Midline Sparing Bilateral Laminotomies Prevents Disc Collapse as Compared to Traditional Laminectomy—A Biomechanical Finite Element Analysis

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Abstract

Objective: To biomechanically compare two competing surgical techniques for alleviating spinal stenosis.

Summary and Background Data: Traditional laminectomy is the long standing surgical gold standard for relief of pain induced to spinal stenosis. However, loss of the posterior tension band due to this technique may result into settling of the motion segment leading to neural foraminal stenosis and recurrence of the symptoms. An alternative technique, which conserves the posterior tension band through the midline sparing bilateral laminotomies, may provide good long term outcomes.

Methods: An experimentally validated finite element model of the intact L3/S1 segment was used to simulate the laminectomy and bilateral laminotomies across the L4/L5 level. Segmental Motion, intra-discal pressure (IDP), facet load and foramina opening were compared between the intact and surgical models in response to 400N of axial compression and 10Nm moments.

Results: Segmental motion and IDP after L4 laminectomy increased in flexion, especially at L4/L5 disc level. The laminotomy model had biomechanics close to the intact model, especially in flexion. The distance of L4/L5 foramina in both surgical models decreased in extension, lateral bending and axial rotation compared with the intact model. However in flexion the distance in foramina opening increased in laminectomy model. Facet loads at L4/L5 after both procedures decreased in extension, lateral bending, and axial rotation.

Conclusion: The midline laminotomy surgery induced much less alterations in biomechanics of spine compared to traditional laminectomy. The increase in IDP and motion for laminectomy model means that the load on the disc is higher as compared to the midline sparing which may lead to long-term disc degeneration. The findings of the current study show that midline sparing laminotomies may prevent disc collapse due to reduced disc loading without sacrificing the opening of foramina, as compared to the traditional laminectomy.

INTRODUCTION

Degeneration and overgrowth of the facet joints and ligamentum flavum hypertrophy result in lumbar spinal canal central and foraminal stenosis. Lumbar spinal canal stenosis is the leading cause for spinal surgery for patients over the age of 65 [1-4]. Traditional surgical treatment of lumbar stenosis has involved a wide bilateral laminectomy, medial facetectomy, and foraminotomy [3-6]. The concern with this technique is the loss of the posterior tension band represented by midline supraspinous and interspinous ligaments. This contributes to a loss of flexion stability and increases the risk of delayed spinal...
instability, which may result in the need for revision surgery with fusion [7-9].

With the advances in imaging it has become evident that the majority of neurologic compression is seen at the level of the interlaminar window [10,11]. Many surgeons have reported variations of laminotomies as an alternative to wide laminectomy [3,10-13]. In vitro studies have shown that laminectomy increases and produces segmental instability unless fusion is performed [14-16]. Previous finite element and in vitro studies have shown that facetectomy has little effect on motion until 75% of the facets have been removed. However, no data exist comparing the biomechanical impact on IDP, facet load and foraminal opening when midline sparing technique is compared to traditional laminectomy [17-19].

The objective of the current study is to biomechanically compare two competing surgical techniques for alleviating spinal stenosis. Our working hypothesis is that traditional laminectomy will be associated with increased IDP and motion as compared with midline sparing laminotomy and there is more stability at the neural foramina with the midline sparing technique as compared to traditional laminectomy.

MATERIALS AND METHODS

A previously validated nonlinear 3-dimensional intact lumbar finite element model (L3–S1) developed in ABAQUS (Simulia, RI) FE package was used in the current study (Figure 1) [20-23].

The FE spine includes 27,540 elements and 32,946 nodes and is symmetric across the mid-sagittal plane. A lordotic curve of approximately 27° was simulated across the L3-S1 level, with mid L3-L4 disc plane kept horizontal. The Material properties of the FE model components are selected from the literature, including our own experimental data. The cortical bone, cancellous bone, posterior elements, endplates, facet cartilage, and nucleus pulposus were modeled as 8-node, isoparametric brick elements. The contact behavior of articular facet joints was simulated with three dimensional gap elements (GAPUNI). These elements transferred force between nodes along a single direction as the specified gap between these nodes closed. The cartilaginous layer between the facet surfaces was simulated using nonlinear contact option allowing an exponentially adjusted force transfer across the joint depending on the size of the gap.

The intervertebral disc was modeled as a composite of annulus fibrosis and ground substance surrounding nucleus pulposus. To simulate fibrocartilage layers of annulus fibrosus, the REBAR elements with “no compression” option were used with alternating angular orientations of ±30° with respect to horizontal. The fiber thickness and stiffness increased in the radial direction. The nucleus pulposus was defined using continuum hexagonal elements with isotropic material property and stiffness of 1 MPa and Poisson’s ratio of 0.499. These properties simulated incompressibility and hydrostatic characteristics of nucleus. The seven major ligaments, anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, interspinous ligament, intertransverse ligament, supraspinous ligament, and capsular ligament were modeled by 2-node nonlinear truss elements with their attachment points and material properties taken from the literature.

Two additional models were created from the intact model to simulate the anatomic changes after two posterior surgical approaches used to achieve decompression of lumbar stenosis at L4–L5: bilateral midline sparing laminotomies and complete laminectomy.

Bilateral midline sparing laminotomies was achieved by resecting the bone from the inferior 1/3 of the L4 lamina and superior 1/3 of the L5 lamina on the right and left sides. Then the ligamentum flavum was removed. The medial 1/3 of the right and left L4–5 facet joints were resected to enlarge lateral recess and foramin. The spinous process, supraspinous, and interspinous ligaments, pars interarticularis and facet capsule were preserved. Complete L4-5 laminectomy was achieved by removing the spinous process, supraspinous and interspinous ligaments, L4 lamina up to L4 pedicle level and down to L5 pedicle level. The ligamentum flavum was removed. The medial 1/3 of the right and left L4-5 facet joint was resected (Figure 2).

The follower load technique was used to simulate the vector sum of trunk muscle coactivation by using a single internal force vector that acts tangent to the curvature of the spine passing through each segmental center of rotation [24]. This “follower” path acts tangent to the curvature of the spine, thus mimicking the physiologic compressive loads on the lumbar spine seen in vivo. The follower load had the magnitude of 400N which applied at each motion segment in the model by a pair of connector wire elements (ABAQUS). The wires were attached bilaterally to the cortical shell of the vertebrae at each motion segment. Each truss spans the disc space passing through the instantaneous center of rotation at each motion segment, thereby optimizing the follower load path [25]. Following application of the pre-compressive load, a bending moment of 10Nm was applied to simulate physiological loadings of, flexion (Flex), extension (Ext), lateral bending (LB) and axial rotation (AR). Due to symmetry of model with respect to sagittal plane only left bending and left rotation were simulated to represent lateral bending and axial rotation loadings respectively. The sacrum was fixed in all degrees of

Figure 1 Loads and boundary conditions applied to the FE spine.
freedom (Figure 1). The segmental motion, intradiscal pressure, facet loads and changes in foramina opening were computed and compared for all models in different loading conditions.

RESULTS

The segmental motion at the upper segment (L3-4) did not change significantly in any of the loading conditions after surgery except in flexion where the laminectomy model had a 26% increase in motion. The motion at L4-5 varied following laminectomy in all loadings except in lateral bending. These variations were 71%, 68% and 65% increase in motion in flexion, extension and axial rotation respectively. In bilateral midline sparing laminotomies, the only significant motion changes were 37% extension and 17% axial rotation with respect to intact. At L5-S1 segment both laminectomy and bilateral midline sparing laminotomies models had motions close to intact lateral bending, axial rotation and extension (6% increase); in flexion the laminectomy model had 14% increase with respect to intact whereas the motion did not change markedly in laminotomies model (Figure 3).

IDP has significantly increased in flexion in the laminectomy compared to laminotomies and intact models at L4-5 and to a lesser extend at L3-4 and L 5-S1 segments. There was mild increase in the IDP in extension at L4-5 level in both the laminectomy as well as the laminotomies models; however the increase was slightly higher in the laminectomy model. All models showed no changes in the IDP at any segments in axial rotation and lateral bending (Figure 4).

The facet loads did not alter at L3-4 in any of the models after surgery. At L5-S1 the load on each facet decreased by almost 12% in extension after laminectomy or laminotomies; in other motions, the facet loads where similar to intact. At L4-5, the laminotomies model had facet loads close to intact in all loading cases except in lateral bending where the load on contra-lateral facet decreased by 21%. In laminectomy model the facet load decreased by %17 and 20% in extension and axial rotation and decreased by 21% on contra-lateral side in lateral bending (Figure 5).

At L4-5 both surgery models associated with 6% decrease in foramina opening distance in lateral bending and axial rotation. In extension, both models had less than 3% decrease in foramina opening distance as compared to intact. In flexion however, the distance increased by 4% in laminectomy and decreased by 4% in laminotomies (Figure 6).

DISCUSSION

Although the pathophysiology of lumbar stenosis is complex and multifactorial, compression of neural elements is generally because of a combination of degenerative changes including ligamentum flavum hypertrophy, bulging of the intervertebral disc, and facet thickening with arthropathy [11,12,26,27]. The advancement in less invasive surgical decompression procedures has lead many surgeons to use these procedures. Using finite element method the objective of the current study was to compare the biomechanical effect of midline sparing bilateral laminotomies procedure with laminectomy for treatment of lumbar stenosis. The study highlighted the advantages of preserving the posterior tension band structure on the spine biomechanics after lumbar spine decompression surgery.

The current study showed that following laminectomy at L4-5 the motion increased in all loadings except in lateral bending at that motion segment. These involved 71% flexion, 68% extension and 65% axial rotation. In bilateral midline sparing laminotomies, the only significant motion changes were 37% extension and 17% axial rotation.
The motion at adjacent segments, cephalad to decompression

Figure 4 Changes in intra-discal pressure (IDP) at different levels. IDP has significantly increased in flexion in the laminectomy compared to laminotomies and intact models at L4-5 and to a lesser extend at L3-4 and L5-S1 segments.

Figure 5 Changes in facet loads at different levels. The facet loads did not alter at L3-4 in any of the models. At L5-S1 the load decreased by 12% in extension after laminectomy or laminotomies. At L4-5, the laminotomies model had facet loads close to intact in all loading cases except in left bending where the load on contra-lateral facet decreased by 21%. In laminectomy model the facet load decreased by 17% extension, 28% axial rotation and 21% on contra-lateral side in lateral bending.

Figure 6a The foramina opening distance measured from the medial-caudal edge of the pedicle to the medial-superior edge of superior facet joint process

Figure 6b Percentage changes in foraminal opening with respect to intact at different levels. At L4-5 both surgery models associated with 6% decrease in foraminal opening distance in lateral bending and axial rotation. In extension, both models had less than 3% decrease in foramina opening distance. In flexion the distance increased by 4% in laminectomy and decreased by 4% in laminotomies.

axial rotation with respect to intact. The current study showed that the increase in flexion, extension and rotation were linked to the extent of posterior element removal. This is concurring with experimental findings of and Teo et al, who found that motion in axial rotation and flexion-extension was markedly increased with increased posterior element resection and that during lateral bending the amount of resection only slightly affected the study parameters [28].

The motion at adjacent segments, cephalad to decompression (L3-4 segment) and caudal to the decompression (L5-S1 segment) did not change significantly in any of the loading conditions after bilateral laminotomies. However, the adjacent segment motion has increased in flexion by 26% at L3-4 and 14% at L5-S1 after

Figure 7

Table 1

<table>
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<th>Level</th>
<th>Flexion</th>
<th>Extension</th>
<th>Lateral Bending</th>
<th>Axial Rotation</th>
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<td>110</td>
<td>100</td>
<td>105</td>
</tr>
<tr>
<td>L4-5</td>
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<td>105</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>L5-S1</td>
<td>95</td>
<td>90</td>
<td>85</td>
<td>80</td>
</tr>
</tbody>
</table>

Central study parameters [28].
laminectomy as compared to intact model. Preservation of the posterior tension band induced more stability to the adjacent segment. These results echo those seen clinically where increased rates of subsequent degeneration at the cephalad end of a surgical segment are suspected to reflect the greater flexibility of these segments and the increased lever arm applied to them [29].

IDP has significantly increased in flexion in the laminectomy compared to laminotomies and intact models at L4-5 and to a lesser extend at L3-4 and L 5-S1 segments. There was mild increase in the IPD in extension at L4-5 level in both the laminectomy as well as the laminotomies models; however the increase was slightly higher in the laminectomy model. The increase in the IPD after laminectomy as compared with midline sparing and intact models is linked to the increase in segmental motion at the decompressed as well as adjacent segments after such procedure. These results match the conclusions reached by Teo [28] and Dai [30] who both have shown that increased flexibility after posterior element removal leads to an increase in annular stresses. The posterior tension band structures influence lumbar spine segmental motion and the removal of the supraspinous and interspinous ligaments could contribute to the pathogenesis of postoperative instability by altering motion and load bearing characteristics of the normal spine [31].

The facet loads did not alter at L3-4 in any of the models after surgery. At L5-S1 the load on each facet decreased by 12% in extension after laminectomy or laminotomies. At L4-5, the laminotomies model had facet loads close to intact in all loading cases except in lateral bending where the load on contra-lateral facet decreased by 21%. In laminectomy model the facet load decreased by %17 and 20% in extension and axial rotation and decreased by 21% on contra-lateral side in lateral bending. The reduction in facet loads in the laminectomy model was probably due to loss of posterior bone support connecting the left and right facets. This resulted into decrease in stiffness and in the load carried by each facet joint. The distance of L4/L5 foramina in both surgical models decreased in extension, lateral bending and axial rotation compared with the intact model. However in flexion the distance increased by 4% in laminectomy and decreased by 4% in laminotomies. Partial removal of the bone in both models led to decrease in the load going through the posterior bone which resulted in lesser deformation or changes in foramina opening distance compared to the intact case in extension, lateral bending and axial rotation loadings. In flexion however, removal of the posterior band in the laminectomy model led to a different load distribution that may contributed to 4% increase in distance of foramina opening compared to intact.

The use of the finite element method for studying the changes in the segmental motion and IDP after different lumbar spine decompression surgical techniques confirmed the important role of the posterior tension band and highlighted the importance of keeping these structures intact in surgical techniques to improve long term outcome and to lessen the incidence of disc degeneration at the decompressed as well as the adjacent segments. The limitation of the current finite element model is that it did not account for variation in muscle forces at the motion segment that might occur after the surgical procedure.

Future research will involve the development of a model that will incorporate changes in muscle force and their mechanical influence on various surgical techniques.

REFERENCES


