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Original article

# Finite element analysis of posterior cervical fixation

Y. Duan [1], H.H. Wang [1], A.M. Jin, L. Zhang, S.X. Min, C.L. Liu, S.J. Qiu, X.Q. Shu *

*Department of Orthopaedics, Zhu Jiang Hospital, Southern Medical University, No. 253, Gongye Big Road, 510282 Haizhu District, Guangzhou, People's Republic of China*

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A B S T R A C T

*Background context:* Despite largely, used in the past, biomechanical test, to investigate the fixation techniques of subaxial cervical spine, information is lacking about 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 three-column injuries (TCI).
*Hypothesis:* The different posterior cervical fixation techniques (pedicle screw PS, lateral mass screw LS, and transarticular screw TS) have respective indications.
*Materials and methods:* A detailed, geometrically accurate, nonlinear C3–C7 finite element model (FEM) had been successfully developed and validated. Then three FEMs were reconstructed from different fixation techniques after C4–C6 TCI. 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 FEMs.
*Results:* The ROM results showed that there were obvious significant differences when comparing the different fixation techniques. PS and TS techniques can provide better immediate stabilization, compared to LS technique. The stress results showed that the variability of von Mises stress in the TS fixation device was minimum and LS fixation device was maximum. 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 higher stress concentration at the actual cap–rod–screw interface.
*Conclusions:* The research considers that spinal surgeon should first consider using the TS technique to treat cervical TCI. If PS technique is used, we should eventually prolong the need for external bracing in order to reduce the higher risk of fracture on fixation devices. If LS technique is used, we should add anterior cervical operation for acquire a better immediate stabilization.


## 1. Introduction

Injuries to the cervical spine present a significant clinical dilemma with potentially devastating outcomes. Injuries to the subaxial cervical spine accounts for the majority of cervical injuries, making up about 65% of fractures and > 75% of all dislocations [1]. In the last past few decades, posterior cervical fixation for subaxial cervical reconstruction has proliferated largely as a result of better outcome. The use of posterior cervical fixation offer immediate stability for the injured spine, and prevents the sequelae of acute cervical spinal cord injury, thus allowing early rehabilitation and the potential for improved recovery.

The use of screw-rod systems represents a large step forward from previous posterior cervical fusion devices, which are biomechanically superior to facet and spinous process wiring [2–7]. Furthermore, the screws can be inserted by this technique and often have a polyaxial head that allows for different screw insertion techniques at varying degrees and, by connecting rigidly to a rod, allowing for a degree of compression or distraction [8]. A variety of posterior cervical screw–rod fixation techniques have been developed to internally stabilize the subaxial cervical spine by using a posterior fixation. These include pedicle screw (PS), lateral mass screw (LS), and transarticular screw (TS) technique.

Despite fixation techniques of subaxial cervical spine remains largely descriptive, biomechanical tests were used in the past to investigate the techniques [5,7], lacking detailed 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 three-column injuries (TCI). Though several fine element models (FEMs) of cervical spine have been reported in recent studies, effort in analysing structural response

* Corresponding author.
*E-mail address:* shuxq2012@163.com (X.Q. Shu).
[1] Yang Duan and Hehui Wang contributed equally to this work. Yang Duan and Hehui Wang are co-first authors.

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to external loading, especially to evaluate the posterior internal fixation, is still lacking [9,10].

Therefore, the purpose of this study is targeted to the biomechanical comparison of the fixation devices following three posterior cervical fixation techniques currently used in the treatment of cervical instability after TCI: PS, LS, and TS techniques. Immediate stability, variability and distribution of stresses in posterior cervical fixation devices were evaluated using FEMs.

## 2. Methods

### 2.1. FE modelling 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 study was approved by the ethical committee of Southern Medical University. Coronal CT images were taken with the space interval 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 disc surface. The geometry of the skeletal and intervertebral disc components was processed using Geomagic Studio 10.0 (Geomagic, Inc, Research Triangle Park, NC, USA) to smoothen 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 discs (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 discs, and ligaments. Each intervertebral disc consisted of disc annulus and disc nucleus.

For modelling of vertebral bodies and posterior elements, solid elements were used, but the material was described as isotropic. Two types of bones were taken into consideration: cortical and cancellous. For cortical bone of the vertebral body, which is a very thin sheet, 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 [11] was attached to the solid cancellous elements by sharing the similar node. The endplates were considered to be part of the 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 [12,13]. Material and mechanical properties shown in Table 1 for each spinal component represented the most commonly used values obtained from the literature [14–17].

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. Validation of the intact model was done by comparing the predicted results with those reported in the literature. All the predicted responses were in good agreement with the published data reported in the literature about in vitro studies. Our previous study shows the details of the in vitro data used in the comparison [18].

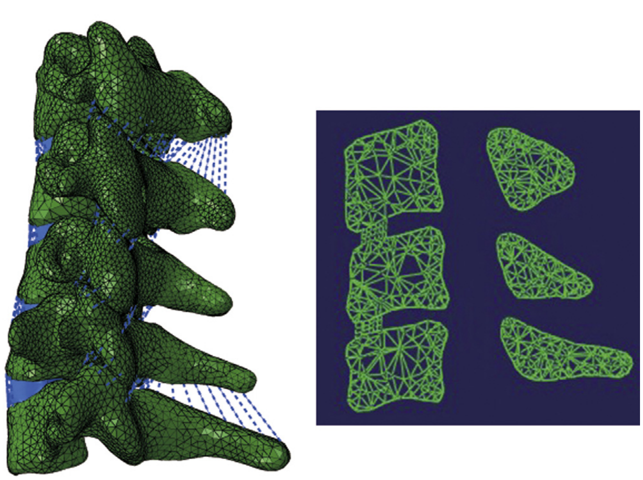

**Fig. 1.** The surgery-simulated FE models.

### 2.2. FE model surgery simulation

All models were based on a validated model of the aforementioned intact C3–7 model. It was then imported into the FE package ABAQUS to build the two-level TCI simulation model. The spinous ligamentum, the ligamentum flavum, posterior longitudinal ligaments, capsular ligaments and the middle and posterior part of discs were excised to simulate as closely as possible to the three-column injuries condition.

Three FEMs were built, each model simulated posterior cervical fixation after two-level TCI at C4–6. The internal fixation systems were implanted with three fixation techniques in the models after two-level TCI (C4–6). The size and location of screws and rods were confirmed in the intact C3–7 model using MIMICS to obtain the appropriate internal fixation systems. The surfaces of the screws and screw holes were simulated by imposing an ideal rough behaviour (infinite friction coefficient) to the tie-contact pair, thus preventing extraction. The internal fixation system material was assumed to be titanium and modelled as linear elastic isotropic with an elastic modulus of 145 GPa. The 3 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 3 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 1.8Nm in different directions (flexion–extension, lateral bending, and axial rotation) to the upper endplate of C3.

### 2.3. Biomechanical comparison

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

Stress analyses were carried out and the variability of von Mises stress and high stress-level 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 the variability of von Mises stress and high stress-level. The maximum variability and stress-level of von Mises were analysed as a measurement were analysed as a measurement of the potential for fracture due to different fixation techniques, based on the assumption that maximum variability