Posterior cervical fixation following laminectomy: a stress analysis of three techniques

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Abstract The aim of this study was to compare the following three main fixation techniques: pedicle screw (PS) technique, lateral mass screw (LS) technique, and transarticular screw (TS) technique. A detailed, geometrically accurate, nonlinear C3–C7 FE model had been successfully developed and validated. Then three finite element (FE) models were reconstructed by different fixation techniques following C4–C6 level laminectomy. A compressive preload of 74 N combined with a pure moment of 1.8 Nm in flexion, extension, left–right lateral bending, and left–right axial rotation was applied to the models. The results showed that maximum von Mises stress on the fixation devices was much higher in the FE models of TS technique, compared with the models of PS and LS techniques. Furthermore, the screws inserted by TS technique had high stress concentration at the middle part of the screws. Screw inserted by PS and LS techniques had high stress concentration at the actual cap–rod–screw interface. The highest level of maximal stress was obtained with the fixation device of the TS technique. TS technique induces noticeable differences in the stress compared to the posterior cervical fixation technique, regarding the higher stress level on fixation devices.

Keywords Laminectomy · Finite element · Posterior cervical fixation · Stress

Introduction

Cervical laminectomy remains a useful operative alternative for the management of cervical disorders where the cervical lordotic curvature is well preserved [1]. However, laminectomy causes structural changes and affects the biomechanics of the cervical spinal components. There were significant problems associated with postlaminectomy kyphosis secondary to iatrogenic destabilization of the cervical spine [2]. Kyphosis progression causes most weight to be borne by the disks and anterior vertebral bodies, which leads to further degeneration and spondylosis [3].

Rigid posterior internal fixation strategies have been established that an extensive cervical decompressive laminectomy may lead to the loss of cervical lordosis and the development of postlaminectomy kyphosis in the management of cervical myelopathy [4]. In summary, it is becoming increasingly evident that rigid posterior instrumentation is an important method of stabilization after long anterior column reconstructions in the setting of cervical spondylosis [5, 6].

The posterior fixations provide stability by reinforcing the posterior tension band, which attempts to avoid the loss of cervical lordosis and the development of postlaminectomy kyphosis. Options for posterior internal fixation in the cervical spine include wiring techniques, laminar clamps, and screw fixation with rods or plates. Traditional wiring techniques and laminar clamps are, to a large extent, being supplanted by the more rigid fixation provided by screw fixation with rods or plates that do not require intact posterior elements for their application, especially the screw–rod systems [7]. Contemporary screw–rod systems often have a polyaxial head that allows for different screw insertion techniques at varying degrees and, by connecting

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rigidly to a rod, allow for some degree of compression or distraction.

Posterior cervical screw–rod fixation is currently performed using several techniques, such as pedicle screw (PS) technique, lateral mass screw (LS) technique, and transarticular screw (TS) technique. The PS and LS techniques are the common techniques for stabilization of the cervical spine after posterior decompressions. However, PS and LS techniques are expensive and technically demanding. Damage to neurovascular structures, especially with PS technique, has been reported [8]. TS technique should be less technically demanding to insert with less risk to the patient. Takayasu et al and Xu et al recently published that TS technique was safely used in the cervical spine as an anchor screw in combination with posterior instrumentation or as stand-alone fixation [9, 10].

However, despite fixation techniques of subaxial cervical spine remains largely descriptive, biomechanical test was used in the past to investigate the techniques [11, 12], lacking detailed the internal structural response to external loading. It is not yet clear which technique represents the best choice and whether stabilization devices can be efficient and beneficial for postlaminectomy. Mathematical models such as the finite element (FE) method can be used to find the structural response to external loading, but have a more important function in establishing the internal structural response such as stress to external loading [13].

Though several models of cervical spine have been shown in recent studies, effort in analyzing internal stress, especially to evaluate the posterior internal fixation, is lacking [14]. Therefore, the purpose of the FE study is targeted to the stress analysis of the fixation devices following the fixation techniques currently used in the treatment of cervical instability after laminectomy: PS, LS, and TS techniques. Stress distribution in posterior cervical fixation devices were evaluated using FE models.

Methods

FE modeling and validation

The C3–C7 was developed by the reconstruction of a 3D CT of the cervical spine of a male subject (age 32, height 170 cm, weight 68 kg). The present study was approved by the ethical committee of Southern Medical University. Coronal CT images were taken with space intervals of 0.625 mm in the neutral unloaded position. The images were segmented using MIMICS 12.1 (Materialise, Leuven, Belgium) to obtain the boundaries of the skeletal and intervertebral disk surface. The geometry of the skeletal and intervertebral disk components was processed using Geomagic Studio 10.0 (Geomagic, Inc, Research Triangle Park, NC, USA) to smooth the uneven surface caused by the stacking of the medical images. It was then imported into the FE package ABAQUS v6. 9.1. (SIMULIA Inc, Providence, RI, USA) to build the numerical model.

The intact FE model shown in Fig. 1 consists of five vertebrae (C3, C4, C5, C6, and C7), four intervertebral disks (C3–C4, C4–C5, C5–C6, and C6–C7), and includes all the important components of the cervical spine such as cortical bone, cancellous bone, intervertebral disks, and ligaments. Each intervertebral disk consisted of disk annulus and disk nucleus.

For modeling of vertebral bodies and posterior elements, solid elements were used, but the material was described as isotropic. Two kinds of bones were taken into consideration: cortical and cancellous. For cortical bone of the vertebral body, which is very thin sheet in fact, shell elements were used. For cancellous part, solid tetrahedral element was used. To simplify the model, the cortical endplate and cortical shell with 0.4 mm thickness [15] was attached to the solid cancellous elements by sharing the same node. The endplates were considered to be part of the

Fig. 1 The intact FE model view of the C3–C7: **a** front view, **b** side view

Table 1 Material and mechanical properties of different parts used in the finite element model

Component		Young's modulus (MPa)	Poisson's ratio	Element type					
Cortical bone and Endplate		12,000.0	0.3	Triangular shell element					
Cancellous bone		100.0	0.25	Tetrahedral element					
Disk annulus		3.4	0.4	Hexahedral element					
Disk nucleus		1.0	0.49	Hexahedral element					
Titanium		145,000.0	0.3	Tetrahedral element					
Ligament		Nonlinear tension only connector							
Anterior longitudinal		Posterior longitudinal		Spinous		Ligamentum flavum		Capsular	
Deflection (mm)	Force (N)	Deflection (mm)	Force (N)	Deflection (mm)	Force (N)	Deflection (mm)	Force (N)	Deflection (mm)	Force (N)
C3–C5									
0	0	0	0	0	0	0	0	0	0
1	28	1	25	1	7	2	38	2	55
2	52	2	44	2	12.5	4	60	4	130
3	72	3	62	3	18	6	80	6	180
4	89	4	78	4	22.5	8	108	8	210
5	102	5	89	5	26			10	230
6	115			6	30				
7				7	32.5				
C5–C7									
0	0	0	0	0	0	0	0	0	0
1	20	1	20	1	8	2	30	2	75
2	40	2	40	2	14	4	68	4	145
3	58	3	60	3	20	6	102	6	204
4	78	4	78	4	25	8	130	8	250
5	98	5	92	5	29	10	145	10	265
6	112			6	32.5				
7	120			7	35				

cortical structure located in the inferior and superior surface of all the vertebral bodies, and with the same material property used for cortical bone.

Six different ligaments approximating the ligamentous structures in the cervical spine were incorporated into the FE model as tension-only nonlinear connector: anterior and posterior longitudinal ligaments, interspinous ligament, spinous ligaments, ligamentum flavum, and capsular ligaments. Their insertion points were chosen to mimic anatomic observations as closely as possible [16, 17]. Material and mechanical properties shown in Table 1 for each spinal component represented the most commonly used values obtained from the literature [18–21].

Static analysis was conducted by imposing 1.8 Nm of flexion–extension, left–right lateral bending, and left–right axial rotation moments with 74 N of axial compression superior to C3. The boundary condition was simulated by

fixing the inferior surface of the C7 vertebra with all degrees of freedom constrained. The axial precompression force and the moments were loaded to the superior surface of C3. The facet joints were simulated using frictionless contact.

This study was performed using the FE software ABAQUS v6. 9.1. Validation of the intact model was done by comparing the predicted results with those reported in the literature.

FE model surgery simulation

All models were based on a validated model of the aforementioned intact C3–C7 model. It was then imported into the FE package ABAQUS v 6. 9.1 to build the laminectomy simulation model. The spinous ligamentum, the ligamentum flavum, the spinous process, and lamina were

excised to simulate as closely as possible the surgical procedure.

Three FE models were built, and each model simulated posterior cervical fixation following laminectomy at C4–C6. The internal fixation systems were implanted with three fixation techniques in the models after cervical laminectomy at C4–C6. The sizes and locations of screws and rods were confirmed in the intact C3–C7 model using MIMICS v12.1 to obtain the appropriate internal fixation systems. The surfaces of the screws and screw holes were simulated by imposing an ideal rough behavior (infinite friction coefficient) to the tie-contact pair, thus preventing extraction. The internal fixation system material was assumed to be titanium and modeled as linear elastic isotropic with an elastic modulus of 145 GPa. The three models were designed to simulate the stage immediately postoperatively and thus did not take into account bone fusion.

The same boundary and loading conditions were applied to the three models. A compressive preload with 74 N was imposed on the upper endplate of C3 in all simulations. Three simulations were run for each model by applying a pure moment of 1.0 Nm in different directions (flexion–extension, left–right lateral bending, and left–right axial rotation) to the upper endplate of C3.

Biomechanical comparison

Intersegmental rotational motions were analyzed to evaluate the stability of each fixation technique. The stability was measured by intersegmental rotational angle in different loading conditions (flexion–extension, left–right lateral bending, and left–right axial rotation).

Stress analyses were carried out, and stress distributions were compared among the posterior fixation devices to predict the tendency of fracture according to the fixation techniques. It was implicitly hypothesized that fracture tendency is related to high stress-level. The maximum von Mises stress levels were analyzed as a measurement of the potential for fracture due to different fixation techniques, based on the assumption that high stress concentration results in greater possibility of fixation device fracture in the long term.

Results

FE modeling and validation

The final intact model consisted of 130,748 elements and 30,820 nodes. Figures 2, 3, and 4 show the details of the in vitro data used in the comparison. They summarize the comparison of the intersegmental responses between the

intact model and previously published data under combined flexion–extension, left–right lateral bending, and left–right axial rotation. All the predicted responses were in good agreement with the published data reported in the literature about vitro studies [22–26].

FE model surgery simulation

Figure 5 illustrates surgery-simulated FE models with PS, LS, and TS techniques. In this study, the screws and screw holes were assumed to be fully integrated. Their surfaces were simulated by imposing an ideal rough behavior (infinite friction coefficient) to the tie-contact pair, thus preventing extraction. The unit FE size was 0.2 mm, and the total number of FEs was over 3,000,000 for all models so as to incorporate the full details of the complicated lower cervical geometries.

Intersegmental motions analyses

Compared to the normal model, the intersegmental motion of the C4–C5 and C5–C6 segments decreased with posterior cervical fixation, as presented in Figs. 2, 3, and 4. According the intersegmental motions data, three fixation techniques have the no noticeable differences in intersegmental biomechanical stability.

Stress analyses

Qualitative investigation of the stress features on fixation devices can predict the tendency of fracture according to the fixation techniques. Under flexion, extension, left–right lateral bending, and left–right axial rotation conditions, the stress distribution on the fixation devices was shown in Fig. 6. The effect of fixation location on load transfer can be evaluated from the result of stress concentration. Figure 7 shows maximal von Mises stress comparisons among the fixation techniques in flexion, extension, left–right lateral bending, and left–right axial rotation conditions. We noted that the screws inserted by TS technique had high stress concentration at the middle part of the screw. Screw inserted by PS and LS techniques had high stress concentration at the actual cap–rod–screw interface. Maximal stress level of TS was over 120 MPa in flexion condition, while PS and LS were less than 90 MPa in flexion. Under the other conditions, the differences were as appreciable as in flexion besides extension. The highest level of maximal stress was obtained with the fixation device of the TS technique. TS technique induces noticeable differences in the stress compared to the posterior cervical fixation technique, regarding the higher stress level on fixation devices.

Fig. 2 Comparison of intersegmental rotational motions under flexion–extension

Fig. 3 Comparison of intersegmental rotational motions under lateral bending

Fig. 4 Comparison of intersegmental rotational motions under axial rotation

Discussion

As expected, both techniques of instrumentation significantly reduced the ROM of the motion segments.

According the related literatures, there were no significant differences when comparing the different fixation techniques. Kotani et al. [27] and Jones et al. [12] showed that PS technique within the cervical spine achieves fixation

Fig. 5 Iso-posterior view of the C2–C7 (Fig. 1): **a** PS technique, **b** LS technique, and **c** TS technique

Fig. 6 Comparison of von Mises stress distributions on fixation devices in flexion, extension, lateral bending, and axial rotation modes

into both the anterior and posterior columns, providing stability as compared with LS technique. DalCanto et al. [11] recently published that TS technique offers significant

stabilization of two-level motion segments within the human cervical spine that is equivalent to that of LS technique. Moreover, the intrinsic strength of the posterior

Fig. 7 Comparison of maximum von Mises stresses on fixation devices using PS, LS, and TS techniques in flexion, extension, axial rotation, and lateral bending modes

fixation devices provides immediate stabilization, and currently available clinical papers have reported good clinical outcomes [28]. Our FE models can repeat experiments theoretically and study impact responses in supplement of cadaveric tests.

Our study found that there are noticeable differences among the three techniques of fixation in response to stress distribution on fixation devices. The study showed that that maximum von Mises stress level on the fixation devices was much higher in the FE models of TS technique, compared with the models of PS and LS techniques. Furthermore, the screws inserted by TS technique had high stress concentration at the middle part of the screws (maximal stress level was over 120 MPa). Screw inserted by PS and LS techniques had high stress concentration at the actual cap–rod–screw interface (maximal stress levels were less than 100 MPa).

The stress distribution and maximal stress level on fixation devices can reflect a higher risk of fracture. According to the research results, fixation devices with TS technique have the highest risk of fracture, and the fixation devices with LS and PS techniques have the similar risk of fracture. According to the relevance of the stress distribution and maximum von Mises stress level of the TS, suitably prolonging the need for external bracing is necessary for reducing the a higher risk of fracture on fixation devices. The reasons why the fixation devices with TS technique have the highest risk of fracture are caused by many factors. The most important factor is the gap and mobility of the zygapophysial joint. The facet joints need to be burred out, or screw size altered bigger may be an effective mean. The present study focused on the strength of the conventional implanted devices, which was used to

evaluate the risk factor of fractures happened in such surgeries, and the effective means will be analyzed in the next series.

In the present study, the calculated results are dependent on the actual simulated conditions and should be evaluated only from a comparison point of view. The models were designed to simulate the stage immediately postoperatively and thus did not take into account the bone fusion. This worst-case scenario may lead to an overestimation in all simulations. Another limitation of the present study pertains to the bone–screw interface, which was modeled as bonded, thus neglecting any possible micro-motion. Furthermore, spine degeneration was not considered; thus, the anatomy and the material properties were modeled with reference to the healthy condition. Despite this, a comparison between the different fixation techniques is still possible, and analysis results have clinic instructive significance to posterior cervical fixation technique.

Conclusion

The use of posterior cervical fixation offers immediate stability of the cervical spine following laminectomy, thus allowing early rehabilitation. TS technique induces noticeable differences in the stress compared to the posterior cervical fixation technique, regarding a higher stress level on fixation devices. Suitably prolonging the need for external bracing is necessary for reducing the higher risk of fracture on fixation devices.

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