In vitro evaluation of biomechanical effects of multiple hemilaminectomies on the canine lumbar vertebral column

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Objective—To conduct an in vitro investigation of the biomechanical characteristics of the canine lumbar spinal column in flexion and extension and measure the destabilizing effects of multiple consecutive unilateral and bilateral hemilaminectomies.

Sample Population—30 isolated multisegmental spinal units (L1-L4) from nonhypochondroplastic dogs weighing 15 to 30 kg.

Procedures—Physically normal and surgically altered spinal specimens were subjected to 4-point bending in flexion and extension to determine effects of multiple consecutive hemilaminectomies on the basis of analysis of test system load-displacement data. Six groups with 5 spinal columns in each were defined on the basis of the following procedures: hemilaminectomy at L2-L3, 2 adjacent hemilaminectomies at L1-L3, 3 adjacent hemilaminectomies at L1-L4, bilateral hemilaminectomies at L2-L3, 2 bilateral hemilaminectomies at L1-L3, and no hemilaminectomy (intact). Spinal stability before and after surgery was determined in all groups. Each group served as its own control for nondestructive testing. Spinal strength was evaluated through destructive testing to determine deformation at failure, strength to failure, and mine deformation at failure, strength to failure, and mode of catastrophic failure. The intact group served as the control for destructive testing.

Results—Stability in extreme flexion and extreme extension did not change significantly following any hemilaminectomy procedure. Postoperative stability within the neutral zone was significantly decreased in all groups. Range of motion within the neutral zone was not significantly different from the intact condition in any group.

Conclusions and Clinical Relevance—Multiple hemilaminectomies did not decrease stiffness of the lumbar spinal column during flexion and extension. These results support clinical recommendations regarding multiple consecutive hemilaminectomies in dogs. (Am J Vet Res 2003;64:1139–1145)

The vertebral column is a complex 3-dimensional structure stabilized by vertebral bone, intervertebral disks, articular facets with their associated joint capsules, the supraspinous ligament, interspinous ligament, ligamentum flavum, dorsal and ventral longitudinal ligaments, and paravertebral musculature. Disruption of these structures by disease processes, trauma, or surgical procedures can lead to instability with detrimental clinical consequences. Although vertebral surgery is commonly performed in veterinary medicine, relatively little research has been performed investigating the potential destabilizing effects of the procedures.

Biomechanical examination of isolated vertebral segments provides data to quantify effects of surgical alterations to the vertebral column. Vertebral motion units are the smallest functional segments of the vertebral column composed of 2 adjacent vertebral bodies, the intervertebral disk, and connecting ligamentous structures. Multisegmental vertebral units are larger functional vertebral segments made of 2 or more adjacent vertebral motion units and necessary to examine effects occurring over several vertebrae. Four-point bending test systems produce constant bending moments along the region between inner loading points in a multisegmental vertebral unit. This type of test allows quantification of nondestructive (vertebral stability) and destructive (vertebral strength) measures.

Goals of vertebral decompressive surgery include exposure of the spinal cord with minimal cord manipulation. Techniques that impose minimal influence on vertebral stability are also desirable. Types of decompressive vertebral surgery described in the literature include hemilaminectomy, pediculectomy, several variations of dorsal laminectomy, and ventral slot decompression. The specific type of decompressive surgery employed by the surgeon depends on the nature of the compression (ie, extradural, intradural-extradural, and intramedullary), circumferential location of the compression, anatomic segment of the spinal cord affected, extent of exposure required, and surgeon preference. In the thoracolumbar and lumbar vertebral column, intervertebral disk herniation is the most common cause of spinal cord compression in dogs. Because most of these herniations primarily involve a ventral or ventrolateral extradural compression, hemilaminectomy is usually chosen to gain exposure of the spinal cord.

Although myelographic studies including lateral, ventrodorsal, and oblique views have been shown to be highly accurate in identifying the site and circumferential location of disk material, massive cord swelling or incomplete imaging studies can lead to surgical approaches being performed on the wrong side of the vertebral column. Because contralateral compres-
sive disk material is difficult to remove without excessive cord manipulation, bilateral hemilaminectomy is advocated when hemilaminectomies are performed on the wrong side.14

Extensive hemilaminectomy, in which a hemilaminectomy is extended caudad or cranial over multiple vertebrae, has been advocated for massive spinal cord compression resulting from intervertebral disk herniation, cysts, hematomas, or tumors. Extension of the hemilaminectomy over as many as 4 to 5 vertebrae has been recommended in the literature without reported deleterious clinical consequence.14,15

Although extensive hemilaminectomy has become an accepted practice in veterinary medicine without documented adverse clinical effects, scientific data are lacking to detail the destabilizing effects these procedures have on the vertebral column. The purpose of the study reported here was to measure the effect of extensive hemilaminectomy, compared with unoperated control vertebral columns, on biomechanics of the canine lumbar vertebral column. Specifically, this study evaluated alterations in vertebral stability and the ultimate strength of the canine lumbar vertebral column in flexion and extension following hemilaminectomy at 1 site, 2 adjacent sites, 3 adjacent sites, bilateral hemilaminectomy, and bilateral hemilaminectomy at 2 adjacent sites.

Materials and Methods

Thirty canine vertebral columns from the 12th thoracic to the 7th lumbar vertebrae were harvested from 15 to 30 kg, nonhypochondroplastic dogs that were euthanatized for unrelated reasons. Dogs had no neurologic abnormalities on physical examination. Paravertebral musculature adjacent to the vertebrae was removed, leaving vertebral ligaments and articulations intact. Vertebral columns were wrapped individually in saline (0.9% NaCl) solution moistened paper towels, sealed in plastic bags, and frozen at –20°C until the day of testing.

Motion segments were measured from T12 to L6, and vertebral columns were evenly distributed among groups on the basis of length. Six groups with 5 vertebral columns in each were created. Vertebral column groups were defined on the basis of the following procedures: hemilaminectomy at L2-L3 (Hem-1), 2 adjacent hemilaminectomies at L1-L3 (Hem-2), 3 adjacent hemilaminectomies at L1-L4 (Hem-3), bilateral hemilaminectomies at L2-L3 (Bi-1), 2 bilateral hemilaminectomies at L1-L3 (Bi-2), and an intact (control) group.

On the day of testing, vertebral columns were thawed at room temperature (approx 24°C). Vertebral columns were maintained in saline solution-moistened towels and sprayed intermittently during testing to prevent desiccation of the tissues.

Vertebral columns were mounted to swing arms of a custom-testing jig by use of 4 parallel, 3.2-mm-diameter steel pins placed transversely through the vertebral bodies in a plane approximating neutral in flexion-extension. The location of pin placement within each vertebral column was determined by use of a 1:2:1 ratio centered on the L2-L3 intervertebral disk space. Pins were placed in the vertebral bodies of T12, L1, L4, and L6 with equidistant spacing between pins in T12-L1 and L4-L6. This pin configuration isolated the L1-L4 multisegmental motion unit between the inner 2 pins (L1-L4). An electronic caliper was used to measure the distance between the pins to ensure appropriate pin placement for 4-point bending.

Eight stainless steel jig-swing arms were used to mount the spinal column-pin constructs to the testing jig. Attachment of the swing arms to the testing jig allowed free range of motion in the sagittal plane. At the swing-arm connection to the vertebral pins, a ball-joint rod end was used to provide unconstrained motion and eliminate bending moments at the pin sites. To minimize pin deformation, pin stiffness was increased by application of custom designed aluminum sleeves with 3.2-mm-diameter central cores fitted over the pins between the spinal specimen and swing arms of the testing jig. Clamps were applied to each pin lateral to the swing arms to eliminate translation of the swing arms during vertebral deformation.

Testing was performed by use of a servocontrolled hydraulic material testing systema,b coupled to the jig. The jig design (Fig 1) was modeled after a validated 4-point bending system. The load cell of the testing system (2,500 N, 30 newtonmeter biaxial load cell) measured applied forces. The actuator displacement rate was set at 50 mm/min. Actuator displacement was used to estimate angular deformation of
where \(d\) is crosshead displacement and \(r\) is the distance between the outer 2 pins. Applied load and displacement were imported directly into a personal computer spreadsheet. On the basis of dimensions of the jig, angular displacement (\(\theta\)) of the specimen was calculated by the following equation:

\[
\theta = \left(\tan^{-1}\left(\frac{d\pi}{r}\right)\right) \times \left(\frac{180}{\pi}\right)
\]

where \(d\) is crosshead displacement and \(r\) is the distance between the outer 2 pins and \(F_c\) was \(\frac{1}{2}\) the applied force in newtons (Fig 3). Bending moment-angular deformation curves were generated for further data analysis.

Surgical procedure for the single-site hemilaminectomy (Hem-1 group) included removal of the L2-L3 articular facet, articular facet joint capsule, and surrounding laminar bone.

Bone rongeurs were used to remove the articular facet with its associated joint capsule. The laminar bone was cut full thickness to expose the spinal cord by use of an electric rotary drill and high-speed cutting burr. Margins of the hemilaminectomy extended cranial to the caudal aspect of the L1-L2 articual facet, dorsad to the base of the spinous process, caudad to the cranial aspect of the L2-L3 articular facet, and ventrad to the accessory process.

The surgical procedure for the Hem-2 group was equivalent to the single site hemilaminectomy but included removal of the L1-L2 articular facet and extension of the hemilaminectomy margin cranial to the caudal aspect of the T13-L1 articular facet. The Hem-3 group also included removal of the L3-L4 articular facet and extension of the hemilaminectomy caudal to the cranial aspect of the L4-L5 articular facet. The Bi-1 and Bi-2 groups mirrored the surgical procedures of Hem-1 and Hem-2 groups, respectively, but were performed bilaterally.

Each vertebral column was nondestructively tested in the intact and surgically altered state. The order of testing was random. To precondition the vertebral columns, each vertebral column was cycled through 5 extension-flexion cycles before data was collected. Each vertebral column was pushed into extension until the actuator reached –25 mm of displacement. The actuator direction was reversed, and the vertebral column was pulled continuously and at a constant rate from extension into flexion until the actuator reached +25 mm of displacement. The range of actuator displacement (–25 mm to +25 mm) maintained the vertebral columns within the physiologic (elastic) range of flexion and extension. Applied force and actuator displacement data obtained from the fifth trial were converted to bending moment and angular deformation for use in data analysis. Vertebral columns remained mounted in the testing jig while their designated hemilaminectomy procedure was performed. Following surgical alteration, the vertebral columns were preconditioned again through 5 extension-flexion cycles as described for the state before hemilaminectomy. Data from the 5th postoperative cycle were used for data analysis. Results of nondestructive testing provided paired data for stability and range of motion comparison, with each group of vertebral columns acting as their own control.

Following nondestructive testing, each vertebral column was tested to failure in flexion. The actuator pulled the vertebral columns into flexion at a rate of 50 mm/min until catastrophic failure occurred. Bending moment-angular deformation curves were produced to determine the bending moment (N•m) and angular displacement in degrees (deg) at failure. Vertebral columns were visually inspected, and the mode and site of catastrophic failure were recorded. Destructive testing data from the intact (control) group served as the control for comparing effects of hemilaminectomy and extensive hemilaminectomies on vertebral strength. Test specimens that underwent jig system failure (clamp dislodging during high loads) rather than vertebral failure were excluded from destructive analysis.

After testing, vertebral columns were wrapped in saline solution soaked towels and stored at –4°C. Within 24 hours of testing, radiographs of each specimen were obtained to evaluate for preexisting disease and document the mode of biomechanical failure. Vertebral columns of dogs with evidence of preexisting vertebral trauma or degenerative disk disease were excluded from the study.

Bending moment versus angular deformation curves were individually analyzed to determine 6 separate mechanical parameters. These included stability of the vertebral column in extreme flexion (N•m/deg), stability of the vertebral column in extreme extension, stability of the vertebral column within the neutral zone, range of motion (deg) of the vertebral column within the neutral zone, deformation at failure (deg), and...
strength at failure (Nm). The neutral zone was defined as the linear central region of the bending moment versus deformation curve between the neutral position and the initiation point of increased vertebral resistance to flexion or extension (Fig 4). Range of motion within the neutral zone was defined as the degrees of angular deformation corresponding to the linear central portion of the bending moment versus deformation curve. Vertebral stability was determined by measuring slope of the bending moment versus angular deformation curve in extreme flexion, extreme extension, or within the neutral zone. Inspection of the shape of the moment-angular deformation curve yielded regions of elastic zone behavior. Linear regression techniques were used to determine the mean slope of the moment-displacement data within these regions. For nondestructive testing, each group of vertebral columns (before surgery) served as their own control. Stiffness and range of motion of the vertebral columns before and after hemilaminectomy were compared by use of the paired 2-tailed Student t test. For destructive testing, the intact test group served as the control for the surgically altered vertebral columns. Failure strengths of each hemilaminectomy group were compared with the mean failure strength of intact vertebral columns by use of the nonpaired, 2-tailed Student t test. Significance was set at a P value of < 0.05.

Results

Vertebral stability in extreme flexion and extreme extension did not change significantly following any hemilaminectomy or extensive hemilaminectomy procedure (Table 1). Postoperative vertebral stability within the neutral zone decreased significantly in all hemilaminectomy groups. Despite reduced vertebral stability within the neutral zone, the range of motion within the neutral zone was not significantly different from the intact condition following any hemilaminectomy procedure.

Results of destructive testing were statistically inconclusive as a result of jig-system failure, rather

![Graph of the bending moment versus deformation curve.](image)

**Table 1**—Mean (± SD) values and the percent change of nondestructive properties of canine lumbar vertebral columns before (intact) and after hemilaminectomy procedures.

<table>
<thead>
<tr>
<th>Test group</th>
<th>Stability in flexion (Nm/deg)</th>
<th>Stability in neutral zone (Nm/deg)</th>
<th>Stability in extension (Nm/deg)</th>
<th>Neutral zone range of motion (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hem-1</td>
<td>0.566 ± 0.0124</td>
<td>0.045 ± 0.011</td>
<td>0.479 ± 0.112</td>
<td>21.8 ± 2.9</td>
</tr>
<tr>
<td>Mean after surgery</td>
<td>0.563 ± 0.111</td>
<td>0.034 ± 0.012*</td>
<td>0.473 ± 0.102</td>
<td>22.6 ± 2.7</td>
</tr>
<tr>
<td>% change</td>
<td>-0.53</td>
<td>-24.44</td>
<td>-1.25</td>
<td>3.67</td>
</tr>
<tr>
<td>Hem-2</td>
<td>0.503 ± 0.077</td>
<td>0.078 ± 0.030</td>
<td>0.506 ± 0.159</td>
<td>21.7 ± 3.5</td>
</tr>
<tr>
<td>Mean after surgery</td>
<td>0.553 ± 0.076</td>
<td>0.053 ± 0.023*</td>
<td>0.506 ± 0.180</td>
<td>21.3 ± 3.9</td>
</tr>
<tr>
<td>% change</td>
<td>-0.94</td>
<td>-32.05</td>
<td>5.90</td>
<td>-2.76</td>
</tr>
<tr>
<td>Hem-3</td>
<td>0.638 ± 0.111</td>
<td>0.052 ± 0.019</td>
<td>0.505 ± 0.110</td>
<td>22.1 ± 3.0</td>
</tr>
<tr>
<td>Mean after surgery</td>
<td>0.637 ± 0.120</td>
<td>0.037 ± 0.017*</td>
<td>0.507 ± 0.108</td>
<td>21.7 ± 2.9</td>
</tr>
<tr>
<td>% change</td>
<td>-1.56</td>
<td>-28.85</td>
<td>3.96</td>
<td>-1.81</td>
</tr>
<tr>
<td>Bi-1</td>
<td>0.670 ± 0.087</td>
<td>0.070 ± 0.016</td>
<td>0.462 ± 0.038</td>
<td>21.2 ± 1.6</td>
</tr>
<tr>
<td>Mean after surgery</td>
<td>0.629 ± 0.152</td>
<td>0.047 ± 0.031*</td>
<td>0.491 ± 0.039</td>
<td>20.1 ± 2.3</td>
</tr>
<tr>
<td>% change</td>
<td>-6.12</td>
<td>-32.86</td>
<td>6.28</td>
<td>-5.19</td>
</tr>
<tr>
<td>Bi-2</td>
<td>0.578 ± 0.152</td>
<td>0.039 ± 0.017</td>
<td>0.522 ± 0.108</td>
<td>20.2 ± 3.9</td>
</tr>
<tr>
<td>Mean after surgery</td>
<td>0.610 ± 0.140</td>
<td>0.021 ± 0.017*</td>
<td>0.492 ± 0.161</td>
<td>19.5 ± 4.0</td>
</tr>
<tr>
<td>% change</td>
<td>5.54</td>
<td>-46.15</td>
<td>-5.75</td>
<td>-3.47</td>
</tr>
</tbody>
</table>

*Significantly (P < 0.05) different than before hemilaminectomy procedure.

than vertebral failure, in 12 vertebral columns including 4 of 5 vertebral columns from the intact (control) group. Clamp dislodgement and subsequent excessive pin bending resulting from high lateral forces against the clamp during strength testing was the mode of system failure in 11 vertebral columns. A single pin within the Hem-2 group fractured through the ventral aspect of the vertebral body in 1 vertebral column. None of the vertebral columns tested had radiographic evidence of preexisting vertebral disease.

Discussion

Biomechanical studies of explanted columns of dogs provide reliable data on the effects of vertebral trauma, surgical stabilization, and in the current study, surgical destabilization. Studies of this nature, combined with clinical experience, provide a scientific foundation to help base surgical decision making. The goal of our study was to evaluate current surgical practices regarding extensive hemilaminectomy.

Results of prior biomechanical studies indicate that hemilaminectomy, when performed independent of other procedures (ie, fenestration or discectomy), may be performed safely without causing substantial instability in the thoracolumbar and lumbar vertebral column. Smith and Walter reported that hemilaminectomy did not significantly alter stability of the canine lumbar vertebral column in extension, flexion, or the central range. In addition, hemilaminectomy did not affect the ultimate strength of the lumbar vertebral column during flexion. Schulz et al demonstrated no significant differences in vertebral stability during lateral bending resulting from unilateral facetectomy (as a model for hemilaminectomy) in the thoracolumbar vertebral column. Shires et al determined that unilateral facetectomy in the thoracolumbar and lumbar vertebral column did not alter rotational stability.

Studies have also been conducted to examine the biomechanical effects of bilateral hemilaminectomy in the thoracolumbar and lumbar canine vertebral column. Smith and Walter found that stability of the vertebral column in extreme flexion and the central range was unaffected by single-space bilateral facetectomy (modeling bilateral hemilaminectomy). However, the procedure did decrease vertebral stability in extreme extension by 61.6% and reduce ultimate strength in ventral flexion by 43.3%, compared with the intact vertebral column. Results of other studies have indicated no differences in lateral bending or rotational stability resulting from bilateral facetectomy in thoracolumbar or lumbar motion segments.

Unlike these previous investigations, our study evaluated multisegmental vertebral units rather than individual vertebral motion units for vertebral testing. Vertebral motion units are the smallest functional segment of the vertebral column composed of 2 adjacent vertebrae, the intervertebral disk, and connecting ligamentous structures. Several adjacent vertebral motion units make up a multisegmental vertebral unit, and the L1-L4 multisegmental vertebral unit was isolated in our study. Multisegmental vertebral units are necessary to examine effects occurring over several vertebrae. Because many ligaments within the lumbar vertebral column (dorsal and ventral longitudinal ligaments, ligamentum flavum, and supraspinous ligaments) are continuous structures, the multisegmental vertebral unit may also more closely represent in vivo vertebral mechanics than individual vertebral motion units.

Results of our study indicate that removal of as many as 3 adjacent articular facets, their associated joint capsules, and surrounding laminar bone does not significantly disrupt vertebral stability at the extremes of flexion or extension in the canine lumbar vertebral column. Likewise, bilateral hemilaminectomy extending over as many as 2 adjacent sites did not alter vertebral stability at the extremes of flexion or extension. Vertebral stability within the neutral zone decreased by 24.44 to 46.15% following each hemilaminectomy procedure, whereas range of motion within the neutral zone remained unchanged. Because passive vertebral structures (ligaments, facets, joint capsules, and intervertebral disks) do not develop reactive forces that resist vertebral deformation until the extremes of the range of motion, the vertebral column is normally highly flexible within the neutral zone. Consequently, the clinical impact of lower vertebral stability without expansion of the neutral zone range of motion is questionable. Theoretically, decreased stability within the neutral zone can impose additional demands on paravertebral musculature and other components providing stability within the neutral zone.

Performed in a standardized manner, biomechanical studies allow results of different studies and investigators to be evaluated on a comparative basis. The 4-point bending system in our study was modeled after the jig developed and validated by Smith and Walter. Similar vertebral testing systems have been used in the veterinary literature to investigate destabilizing effects of various procedures. Although similar testing systems were used, differences in methods between our study and prior studies limit absolute comparisons. Vertebral stability in extreme flexion and extension in our study was lower, compared with similar groups in the Smith and Walter study. Differences were likely the result of the use of multisegmental vertebral units in our study. Because multisegmental vertebral units in our investigation included 3 intervertebral spaces (L1-L4), as compared with 1 for vertebral motion unit, these structures were predictably less rigid.

Although the biomechanical testing performed in our study provided data to evaluate effects of multilevel hemilaminectomy, several limitations inherent to the study design were present. Four-point bending produces equal and constant loads (bending moments) to all points along the test specimen between the central 2 pins. The 4-point bending model presupposes that the specimen between the outer 2 pins is a rigid body. Because 2 intervertebral disk spaces were present between the outer 2 pins on either side of the test specimen, a violation of the rigid body assumption occurred in our study. However, the vertebral column is a structure, not a material, and variables of the vertebral structure are part of the analysis during this testing. Although a rotational variable differential transducer mounted directly on the specimen would have...
measured the angle of rotation at 1 point along the multisegmented structure, when comparing overall change in segment behavior with multilevel surgical procedures, it is reasonable to use data that compares overall segment displacement to estimate rigidity. This biomechanical design is recognized in human and veterinary biomechanical studies,\textsuperscript{17,18,21,22} and was felt to accurately reflect vertebral stability. The precise influence of this assumption is not known, but was consistent with prior reconstructive techniques in the dog.\textsuperscript{17,23,24} In theory, enhancement of the paravertebral musculature could adapt to small alterations in neutral zone rigidity to maintain vertebral stability.\textsuperscript{25} Although precise roles of paravertebral musculature have not been investigated in veterinary research, inclusion of its contribution to vertebral stabilization would more optimally simulate in vivo conditions. Regardless, paravertebral musculature was removed prior to biomechanical testing, negating passive and active muscular influence in our study.

As investigators of prior studies,\textsuperscript{17,19,21} have acknowledged examination of a single mode of vertebral loading represents an oversimplification of the complex movements in the clinically normal and postoperative patient. In our study, testing was limited exclusively to flexion and extension bending. The canine lumbar vertebral column has the greatest range of motion in flexion and extension.\textsuperscript{26} Although precise roles of paravertebral musculature have not been investigated in veterinary research, inclusion of its contribution to vertebral stability would more optimally simulate in vivo conditions. Regardless, paravertebral musculature was removed prior to biomechanical testing, negating passive and active muscular influence in our study.

Contrary to patients predisposed to conditions warranting extensive hemilaminectomy, dogs used in our study were nonhypochondroplastic breeds free of recognizable disk disease. In a human cadaveric lumbar vertebral study,\textsuperscript{27} motion segment stiffness was altered with varying degrees of intervertebral disk degeneration. Biomechanical effects of degenerative disk disease have not been evaluated in dogs but likely have a role in vertebral stability in the postoperative patient.

Vertebral radiographs were obtained following biomechanical testing to screen for preexisting vertebral disease while concurrently documenting radiographic evidence of the mode of destructive vertebral failure. Because study dogs were young and healthy with no neurologic abnormalities on physical examination, the authors expected that the dogs would be free of radiographic vertebral abnormalities. If vertebral disease were present, however, radiographs obtained prior to biomechanical testing would have permitted replacement of the affected specimen.

Results from destructive strength testing were inconclusive as a result of system failure rather than vertebral failure in 12 of the 30 vertebral columns tested, including 4 of 5 control vertebral columns, as pins bent during testing. This occurred despite placement of 1.27-cm-diameter aluminum sleeves around the pins between the swing arms and the vertebral specimen to increase stiffness. A clamp was also applied to each pin external to the swing arm. The destructive nature of the procedure did not permit retesting with the vertebral columns used. Because the nondestructive stability testing was the primary focus of our study, destructive experimentation was not repeated with additional specimens. These results are reported to recommend revision of future destructive testing protocols. Increasing pin stiffness by potting around the pins with polymethylmethacrylate has been successful in prior vertebral destructive testing.\textsuperscript{17}

Results of our study indicate that extension of a hemilaminectomy up to 3 adjacent sites or bilaterally up to 2 adjacent sites would not increase the risk of injury to the lumbar vertebral column during flexion and extension bending. The clinical importance of altered stability within the neutral zone is unknown. Findings of our study do not contradict current recommendations in the literature regarding extensive hemilaminectomy. Future investigation using test systems that can nondestructively evaluate vertebral stability in 6 degrees of freedom and apply complex coupled loads will build on this baseline of work. Incorporation of effects of paravertebral musculature and varying degrees of disk degeneration will more completely model the patient with vertebral column and spinal cord disease.

References

9. Henry WB. Dorsal decompressive laminectomy in the treat-


