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Original Article

Biomechanical evaluation of four different posterior screw and rod fixation techniques for the treatment of the odontoid fractures

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Abstract: Problems that screw cannot be inserted may occur in screw-rod fixation techniques such as Harms technique. We compared the biomechanical stability imparted to the C-2 vertebrae by four designed posterior screw and rod fixation techniques for the management of odontoid fractures. A three-dimensional finite element model of the odontoid fracture was established by subtracting several unit structures from the normal model from a healthy male volunteer. 4 different fixation techniques, shown as follows: ① C-1 lateral mass and C-2 pedicle screw fixation (Harms technique); ② C-1 lateral mass and unilateral C-2 pedicle screw fixation combined with ipsilateral laminar screw fixation; ③ Unilateral C-1lateral mass combined with ipsilateral C-1 posterior arch, and C-2 pedicle screw fixation; and ④ Unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation was performed on the odontoid fracture model. The model was validated for axial rotation, flexion, extension, lateral bending, and tension for 1.5 Nm. Changes in motion in flexion-extension, lateral bending, and axial rotation were calculated. The finite element model of the odontoid fracture was established in this paper. All of the four screw-rod techniques significantly decreased motion in flexion-extension, lateral bending, and axial rotation, as compared with the destabilized odontoid fracture complex ($P<0.05$). There was no statistically significant difference in stability among the four screw techniques. We concluded that the first three fixation techniques are recommended to be used as surgical intervention for odontoid fracture, while the last can be used as supplementary for the former three methods.

Keywords: Odontoid fracture, internal fixation, finite element, screw-rod fixation

Introduction

In recent years, the incidence of upper cervical vertebrae injury has an upward trend year after year because of traffic accidents increasing. Injury of the upper cervical vertebrae with spinal cord has become a serious impact on people's body health and quality of life in the field of orthopedic disorders. The biomechanical analysis of upper cervical vertebrae has an important clinical significance such as fracture types, treatment choices, prognosis judgments, and so on. At present, the finite element method (FEM) has been generally used in spine biomechanical research, but because of complicated anatomy structure of cervical vertebrae, the heavy workload for three-dimensional modeling and other reasons, the building and application of finite element model for the cervical vertebrae start relatively late.

Odontoid fracture accounts for up to 20% of all cervical spine injuries and most often occurs during high-speed motor vehicle collisions [1, 2]. At present, studies about the biomechanics of the cervical internal fixation devices are carried out mainly using cadaver experiments and finite element analysis [3]. Among them, the cadaver experiment is mostly confined to the range of the three-dimensional movement of the spine and the internal fixation devices, and the pull-out strength of the screw. Finite element analysis simulates and analyzes various structures in the human body and their pathological changes using a computer. Its results are not affected by other factors and it can analyze the internal stress and strain, which are difficult to study using general experimental methods. Moreover, it has advantages such as the high accuracy and repeatability [4].

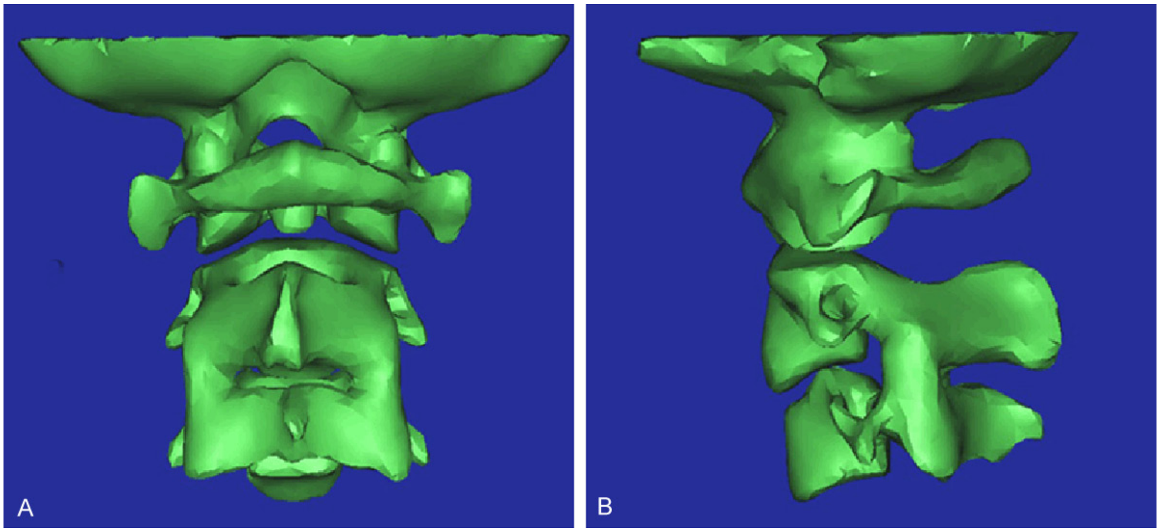

Figure 1. The finite element model of odontoid fracture. A: frontal view; B: lateral view.

Table 1. Material properties used for various components of the model

Material	Young's modulus (Mpa)	Poisson's ratio
Bone	10000	0.3
Internal fixator	105000	0.3

In this present study, we established a finite element model of the odontoid fracture including the inferior extremity of the occipital bone, and C1-C3 vertebral body. Furthermore, we designed four different internal fixation techniques for the management of odontoid fracture, and performed a preliminary analysis to compare the biomechanical stability of the four C0-C3 transarticular screw and rod fixation techniques.

Methods

Finite element model of the odontoid fracture

The present study was approved by the Ethics Committee of Shengjing Hospital of China Medical University. A 28-year-old healthy male volunteer gave his written informed to participate in our study. He was 174 cm tall and weighed 65 kg. Cervical disease was excluded via X-ray examination.

Continuous computed tomography (CT) scanning was performed from the base of the occipital bone to C3 vertebrae by using a Philips-Marconi MX8000 CT Scanner (Philips Medical Systems, Bothell, WA, USA) and the scanning data were collected and stored in Dicom format for the reconstruction of 3D bone structure using Mimics 10.0 (Materialise Technologies, Leuven, Belgium). The Freeform Plus software (Geomagic Sensable group, Wilmington, MA, USA) was applied to sand, fill, denoise, remove odontoid and bony component adjacent to C-2 vertebral body to optimize the model structure. These data were then imported to the Ansys 11.1 software (ANSYS, Inc. Canonsburg, PA, USA) as IGES files to produce a finite element model of the odontoid fracture (**Figure 1**). Grid division was carried out on each part of the bony model by a combined artificial and automatic division method to create a total of 108,325 nodes and 546,430 elements. The model data are summarized in **Table 1**.

Finite element model with four different posterior implants

The lateral screw and rod fixation system of upper cervical spine were modeled by using SolidWorks software (Dassault Systèmes, Paris, France). This model is consisted of 2 universal screws (length, 24 mm) and 1 connection rod (length, 35 mm). The images were then converted and saved as an STL file format. Next, the generated DXF files were loaded into the Mimics software to perform smoothing and meshing operation to establish a finite element model for the treatment of odontoid fractures using four different posterior screw and rod fixation techniques by using Magics9.9 software which implemented in Mimics (**Figure 2**). Four

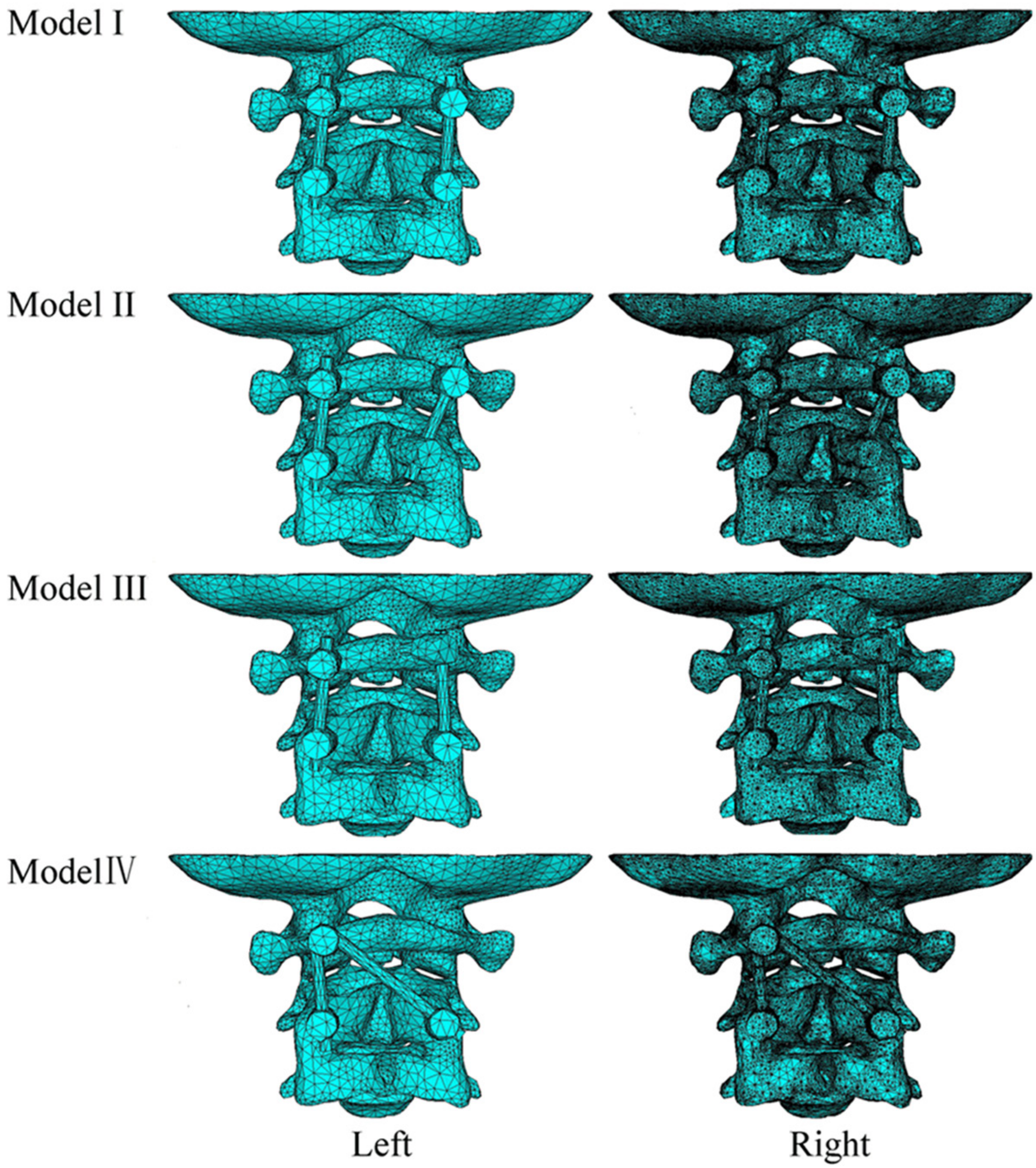

Figure 2. The finite element model treating odontoid fracture with posterior screw-rod fixation system. Left: surface mesh; Right: volume mesh.

distinct posterior screw and rod fixation technique drawn using Mimics software were shown as follows: ① C-1 lateral mass and C-2 pedicle screw fixation (Harms technique); ② C-1 lateral mass and unilateral C-2 pedicle screw fixation combined with ipsilateral laminar screw fixation; ③ Unilateral C-1lateral mass combined with ipsilateral C-1 posterior arch, and C-2 pedicle screw fixation; and ④ Unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation.

Boundary and loading conditions

The range of motion at the base of the C3 vertebra was defined in all directions as 0. Forty Newtons of vertical downward pressure were imposed on the surface of the occipital condyle

Table 2. Nodes and elements of odontoid fractures and four posterior screw and rod fixation model of the upper cervical spine

	Nodes	Elements
Odontoid fractures model	108325	546430
Model I	168785	869022
Model II	191237	991730
Model III	151436	771929
Model IV	142148	719880

Model I, C-1 lateral mass and C-2 pedicle screw fixation (Harms technique); Model II, C-1 lateral mass and unilateral C-2 pedicle screw fixation combined with ipsilateral laminar screw fixation; Model III, Unilateral C-1 lateral mass combined with ipsilateral C-1 posterior arch, and C-2 pedicle screw fixation; and Model IV Unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation.

to simulate the weight of the head due to gravity. Approximately 1.5 Nm torque was imposed on the model from various directions to produce flexion, extension, lateral bending and axial rotation. The models of the four different posterior screw and rod fixation techniques for the management of odontoid fractures posterior were compared using an Ansys 11 post-processor.

Statistical analysis

SPSS software version 20.0 (SPSS Inc., Chicago, IL, USA) was used for data analysis. Rotational stiffness (axial rotation, flexion/extension, and lateral bending) was defined as a ratio of applied torque (Nm) to the corresponding angular deformation (degrees). The degrees of ROM at C1-C2 and at the levels above and below were statistically compared using a one-way analysis of variance (ANOVA) combined with Student-Newman-Keuls test at 95% confidence. Differences were considered statistically significant when P<0.05.

Results

In this study, we first established a finite model of odontoid fracture of upper cervical spine. The model appearance was matched with geometric profile and size, which consists of 108325 nodes, and 546430 elements. Based on the established finite model of odontoid fracture, we designed four different posterior screw and rod fixation model for the treatment of odontoid fracture. This four fixation model consists of 168785, 191237, 151436, 142148, nodes and 869022, 991730, 771929, and 719880 elements, respectively (**Table 2**).

Stress diagrams and displacement diagrams

In this present study, forty newtons of vertical downward pressure were imposed on the surface of the occipital condyle to simulate the weight of the head, and approximately 1.5 Nm torque was imposed on the model from various directions to produce flexion, extension, lateral bending and axial rotation. Stress diagrams and displacement diagrams were analyzed and compared among the four screw-rod system (**Figures 3-6**).

ROM data

Total C1-C2 ROM data for all the fixation scenarios and the statistical significance of these data are shown in **Table 3**. The average ROM was 36.8°C in combined flexion extension, 20.8 in combined lateral bending, and 75.2 in axial rotation. These values are in good agreement with ROM data obtained from previously published studies [5] .

All of the four different posterior screw and rod fixation techniques significantly reduced motion of flexion-extension, lateral bending, and axial rotation, as compared with the destabilized odontoid fracture complex (P<0.05). No statistical difference for any motion was demonstrated among our first three posterior screw and rod fixations (P>0.05); however, Model IV (Unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation) was significantly different from the other three fixation technique (P<0.05), showing unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation have a relative weak stability.

Discussion

The C1-C2 articulation accounts for 50% of the rotation (47°C) and 12% of flexion/extension of the cervical spine [6]. Many disorders can cause instability of the atlantoaxial complex such as odontoid fractures, malignancy, rheumatoid arthritis, congenital anomalies, or infectious diseases [7]. The unique anatomic shape of the atlantoaxial segment permits the highest mobility of all the spinal segments. Surgical attempts to achieve stabilization in this region need to address this challenge. Posterior wiring combined with structural bone graft was the

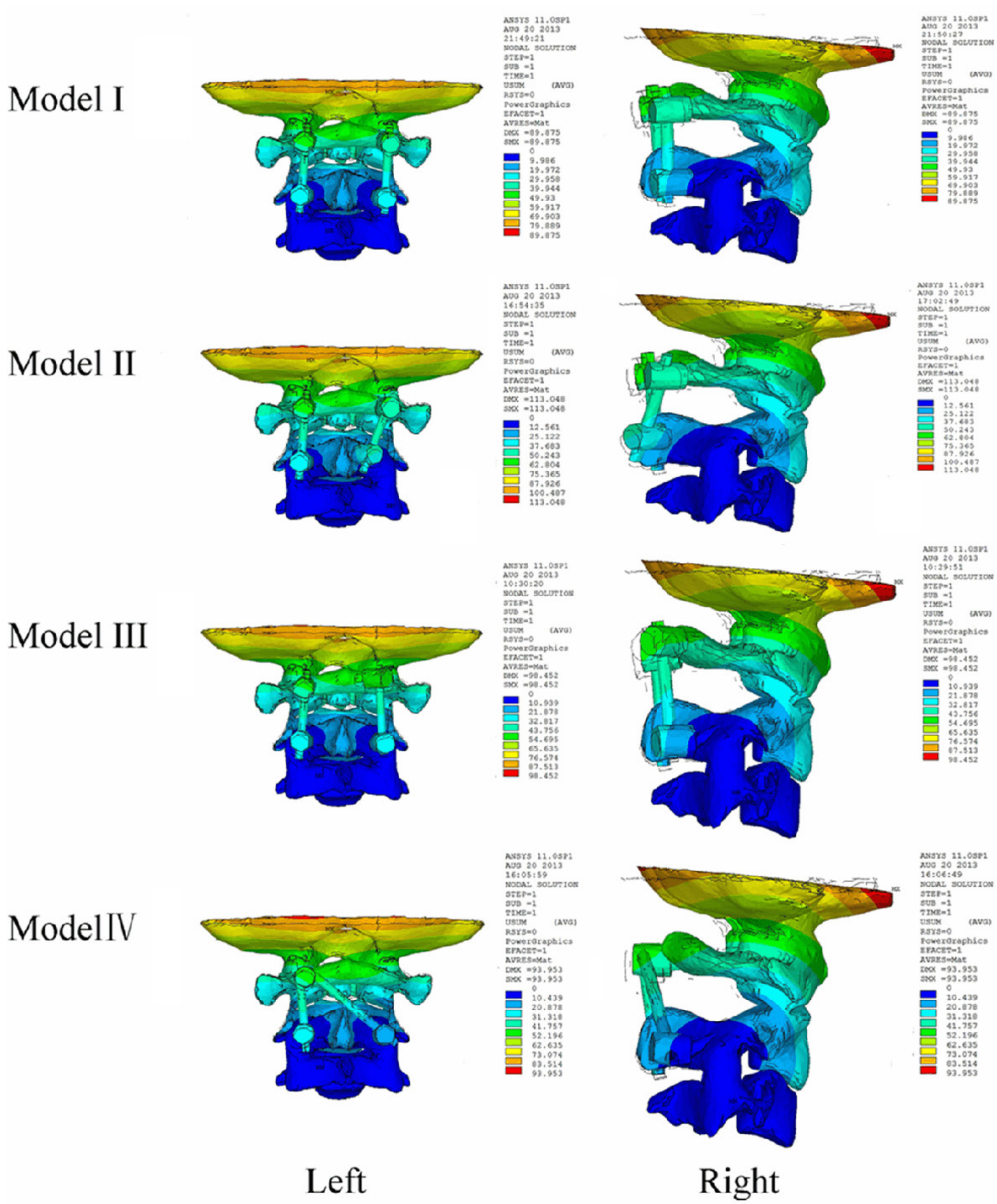

Figure 3. The displacement and stress diagram of four screw-rod fixation system under flexion motion. Left: frontal view; Right: lateral view.

first standardized operative techniques for fusing C1 and C2 [8-11]. More recently, wiring with bilateral transarticular screw fixation has become the gold standard for achieving atlantoaxial arthrodesis [12-16]. A novel method that uses direct polyaxial screw fixation to the lateral masses of C1 and the pedicle of C2 have recently been described [5, 17]. The screws are fixed via bilateral longitudinal rods. In theory, this fixation has the ability to provide adequate stability that is not dependent on the integrity of the posterior arch of C1 or any structural bone grafts. Also, because of the insertion sites of the screws, the operative exposure is

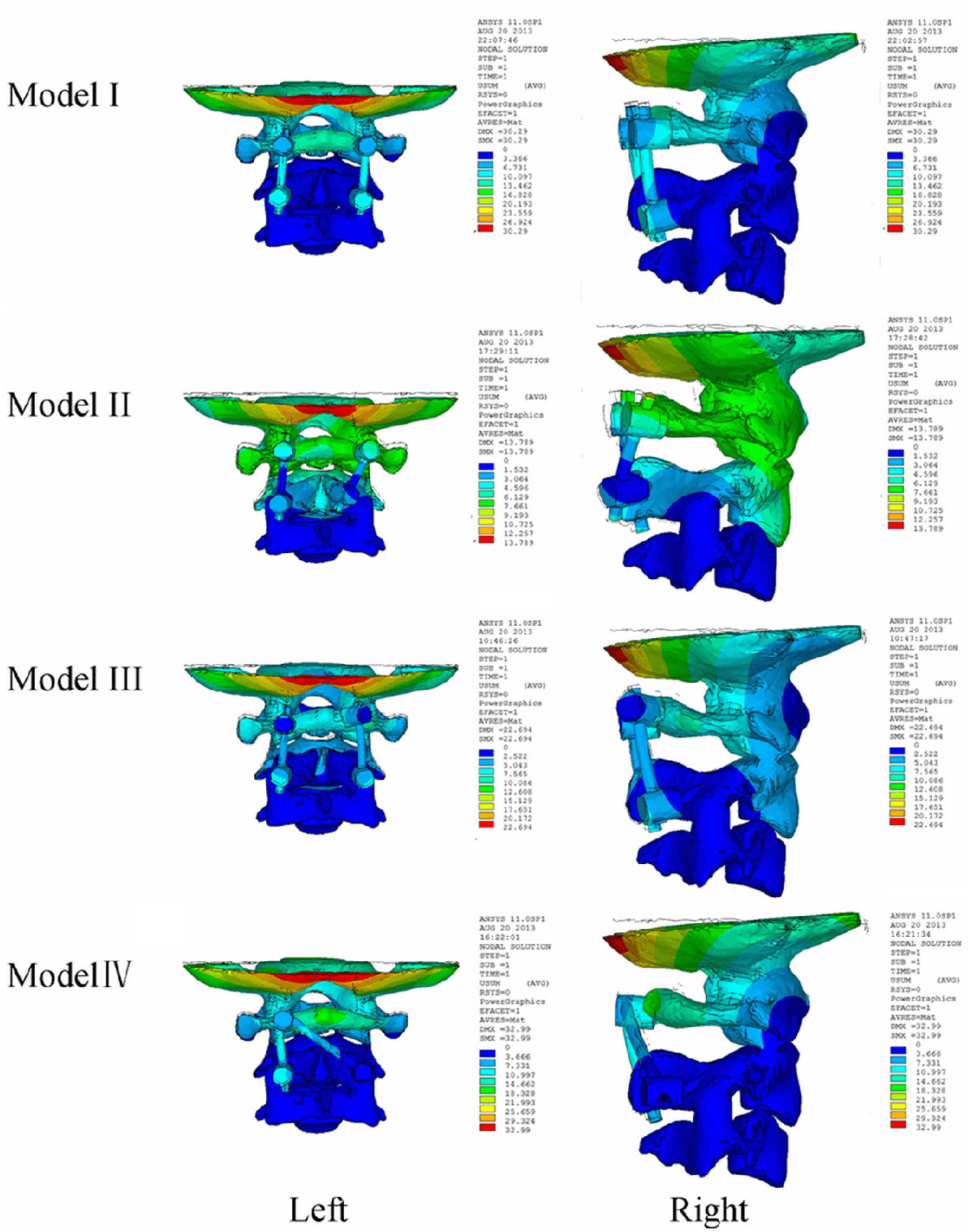

Figure 4. The displacement and stress diagram of four screw-rod fixation system under extension motion. Left: frontal view; Right: lateral view.

the same regardless of the degree of thoracic kyphosis. Finally, a reduction maneuver, if necessary, may be performed after screw placement. Incorporation as part of a posterior fixation device for extended fusion in the occipitocervical area is possible. However, to date there have been as yet no consensuses for occipitocervical reconstruction.

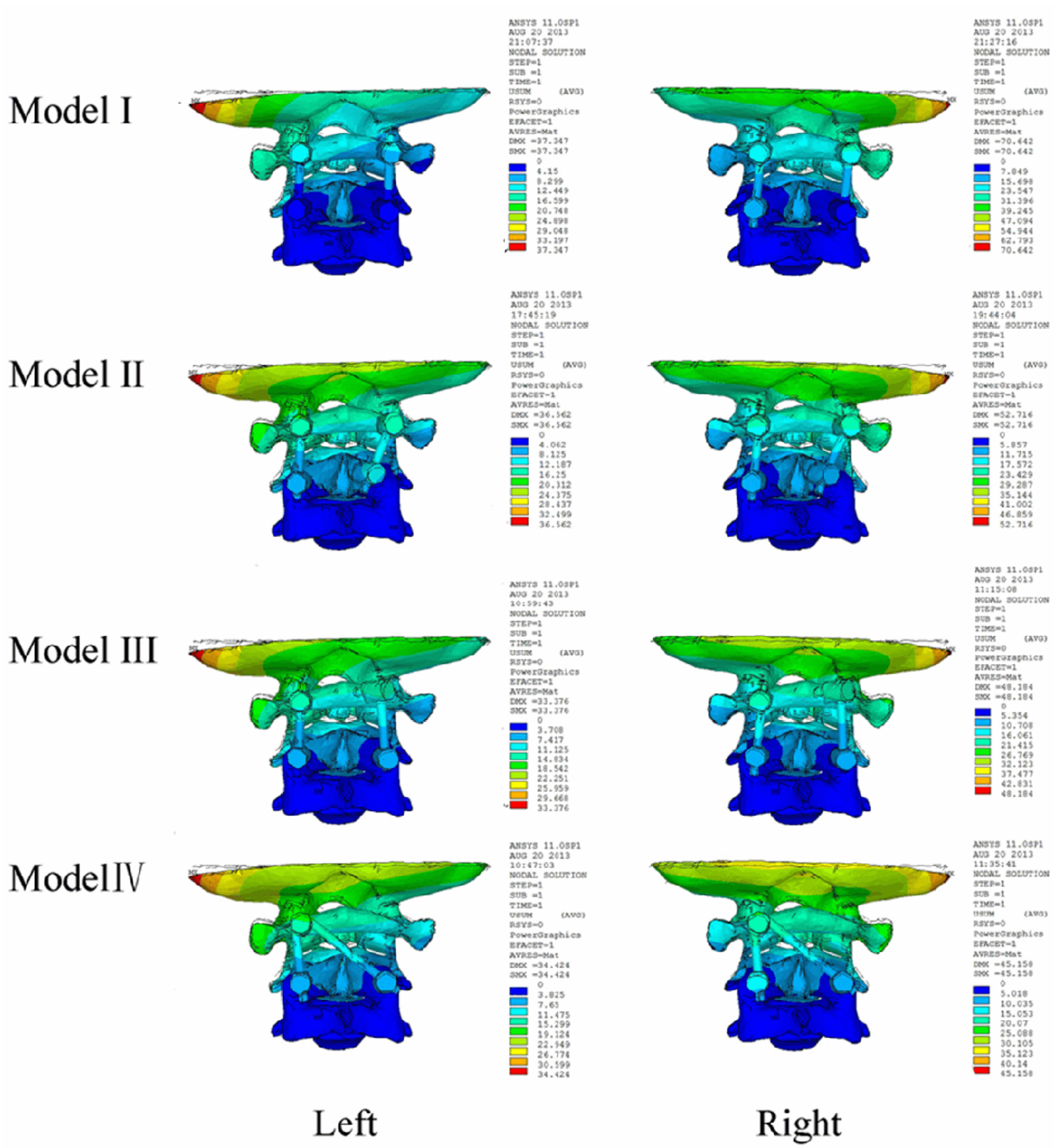

Figure 5. The displacement and stress diagram of four screw-rod fixation system under flexion motion. Left: left lateral bending; Right: Right lateral bending.

Finite elements models have their current origin and real use in mechanical engineering analysis and design. They provide interesting local information in terms of displacement, strain and stress. This local information is generally difficult to obtain experimentally. The invasive nature of the direct methods decrease their reliability: insertion of experimental devices, such as strain gauges, inside the structure can induce damage to its tissues, while placing the measuring device in or between the dental arches can be inefficient [18]. Furthermore, these experimental techniques deliver local measurements in specific points, giving an approximation of the biomechanical behavior [19]. Accordingly, experimental studies of the biologic effects of various magnitudes of force acting on the condyle, discs or the fossa are not available in vivo.

Biological applications of finite element analysis have been successful in biomechanical field

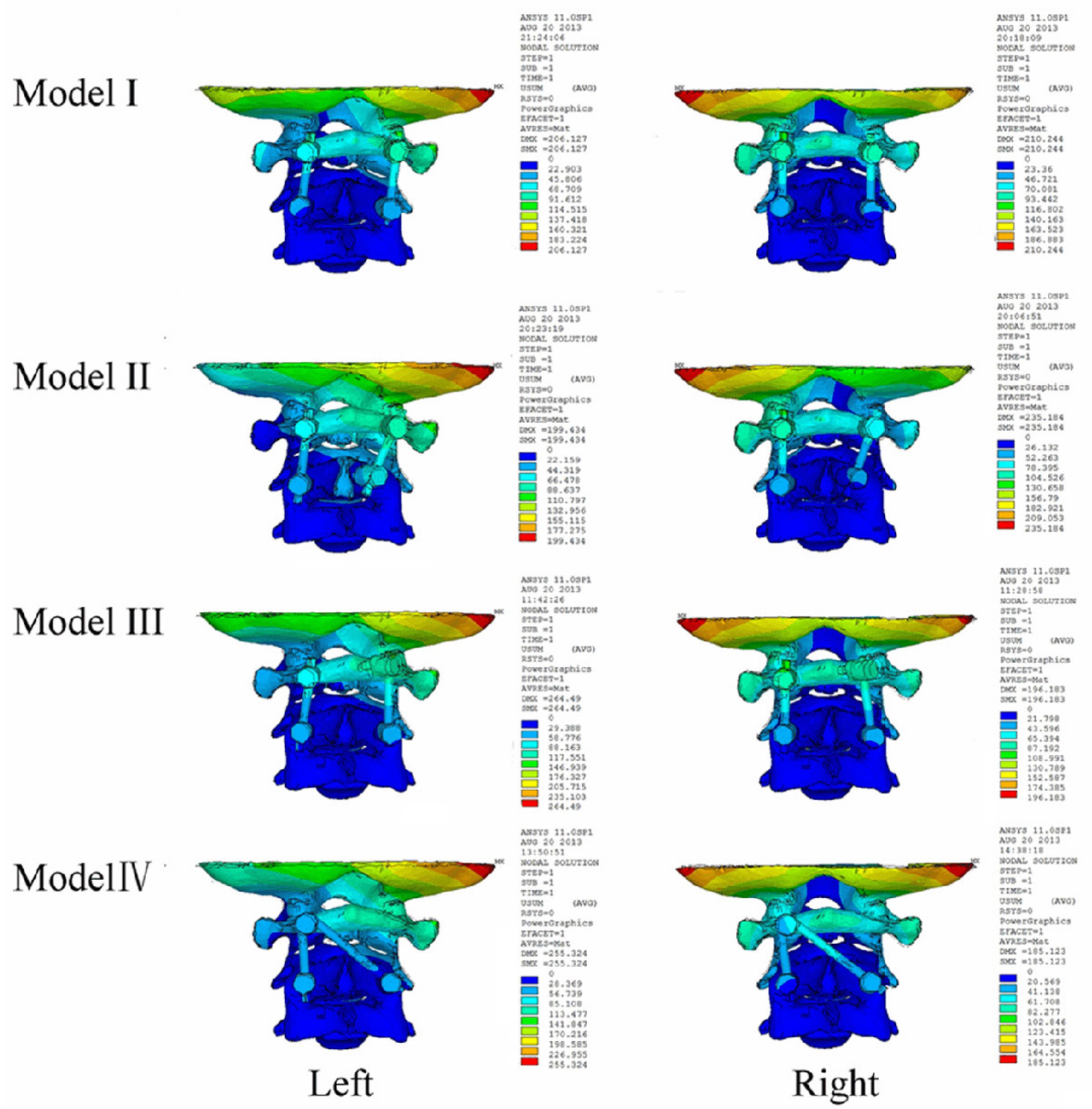

Figure 6. The displacement and stress diagram of four screw-rod fixation system under axial rotation. Left: left axial rotation; Right: right axial rotation.

such as upper cervical spine [20-23]. The main purpose of surgical intervention, in the case of atlantoaxial instability, is to obtain immediate stability and promote bony fusion of the atlantoaxial joint [3]. Therefore, it is very important to evaluate the biomechanical properties of various atlantoaxial fixation methods. In this study, we designed four new posterior screw-rod fixation techniques for the management of odontoid fracture. Our findings indicated that the four screw-rod system may provide a new option for internal fixation using the posterior upper cervical approach.

The current model involved two levels (C0 and C3) that were not directly part of the fixation. The authors thought inclusion of the occiput was important considering the dependence of the kinematic behavior of the atlas and axis on ligamentous connections with the occiput (*i.e.*, the alar ligaments and the tectorial membrane). Mechanical evaluation of the isolated atlantoaxial segment is difficult and would have provided a less physiologically meaningful model. One subaxial level, C3, was included in the preparation to allow for obtaining the correct transarticular screw trajectory. Previous work

Table 3. Comparison of C1-C2 range of motion (ROM) data in flexion, extension, lateral bending, and axial rotation for the current study with previously reported investigations

Category	Melcher*	Odontoid fracture model	Model I	Model II	Model III	Model IV
Flexion	35.2	20.2	1.2	1.5	1.3	1.8
Extension		16.6	0.5	0.7	0.8	1.2
Left Lateral Bending	20.0	10.4	0.6	0.8	0.7	2.0
Right Lateral Bending		10.4	0.6	0.8	1.0	1.6
Left Axial Rotation	77.0	37.6	0.8	0.7	1.1	1.5
Right Axial Rotation		37.6	0.8	0.9	0.7	1.3

*ROM data in combined flexion-extension, combined lateral bending, and combined axial rotation.

indicated that the potting material interfered with the surgeon's ability to access the osseous entry point when C3 was chosen as the inferior level in the preparation [5].

The current data reported that changes in ROM after destabilization also had a good concordance to those in previously published data [15, 24-27]. Besides, we found no statistical difference for any motion among our first three posterior screw and rod fixations; however, Model IV (Unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation) was significantly different from the other three fixation technique, showing unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation have a relative weak stability.

Conclusion

In summary, the finite element model of the odontoid fracture was established in this paper. The model appearance was matched with geometric profile and size. Fixation of atlantoaxial complex using C-1 lateral mass and C-2 pedicle screw fixation is biomechanically equivalent to C-1 lateral mass and unilateral C-2 pedicle screw fixation combined with ipsilateral laminar screw fixation, and unilateral C-1lateral mass combined with ipsilateral C-1 posterior arch and C-2 pedicle screw fixation. All of the three fixation techniques are biomechanically superior to unilateral C1 lateral mass screw connected with bilateral C2 pedicle screw fixation in axial rotation. In order to simulate the physiological state and to analyze the biomechanical, additional biomechanical experiments should be performed to verify the reliability of our new internal fixation system.

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Disclosure of conflict of interest

None.

Abbreviations

CT, computed tomography; ROM, range of motion; FEM, finite element method.

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