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The biomechanical study of different fixation techniques for combination fractures of atlas and axis: a finite element analysis

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Abstract

Combination atlas–axis fractures are less studied but relatively common with a higher incidence of neurological deficits than isolated C1 or C2 fractures. Several authors focused on the treatment strategies, but there is no study to compare the stability of different fixation methods; neither not yet clear which technique represents the best choice and whether stabilization devices can be efficient and beneficial for complex atlantoaxial fractures. The aim of this study was to compare the biomechanical properties of three fixation techniques: atlantoaxial pedicle screws fixation (PSF), occipital–cervical fusion (OCF) and transarticular screw fixation (TSF) based on combination factures model. Our results showed the range of motion (ROM) of fracture model increased obviously than intact model. The ROM in flexion/extension and rotation of C0–C1 in PSF and TSF models were increased. The ROM of C1–C2 in all conditions in PSF, OCF and TSF models were decreased. The ROM of C2–C3 was decreased in OCF, but remains the same stage in PSF and TSF. These suggested that three surgical methods are effective for the combination fractures of atlas and axis, which can ensure good stability. It can properly increase the ROM of C0–C1 when using PSF. These findings would aid in the treatment of this complex fractures.

Keywords Atlas, Axis, Pedicle screw fixation, Transarticular screw fixation, Occipital–cervical fusion, Finite element method

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Introduction

Combination fractures of atlas and axis account for nearly 3% of cervical spine lesions and 12% of upper cervical spine fractures with a higher incidence of neurological morbidity than isolated C1 and C2 fractures [1–3]. The characteristics and treatment strategies are not well known due to the occurrence of the two fractures in combinations often implies a more significant structural and complex mechanical injury. Most patients with combination atlas–axis fractures can be treated successfully with an external immobilization. However, patients who are at high risk for nonunion or non-operative therapy has failed require early surgical, stabilization and fusion. Several authors have focused their reports specifically on combination C1–C2 fractures and their management, but, to the best of our knowledge, no studies have compared the ROM and von Mises stresses of different internal fixations. In this study, we investigated the biomechanical comparison of three surgery techniques: PSF, OCF and TSF, which were performed in combination fractures of atlas and axis based on a finite element model of the intact cervical spine from C0 to C3. The ROM of the cervical, von Mises stress of internal fixation and intervertebral disc were evaluated. Through the study, we can speculate the stability of different surgical methods.

Materials and methods

The intact and fracture model

The model of atlantoaxial complex was developed from the computed tomography (CT) images of a healthy volunteer (24-year-old, male, height 172 cm, weight 70 kg). Ethics committee approval for use of individual participant data was granted by the ethics committee of Shanghai First People's Hospital prior to this study. Informed consent in the study was also obtained from the participant. The CT images were scanned with a thickness slice of 0.625 mm and were imported into finite element modeling software of Simpleware3.0 (Simpleware Ltd, United Kingdom) to construct a geometrical surface model of atlantoaxial complex. Then, after smoothed by Geomagic 8.0 (Geomagic, Inc. Research Triangle Park, NC, USA), the model was meshed as solid model in Hypermesh 10.0 (Altair engineering, Inc. Executive Park, CA, USA).

The model including vertebral body, disc, facet and major ligaments. Each vertebral body consisted of cortical bone and cancellous bone, and each vertebral disc was composed of nucleus pulposus, annulus fibrosus, and endplates. To simplify the model, 0.5 mm and 6-noded solid elements C3D6 were used for modeling the cortical bone and endplate, 0.5 mm and 4-noded solid elements C3D4 were used for cancellous bone and posterior elements of the vertebrae. The intervertebral discs were composed of nucleus pulposus and annulus fibrosus and modeled based on anatomical data. Major ligaments mimicking the ligamentous structures in the cervical spine were incorporated into the model, including anterior atlanto-occipital membrane (AAOM), Posterior atlanto-occipital membrane (PAOM), apical ligament (AP), alar ligament (AL), tectorial membrane (TM), transversal ligament (TL), anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), ligamentum flavum (LF), joint capsules (JC), cruciated ligaments (CLV), interspinous ligament (ISL), Supraspinous ligament(SSL). Ligament insertion points and area were closely matched with published data [4–6]. The detailed values for various materials are tabulated in Table 1 and other ligament properties shown in Table 2, which are the most commonly used values derived from the literature [4, 7, 8]. Cut off the bottom of the odontoid process and cut off the junction between the anterior arch and lateral mass, and the junction between the posterior arch and lateral mass to simulate Jefferson & type II odontoid fracture (Fig. 1). The segmental ROM was also calculated to compare with the intact model.

Fixation models

Three fixation models were established under the condition of Jefferson & type II odontoid fracture by the soft of Rhino4.0 (Robert McNeel & Associates, USA) according to the system sizes and surgery technical specifications. The fixation models are shown in Fig. 2.

Boundary and loading conditions

The inferior endplate of C3 was constrained in all degrees of freedom. A pure moment of 1.5 N·m combined with a

Table 1 Material properties used in the finite element model

Description		Level	Element	Young's modulus (MPa)	Poisson's ratio
Vertebra	Cortical bone	C0–C3	3-D solid(6 node)	12,000	0.29
	Cancellous bone	C0–C3	3-D solid(4 node)	450	0.29
Posterior elements		C1–C3	3-D solid(4 node)	3500	0.29
Endplate		C1–C3	3-D solid(6 node)	500	0.4
Disc	Annulus ground substance	C2–C3	3-D solid(8 node)	3.4	0.4
	Nucleus	C2–C3	3-D solid(8 node)	1	0.49
	Annulus fibrosus	C2–C3	Tension-only linear contact element(2 node)	450	0.3
Transverse ligament		C1	Orthotropic	E1 = 86 E2 = 6	0.016
Implants		C0–C3		120,000	0.3

E1 is perpendicular to the disc radius, in the axial plane. E2 is perpendicular to E1

Table 2 Material properties of the other ligaments

Ligaments	d_f (mm)	f_f (N)	d_n (mm)	f_n (N)	Parabola coefficient
AAOM	18.9	232	3.78	23.2	1.623695
PAOM	18.1	83	6.033333	8.3	0.228015
JC(CO-C1)	9.9	320	3.3	32	2.938476
JC(C1–C2)	9.3	314	4.65	31.4	1.452191
JC(C2–C3)	9	210	3	21	2.333333
ALL	10	300	2	30	7.5
LF(C1–C2)	9.6	111	3.2	11.1	1.083984
LF2(C2–C3)	6	90	2	9	2.25
AP	8	214	1.6	21.4	8.359375
AL	14.1	357	2.82	35.7	4.489211
CLV	12.5	436	2.5	43.6	6.976
TM	11.9	76	3.966667	7.6	0.483017
PLL	10	80	3.333333	8	0.72
ISL	7	37	2.333333	3.7	0.679592

pre-compressive load of 50N was applied to C0. Flexion, extension, left/right lateral bending, and left/right axial rotation were simulated.

Validation of the model

The model was loaded in quasi-static loads to validation the rationalities, pure moments (sagittal, transverse and frontal planes) of 1.5 N·m and a compressive load of 50 N were applied to C0 with the C3 firmly fixed. These loading conditions are adopted from the biomechanical experiments and published finite element analysis. The ROM was compared against the in vitro experimental data of Panjabi et al. [9] to assess the validity of the intact model (Fig. 3).

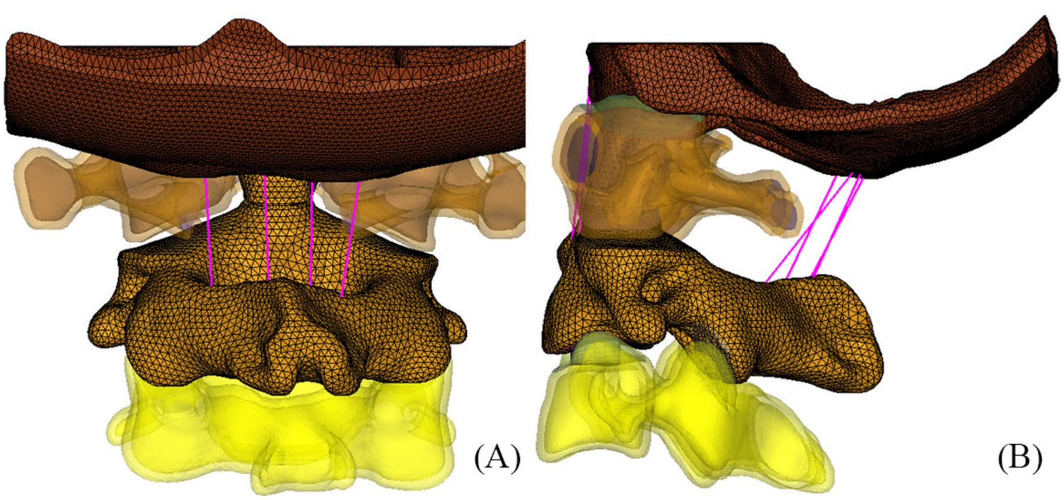

Fig. 1 The finite model of Jefferson fracture combines with type II odontoid fracture. **A** The A–P view; **B** the sagittal view

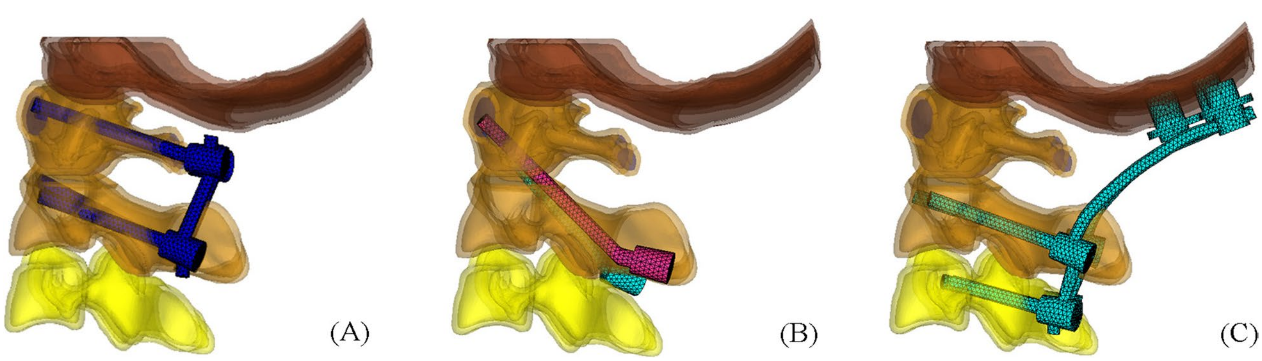

Fig. 2 The finite model of different fixation systems. **A** Atlantoaxial pedicle screws fixation; **B** transarticular screw fixation; **C** occipital–cervical fusion

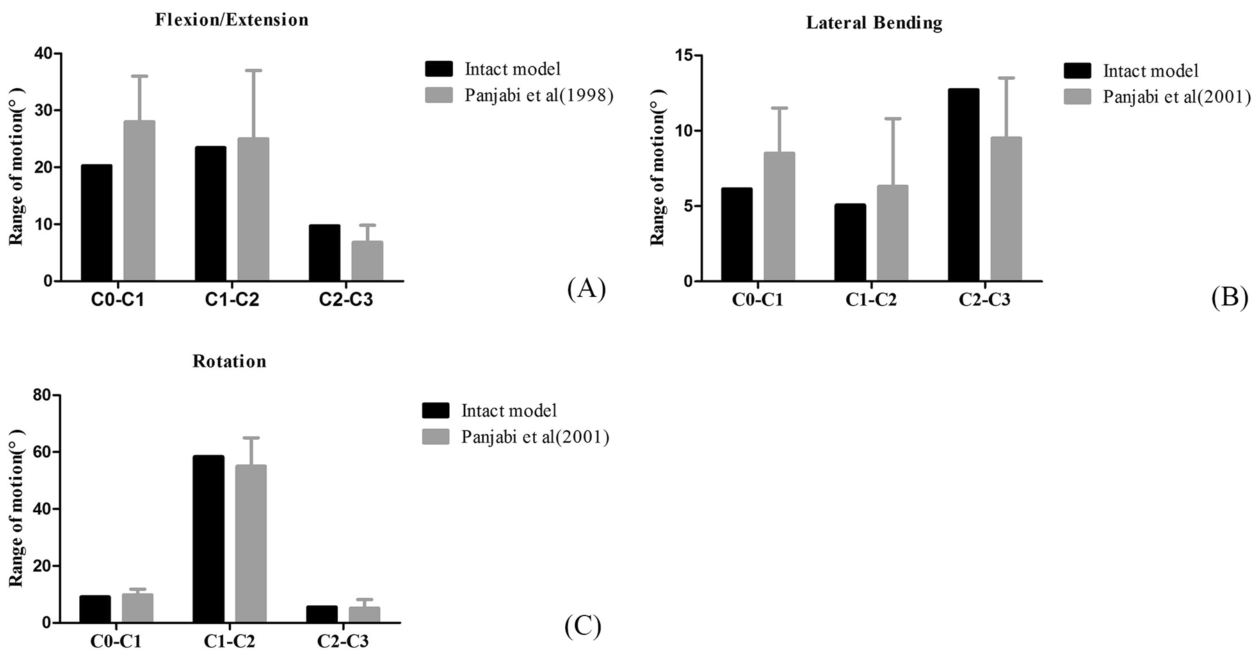

Fig. 3 Comparison of the ROM between the present intact model and the literature (Panjabi et al. 1998, 2001). **A** Flexion/extension condition; **B** lateral bending condition; **C** axial rotation condition

Assessment indexes

The ROM of C0–C3, von Mises stress and stress of the pedicle screws and rods of the three fixation finite element models under six loading conditions(flexion, extension, left/right lateral bending, and left/right axial rotation) were analyzed using the software of Abaqus6.9 (Simulia, USA). No statistical analysis was performed in the manuscript because only one subject was modeled.

Results

Finite element modeling and validation

The intact FE model included 211,371 elements and 66,517 nodes and all the critical components such as discs, facets and major ligaments. There is little difference between the intact model with the previously published models (Fig. 3). Therefore, the model in the present study is effective for further analysis. Figure 4 shows the comparison of the motions of fracture model with intact model under the load-controlled method. Under each loading type, the greatest biomechanical changes occurred in all motions and all segment especially in flexion and extension increased 72.1%, left and right rotation increased 43.8% in C1–C2.

ROM of the fixation models

Compared with the intact model, the ROM in flexion/extension and rotation of C0–C1 was increased over the non-destructive state in PSF of 59.2% and 68.3%, and in TSF of 49.1% and 29.1%. All states of motions of C1–C2 in PSF, OCF and TSF is decreased than the non-destructive state, especially in rotation, and the ROM was the smallest in TSF, followed by PSF and OCF models. The ROM of C2–C3 was decreased than normal in OCF but remain the same stage in PSF and TSF because we choose the segment to fixation in OCF is C3 due to the lateral mass of C1 may not be intact in some cases so that pedicle screw will not be suitable (Fig. 4).

Von Mises stress of the vertebral body and implants

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 bending, and left–right rotation conditions. The maximal von Mises stress all occurred in the root of screw and rod in all conditions and all fixation models. The maximal von Mises stress of the PSF is 321.19 MPa in left rotation, 228.84 MPa of the OCF in left bending, 306.71 MPa of the TSF in left rotation (Figs. 5, 6, 7, 8).

Von Mises stress of discs

The values of the largest maximal von Mises stress of the intervertebral disc (C2–C3) in flexion and extension were 5.85 MPa, 1.38 MPa, 5.85Mpa, 3.45 MPa, 0.68 MPa, 3.47Mpa in bending, 3.58 MPa, 0.68 MPa, 3.57 MPa in rotation, in PSF, OCF and TSF, respectively (Figs. 9,10).

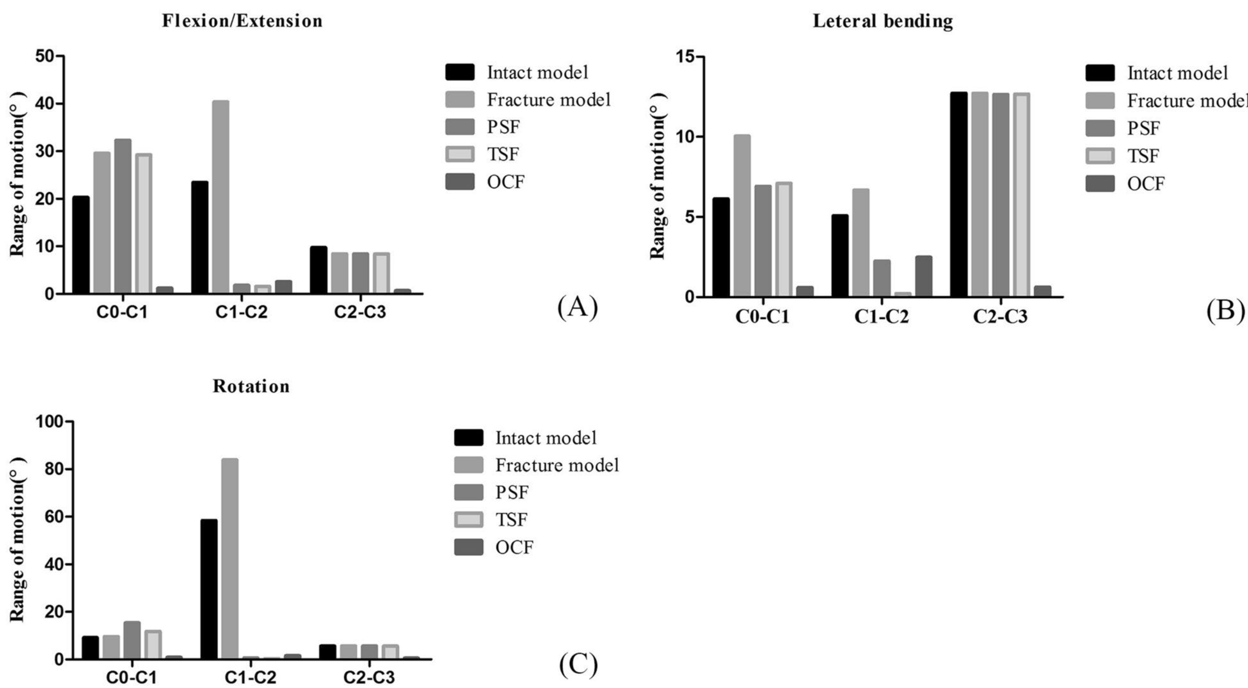

Fig. 4 Comparison of the ROM in intersegmental motions under all conditions in the model of PSF, TSF and OCF. **A** Flexion/extension condition; **B** lateral bending condition; **C** axial rotation condition

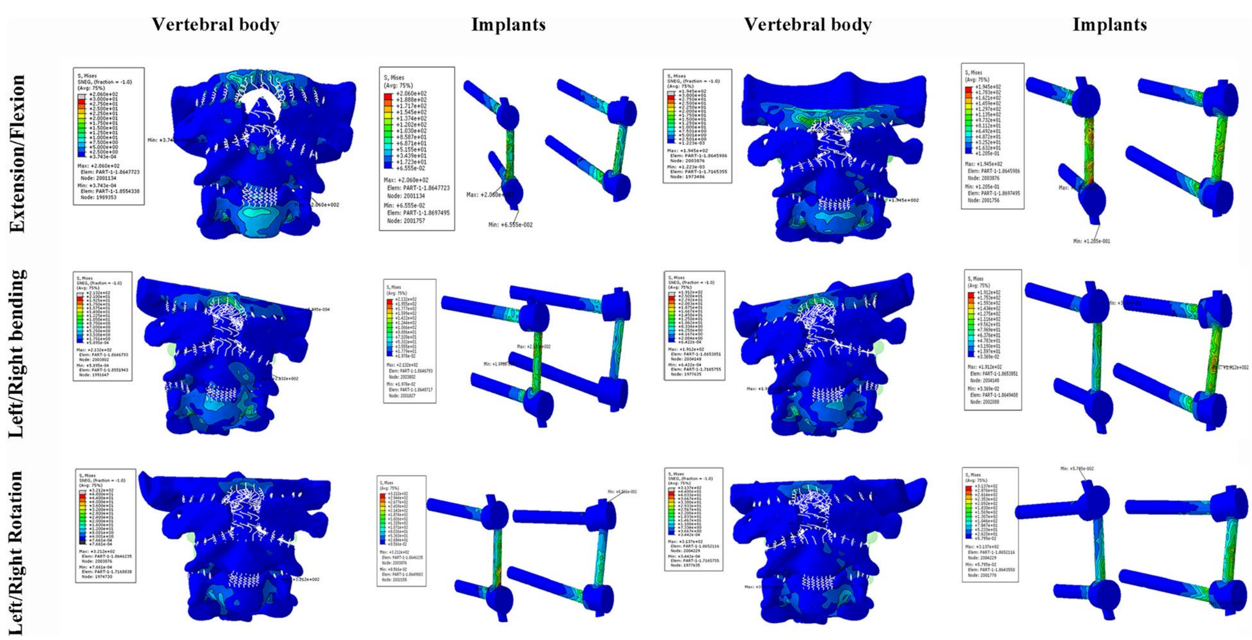

Fig. 5 The von Mises stress distribution of the vertebral body and implants of the model of atlantoaxial pedicle screw fixation

Discussion

Actually, any fracture of axis can be accompanied by atlas fracture and vice versa, and once the injuries occur, often implies a complex mechanical injury with more frequently neurological impairment, sometimes fatal [10]. Virtually, it is a challenge to make the treatment of C1–2 instability in which ruptures of the transverse, alar, and apical ligaments [11, 12], dens fractures [13],

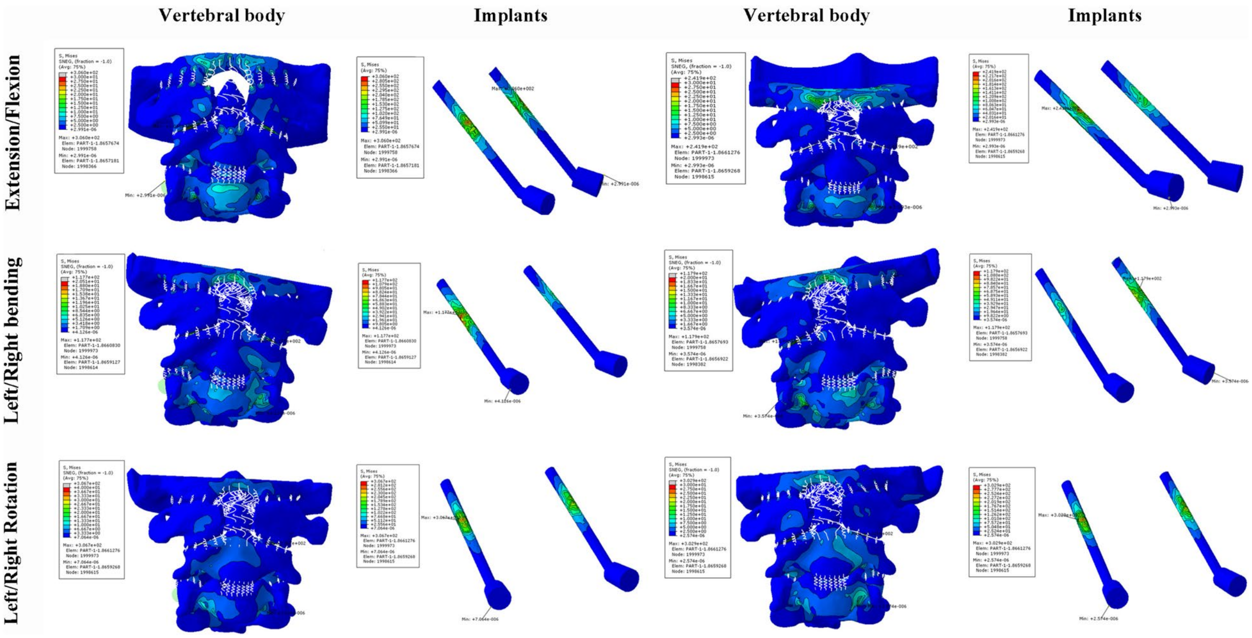

Fig. 6 The von Mises stress distribution of the vertebral body and implants of the model of transarticular screw fixation

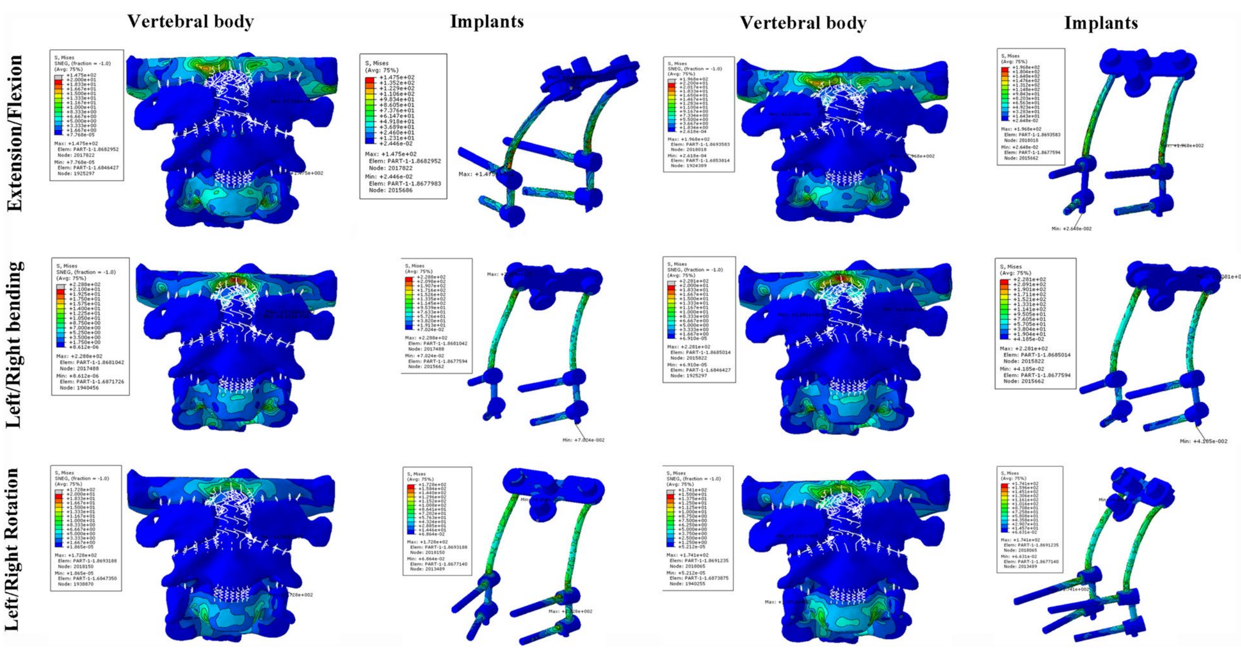

Fig. 7 The von Mises stress distribution of the vertebral body and implants of the model of occipital–cervical fusion

and odontoidectomies [14] are the common causes of atlantoaxial destabilization that have been studied biomechanically, due to the unique and complex biomechanics of the atlantoaxial. Though several screw-based constructs have been developed for atlantoaxial fixation and the biomechanical properties of these constructs have been assessed in numerous cadaver studies, and several biomechanical studies have compared posterior occipito-atlantoaxial fixation techniques and have generally concluded that the presence of transarticular screws or pedicle screws improves the stability of the construct over provided by other constructs, such as posterior

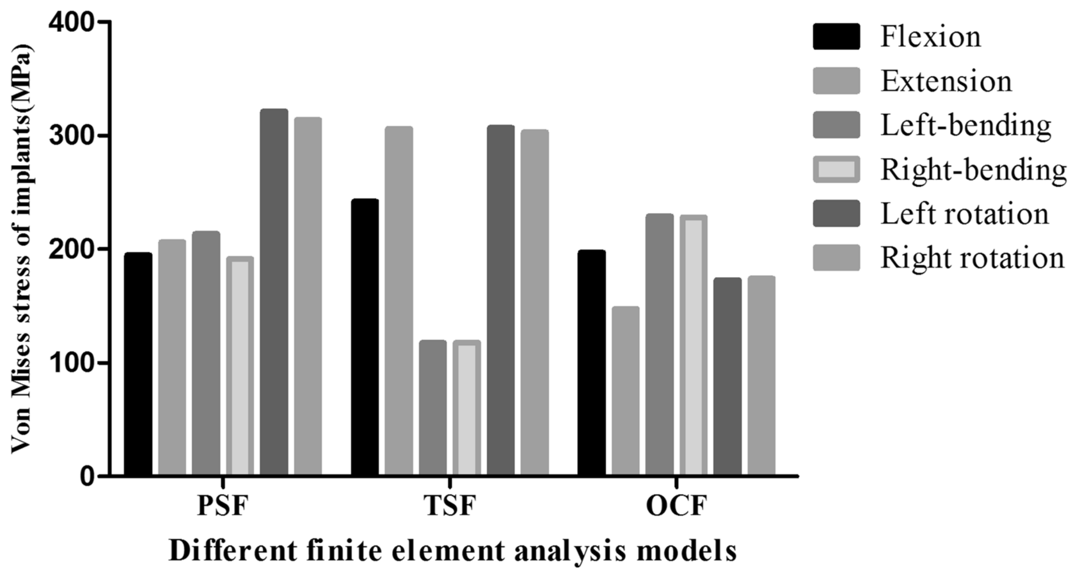

Fig. 8 Comparison of the maximal stress of the implants under all conditions in all fixation models

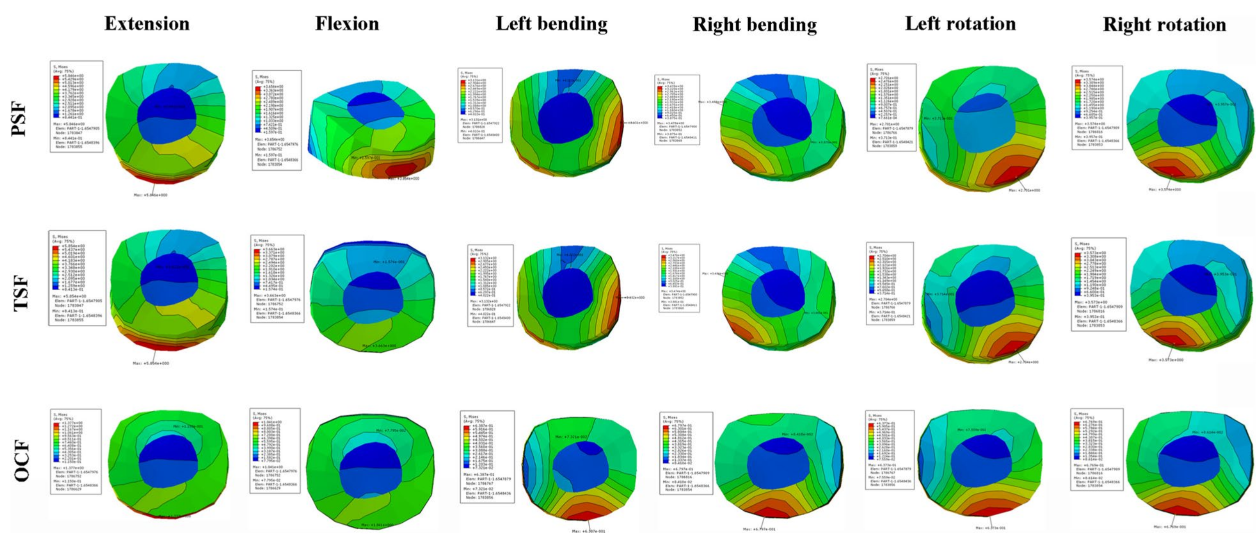

Fig. 9 Stress nephogram of the intervertebral disc (C2–C3)

wiring [15, 16]. But combination fractures of atlas and axis is more complicated, the influence on the stability of upper cervical spine is more serious and it is difficult to determine the specific treatment provided to and outcome for most of those patients. Several authors have focused their reports specifically on combination C1–C2 fractures and their management such as atlantoaxial fixation (Gallie, Brooks, Fielding, posterior atlantoaxial pedicle screw fixation, etc.), occipital–cervical fusion and triple anterior screw fixation [1, 2, 17], these techniques have been demonstrated to be safe and effective method for C1–C2 stabilization in most patients, however there is no published finite element analysis study of different fixation techniques; neither not yet clear which technique represents the best choice and whether stabilization devices can be efficient and beneficial for complex atlantoaxial fractures. Therefore, the purpose of this finite element study was to establish a finite element model of Jefferson & type II odontoid fracture based on a validated intact C0–C3 spine model and evaluate the biomechanical properties of different fixation methods (PSF, OCF, TSF) for combination fractures of atlas and axis.

In the current study, we attempted to create a Jefferson & type II odontoid fracture model by cutting off the

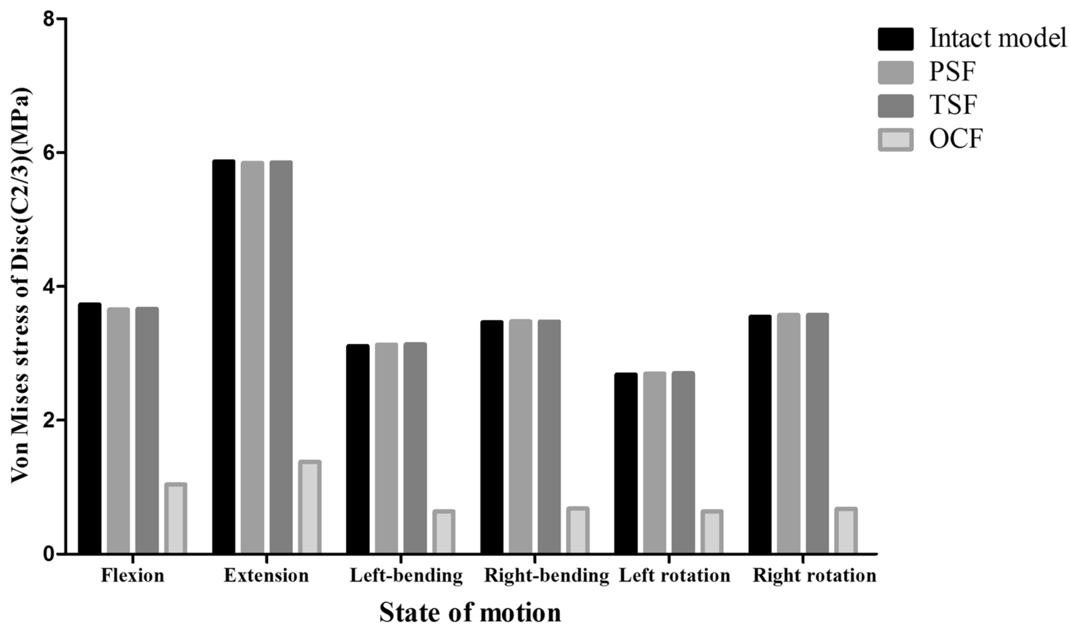

Fig. 10 Comparison of the maximal stress of the disc under all conditions in all states

bottom of the odontoid process and the junction between the anterior arch and lateral mass, posterior arch and lateral mass based on the validated atlantoaxial complex three-dimensional finite element model. The fracture model was built clearly and distinctly, with good geometric similarity. The data generally indicate an increase ROM in all states of motion, especially in flexion/extension increased 72.1%; rotation increased 43.7% of C1–C2, compared with the intact model. For the first time, the loading profiles changes in the upper cervical spine associated with instrumentations have been predicted. Compared with the intact model, three fixation models showed a decrease ROM in all states of motion of C1–C2, the changes of flexion/extension, lateral bending and rotation were 92.2%, 55.7%, 99.0% in PSF; 93.3%, 95.6%, 99.6% in TSF; 89%, 51%, 97.4% in OCF, respectively, and which is consistent with the findings of Li et al. [18]. These predictions certainly seem to suggest that TSF technique in this study contributed most to stability in lateral bending as previously described [19, 20], However, some drawbacks of TSF technique remain: The main disadvantages of C1–C2 transarticular screw fixation are the limitations imposed by the position of the vertebral artery and the acute angle of approach needed for screw place. The PSF method was similarly effective to TSF, both of which were more effective than OCF, one possible reason was we put screws in C2 and C3 rather than C1 and C2 because OCF approach is usually reserved for patients with disruption of the C1 arch and gross C1–C2 instability, in which C1 screw may not be suitable. The result is unexpected that the ROM in all states of motion of C0–C1 was increased in PSF and TSF models, especially in flexion/extension(59.2% of PSF and 49.1% of TSF) and rotation(68.3% in PSF and 29.1% in TSF), potentially predisposing it to accelerated degeneration, while the ROM of C2–C3 remained basically the same. Interestingly, Li reported that C0–C1 or C2–C3 segment may not be more susceptible to degeneration than other nonfixed segments after C1/2 fixation though the ROM of the C0–C1 and C2–C3 segments increased after C1–C2 fixation, This discrepancy may be related to differences in the biomechanical models used or the specific fixation techniques evaluated. On the basis of these findings, the mobile of atlanto-occipital joints may compensatory increase after the fixation of atlantoaxial joints.

The maximal von Mises stress of pedicle screws both happened in rotation among PSF and TSF, but bending in OCF. As showed in the stress distribution results, a maximum level of pedicle screws stress was apparent at the root of the screws under all loading conditions. In clinical practice, the majority of screw breaks occur at this site. Compared with intact model, the stress of intervertebral disc of C2–C3 seemed to be constant at the same level. This result reflects from another aspect, unlike C0–C1, the fixation of C1–C2 had little effect on C2–C3.

An inherent limitation of our study is that it is a finite element analysis, which does not truly reflect clinical application and we only simulate one type of combination fractures and three common fixation methods. Future work may include additional fracture types and fixation techniques, such as anterior methods (Harms plate, TARP, and ATS) and an enhanced posterior Magerl technique with dorsal fixation of the screw base to the axis, to further investigate their biomechanical properties and clinical outcomes. According to the previous finite element analysis studies, all finite element models were reconstructed from single patient's imagine data and the studies were absent of statistical analysis. Bur we think if we chose more healthy patients, we can build a more standard model and we will keep on with the study.

One of the main advantages of using the finite element method is its time efficiency and computational exactness. From this, it may be possible to identify which aspects of certain fixations are critical to their success and to implement these aspects in current and future designs.

Conclusion

To the authors' best knowledge, this serves as the first report of application of the finite element method to complex atlantoaxial fractures instrumentations. The data provided by this study demonstrate that all three screw fixation techniques limit motion at the C1 to C2 articulation, provide adequate stability for promotion of fusion. This study indicates that TSF provides superior fixation to the other two. Also, short segment fixation in C1–C2 such as TSF and PSF may affect the stability of C0–C1, but not C2–C3. OCF should be considered as an alternative to PSF and TSF when C1 arch was disruption.

Clinical perspectives

In this work, we established a finite element model of combination fractures of the atlas and axis, and different fixation methods were performed to compare the biomechanical properties.

The finite element study showed that all three fixation techniques can reduce the ROM of C0 to C3 and TSF fixation may offer higher stability to PSF fixation in flexion/extension, lateral bending and rotation in C0–C1.Compared with OCF fixation, short segment fixation in C1–C2 such as TSF and PSF may affect the stability of C0–C1.

This study serves as the first report of application of the finite element method to complex atlantoaxial fractures instrumentations and could provide theoretical reference for the clinical study.

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Author contributions
C.L. and K.H. conceptualized the study and designed the experiments. C.L. performed the experiments and analyzed the data. L.D. contributed to data analysis and interpretation. XG.H. prepared Figures and assisted with experimental procedures. XJ.Z. provided critical feedback and helped shape the research, analysis, and manuscript. C.L. and K.H. and L.D. wrote the main manuscript text. All authors contributed to manuscript revision, read, and approved the submitted version.

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Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Ethics committee approval for use of individual participant data was granted by the ethics committee of Shanghai First People's Hospital prior to this study (No. 2014KY063).

Competing interests
The authors declare no competing interests.

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