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Biomechanical Comparison of Different Vertebral Plate Designs for Anterior Cervical Discectomy and Fusion Using Nonlinear C3-T2 Multi-Level Spinal Models

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ABSTRACT

Anterior cervical discectomy and fusion is a common surgical procedure to treat spinal cord or nerve root compression. However, the clinical complications of anterior cervical plate system still occur. Past researchers have tried to improve the clinical complications by changing the screw thread or the screw orientation. The conclusion on the screw thread is quite consistent. Unfortunately, the studies on the screw orientation reached inconsistent conclusions. In addition, the effects of the screw orientation which are determined before the surgery are mainly based on the surgeon's experiences without biomechanical evidences. Therefore, the purpose of this study was to investigate the clinical performances of anterior cervical plate for the anterior cervical discectomy and fusion. Three-dimensional nonlinear finite element model, which consisted of C3-T2 multi-level spine and anterior cervical plate system, was developed to investigate the fixation stability by using ANSYS Workbench 14.5. Six design variables of the anterior cervical plate system were considered in this study. Both flexion moment and body weight were considered and the total strain energy was calculated to evaluate the fixation stability of the anterior cervical plate systems. To discover the key control variables, the parametric study of anterior cervical plate was determined with the use of Taguchi robust design methods. The results of this study showed that changing the screw orientation in a superior-inferior direction could significantly improve the fixation stability. In addition, the insertion angle of locking screw inserted in C5 segment in Superior-Inferior direction (C5SI) and the insertion angle of locking screw inserted in C7 segment in Superior-Inferior direction (C7SI) were the key control variables of the anterior cervical plate systems. This study could directly provide the surgical suggestion and biomechanical rationale to orthopedic surgeons.

Keywords: anterior cervical discectomy and fusion, finite element analyses, cervical plate, fixation stability.

1. INTRODUCTION

Anterior cervical discectomy and fusion was developed by Robinson et al. [9]. This surgical technique is a highly successful procedure to treat neural compression by disc material or osteophytes [1]. In clinical application, a cervical disc with degenerative disease is incised and removed. Then, an intervertebral cage or a small block of bone graft is placed between the vertebrae. Finally, a metal cervical plate is held in front of cervical vertebrae by metal screws [7]. However, clinical complications of anterior cervical plate system still occur, such as weak fixation stability or screw loosening. In the past, researchers have tried to improve the clinical complications by changing the screw thread or the screw orientation. The conclusion on the screw thread is quite consistent [8]. Unfortunately, past studies on the screw orientation reached inconsistent conclusions [2,11]. To achieve the required fixation stability, Rodríguez-Olaverri et al developed a biomechanical study in calf spines to determine the effect of end screw angulation on instrumentation construct stability after cyclic, lateral bending [10]. However, the insertion angles of locking screws used in anterior cervical plate systems were mainly determined according to the researchers' or surgeons' experience. To the best of our knowledge, there has been no research discovering the key control variables of the anterior cervical plate systems by using finite element analyses and Taguchi robust design methods. In the present study,

Computer-Aided Design & Applications, 12(2), 2015, 226–231, http://dx.doi.org/10.1080/16864360.2014.962435

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three-dimensional nonlinear finite element models of C3-T2 multi-level spine with an anterior cervical plate system were created to analyze the fixation stability of the anterior cervical plate systems. Then, Taguchi robust design methods were used to find the key control variables of the anterior cervical plate systems. Finally, the optimum combination of the anterior cervical plate design was obtained and compared to the other plate designs. The purpose of this research was to apply the finite element analyses and Taguchi robust design methods to discover the key control variables for anterior cervical plate systems to achieve required fixation stability.

2. MATERIALS AND METHODS

2.1. Designs of Anterior Cervical Plate Systems

Anterior cervical plate systems used in this study consisted of one bone plate and six locking screws. According to commercially available products of anterior cervical plate systems, the plate systems with varied insertion angles of locking screws were found. To analyze anterior cervical plates with different insertion angles of locking screws, six design variables of the anterior cervical plate systems were considered including the insertion angle of locking screw inserted in C5 segment in Superior-Inferior direction (C5SI), the insertion angle of locking screw inserted in C5 segment in Medial-Lateral direction (C5ML), the insertion angle of locking screw inserted in C6 segment in Superior-Inferior direction (C6SI), the insertion angle of locking screw inserted in C6 segment in Medial-Lateral direction (C6ML), the insertion angle of locking screw inserted in C7 segment in Superior-Inferior direction (C7SI), and the insertion angle of locking screw inserted in C7 segment in Medial-Lateral direction (C7ML) (Fig. 1). Design ranges for each variable were defined as follows: 5 ∼ 15º for the C5SI, -5 ∼ 10º for the C5ML, -5 ∼ 15º for the C6SI, -5 ∼ 10º for the C6ML, -10 ∼ 15º for the C7SI, and -5 ∼ 10º for the C7ML. The design ranges of each variable were determined according to design range of the commercial products and anatomic geometry of the C3-T2 spine model. To fairly compare the designs to each other, all of the locking screws have the same screw length and geometry.

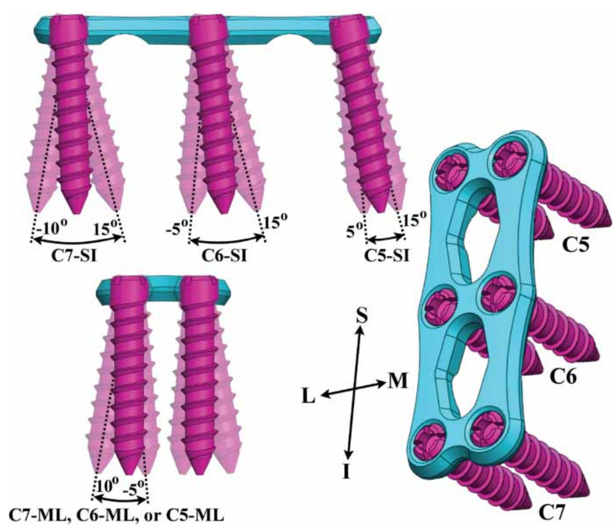

Fig. 1: Design variables of anterior cervical plate system.

2.2. Finite Element Models of C3-T2 Multi-level Spine

Three-dimensional solid models of C3-T2 multi-level spine were constructed from computed tomogaphy scans in a healthy volunteer. The C3-T2 spine model consisted of vertebral bodies, posterior elements, intervertebral discs, and ligaments. The vertebral bodies were composed of both cortical bone and cancellous bone. The intervertebral discs were composed of annulus fibrosus and nucleus pulposus. For the ligaments, there are five spinal ligaments were considered in the numerical model including anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, facet capsulary ligament, and interspinous ligament. All five ligaments of the C3-T2 spine model were represented using tension-only spring elements. For developing the orthopaedic implant, the anterior cervical plate system was first created using SolidWorks 2013 (SolidWorks Corporation, Concord, MA, USA). This plate system consisted of one cervical plate and six locking screws. Then, the anterior cervical plate was inserted at the front of C5-C7 vertebrae. Finally, all of the locking screws were inserted into the vertebrae to fix the anterior cervical plate (Fig. 2a). The solid models of the C3-T2 spine with the anterior cervical plate system were transformed into ANSYS Workbench R14.5 (ANSYS, Inc., Canonsburg, PA, USA) with the use of the Parasolid

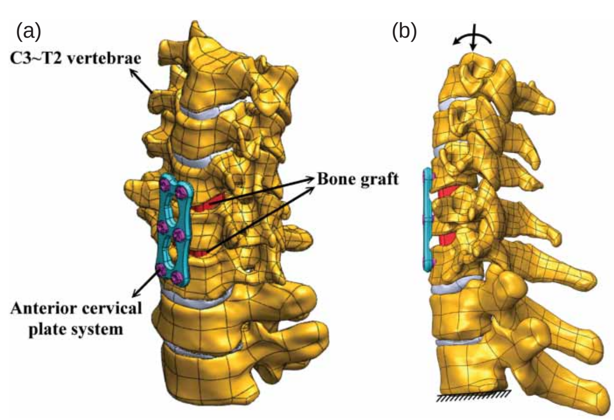

Fig. 2: The numerical models: (a) C3-T2 spine with anterior cervical plate system, (b) loading and boundary conditions of the finite element models.

format. Both the C3-T2 spine and the anterior cervical plate system were free-meshed using 10-node tetrahedral elements. To ensure the numerical accuracy, a convergent analysis was conducted by adjusting the element size. For the material properties of the numerical models, the elastic modulus and the Poisson's ratio of the anterior cervical plate systems were 114 GPa and 0.3, respectively. The C3-T2 spine models were assumed to be homogenous and their material properties were assigned based on the past studies [6]. For the interface condition, the interfaces between the anterior cervical plate system and the C3-T2 spine were assumed to be contact and surface-to-surface contact elements were used in this study. In the loading condition, a flexion moment of 1.5 N-m and a body weight of 73.6 N were applied on the top surfaces of the C3 vertebra. The boundary conditions were constrained on the bottom surfaces of T2 vertebra (2b). In the postprocessing, the total strain energy of the anterior cervical plate system was calculated to evaluate the fixation stability of the cervical plate.

2.3. Parametric Analyses Using Taguchi Robust Design Methods

To investigate key control variables of anterior cervical plate systems, Taguchi robust design method was applied in this study. The Taguchi method can be used for evaluating improvements in materials, products, and equipment [4]. It used a fractional factorial design to replace a full factorial design. This can significantly decrease the number of experimental runs. In this study, a lower total strain energy obtained from the finite element model represented better fixation stability of the anterior cervical plate system. Thus, the total strain energy was transformed into a the-smaller-the-better signal-to-noise ratio. Six design variables for the anterior cervical plate system were selected including C5SI, C5ML, C6SI, C6ML, C7SI, and C7ML. Discrete values for each variable were also defined (Tab. 1). The *L25* orthogonal array, which could control six variables at five levels, was used. According to the arrangements of the *L25* orthogonal array, the matrix experiments were conducted (Tab. 2). The optimum variable-level combination of the anterior cervical plate system was determined

Level	C5SI	C5ML	C6SI	C6ML	C7SI	C7ML
1	5	− 5	− 5	− 5	− 10	− 5
2	7.5	− 1.25	0	− 1.25	− 3.75	− 1.25
3	10	2.5	5	2.5	2.5	2.5
4	12.5	6.25	10	6.25	8.75	6.25
5	15	10	15	10	15	10

Tab. 1: Discrete values of design variables.

Run	C5SI	C5ML	C6SI	C6ML	C7SI	C7ML
1	5	− 5	− 5	− 5	− 10	− 5
2	5	− 1.25	0	− 1.25	− 3.75	− 1.25
3	5	2.5	5	2.5	2.5	2.5
4	5	6.25	10	6.25	8.75	6.25
5	5	10	15	10	15	10
6	7.5	− 5	0	2.5	8.75	10
7	7.5	− 1.25	5	6.25	15	− 5
8	7.5	2.5	10	10	− 10	− 1.25
9	7.5	6.25	15	− 5	− 3.75	2.5
10	7.5	10	− 5	− 1.25	2.5	6.25
11	10	− 5	5	10	− 3.75	6.25
12	10	− 1.25	10	− 5	2.5	10
13	10	2.5	15	− 1.25	8.75	− 5
14	10	6.25	− 5	2.5	15	− 1.25
15	10	10	0	6.25	− 10	2.5
16	12.5	− 5	10	− 1.25	15	2.5
17	12.5	− 1.25	15	2.5	− 10	6.25
18	12.5	2.5	− 5	6.25	− 3.75	10
19	12.5	6.25	0	10	2.5	− 5
20	12.5	10	5	− 5	8.75	− 1.25
21	15	− 5	15	6.25	2.5	− 1.25
22	15	− 1.25	− 5	10	8.75	2.5
23	15	2.5	0	− 5	15	6.25
24	15	6.25	5	− 1.25	− 10	10
25	15	10	10	2.5	− 3.75	− 5

Tab. 2: *L25* orthogonal array.

based on the factor levels corresponding to the maximum S/N ratio. The optimum combination of the anterior cervical plate system was compared with other designs to demonstrate its biomechanical performance. The significance of the design variable of the anterior cervical plate system was studied with the use of the analysis of variance (ANOVA) statistical method.

3. RESULTS

3.1. Finite Element Analyses

Twenty-five finite element models were created in accordance with the design variable combinations specified in the *L25* orthogonal array table. All of the solid models were adequately meshed and successfully solved. The numerical models consisted of 728,000 nodes and 447,000 elements on average after mesh generation. In the convergence analysis, the convergence of the finite element models on the total strain energy was achieved by decreasing the element size, and the percentage error caused by the element size was less than 10% (Fig. 3). For the results of displacement distribution, the maximum displacement for all finite element models occurred at the C3 vertebra (Fig. 4a). In addition, the strain energy distribution of the anterior cervical plate system was obtained. The cervical plate of the anterior cervical plate system revealed higher strain energy (Fig. 4b).

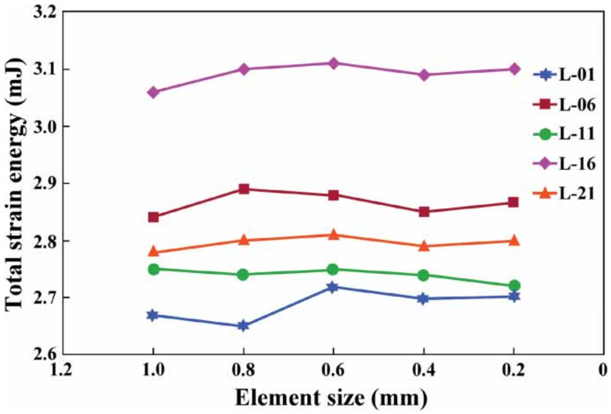

Fig. 3: The results of the convergence analyses.

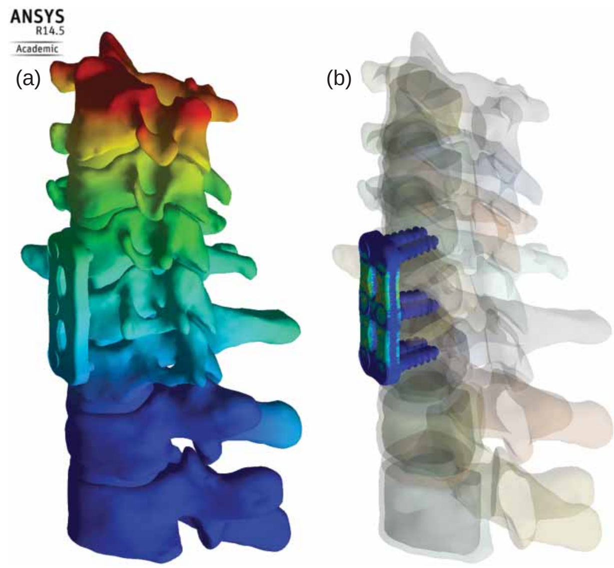

Fig. 4: The results of finite element models: (a) displacement, (b) strain energy.

Variables	Degrees of freedom	Sum of squares	Mean square	Contribution
C5SI	4	0.526	0.131	7.8%
C5ML	4	0.121	0.030	1.8%
C6SI	4	0.302	0.075	4.5%
C6ML	4	0.259	0.065	3.9%
C7SI	4	5.228	1.307	77.9%
C7ML	4	0.275	0.069	4.1%
Total	24	30.081		100%

Tab. 3: ANOVA table for total strain energy.

3.2. Parametric Analyses

According to the results of the *L25* orthogonal array, the total strain energy was transformed into a the-smaller-the-better signal-to-noise ratio. To understand the optimum combination of the anterior cervical plate systems, the S/N ratio plots of the total strain energy at each level of every control variable were obtained (Fig. 5). The optimum factor level combination of the anterior cervical plate systems was C5SI1C5ML2C6SI3C6ML4C7SI3C7ML3. This optimum combination correspond to C5SI of 5^o, C5ML of -1.25^o, C6SI of 5^o, C6ML of 6.25^o, C7SI of 2.5^o, and C7ML of 2.5^o. The optimum combination of the anterior cervical plate systems had the lowest total strain energy of 2.6 mJ compared with the results of twenty-five designs arranged by the *L25* orthogonal array. To discover the key control variables, an ANOVA table was developed according to the results of the *L25* orthogonal array. The results showed that the C7SI had the highest contribution (77.9%) to the fixation stability of the anterior cervical plate systems. Following this, the descending order of contribution was the C5SI (7.8%), the C6SI (4.5%), the C7ML (4.1%), the C6ML (3.9%), and the C5ML (1.8%) (Tab. 3). Thus, both the C7SI and the

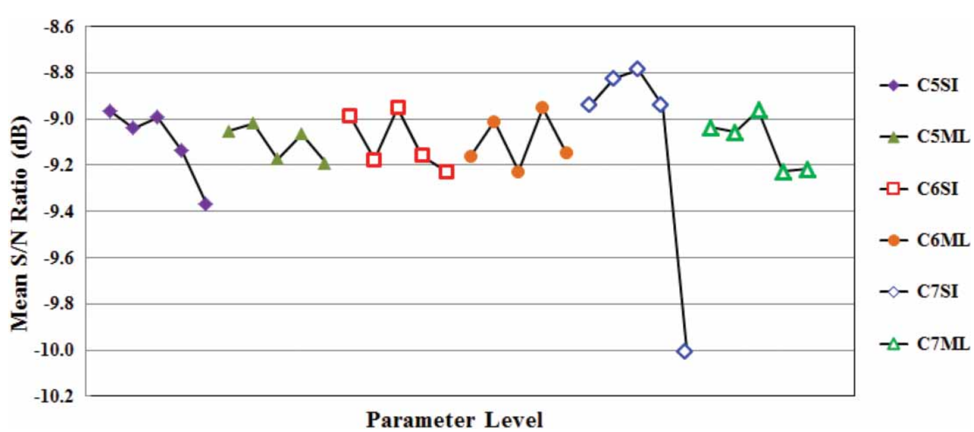

Fig. 5: The S/N ratio plots of total strain energy.

Computer-Aided Design & Applications, 12(2), 2015, 226–231, http://dx.doi.org/10.1080/16864360.2014.962435

C5SI were the key control variables for the anterior cervical plate systems.

4. DISCUSSIONS

The nonlinear finite element models of C3-T2 multi-level spine with anterior cervical plate systems could successfully and effectively investigate their fixation stability. These numerical models considered complex geometries of C3-T2 multi-level spine and real implant designs simultaneously. Actually, it is a rare for considering both complex bone geometries and real implant designs in past researches. Hussain et al. [6] developed a three-dimensional finite element model of C3-T1 motion segment to analyze three different multilevel reconstruction techniques. However, the geometry of locking screws used in the anterior titanium plate was assumed to be axial symmetry. Faizan et al. [3] created three-dimensional, ligamentous, finite element model of C3-C7 cervical spine segments to compare the adjacent level biomechanics of different surgical techniques. Although screw threads of locking screws were considered in their study, only five motion segments were constructed. This might impede to investigate adjacent level effects of their numerical models because the loading point and fixed area are too close to the adjacent level. Thus, the current study had adequately constructed the nonlinear finite element models of C3-T2 multi-level spine with anterior cervical plate systems. This C3-T2 spine model could also be applied to study other biomechanical problems. Due to complex geometries of bones and implants, a numerical model with complex geometries might easily fall into a divergent solution. In the present study, the geometries of both the C3-T2 multi-level spine and anterior cervical plate systems were complicated. Thus, a convergence analysis should be conducted carefully in this study. The variation caused by the mesh quality was less than 10% and all numerical models were converged properly.

The optimum combination of the anterior cervical plate systems could be determined with the use of the results of the S/N ratio plot. The optimum design provided by the Taguchi robust design methods had the lowest total strain energy compared with the results of twenty-five designs. Lower total strain energy represents that anterior cervical plate systems had better fixation stability. This meant that the Taguchi robust design method could effectively discover the optimum combination of the anterior cervical plate systems. Although the optimum design provided by the Taguchi method was superior to the other designs, the optimum design might yield a locally optimal solution [5]. The reason was that the Taguchi method used the combinations of the design variables with discrete levels. Thus, not all of anterior cervical plate designs were considered and analyzed. To discover a global optimal design, advanced engineering algorithms should be applied in the future work.

The results of ANOVA showed that the contribution of the C5SI was higher than that of the C5ML. Similarly, the contribution of the C6SI and the C7SI were higher than that of the C6ML and the C7ML, respectively. Thus, the insertion angle of locking screw in Superior-Inferior direction had the higher contribution than that of locking screw in Medial-Lateral direction. This meant that changing the insertion angle of locking screw in Superior-Inferior direction could obviously improve the fixation stability of the anterior cervical plate systems. The ANOVA table also showed that the contributions of the C7SI and the C5SI were 77.9% and 7.8%, respectively. Thus, both the C7SI and the C5SI were the key control variables in this study, and changing both of them could significantly improve the fixation stability of the anterior cervical plate systems.

The potential limitations of the present study are mentioned below. First, the material properties of the C3-T2 multi-level spine were assumed to be isotropic, linear elastic, and homogeneous. This might impede the applicability of the numerical models. Second, the loading condition applied to the finite element models simulated a flexion condition. However, the optimum combination for the anterior cervical plate system might be changed if another loading condition was applied. Third, Taguchi robust design methods only provide the discrete value of each design variable and rough out the optimum design of the anterior cervical plate system. The global optimum design of anterior cervical plate system might not be discovered. Fourth, only the fixation stability of the anterior cervical plate systems was considered in this study. However, the optimum combination might be changed if other biomechanical performances were considered, such as interface loosening.

5. CONCLUSIONS

The fixation stability of the C3-T2 multi-level spine with the anterior cervical plate system was analyzed using three-dimensional nonlinear finite element simulations and Taguchi robust design methods. The C7SI and the C5SI were the key control variables, and changing the screw orientation in a superior-inferior direction could significantly improve the fixation stability. The outcomes of the current study could assist orthopedic surgeons in understanding the biomechanical performance of anterior cervical plate systems. In addition, the nonlinear finite element models of the C3-T2 multi-level spine could also be applied to study other biomechanical problems.

ACKNOWLEDGEMENTS

This work was sponsored by the Mackay Memorial Hospital - National Taiwan University of Science and Technology Joint Research Program under the Grant No: MMH-NTUST-102–02.

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