Construction of Finite Element Model for an Artificial Atlanto-Odontoid Joint Replacement and Analysis of Its Biomechanical Properties

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ABSTRACT

AIM: To investigate the stress distribution on artificial atlantoaxial-odontoid joint (AAOJ) components during flexion, extension, lateral bending and rotation of AAOJ model constructed with the finite element (FE) method.

MATERIAL and METHODS: Human cadaver specimens of normal AAOJ were CT scanned with 1 mm -thickness and transferred into Mimics software to reconstruct the three-dimensional models of AAOJ. These data were imported into Freeform software to place a AAOJ into a atlantoaxial model. With Ansys software, a geometric model of AAOJ was built. Perpendicular downward pressure of 40 N was applied to simulate gravity of a skull, then 1.53 N• m torque was exerted separately to simulate the range of motion of the model.

RESULTS: An FE model of atlantoaxial joint after AAOJ replacement was constructed with a total of 103 053 units and 26 324 nodes. In flexion, extension, right lateral bending and right rotation, the AAOJ displacement was 1.109 mm, 3.31 mm, 0.528 mm, and 9.678 mm, respectively, and the range of motion was 1.6°, 5.1°, 4.6° and 22°.

CONCLUSION: During all ROM, stress distribution of atlas-axis changed after AAOJ replacement indicating that AAOJ can offload stress. The stress distribution in the AAOJ can be successfully analyzed with the FE method.

KEYWORDS: Biomechanics, Finite element method, Atlanto-odontoid joint, Atlanto-axial joint, Arthroplasty

INTRODUCTION

The anterior high cervical spine fusion technique is often performed to relieve ventral compression and to improve the stability of the craniovertebral junction (CVJ) (8,10,17,24). Some of the indications include congenital atlanto-occipital fusion induced C1-C2 joint laxity and chronic dislocation; basilar invagination; congenital odontoid malformation caused C1-C2 dislocation; rheumatoid arthritis induced compression and C1-C2 dislocation; and brainstem and cord compression from CVJ tumors. These are typically treated by transoral decompression combined with posterior fusion (1,2,5).

However, intraoperative flipping of a patient may aggravate cervical spinal cord injury. To solve this problem, some (1,28) have adopted the transoropharyngeal atlantoaxial reduction plate (TARP); however, this fusion technique restricts normal physiological range of motion (ROM) of the upper cervical spine. Several prospective studies of artificial atlanto-odontoid joint (AAOJ) replacement have been reported (11-13,18) but finite element biomechanical analysis of AAOJ has not yet been reported to the authors knowledge. We reported a design of an AAOJ that can not only rebuild the stability of the atlanto-axial joint, but also reserve the rotation function.
between atlas and axis. This AAOJ is suitable for restoring physiological function of C1-2 after surgical decompression of CVJ (11). However, like other artificial joints, AAOJ also has problems of prosthesis loosening, wearing, etc. This paper constructed a FE model of atlantoaxial joint after AAOJ replacement, analyzed the stress distribution, determined the range of motion (ROM), and evaluated the biomechanical stability of the joint, so as to validate its efficacy and to provide a theoretical basis for AAOJ development and clinical application.

**MATERIAL and METHODS**

Main components and properties of AAOJ

The designed AAOJ is divided into atlas and axis components. The atlas component is composed of atlas rotating sleeve and lateral mass fixing plate, while the axis component includes axial rotation axis, axial base and lateral mass fixing plate. AAOJ is made of titanium alloy Ti-6Al-4V whose mechanical strength, corrosion resistance and anti-fatigue properties are superior to stainless steel or cobalt chromium alloy but with poor wear resistance.

**Atlanto-axial joint geometric model after AAOJ replacement**

A fresh cervical cadaveric specimen (male, 28 years old, height: 174 cm, weight: 70 kg) was selected, and the open mouth view of upper cervical spine and cervical lateral X-rays were obtained to exclude cervical disease. The atlas and axis were cleared of the ligaments, muscles and other soft tissues. Both Occiput to C2 and AAOJ were imaged with volumetric computed tomography (CT) scanning (Philips Brilliance 64 CT, Philips Medical Systems, Netherland) with 1-mm slice thickness and then stored in Digital Imaging and Communications in Medicine (DICOM) format to create 3D models of the atlas-axis complex and AAOJ. Both models were transferred in STL (Stereo Lithography) format to the Freeform Software (U.S. Phantom) and then, with reference to clinical practice, the anterior arch of the atlas, dens and part of the axis were removed to simulate anterior decompression. The artificial atlanto-axial joint model was installed into the decompressed atlanto-axial model. During the installation, the relation between the atlas/axis and screws were defined as union, which simulates fixation in a non-loosening state; the relation of the locking screws and plate was defined as being locked, and the artificial atlanto-axial joint was defined as contact. Using the pavement function of Freeform software, all components of the integrated artificial atlanto-axial joint model were imported to Ansys software in IGES format to build an artificial atlanto-axial joint geometric solid model (Figure 1A,B). The material properties of each component and the unit node information are demonstrated in Table I.

**Constructing mesh model, ligaments and joint contact**

Using the Ansys self-adaptive meshing design, the model was meshed with the solid185 tetrahedral element solid model

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**Table I: Material Properties Used in the Finite Element Model**

<table>
<thead>
<tr>
<th>Components</th>
<th>Young's Modulus (MPa)</th>
<th>Poisson's Ratio</th>
<th>Units</th>
<th>Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancellous bone</td>
<td>500</td>
<td>0.25</td>
<td>23187</td>
<td>5744</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>10000</td>
<td>0.25</td>
<td>17613</td>
<td>6012</td>
</tr>
<tr>
<td>Titanium alloy</td>
<td>11300</td>
<td>0.25</td>
<td>61547</td>
<td>14005</td>
</tr>
<tr>
<td>Articular ligaments</td>
<td>7</td>
<td>0.25</td>
<td>159</td>
<td>318</td>
</tr>
<tr>
<td>Interspinal ligaments</td>
<td>8</td>
<td></td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>Supraspinal ligaments</td>
<td>8</td>
<td></td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Cartilage</td>
<td>20</td>
<td>0.25</td>
<td>525</td>
<td>201</td>
</tr>
<tr>
<td>Contact elements</td>
<td></td>
<td></td>
<td>4388</td>
<td>2296</td>
</tr>
</tbody>
</table>

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**Figure 1:** The C1-2 constructed with AAOJ. **A)** Geometric model in anterior view, **B)** Geometric model in superior view, **C)** Mesh model in anterior view, **D)** Mesh model in superior view.
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with careful control of the mesh density. The related ligament structures in the model were added to the mesh model. The involved ligaments were as follows: atlanto-axial ligaments, zygapophyssal joint capsular ligament, interspinous ligament, supraspinous ligament. The solid model (atlanto-axial cortical bone, cancellous bone and AAOJ) was assumed as the solid185 tetrahedral element, and the ligament was defined as a low elastic two-node cord unit, which cannot transfer the stress. Each ligament was defined with different elastic modulus according to the neutral zone and elastic zone (22) to simulate the non-linear property of ligaments. Sliding contact definition with a friction coefficient of 0.1 was used for the facet joints between the bilateral atlanto-axial joints and AAOJ (4). The relationship between vertebrae and screws, screws and plate, and atlas plate and axis plate were defined as closely binding, non-loosening contact, and frictionless contact respectively. Figure 1 C,D show the final mesh model.

Border constraint, load setting, and validation of the three-dimensional FE model after AAOJ replacement

The displacement in each direction at all the nodes along the lower edge of C2 was set as 0 mm. A fixed handle above the atlas was designed to simulate the occipital bone. A 40 N perpendicular downward pressure on the fixed handle was applied to simulate the gravity of skull, then 1.53 N • m torque was exerted separately to simulate flexion, extension, lateral bending and rotation while observing the stress distribution of AAOJ components in each motion. Each unit had adequate stability under stress, and force deformation of materials and the micromotion between the screws and bone were not taken into account. With the lower plane of axis as a fixed point, the stress on the atlantoaxial joint in flexion, lateral bending, extension, rotation after AAOJ replacement were recorded. The analysis included two parts: 1. Contrast validation was performed with our previous biomechanical results (13) and if the angular displacements under the same load were similar, the model was regarded as valid; 2. Self-validation.

RESULTS

Atlanto-axial joint geometric model validation after AAOJ replacement

The three-dimensional model of the artificial atlanto-axial joint before and after assembly (Figure 2A-F), the geometric solid model of the atlanto-axial joint (Figure 1 A,B) after AAOJ replacement, and the FE model after ligament loading and meshing (Figure 1 C,D) showed an excellent bionic effect and geometric similarity. A total of 103,053 units and 26,324 nodes comprised this model. After loading on the FE model, the stress and displacement data for all nodes were obtained. The displacement of AAOJ was 1.109 mm, 3.31 mm, and 0.528 mm in flexion, extension, and right lateral bending respectively, which was relatively small. The displacement in right rotation was 9.678 mm. After further calculation and analysis, the ROM of the artificial atlanto-axial joint in each position was determined and these are illustrated in Table II (Figure 5). It was proved that the angular displacement of each functional unit of the model was inline with our previous in vitro biomechanical experimental results (13) (Table II), in which the

Table II: The Comparison Between the FE Model of C1-C2 and Biomechanical Experiment in Vitro (Hu et al. (13))

<table>
<thead>
<tr>
<th>Item</th>
<th>Hu et al (13)</th>
<th>FE model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1~2</td>
<td>C1~2</td>
</tr>
<tr>
<td>Bending moment (Nm)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Flexion (°)</td>
<td>5.5±0.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Extension (°)</td>
<td>4.8±0.9</td>
<td>5.1</td>
</tr>
<tr>
<td>Lateral bending (°)</td>
<td>1.4±0.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Rotation (°)</td>
<td>32.7±3.8</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 2: The 3-D model. A) Atlas part of AAOJ, B) Axis part of AAOJ, C) Screws, D) C1 without anterior arch, E) Dredged part of vertebral bone at C2, F) The C1-2 constructed with AAOJ.
values in rotation and lateral bending were unilateral. The FE model of the atlanto-axial joint after AAOJ replacement was based on CT scan data of human atlanto-axial specimens and their corresponding artificial joint, and refined by Freeform software and thus showing high shape accuracy.

**FE analysis on biomechanical properties of the atlanto-axial joint bone structure after AAOJ replacement**

In anterior flexion, besides the screw holes, the stress was mainly concentrated at the junction of atlas lateral mass and atlas posterior arch, which were also the affected area of typical Jefferson fracture, with the maximum stress value of 0.138 × 10^9 N / m². The stress at axis was mainly concentrated at screw holes, the contact surface of the plate and axis, and axial vertebral arch, with the maximum stress value of 0.201 × 10^8 N / m². In lateral bending, the stress of atlas focused on the screw hole of right lateral mass, with a maximum stress value of 0.124 × 10^8 N / m²; besides axial vertebral arch, the contact site of axis and right side of plate bore the maximum stress concentration, with the maximum stress value of 0.178 × 10^8 N / m² (Figure 3D,E). In right lateral bending, the stress at axis plate was 0.396 × 10^9 N / m², which was mainly focused on screw holes and locking hole. The maximum stress value at plate was 0.124 × 10^9 N / m² which was mainly focused on screw holes and locking hole.

In right rotation, the stress distribution of components is illustrated in Figure 3L. The maximum stress value of the atlas plate was 0.176 × 10^9 N / m² and the maximum stress concentration was at screw holes and locking holes. The maximum stress value at axis plate was 0.124 × 10^9 N / m², but not at the axis screw root, as shown in Figure 3C,F. The maximum stress value was 0.345 × 10^9 N / m² in the anterior flexion, which was mainly focused on screw holes and above the left lateral wall of artificial dens.

**FE analysis on three-dimensional stability of the atlanto-axial joint after AAOJ replacement**

Three-dimensional displacement of the atlanto-axial joint in four working conditions under different loads is demonstrated in Figure 4A-H. The symmetrical data between left and right side showed no significant difference (p> 0.05). The displacement of AAOJ was 1.109 mm, 3.31 mm, 0.528 mm in flexion, extension, and right lateral bending respectively, which were relatively small. The displacement in right rotation was 9.678 mm. According to the overall displacement and the configuration of the model, using trigonometric function, ROM was 1.6°, 5.1°, 4.6° and 22° in flexion, extension, right lateral bending and right rotation respectively.

**DISCUSSION**

The first problem is to find a feasible model that is the basis of subsequent meshing and FE analysis. It determines the accuracy and speed of the FE calculation. We simplified the structure of the model based on the smallest functional segment, making it more convenient for the following biomechanical analysis. The established model shows good morphological similarity to the atlanto-axial joint after AAOJ replacement. Compared with the biomechanical analysis of specimens, FE analysis has some advantages. It can simulate the complex geometric structure of cervical vertebrae in computer based on the scan data (6,16,20,26), and the experiments can be repeated dozens of times in computers cutting the cost (7,21,29). The biomechanical experiments on specimens can only measure the mechanical properties of bone surface, while FE analysis show high efficiency on mechanical analysis of the internal structure of the cervical vertebrae. In addition, the traditional biomechanical analysis cannot well reflect the influence of the surrounding tissues on cervical spine but in FE analysis we can set some supplemental conditions, allowing it to achieve a bionic effect to a certain degree. Therefore the biomechanical results of FE model analysis can validate (15) a more comprehensive understanding of biomechanical changes in cervical joint activities. So far, there have been no reports on the FE analysis of AAOJ in literature domestically or abroad.

Under an axial static compressive load, stress on C1 cadaveric specimen and C1 Finite Element model is mainly
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Our study demonstrated that after the AAOJ replacement, stress increased on the screw holes and the junction of lateral mass - posterior arch. The stress concentration at the junction of atlas lateral mass - posterior arch is still a potential risk factor of fractures, such as a Jefferson fracture. The mechanism of a Jefferson fracture is related to the junction of lateral mass of atlas and anterior/posterior arch is the vulnerable spot, coupled with axial stress acts on the atlas. Atlas pedicle screw fixation may be performed to increase the load capacity; however, taking the risk of vertebral artery injury by screws into account, atlas was fixed with single cortical, hollow, lateral mass screws with lateral holes. As long as single cortical lateral mass screws of atlas do not penetrate the posterior surface of lateral mass, the fixation can be regarded as safe from the anatomical point of view. Atlas screw hole stress (take posterior extension for example) is mainly concentrated in the...

Figure 3: Stress distribution. A) C1 flexion in superior and inferior, B) C2 flexion in anterior and superior, C) AAOJ and screws in flexion, D) C1 extension, E) C2 extension, F) AAOJ and screws in extension, G) C1 right bending, H) C2 right bending, I) AAOJ in right bending J) C1 right rotation in superior and inferior, K) C2 right rotation, L) AAOJ in right rotation.

Figure 4: The displacement and its numerical value. The model combined by the white dotted line was at the original position, and the model combined by the blue was moving from the original position. A,B) Flexion, C,D) Extension, E,F) Right bending, G,H) Right rotation.

Figure 5: Comparisons of the ROM under pure moment of 1.5 Nm between biomechanical experiment in vitro studies (Hu et al. (13)) and the present study.
The atlas-axial joint is a rotary joint along central axis with relatively large mobility. In normal rotation of neck, the atlanto-odontoid joint revolves with a constantly changing center of rotation or multiple rotation centers, rather than along a fixed axis. This study showed that after AAOJ replacement, the ROM of atlanto-axial joint was 1.6°, 5.1°, 4.6° and 22° in flexion, extension, right lateral bending and right rotation, respectively. This is consistent with previous studies on cadaver, indicating that this modified AAOJ can not only stabilize the vertebrae but also retain the mobility. We analyzed the following conducive aspects: 1) Atlas rotating sleeve and axial rotation axis work closely together to rebuild the button-lock relationship of atlas odontoid joint, so that the axis of rotation is relocated to the atlas odontoid joints, thereby restricting flexion, extension and axial lateral bending. 2) Excessive sliding is restricted because the angular movement of the normal atlanto-axial joint should couple with sliding, and the limited sliding ROM actually confines the ROM of angular movement. ROM of normal atlas-axis in flexion-extension and lateral bending is limited and mainly accounted by the atlanto-occipital joint and cervical intervertebral joints below the axis (including the vertebral disc and the lateral mass joints) (27). After AAOJ replacement, the reduction of ROM of atlanto-axial joint in flexion, extension and lateral bending has little impact on the movement of head and neck (19). Lu et al. (19) designed a restriction structure in artificial joint to prevent over-rotation. The originality of our design lies in the locking holes, AAOJ can achieve the rotation of 22° under 1.53 N·m torque, which is not beyond the normal ROM.

■ CONCLUSION

During all ROM, stress distribution of atlas-axis changed after AAOJ replacement indicating AAOJ can offload stress. The stress distribution in the AAOJ can be successfully analyzed with the FE method.

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