Effect of Annular Incision Type on the Change in Biomechanical Properties in a Herniated Lumbar Intervertebral Disc

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The technique used to incise the disc during discectomy may play a role in the subsequent healing and change in biomechanical stiffness of the disc. Several techniques of lumbar disc annulotomy have been described in clinical reports. The purpose of this paper was to study the influence of annulotomy technique on motion segment stiffness using a finite element model. Four incision methods (square, circular, cross, and slit) were compared. The analyses showed that each of the annular incisions produced increase in motions under axial moment loadings with circular incision producing the largest change in the corresponding rotational motion. Under shear loading mode, cross and slit-type annular incisions produced slightly larger changes in the principal motions of the disc than square and circular incisions. All other incision types considered in the current study produced negligibly small increase in motion under rest of the loading conditions. In addition to annulotomy, when nucleotomy was also included in the analyses, once again cross and slit incisions produced larger change in motion under shear loading mode as compared to the other two incision types. A comparison between the four types of annular incisions showed that cross incision produced an increase in motion larger than those produced by the other three incisions under flexion/extension and lateral moment loading and both shear force loadings. Circular incision produced the largest increase in motion under axial moment load in comparison to those produced by square, cross, and slit incisions. Sagittal plane symmetry was influenced by the incision injury to the motion segment leading to coupled motions as well as increased facet loads. From the study it can be concluded that the increase in flexibility of the disc due to annulotomy depends on the type of annulotomy, and the annulotomy also produce asymmetrical deformations leading to increased facet loading. [DOI: 10.1115/1.1449906]

Introduction

It is known that the physiological resilience of an intervertebral disc and its biomechanical characteristics are largely dependent on the organization of the intradiscal components. It is logical to conclude that a surgical incision through the annulus, as might be done in the treatment of a symptomatic lumbar disc herniation, would alter the biomechanical properties of the involved disc.

Several authors have studied the effect of partial removal of the annulus in addition to partial denucleation on the change in stiffness of motion segments using in vitro experiments conducted on human as well as animal models. Brinckmann and Horst [1] showed that partial discectomy increases the radial bulge while at the same time decreasing disc height under compressive load. Brinckmann [2] introduced annular injury in human cadaveric samples by internal division of the annulus fibrosus sparing only a thin peripheral layer. Under compression load a small amount of disc bulge was observed in the region of injury. He concluded that a radial incision of the annulus is not sufficient to produce a clinically relevant disc herniation. Seroussi et al. [3] loaded the motion segment in compression or flexion and found that denucleation of the disc resulted in an increase in the outward radial bulging of the outer disk annular fibers as well as an increase in the inner bulging of the inner annular fibers. Shia et al. [4] showed that discectomy significantly increased the radial bulge posterolaterally as well as anteriorly under compressive load. Most of the above studies were done for compression loading mode alone. Panjabi et al. [5] using human cadaveric spine applied compression loading as well as moment loadings and found that larger motions occurred due to nucleus removal than due to annulus injury alone. Sagittal plane symmetry was disturbed by the interventions resulting in asymmetric facet joint movement. Goel et al. [6] also used human cadaveric specimen and found that the most significant increase in motion for specimens with partial discectomy occurs in the flexion mode followed by axial rotation and lateral bending. Thus extensive literature exists which shows that surgical management of lumbar herniated nucleus pulposus has mechanical consequences to the stiffness of the motion segment and the load distribution. But none of these studies have clarified the effect of different types of annular incisions, all used clinically as part of the surgical procedure, on the mechanical function of the involved disc post surgery.

Clinical studies report [7–9] the use of four different techniques of annulotomy: circular, rectangular, cross, and slit incisions. The technique used to incise the annulus during discectomy may play a role in the subsequent healing and change in biomechanical stiffness of the disc. A few studies have used animal models to address this question but there are no studies involving human lumbar motion segments either experimentally or analytically. Either et al. [10] used a goat model and compared the effect of three annulotomy techniques (full thickness annular window, full thickness cruciate annulotomy, and full thickness annulotomy developed by inserting a circular trocar into the disc) on the change in stiffness of the disc. The biomechanical test of the spine in torsion showed that the trocar annulotomy specimens were significantly stiffer in torsion than the specimen in the window annulotomy

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group. Ahlgren et al. [11] also studied the effect of two types of annular incisions on the biomechanical flexibility of the corresponding motion segment. Their experiments were conducted on sheep and compared a full thickness annular window and a full thickness straight transverse slit through the annulus. Large amounts of motion were seen with the box incision when compared with the slit incision in all pure moment loadings.

A few analytical models have also been used to study discectomy. A finite element study conducted by Shirazi-Adl et al. [12] showed that the compressive stiffness of a vertebra-disc-vertebra unit reduced by half by nucleotomy. A three-dimensional finite element study by Kim and Goel [13] investigated the effect of total denucleation of the disc with and without laminectomy and facetectomy. Removal of the nucleus decreased the disc bulge. Further they concluded that the load sharing mechanism between the disc and facets changed after removal of the nucleus.

The sagittal symmetry in the disc that normally exists under external loads is altered by the incision in the lateral portion of the disc. Change in sagittal symmetry will produce larger facet loads under certain type of loads such as extension and lateral bending moments and shear force. Also, sagittal asymmetry might produce larger coupled motions such as lateral translation and rotation. Existing literature has not addressed these aspects.

From the literature review it is clear that several investigators have studied the effect of surgical procedures such as denucleation and annulotomy on the mechanical behavior of the motion segments using both experimental and analytical models. Even though several techniques of annulotomy have been described, no clinical report has addressed the influence of annulotomy type on recurrence or on change in motion segment flexibility. This may be due to the tendency at a surgical center to opt for one annulotomy technique and consistently use the same technique for all patients. Although there are two animal studies [10,11] investigating the influence of annulotomy type on subsequent disc function, there are no studies which address the effect of different types of annulotomies on the change in stiffness of human lumbar discs. Also the existing studies have not addressed the problem in a systematic fashion and therefore a clinician is still faced with a value judgement.

The purpose of this study was to provide biomechanical information on the effect of four commonly used techniques of annulotomy performed for posterolateral disc herniation. The results of this study may be used as a basis for developing recommendations concerning the type of annulotomy to be used in the surgery for disc herniation. We hypothesized that

1 loss of motion segment's stiffness will depend on the type of annulotomy performed at the time of surgery;

2 the additional decrease in motion segment stiffness due to nucleotomy will also depend on the type of annulotomy performed; and

3 load transfer through the disc will change due to annulotomy as well as in the presence of nucleotomy thus making the facet joints carry a larger proportion of the external load. Asymmetry due to annulotomy will also introduce larger amount of coupled motions.

Methods

The geometric shape of a lumbar motion segment was generated from a serial computed axial tomographic scan (CT) of an L3-L4 disc body unit. Using this CT scan a three-dimensional finite element model was generated for the motion segment consisting of vertebra-disc-vertebra unit using a CAD station. This model was earlier used to study the effect of graded facetectomy on flexibility of the disc [14] and to study the influence of disc geometrical property on the mechanical response to loading [15]. Increasing the number of elements that describe the motion segment by nearly eight times and used for the current study further refined this model. Salient features of the model will only be mentioned here. The top and bottom vertebrae consisting of cortical and cancellous bone were modeled by three-dimensional elements. The annulus that surrounds the nucleus was assumed as a composite material consisting of annular fibers (several layers of fibers inclined alternatively at an angle of 30 deg to the horizontal plane) embedded in a homogeneous matrix material. The cross section of the annular fibers was assumed to be largest at the outer surface of the annulus and least at the inner surface. The modulus of elasticity of the fibers was assumed to vary through the thickness of the annulus with a maximum value near the outer annulus surface. Annular fibers were modeled as nonlinear cable elements. The nucleus, which contains a gelatinous type of material, was modeled by fluid three-dimensional elements. Seven different ligaments modeled by nonlinear cable elements approximated the ligamentous structure in the motion segment and their attachment points to the bony prominence were obtained from literature. The posterior element was modeled by three-dimensional elements. Both the right and left facet joints were modeled by 20 flat contact surface elements (CONTACT 3) attached to bony posterior elements.

Validity of the finite element model was tested and found to agree well with in vitro study results published by Panjabi et al. [5]. The current finite element model was validated by comparing both the translational and rotational motions under various loading modes (1) for intact motion segment condition, (2) when a square annular incision was introduced in the postero-lateral quadrant of the disc, and (3) when nucleotomy was also considered (Fig. 1). Finite element model predicted motions under direct as well as under moment loads within the experimental range of values both under intact motion segment condition as well as when square annular incision was introduced in the motion segment. Finite element model results also fell within the experimental range of

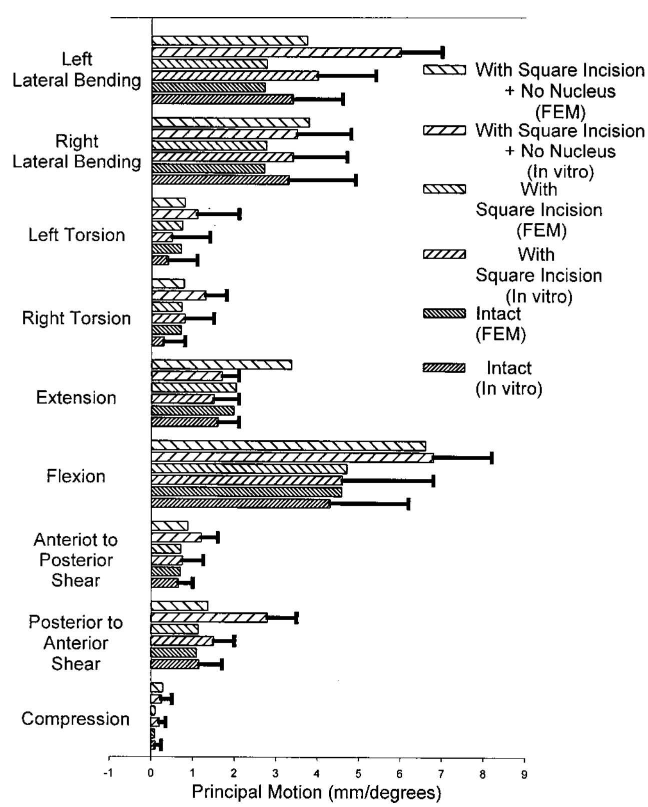


Fig. 1 Finite element model prediction of the motion segment's mechanical behavior in an intact motion segment, in a motion segment with square annular incision and in a segment with annular injury combined with nucleotomy under all loads compared favorably with experimental results of Panjabi et al. [5]

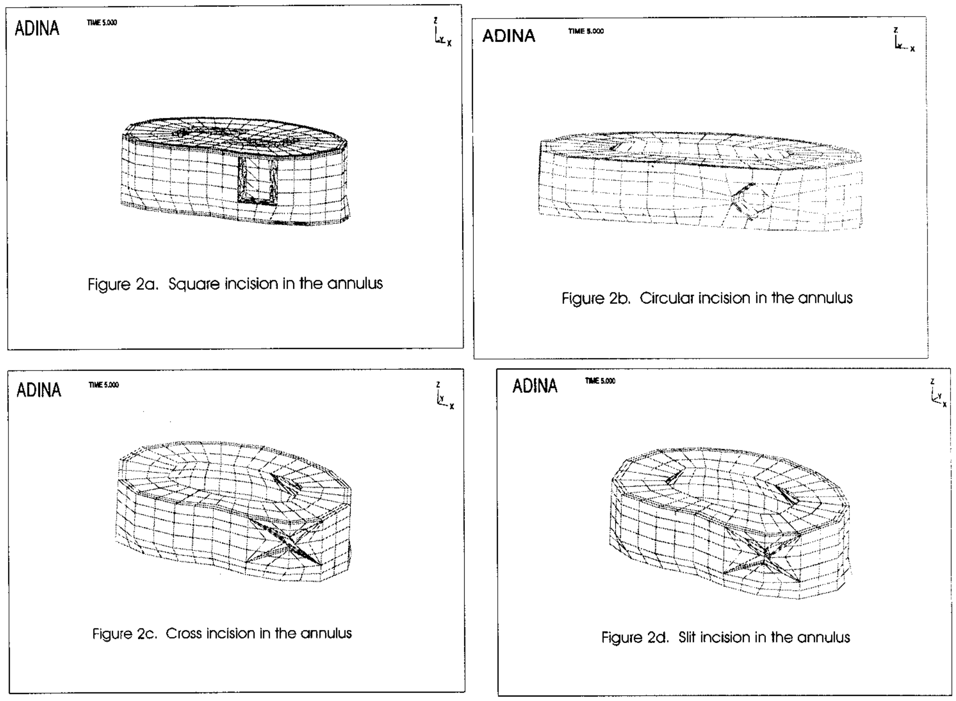


Fig. 2 Finite element mesh of the annulus with the four incisions included in the current study are shown here. Even though the circular incision is circular in shape, the graphical package could only reproduce it with straight edges. One of the slits in the cross incision was filled with finite elements to model the slit incision.

values when nucleotomy was considered except under posterior-anterior shear load, extension moment and under left lateral bending moment loads. The experimental results also showed that left lateral bending moment produced much larger motion in a motion segment with nucleus removed as compared to the motion produced by the right lateral bending moment. This asymmetry in the motion under lateral bending moment was not observed in the finite element model results. However, out of a total of 27 different motions that were used for validation of the current finite element model, only three values obtained from the model study did not fall within the experimental range.

Four types of annular incisions (Fig. 2) in the right posterolateral quadrant at the midsection of the annulus were considered in this study. A full thickness rectangular incision (size: 4 mm width×6 mm height) was modeled (Fig. 2(*a*)) by removing appropriate annular elements through the entire thickness of the annulus. The initial step in modeling circular (Fig. 2(*b*)), cross (Fig. 2(*c*)) and slit incisions (Fig. 2(*d*)) was to modify the mesh representing the annulus to suit the formation of the particular type of annular incision under study. Subsequently, appropriate elements in the annulus were removed to represent the corresponding annular incision. Trocar annulotomy was modeled in the posterolateral quadrant of the disc by removing elements representing a circular hole of 6 mm in diameter. Cruciate (cross) annulotomy was modeled by two slits each 4 mm long and 1 mm wide through the entire thickness of the annulus. The first slit in the annulus was made at an angle of 30 deg to the horizontal. The other slit was modeled by locating the new slit at the midpoint of the first slit and counter rotating 90 deg. A single slit as explained for the cruciate annulotomy above modeled slit annulotomy. Analyses were conducted for: compression (400 N), flexion/extension moments, right and left lateral bending moments, right and left torsion moment, and anteriorly as well as posteriorly directed shear load of 150 N. The magnitude of the moment load was 7.5 Nm. Compressive preload of 400 N representing the upper body weight of normal human subjects was considered along with the moment loads. The preload load was distributed as a uniform pressure on the superior surface of the top vertebra. The moment load was generated by applying two equal and opposite forces at the anterior most and posterior most nodal points in the superior surface of the top vertebra. The entire inferior surface of the bottom vertebra was fixed in all the three directions.

Material properties of the components were the same as those reported in our earlier studies [14,15].

Biomechanical characteristics (both the principal and the coupled motions) of an intact motion segment were compared with characteristics of a motion segment with an annular incision in which the nucleus was either completely removed or remained intact. The finite element analyses were conducted using ADINA 7.4 [16]. Automatic time stepping technique (ATS) was used with the full load applied in five time steps.

Results

Role of Annular Incision Type on Motion Segment Flexibility. The incision type did have an effect on the change in disc flexibility but the change was nominal for all loading modes (Figs. 3(*a*) and 3(*b*)). A circular-annular incision produced an increase in motion of 22 percent under axial moment load compared to the corresponding motion in an intact motion segment. A much smaller increase in motion of 2 percent under posterior shear load was produced by the circular incision. Both cross and slit annular incisions produced an increase in motion of 4 percent to 8 percent under axial moment load as well as under shear force loads. Square incision created an increase in motion of 6 percent under axial moment load. On an average no increase in motion was observed under all other loading modes as compared to the corresponding motions in an intact segment. A comparison among the four types of annular incisions showed that all the four annular incisions produced an increase in motion under axial moment loadings with circular incision producing the maximum change in the corresponding rotational motion.

Disc flexibility increased by a large amount as compared to the corresponding flexibility in an intact segment when in addition to

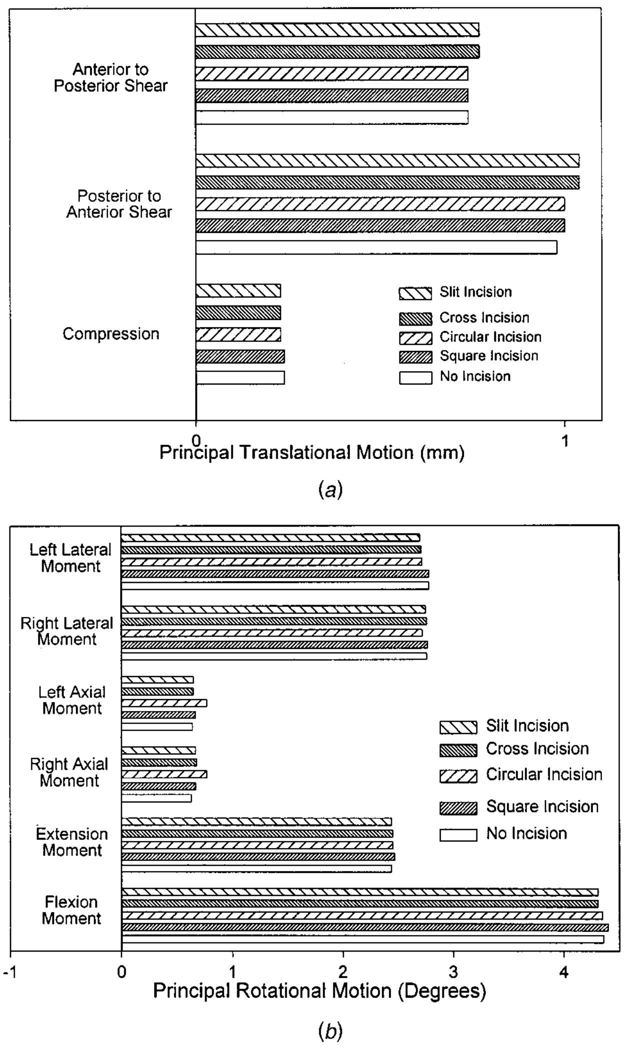


Fig. 3 Cross and slit incisions produced similar increase in motions under shear loads. Circular incision produced largest increase in motion under axial moment loading modes.

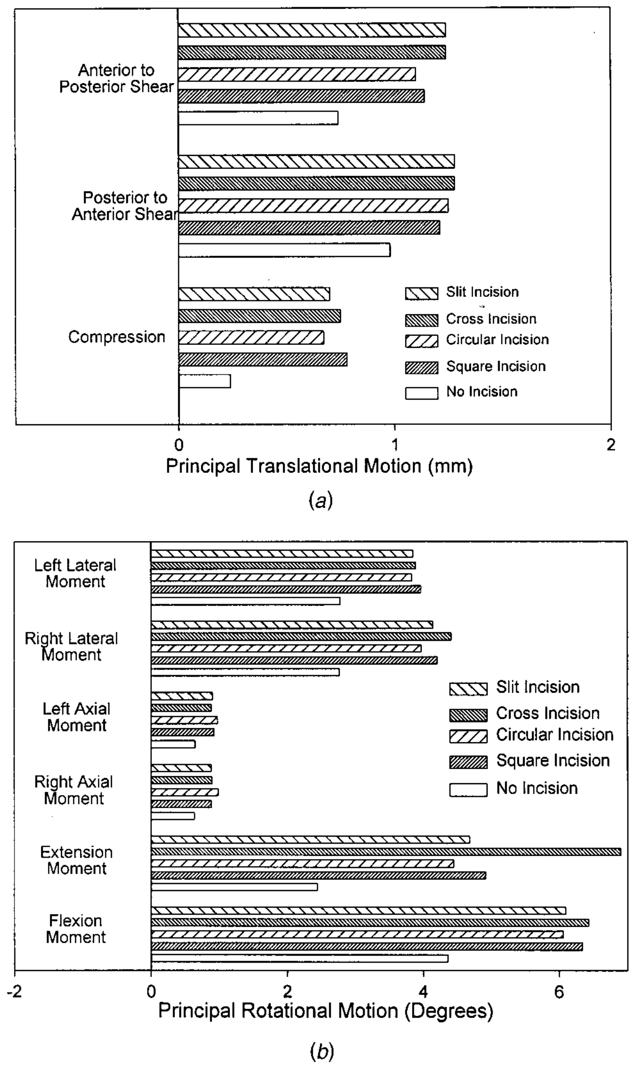


Fig. 4 Disc flexibility increased by a large amount when in addition to the annular incision, nucleus was removed. Cross and slit incisions produced largest increase in motion under shear forces. Cross incision produced largest increase in motion in all moment loads except axial moment. Circular incision produced the largest increase in motion under axial moment.

the annular incision the nucleus was also removed (Figs. 4(*a*) and 4(*b*)). This increase in flexibility was also dependent on the incision type. Cross incision produced an increase in motion in the range of 40 percent to 180 percent under moment loads, an increase in motion of 30 percent to 60 percent under shear force and a 200 percent increase in motion under compression load. Increase in motion due to the slit incision was in the range of 40 percent to 90 percent under moment loads and in the range of 30 percent to 60 percent under shear force loads. Square incision and nucleotomy produced increase in motion in the range of 40 percent to 100 percent under all moment loads. A 200 percent increase in motion occurred with the square incision under compressive load. Circular incision along with complete removal of nucleus produced the least increase in motion (30 percent to 80 percent) under all moment loads. A comparison between the four types of annular incisions showed that cross incision produced larger increase in motion than those produced by the other three incisions under flexion/extension and lateral bending moment loadings and both shear force loadings. Circular incision produced the largest increase in motion under axial moment load in comparison to those produced by square, cross and slit incisions.

Role of Incision Type on Facet Joint Loading. The posterolateral annular incision nominally did increase the load carried by the facet joints due to asymmetry. The incision type did control this increase in facet load. Facet joint loads presented here are the resultant of the x, y, and z components of the contact forces at the facet surfaces. The change in facet load was calculated by subtracting the facet load in an intact motion segment from the corresponding facet load when the incision was included in the model. Maximum increase in facet load was calculated under extension moment load for all incision types considered (Fig. 5). Circular annular incision produced an increase in facet load of 4N while the square and cross incisions produced an increase of 2N under extension moment. Cross incision produced an increase in facet load of 3N under left axial moment load. Slit incision produced an increase in facet load of 2N under left axial moment and 1N under extension moment.

The increase in facet load due to combined annulotomy and nucleotomy was much larger (at least one order higher) as compared to increase in facet load due to annular incision alone. The incision type did have an effect on the change in the amount of load carried by the facet surfaces (Fig. 6). The results that are discussed below are for the cases in which in addition to annular incision the nucleus was also completely removed. Large increase in facet load was observed when the motion segment was loaded

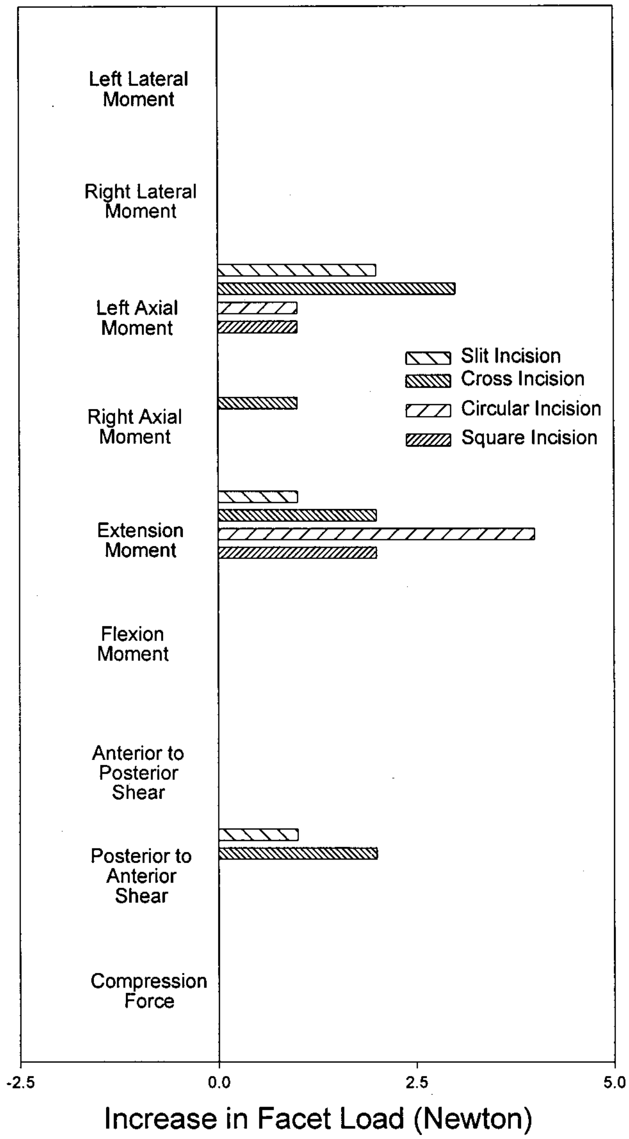


Fig. 5 The largest increase in facet load occurred in a motion segment with the circular incision. Increase in facet load was observed under anteriorly directed shear force, extension moment, and left axial moment loads.

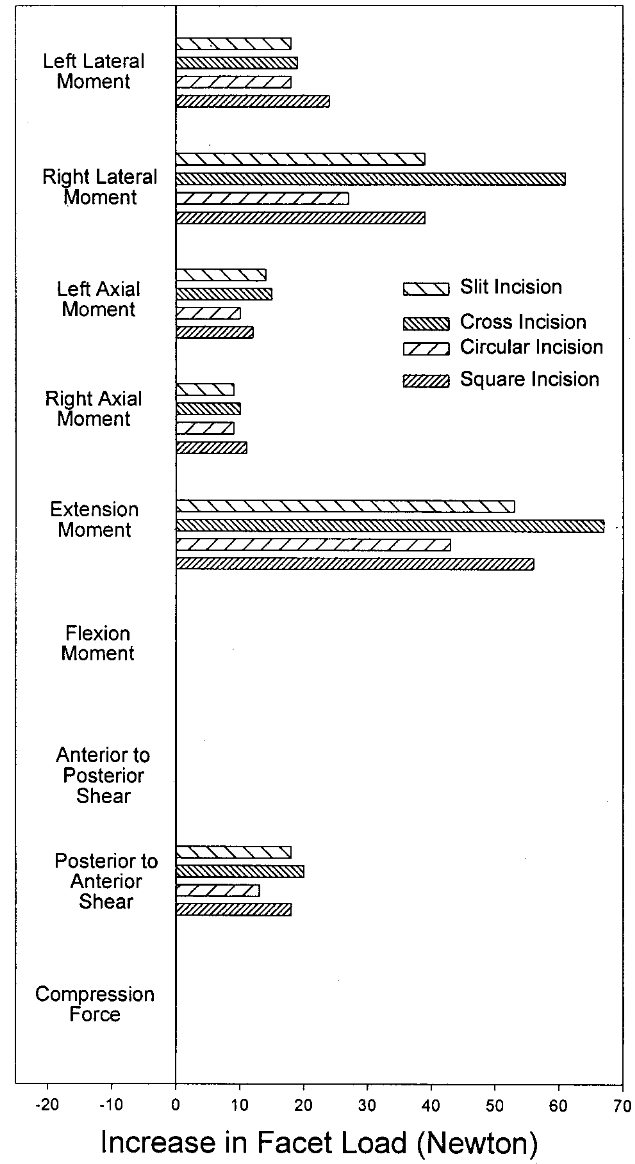
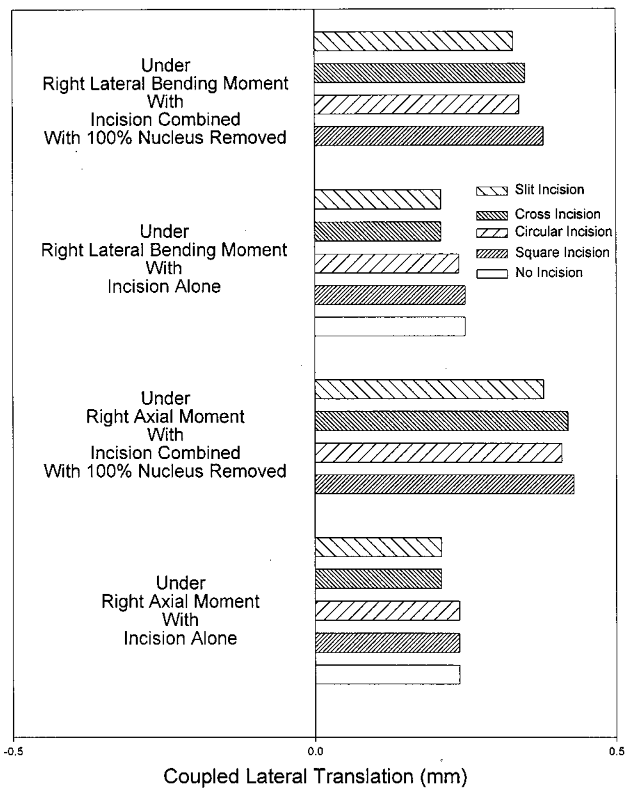


Fig. 6 The increase in facet load due to combined annulotomy and discectomy was much larger as compared to increase in facet load due to annular incision alone. The largest increase in facet load was produced by cross incision while the smallest increase in facet load was produced by the circular incision.

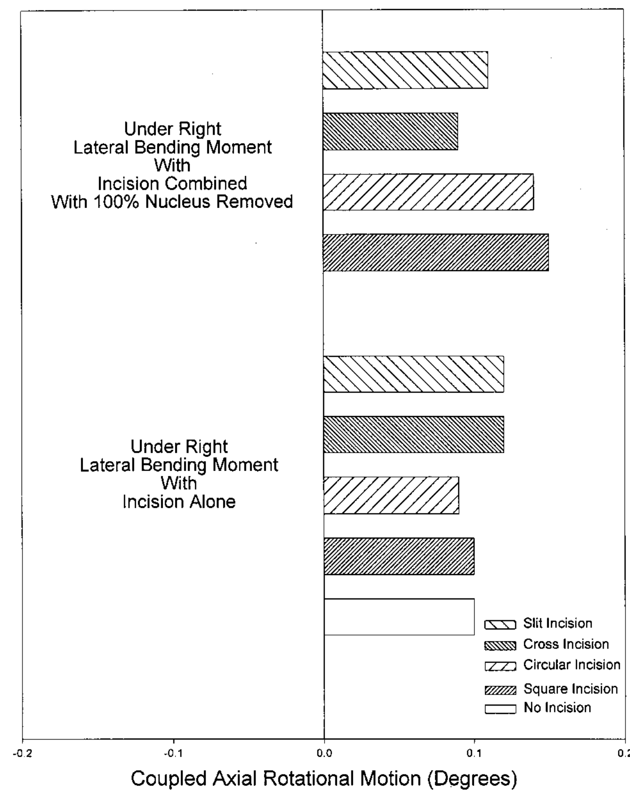
either under extension or right lateral bending or anterior shear force. Cross incision produced the largest increase in facet load of 67N under extension moment load (Fig. 6), an increase of 61N and 21N under right lateral bending and anterior shear force respectively. The square incision increased the facet load by 56N under extension moment, 39N under right lateral bending and 18N under anterior shear force. A slit incision produced an increase in facet load of 53N under extension moment, 39N under right lateral bending and 18N under anterior shear force. The smallest increase in facet load was produced by the circular incision: 43N under extension moment, 21N under right lateral bending and 13N under anterior shear force. All the four types of incisions produced larger increase in left facet load as compared to the right facet load under extension and right lateral bending moment loads. On the other hand, all the four incision types induced larger facet loads on the right facets under anterior shear force.

Role of Incision Type on Coupled Motions. As observed by Panjabi et al. [5] we also observed significant coupled motions (lateral translation, lateral rotation, and axial rotation) particularly when nucleus was removed in addition to annular incision. The type of annular injury did have an effect on the coupled lateral translation. Even though this coupled motion existed under all moment loadings, only under right axial moment and right lateral bending moment loadings it was prominent and is presented here. Lateral translation motion was of the same order as in the intact motion segment for all incision types when incision alone was considered (Fig. 7(*a*)). However, when the nucleus was also removed the coupled lateral translation increased as compared to the coupled lateral translation motion in an intact motion segment. The largest increase (80 percent under axial moment and 52 percent under right lateral bending) was seen with square incision while the smallest increase (58 percent under axial moment and 32 percent under right lateral moment) was produced by slit incision.

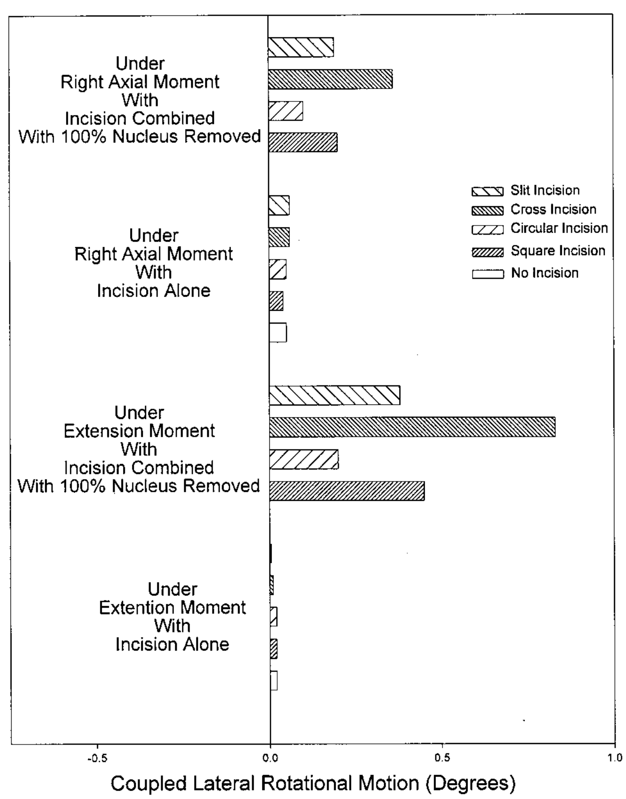
Coupled lateral rotation motion was present under all loading modes but was prominent under extension and right axial moment loading and is presented here. Lateral rotational motion was of the same order as in the intact motion segment for all incision types



(a)



(c)



(b)

Fig. 7 Coupled lateral translation and lateral rotational motions were large when nucleus was removed in addition to annulotomy. Lateral bending coupled motion was more pronounced with cross and slit incisions under extension and right axial moment loads. Axial rotation coupled motion was also found to increase predominantly under cross and slit incisions under right lateral bending moment load.

when incision alone was considered (Fig. 7(*b*)), but showed a large increase when nucleus was also removed. Under extension moment load largest increase was produced by cross incision (0.83 deg) while the smallest increase was due to the circular incision (0.20 deg) as compared to the lateral rotational motion of 0.02 deg in an intact segment. Similarly, under right axial moment load largest increase was produced by the cross incision (0.36 deg) and the smallest increase by the circular incision (0.1 deg) as compared to 0.05 deg in an intact segment.

Lateral bending moment produced a coupled axial rotation motion. In contrast to the other two-coupled motions presented here, coupled axial rotation was of the same order as in an intact motion segment both in motion segment with incision alone or with incision combined with no nucleus. All the four types of annular incisions produced the coupled axial rotation motion varying from 0.1 deg to 0.15 deg (Fig. 7(*c*)). This coupled axial rotation was about 20 percent of the principal axial rotation (produced in an intact motion segment by an axial moment).

Discussion

A validated three-dimensional finite element model of a motion segment has been used to predict the effect of four different types of annular incisions on change in flexibility of the motion segment. The results of the finite element model were compared with the in vitro model results [5] and found to agree well in the intact as well as in the square annular incision case for all loading modes. Thus it can be assumed that the results obtained from the current finite element model for the other three incision types considered in the current study are reliable. As far as comparison for the case with no nucleus, finite element model predicted results for the displacements within the experimental range for all loading modes except anterior shear, extension moment and left lateral bending moment loads. Under extension moment, anterior shear and left lateral bending loads, finite element model results showed an increase in motion due to nucleotomy in a manner similar to those seen in other loading modes. But in vitro motions under anterior shear and left lateral bending loads showed that nucleotomy increased the motion nearly twice as compared to the corresponding motion in an intact segment, not observed in any other loading modes. Since the finite element model results predicted a consistent increase in motion for all loading modes due to nucleotomy, and also the finite element model results fell within the experimental range of values for about 90 percent of the in vitro model results, one can conclude that the current finite element model can accurately predict the effect of annular incisions on changes in the motion segment flexibility. In the in vitro study, it is not clear how much of the nucleus was removed, while in the finite element model the entire nucleus was removed. This might also explain why finite element results did not agree in all the 9 loading modes considered in this study.

Both cross and slit-type annular incisions produced similar changes in the principal motions of the disc. The percent increase in motion as compared to corresponding motions in an intact motion segment was higher with cross and slit incisions than with square and circular incisions in the shear loading modes. Under moment loads, circular incision produced the largest increase in rotational motion. Thus if the recommended surgery is an annular incision alone, which is clinically unusual, protection of the disc movement against axial rotation and movement along anterior/posterior direction will help to reduce excess motion of a segment with an annular injury.

Nucleotomy produced substantial changes in motion, which could change the stiffness of the disc under external loadings. It is known that the compressive load is predominantly carried by the nucleus and the current model analyses showed that its removal produced the greatest increase in flexibility. Moment loadings to a large extent are shared by annular fibers and removal of a small percentage of these fibers increased the flexibility only by a small amount. Thus annular incisions, which produce the largest increase in motion, are capable of producing unstable motions under compression load but will not produce instability under moment loadings.

The large increase in maximum principal motions by the annular incisions is capable of producing failure of the matrix, in particular near the incision site. Cyclic loading and unloading that occurs during daily normal activities, in the presence of annular incisions, will eventually produce fatigue failure in the annular matrix. If the stresses in the matrix material increase beyond its failure values, it will cause breakage of the annular matrix thus producing cleft formation in the inner surface of the annulus. This degenerative process in turn will reduce the load-carrying capacity of the disc. Further due to annular incisions, as seen in the current study, part of the load carried by the disc was transferred to facet joints. Thus the surgical intervention to the disc not only reduced the mechanical strength of the disc but also changed the pathway by which the external load is transferred by a lumbar motion segment.

The three-dimensional study showed that annular injury not only affected the main motion, but also altered the coupled motions. Sagittal plane symmetry was disturbed, resulting in asymmetric facet joint movement. Increase in facet loading due to the presence of annular incision was seen with cross and slit incisions. The increase in facet load with cross or slit incision was greatest under axial moment load and anteriorly directed shear force. Once the nucleotomy was included in the analyses, the increase in facet load was greatest with the cross annular incision as compared to the other three types of incisions. Extension moment and right lateral moment produced large increase in facet loads in the presence of any one of the annular incisions combined with nucleotomy. In these two moment loadings, facet load increase was more on the left facets than on the right facet surfaces. This may be due to the fact that both extension and right lateral bending would tend to produce more motions on the right lateral quadrant of the disc where the incision is located. This excess motion on the right side will open up the right facet joint while closing the left facet joint inducing larger contact force on the contra-lateral side. To prevent damage to the facet cartilage, the current study showed that in the presence of annulotomy with nucleotomy anteriorly directed shear load, extension and right lateral moments should be reduced. From the standpoint of increase in facet load, the circular annulotomy seems to produce the least increase in facet load and thus may be recommended. Cross and slit incisions produced considerable increase in facet loads.

The calculation of coupled motion in the presence of annular injury is helpful to determine the sagittal plane asymmetry. The current analyses showed that sagittally symmetric forces and moments make the vertebra move asymmetrically in the presence of surgical interventions. The coupled motions (axial rotation and lateral translation and rotation) indicate this asymmetry. The study showed that in an intact motion segment these coupled motions were small. However, these small-coupled motions increased with the disc injuries. The type of incision had an effect on the coupled motions. Square incision produced the largest lateral translation under right axial and right lateral moment loads, while lateral bending coupled motion was more pronounced with cross and slit incisions under axial and extension moment load. Axial rotation coupled motion was also found to increase predominantly under square and circular incisions under right lateral bending load.

Another indicator of asymmetry is the difference in the motion response due to mirror image loads. Change in motion due to annular injury alone under right lateral and left lateral moment loads were the same. The difference in response due to mirror image loads was more prominent when the nucleus was also removed. For example, the percent increase in principal motion due to annular incision under left lateral bending moment was smaller than the corresponding increase produced under right lateral bending moment. Also, the increase in facet loads was larger under the left than under the right axial moment. Similarly, the right as opposed to the left lateral moment produced a larger increase in facet loads. It is to be noted that in an intact motion segments, both right and left lateral bending moments produce the same amount of motion [15]. This showed that the motion segment did not deform symmetrically about the sagittal plane once annulotomy was performed.

This asymmetry produced by the disc injury causes increases in facet forces as shown in the present study. Annulotomy alone produced nominal increase in facet loads, while annulotomy combined with nucleotomy produced substantial increase in facet loads. This is particularly true under anteriorly directed shear force loading, extension, and lateral moments. It is known that excessive facet load may produce cartilage degeneration and osteoarthritis [5].

The following conclusions thus can be derived from the current study: (1) increase in flexibility of the disc due to annulotomy depends on the type of annulotomy. Cross and slit incisions produce larger increase in motion than square or circular incisions under shear loads while circular incision induced larger axial rotations. (2) The increase in motion is much larger when the nucleus is removed. Under moment loading the cross incision produced the largest increase in motion compared to other types of incisions. (3) Injury to the motion segment produced asymmetrical deformation in the sagittal plane under load. This phenomenon produced coupled motions as well as increased facet loading.

It is well known that the finite element models cannot duplicate exactly the results obtained from in vitro model study, because the model is not built to the exact dimensions of the in vitro specimen. Further, the material properties of various components in the model were taken from the literature and may not compare with an in vitro model specimen. The difference between in vitro results and model results get further amplified because of additional variables such as exact nature of surgery (actual size of annular incision), exact location of the surgical intervention in the annulus, and the amount of nucleus removed.

The current study was performed on the L3-L4 disc. The results from L4-L5 and L5-S1 discs, which are more wedge shaped, may be different, but the conclusions would still hold true. Further, the study results were restricted to loads experienced by the motion segment during normal daily activities and are not applicable to potentially damaging loads.

Acknowledgments

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