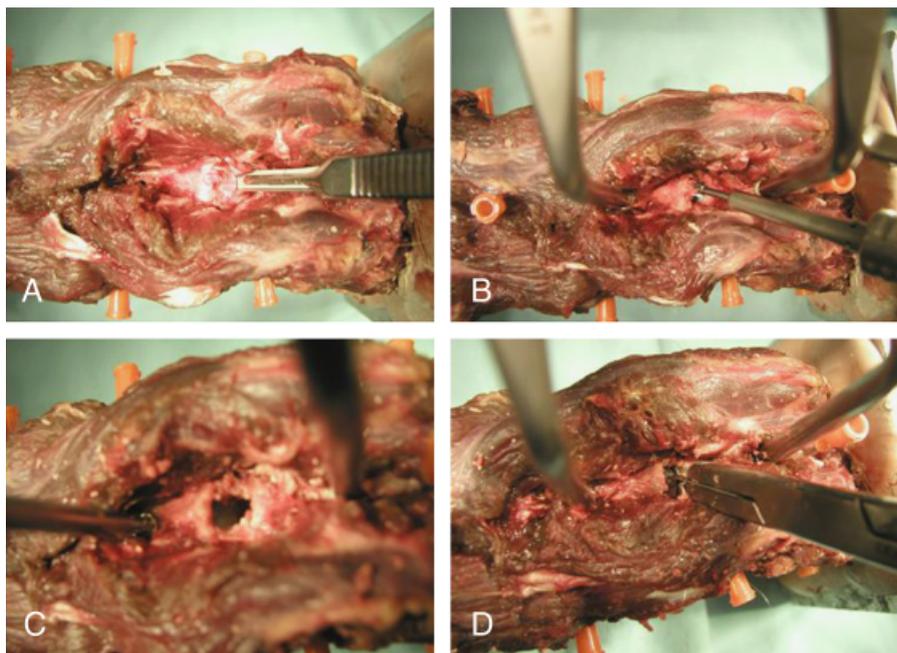
**Fig 3.** Choice of prosthesis. The size of the prosthesis to best fit in the intervertebral space was chosen on overlapping the implant to the lateral (A) and ventrodorsal (B) radiographic projections of the cervical specimen. The 2 parts of the prosthesis are held together using a large needle holder. (C) Radiograph taken after testing shows the prosthesis in place, the needles in the vertebrae used to attach the extensometers and the fins still attached to the prosthesis are also visible.

applied on to the grips holding the 2 extremities of the specimen. The polyester resin was mixed at room temperature, poured in the mold, and allowed to flow around the pins while the specimen was held in place for a minimum of 20 minutes. The amount of PMMA used was enough to reach the edge of the preformed paper mold (Fig 5B).

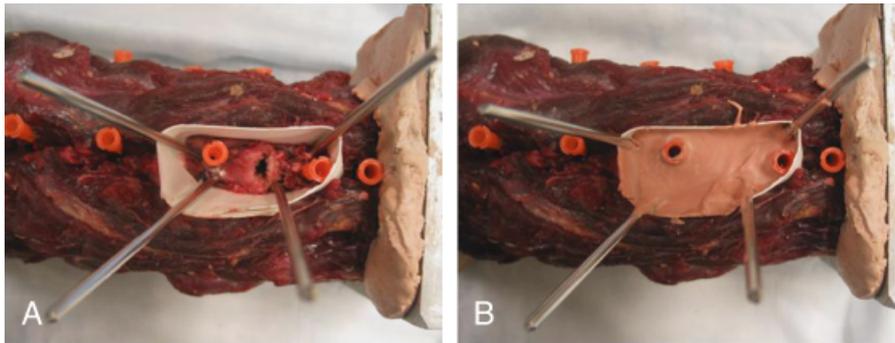
#### *Mechanical Testing Protocol*

Four modes of testing were performed: axial compression, flexion, and extension and lateral bending moments were applied to specimens in the 4 specimen conditions. Signals from the force transducers and extensometers were collected with a dedicated analog-to-digital data acquisition system sampling at 50 Hz.

In the axial compression test, spines were subjected to a 0–50 N haversine compressive force, which was applied at (0.5 Hz) while other degrees of freedom remained unconstrained and while rigid body motion was measured between vertebrae with extensometers. Because relatively long canine cervical spines were used, a large preload would cause buckling. Hence, during torsion, flexion, extension and lateral bending, a small static preload (5 N) was applied in axial compression and maintained throughout testing. Throughout these tests, other degrees of freedom were unconstrained and the relative displacements and rotations between vertebrae were computed from the extensometer and rotational extensometer data. Five cycles of sinusoidal (0.5 Hz) moment with amplitudes of  $\pm 1$  Nm were applied to the spines for these modes of loading. The first 4 cycles were considered to be preconditioning and data were collected on the 5th cycle.



**Fig 4.** Cervical arthroplasty procedure. (A) Fenestration (B) creation of the ventral slot with the Gasper retractor in place; vertebral distraction is applied during the ventral slot to better visualize the vertebral end plates during burring; (C) the ventral slot is completed and the Gasper retractor is further distracted to facilitate the insertion of the prosthesis; (D) insertion of the prosthesis.



**Fig 5.** Pin-PMMA distraction–fixation procedure. (A) Pins are inserted at approximately 30° from the sagittal plane; a preformed paper mold is placed around the pins to contain the pouring of the polyester resin; (B) the polyester resin is poured in the mold while the specimen is maintained linearly distracted.

For axial compression, flexion–extension, and lateral bending, two linear extensometers were used to monitor the relative displacements between vertebral bodies. Data from these were used to compute mean displacement and relative rotation between bodies (Fig 6). After the spine was mounted in the test machine and extensometers were attached (but before loading), basic geometric information such as ventral height ( $h_1$ ), dorsal height ( $h_2$ ), and width ( $w$ ) were measured with digital calipers. Height changes were measured as a function of time by ventral ( $e_1$ ) and dorsal ( $e_2$ ) extensometers. The total ventral, dorsal, and mean height were calculated by  $H_1 = h_1 + e_1$ ,  $H_2 = h_2 + e_2$ , and  $H_M = (H_1 + H_2)/2$ , respectively. Relative displacements and rotations between the two vertebral bodies were deduced from  $D_M = H_M - h_M = (e_1 + e_2)/2$  and  $\Theta = 2\theta = 2\arctan\left(\frac{H_1 - H_2}{2w}\right) \frac{180^\circ}{\pi}$ , respectively. Lateral rotations were similarly computed from extensometers on each side of the vertebral bodies.

The data were processed as indicated above using custom-designed software routines and collected in a spreadsheet file for later statistical analysis. Specimens were removed and subsequently reinserted in test fixtures between treatments. Data for the C3–C4, C4–C5, C5–C6, and C6–C7 were compared among treatments. After testing the specimens in the 4

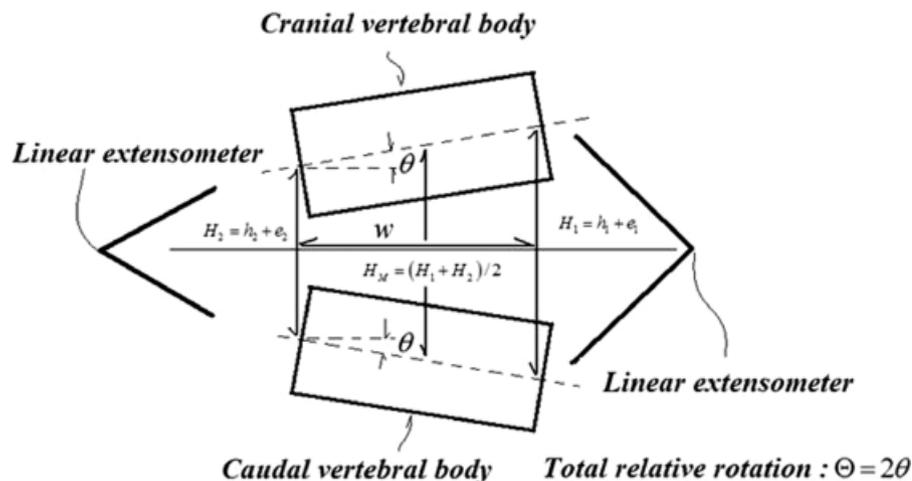
different conditions, radiographs of the specimens were repeated to assess pins placement and to evaluate potential vertebral fracture.

#### Statistical Analyses

Mean  $\pm$  SD for all data were calculated. A 1-way ANOVA was used to evaluate the effect of cervical level on the mechanical properties of each group and repeated measures ANOVA was used to determine the effect of group at each cervical level. When ANOVA revealed significant differences, a Duncan's multiple range test was performed to separate these differences. Differences were considered to be significant at a probability level of 95% ( $P < .05$ ). All statistical analyses were performed with a commercially available software program (SAS Version 8e, SAS Institute Inc., Cary, NC).

## RESULTS

Each mode of loading is discussed separately with accompanying figures showing the peak displacements or rotations for the 50 N load or the 1 Nm moment.



**Fig 6.** The method to measure relative displacements between vertebral bodies with 2 linear extensometers is shown.

*Axial Compression*

The intersegmental kinematic responses to a 50 N compressive load are shown in Figs 7A and 8A. Overall, displacements are larger cranially and smaller caudally in all groups except for the pin-PMMA group where the difference in displacement at C6–C7 VMU compared with C3–C4 VMU was not significant. The VMUs displacements after implantation with an artificial disk showed no significant difference to the intact spine at all 4 levels. C5–C6 VMUs with a ventral slot had a higher inter-segmental stiffness (lower motion) than the other treatments. Pin-PMMA fixation specimens at C5–C6 VMUs showed no significant difference in displacement compared with intact and arthroplasty segments (Fig 7A), although significantly larger displacements were induced in the adjacent VMUs (Fig 8A). At the treated VMU, except for the ventral slot there was no significant difference between the arthroplasty, intact, and Pin-PMMA groups (Fig 7A).

*Torsion*

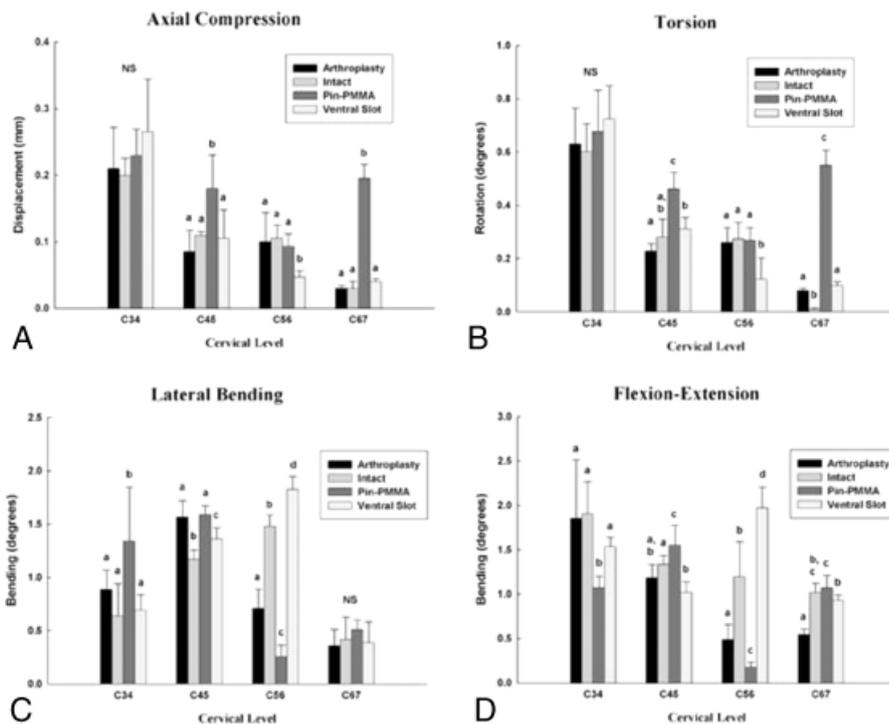
The intersegmental kinematic responses to the torsional loading are shown in Figs 7B and 8B. The pattern is similar to axial compression with inter-segmental rotations larger cranially and smaller caudally except for the pin-PMMA group. The VMUs after implantation with the

artificial disk showed no significant difference to the intact spine, except at C6–C7, which had more motion than the intact group. The C5–C6 VMUs with a ventral slot had higher inter-segmental stiffness than the other treatments. Pin-PMMA fixation specimens at C5–C6 VMU showed no significant difference in displacement to intact and arthroplasty specimens although larger displacements were induced in the adjacent VMUs. The resulting displacements at the adjacent VMUs were significant compared with the other treatment groups (Fig 8A).

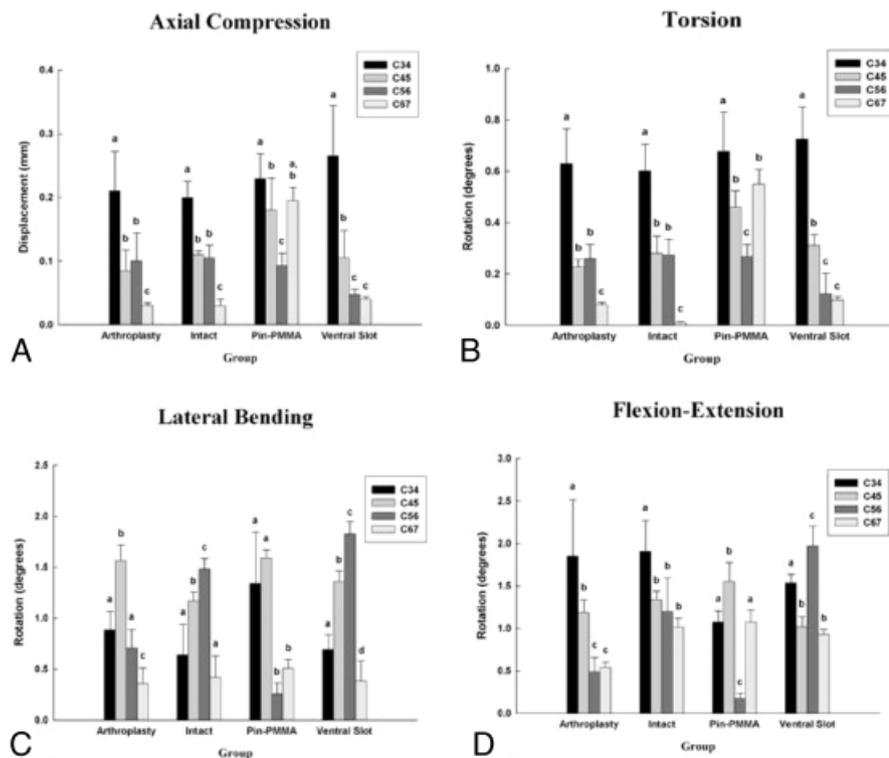
At C5–C6 VMU, results were similar to axial compression, and except for the ventral slot, there was no significant difference between arthroplasty, intact, and pin-PMMA groups (Fig 8B). At the adjacent VMU C4–C5, only the arthroplasty group had similar motion to the intact group (Fig 8B). At the adjacent VMU C6–C7 there was a significant difference between all treated groups and the intact specimens (Fig 8B). No significant difference was observed at C3–C4 VMU between all groups.

*Lateral Bending*

The inter-segmental kinematic responses to lateral bending are shown in Figs 7C and 8C. The motion in spines with a ventral slot were similar to intact spines except for increased motion at C4–C5 and C5–C6 VMUs. Pin-PMMA fixation showed an abrupt change between the fixed C5–C6 VMU and adjacent VMUs with an in-



**Fig 7.** Effect of cervical level on the mechanical properties of each group. Difference were considered significant at a probability level of 95% ( $P < .05$ ). The operative procedures were performed at the C5–C6 level.



**Fig 8.** Effect of group at each cervical level. Difference were considered significant at a probability level of 95% ( $P < .05$ ). The operative procedures were performed at the C5–C6 level.

creased rigidity of C5–C6 compared with intact and other treatments. At the treated VMU, there was a significant difference between all groups with the intact group demonstrating more motion than the arthroplasty and pin-PMMA groups and less motion than the ventral slot group (Fig 8C). At the adjacent C4–C5 VMU, there was also a significant difference between all treated groups and the intact specimens, while at the adjacent C6–C7 VMU there was no significant difference between the 4 groups (Fig 8C). At C3–C4 VMU, except for pin-PMMA, there was no significant difference between the arthroplasty, intact, and ventral slot groups (Fig 8C).

#### Flexion–Extension

The intersegmental kinematic responses to flexion–extension are shown in Figs 7D and 8D. At the treated VMU, there was a statistically significant difference in motion among all treated groups and the intact specimens and the spines with a ventral slot had increased motion at C5–C6 VMU compared with intact spines and the two treatment groups (Fig 7D). Spines with pin-PMMA fixation showed more rigidity than other treatments at the fixed C5–C6 VMU (Fig 7D) with abrupt changes at adjacent VMUs when compared with other treatments (Fig 8D). At the adjacent VMU C4–C5, ar-

throplasty was the only treatment with no significant difference compared with the intact group, while at the adjacent C6–C7 VMU arthroplasty was the only treatment with significantly different motion compared with intact specimens (Fig 7D). At VMU C3–C4, pin-PMMA fixation had significantly less motion than the intact group and the other 2 experimental groups (Fig 7D).

## DISCUSSION

The goal of this study was to assess the ability of a canine disk arthroplasty to improve the spinal mobility at the adjacent VMUs with the potential to alleviate the domino effect seen clinically.

#### Choice of Material

Three materials are commonly used in contemporary arthroplasty: Titanium (Ti) and Ti-based alloys, stainless-steel alloys, and cobalt alloys.<sup>41</sup> In general, the mechanical properties of the stainless-steel alloys are inferior to Ti and chromium-based alloys. They have inferior compatibility when compared with Ti, and because they cause significant imaging artifacts on computed tomography or magnetic resonance imaging they are inadequate for follow-up studies using these advanced imaging modalities.

Stainless-steel alloys have a long history of clinical use in spine implants and they were chosen in this study because they are inexpensive, have much greater ductility,<sup>41</sup> and are similar in corrosion resistance to the other materials. Stainless-steel alloys contain iron, carbon, chromium, nickel, and molybdenum and it is the chromium oxide formation on the surface of the metal that resists corrosion.<sup>41</sup> The metal-on-metal design used in this study substantially reduced the cost of the several prototypes designed before selecting the one we used for the biomechanical study.

The prosthesis designed for this study is rotationally unconstrained, following the ball-end-socket principle, with 30° of freedom in flexion, extension, and lateral bending, and independent of supplemental fixation. Unconstrained cervical prosthesis designed for people usually allow about 11° of freedom.<sup>29</sup> The higher degree of freedom in our prototype was arbitrarily chosen and was based on the consideration that heterotopic ossifications at the treated site, observed in medium-term clinical studies in people, decrease over time significantly the range of motion at the implanted site.

The concept of disk arthroplasty in people is not new and the initial clinical efforts are attributed to Ferstrom.<sup>42</sup> Over the last decade, clinical experience with Cummins artificial cervical joint<sup>43</sup> (which evolved in Prestige<sup>44</sup>); ProDisc-C<sup>45</sup>; and Bryan Cervical Disk<sup>35</sup> prostheses have been reported. Currently, artificial disks are classified into 3 types: non-, uni-, and biarticulating. The implant may consist of a metal-on-metal design, a metal-on-polymer (ultra-high molecular-weight polyethylene), and less commonly of ceramic-on-polymer or a ceramic-on-ceramic design.<sup>30</sup> The disk is either modular (having replaceable components) or non modular (lacking replaceable components), and some are used in conjunction with supplemental vertebral body screw fixation.<sup>30</sup> Certain artificial disk designs promote biological bone ingrowth at the disk-endplate interface. Artificial disks may be constrained in terms of motion, or they may be semi- or unconstrained. Artificial disks may then be categorized based on the following criteria: articulation, material, design, fixation, and kinematics.<sup>30</sup>

The Cummins artificial cervical joint is a stainless-steel ball-and-socket joint, semiconstrained-bearing surface, which requires internal fixation with screws. Screw pull-out, screw breakage, and joint subluxation were all reported.<sup>43</sup> The refinement of this device evolved in the less-bulky Prestige (Medtronic Sofamor Danek, Memphis, TN) prosthesis with a more hemispherical cup, a shallow ellipsoid saucer, and four screws with a locking mechanism.<sup>44</sup> Reduced complications at the treated site with no screw back out, preserved cervical motion across the implanted site, and minimal effect on adjacent-segment motion at 2-year post-implantation have been reported.<sup>31,32,44</sup>

The ProDisc-C (Synthes, West Chester, PA) is an unconstrained device composed of 2 cobalt-chromium-molybdenum endplates with a metal-on-polyethylene-bearing surface. The polyethylene insert is fixed to the inferior endplate. Bone ingrowth into the plasma-sprayed Ti surfaces at the bone-implant interface allows for long-term stability. A central keel that interdigitates with the vertebral body is designed to provide immediate implant stability.<sup>41</sup> Biomechanical studies *in vitro* showed that ProDisc did not alter the motion patterns at either the treated site or adjacent segments compared with intact spines, except in extension,<sup>45</sup> and short-term clinical study showed that Pro-Disc preserved cervical spine segmental motion within the first 6 months after surgery with clinical results similar to a control group treated with fusion.<sup>39</sup> In a longer term study at 1-year post-surgery, 9.1% of the patients had spontaneous fusion of the treated segment and only 33.8% of the patients did not have signs of heterotopic ossification.<sup>46</sup>

The Bryan cervical disk prosthesis (Medtronic Sofamor Danek) consists of 2 Ti shells enclosing a polyurethane nucleus. A Ti porous coating is applied to the bone-implant interface of each shell to facilitate ingrowth of the bone. A polyurethane sheath surrounds the nucleus creating an enclosed articulating environment and forming a barrier to contain any wear debris and prevent soft tissue ingrowth that may reduce the range of motion of the device.<sup>41,47</sup> Sterile saline is injected into this sheath before implantation and functions as a lubricant.<sup>41</sup> Implantation of the device requires milling of the endplates after establishing the center of the disk space. The milling affords a precision fit of the titanium shells surface with the endplates and provide immediate stability.<sup>41,47</sup> The device is rotationally unconstrained, allows for 11° of motion in flexion, extension, and lateral bending, 2 mm of translation, is coupled to the surrounding soft tissues, and allows for shock absorption.<sup>29</sup> *In vivo* testing in Chimpanzees and goats demonstrated motion preservation, ingrowth of bone into the prosthesis shells, and no inflammatory response in the surrounding tissues.<sup>35</sup> Clinical studies in people, at 2-year post-surgery, showed that patients treated with Bryan disk compared with fusion-treated patients control had a statistically significant better neurologic outcome and a decreased radiographic evidence of degenerative disk disease at adjacent segment.<sup>38</sup>

Intervertebral disk transplantation with fresh frozen composite disk allograft after disk excision has been recently reported in people.<sup>48</sup> In the five patients transplanted, at a 5-year follow-up, the motion and stability of the spinal unit was preserved (7–11° of sagittal motion) in all except 1 of the disk, despite signs of mild disk degeneration on magnetic resonance imaging.<sup>48</sup> Adjacent segments were not investigated in this study.

### *Ventral Slot*

In our study, the slots were created to fit the size of the prosthesis. The length of the slots did not exceed the low end of the clinical recommendations which range from 25% to 33%.<sup>49-52</sup> The width of the slots did not exceed the suggested clinical recommendation, which has been set at 50% of the width of C5-C6.<sup>53</sup> Clinically the ventral slot procedure has been associated with vertebral subluxation when the ratio between slot width and vertebral body width is  $>0.5$ .<sup>54</sup> In addition, following these anatomic recommendations, laceration of the ventral vertebral sinus and basivertebral veins and vertebral subluxation is minimized.<sup>54</sup>

**Treated Site.** Creation of ventral slot yielded significant changes in all modalities tested at the treated site, thus likely enhancing vertebral instability at this level. These findings are also in accord with another study where the loss of the ventral portion of the annulus fibrosus after slot creation allowed excessive cervical extension.<sup>16</sup> It was also suggested that excessive cervical extension can exacerbate spinal cord compression in some dynamic lesions by enhancing protrusion of the dorsal portion of the annulus fibrosus and dorsal longitudinal ligament into the spinal canal.<sup>16</sup> Ventral slot technique may also reduce the energy required to collapse the intervertebral disk place, which could also predispose to foraminal compression and bulging of the residual dorsal annulus fibrosus in the ventral canal.<sup>55</sup> However, in vivo this mechanical instability could be compensated and neutralized by the muscular subsystems.<sup>56</sup> It is also likely that the degree of the vertebral instability induced at the treated site at the time of surgery may decrease during the following months because of secondary fibrosis. Various degrees of fibrosis may induce unpredictable biomechanical changes at the treated site as well as at the adjacent VMUs. The biomechanical dissimilarities observed in vitro studies between the ventral slot and the intact spines may dissipate over time in vivo. This factor may reduce the accuracy of clinical prediction based on in vitro results.

**Adjacent Vertebral Motor Unit.** The changes associated with the creation of the ventral slot affect the mechanism of adjacent VMUs.<sup>16</sup> In the present study, after creation of the ventral slot at the C5-C6 intervertebral space, there was a concomitant increase in rotation at the adjacent C6-C7 VMU, and an increased degree in lateral bending and a decreased degree in flexion-extension at the adjacent cranial VMU. These changes are different from those reported in another study, where a concomitant reduction in the range of motion was seen at both adjacent VMUs<sup>16</sup>; however, our results are difficult to compare with that study because the C4-C5 intervertebral space was the selected treated space. This could also

be a function of the testing method in that a collapse of the disk space decreases VMU compliance.

### *Pin-PMMA*

**Treated Site.** Pin-PMMA fixation resulted in a large reduction in rotation at the treated site in lateral bending and flexion-extension, whereas displacement in axial compression and the rotation in torsion were similar to the intact spines. The resulting reduction of excessive cervical extension at the treated site may prevent exacerbation of bulging of the dorsal annulus fibrosus and dorsal longitudinal ligament in the spinal canal.

**Adjacent Vertebral Motor Units.** Pin-PMMA fixation affected the biomechanics of adjacent VMUs. A larger displacement in axial compression and increased rotation in torsion were induced at both adjacent VMUs; this was particularly evident at the adjacent VMU caudal to the treated site. In lateral bending, increased motion was also induced at the adjacent VMU cranial to the treated site. Because the changes in stiffness and torsion in the pin-PMMA group at the treated site were not significant, it remains difficult to explain the dramatic changes seen at the adjacent VMUs. These changes are more likely the result of compensation for the reduction in mobility at the treated site in bending and flexion-extension. Similar results were also observed in another study.<sup>16</sup> It has been suggested that this overloading at the adjacent VMUs could predispose to disk degeneration and domino lesion.<sup>16,57,58</sup> In this study, the distraction of the VMU C5-C6 during placement of the pins and PMMA could also have had an effect on the adjacent VMUs causing an experimental artifact. However, since the tensile force for distraction was manually applied and just enough to provide a gentle distraction at the treated site, it is unlikely that the energy applied altered the biomechanical properties of the adjacent VMUs. Smooth pins used in this study have less stiffness than threaded pins, which have been used for pin-PMMA fixation.<sup>16</sup> However, it is unlikely that pins stiffness affected the results of this study.

### *Arthroplasty*

**Treated Site.** Arthroplasty resulted in similar displacement in axial compression and torsion compared with intact spines. However, a decrease in rotation was seen in lateral bending and flexion-extension compared with the intact spines. This could be improved by changing the design of the prosthesis to allow more freedom in lateral bending and flexion-extension. However, this may change the similarities seen in axial compression and torsion to the intact spines. It would be ideal, to determine first the range of motion of the intact canine cervical

spine, in vivo and in vitro, and then design a prosthesis able to match these parameters. In selecting the degree of freedom of the device, it is also important to consider that the post-operative fibrosis at the treated site may likely decrease over time the angular deformity of the prosthesis.<sup>46</sup>

**Adjacent Vertebral Motor Units.** The significant decrease of rotation with arthroplasty at the treated site in flexion–extension affected the stiffness of both cranial and the caudal VMUs resulting in a significant decrease in motion at the caudal VMU. These findings were unexpected since with a reduced mobility at the treated site a compensatory mobility at both adjacent sites was expected like in the pin-PMMA group. These changes could be secondary to a non-perfect fit of the implant in the slot. This has the potential to change the biomechanics of the cervical spine, therefore resulting in a domino lesion; however, it may also be beneficial since if an increase in VMU mobility may promote instability an a domino effect, a decrease in mobility may have the potential to decrease this event. This factor needs to be further evaluated and improvements may be made by refining the way to set the device in place.

#### *Implant Corrosion*

Stainless-steel alloys corrode most alloys used in arthroplasty, and there is an 8-fold increase in the incidence of corrosion when dissimilar metal junctions are used, compared with only 7% of cases studied where similar metal junctions were implanted.<sup>59</sup> Because the different metal alloys can play an important role in corrosion of the metal implanted, in the metal-on-metal canine cervical arthroplasty using the same metal for the 2 shells may delay corrosion and this combined with the decrease life span in the dog compared with humans may make stainless-steel alloys prosthesis still a suitable material for canine cervical arthroplasty.

#### *Failure of Joint Arthroplasty*

Failure of joint arthroplasty is most commonly related to wear of the bearing surface and the subsequent inflammatory process induced by wear debris.<sup>60,61</sup> These inflammatory processes are characterized by the expression of several cytokines after exposure to spinal instrumentation undergoing wear or corrosion and have been demonstrated clinically and by laboratory investigation.<sup>60–62</sup> This can result in pain and device loosening.<sup>60–62</sup> Many factors influence the scale of this process, including the particle size, shape, number, material surface chemistry, concentration, and duration of exposure.<sup>60,61,63</sup> Clinical evaluation of patients after arthroplasty in addition to gross mechanical failure should also be a focus on the

less-obvious loosening associated with a debris-induced immune response.

The results of our preliminary study suggest that overall the artificial disk was better able to mimic the behavior of the intact spines compared with the ventral slot and pin-PMMA groups, producing virtually the same displacements and rotations as the intact spines in axial compression and torsion, respectively, but somewhat limiting the rotations in flexion–extension and in lateral bending. An artificial prosthesis with an increased degree of freedom at the treated site could potentially overcome some of the dissimilarities observed between the prosthesis used in this study and the intact spines. Simulation of fusion with pin-PMMA significantly reduced motion in lateral bending and flexion–extension at the surgical site, which was compensated for by increased motion at the adjacent VMUs. This increased motion at the adjacent VMUs may accelerate degeneration of adjacent intervertebral disks. Restoring a cervical spine biomechanically as close as possible to that of the intact spine may reduce the risk of the domino effect. Use of cervical arthroplasty to treat disk-associated CCSM may minimize or alleviate the adjacent domino effect. This warrants further in vivo investigation to determine whether it may be a viable alternative to ventral slot and fusion surgery techniques for the surgical treatment of disc-associated CCSM. Other implants should be designed for dogs, since not all may perform well in the canine patient.

#### ACKNOWLEDGMENTS

Particular thanks to Fabrizio Caroli, MD, chief of spinal surgery section of Istituti Fisioterapici Ospedalieri and Istituti Nazionale Tumori Regina Elena, Rome, Italy, for his invaluable contribution in the preliminary phase of this study

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