

# Biomechanical Assessment of Cervical Spine with Artificial Disc during Axial Rotation, Flexion and Extension

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## ABSTRACT

**Background:** The cervical spine is the most vulnerable part of the vertebral column and the rotational movements are the most dangerous movements which may cause damages to cervical spine. A good treatment option for the cervical disc disease is the replacement of a damaged disc with an artificial disc that has shown satisfactory clinical results.

**Methods:** The C4 to C6 vertebrae of a normal subject and a person with an artificial disc between the vertebrae C5 and C6 were 3d modelled and then analyzed using FEM. The results of stress and deformation in both subjects were calculated and compared for three rotational head movements: axial rotation, flexion and extension. A distributed load of 73.6 N was used to simulate the head weight and a moment of 1.8 N.m was used to create all three rotational movements.

**Results:** The maximum Von Mises stress in the normal subject during the axial rotation was respectively 2.2 and 1.8 times greater than the maximum stress during flexion and extension. These numbers were 2.6 and 2.3 in the subject with artificial disc. Following the artificial disc replacement, the cervical spine strength against the extension improved about 2.7%, however, the strength in axial rotation and flexion decreased 6.9% and 24.3%, respectively. The maximum values of deformation in the normal subject during flexion, extension and axial rotation were 2.8, 2.8 and 2 times of the values in the subject with artificial disc during the similar movements.

**Conclusion:** The flexion and extension involve risks of hurting the cervical spine, however, the axial rotation is much more dangerous regarding the damages it may cause especially to the C5/6 intervertebral disc. Numerically, there is a much greater possibility of cervical spine injury during axial rotation.

**Keywords:** Flexion; Extension; Axial rotation; Cervical spine; Artificial disc; Head movement

ICNSJ 2016; 3 (2) :113-119

www.journals.sbmu.ac.ir/neuroscience

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**Received:** May 12, 2016

**Accepted:** Jun 10, 2016

## INTRODUCTION

The cervical region is the most vulnerable part of the vertebral column to injuries <sup>1</sup> and its investigation is hence of great importance. The cervical spine consists

of 7 vertebral bodies and also intervertebral discs which generally have a load bearing and motion transfer function <sup>2</sup>. One of the most developed and functional branches of neuroscience deals with artificial disc

prostheses of cervical region<sup>3</sup>. Disc replacement is known as a good treatment option for disc disease in the cervical region and has satisfactory clinical results comparing to the anterior cervical discectomy and fusion<sup>4</sup>. Studies in the area of cervical artificial disc replacement can be divided into two groups: the clinical studies and the numerical analysis studies.

The first group includes studies which have used experimental methods to investigate the clinical features in subjects with disc replacement. Hou et al. followed 149 subjects with symptomatic single or two-level cervical degenerative diseases received the Discover cervical artificial disc replacement for a period of time before the surgery up to 6 months after that. Using computed tomography, MRI and static and dynamic cervical spine radiographs, they could evaluate the Neck Disability Index and visual analog scale pain Score in these subjects<sup>5</sup>. Yeh et al. examined 32 individuals who underwent Bryan cervical disc replacement. Using the experimental data and methods, they measured and compared the Japanese Orthopedics Association score, the visual analog scale and the Odom's scale in these subjects<sup>6</sup>. Skeppholm et al. used experimental indices to evaluate the efficacy of disc replacement surgery in promoting the stability of artificial discs in flexion and extension in 28 individuals who underwent artificial disc replacement<sup>7</sup>.

Some studies in this group used the clinical methods to investigate the material and mechanical properties of artificial discs. Dahl et al. put three artificial disc nuclei made of three different materials – polyurethane (PU), polyethylene (PE) and titanium-alloy (Ti) – in a container with controlled temperature and humidity and compared the mechanical stiffness, quasi-static stiffness, energy absorption and energy dissipation in these samples<sup>8</sup>. Inserting an artificial disc in 9 human cadavers and exerting the muscular force, Colle et al. compared the surface strain near the left and right C5–C6 facet joints under flexion, extension, lateral bending and axial rotation statistically<sup>9</sup>. Some other researches in this group studied the efficacy of surgical operations in cervical region<sup>10,11</sup>.

In the second group of studies in the scientific literature, the finite element method (FEM) has been applied for numerical analysis of artificial disc in the cervical spine. Galbusera et al. created a finite element model of C4-C7 with an artificial disc between C5 and C6 and evaluated the physiological motion of artificial disc under flexion and extension<sup>12</sup>. Park et al. presented a 3d FE model of the vertebrae C2 to C7. They analyzed the model with two different artificial discs – Fixed-core and Mobile-

core – and compared the efficacy of each disc<sup>13</sup>. Lin et al. built a 3d FE model of the cervical vertebrae C3 to C7 of a normal subject and a subject with an artificial disc between C5 and C6 and compared the effects of the range of motion, the instantaneous center of rotation and the facet joint force in these subjects<sup>14</sup>. Yu et al. used FEM analysis for biomechanical investigation of a new type of artificial disc between the vertebrae C5 and C6 based on the physiological curvature of the end plate. They also compared the maximum von Mises stress and the range of segmental motion between this new artificial disc and the common artificial discs<sup>15</sup>. Some other researches have been performed with the aim of simulation and biomechanical analysis of cervical artificial disc<sup>16,17</sup>. Gholampour et al. reported in a recent study that the most important cause of cervical spine injuries is the rotational head movements<sup>18</sup>. Therefore in the present study, the rotational head movements were simulated using FEM in a normal subject and a subject with cervical artificial disc and the biomechanical features and ultimately the artificial disc strength against rotational head movements were compared between these subjects.

## MATERIALS AND METHODS

A 3d FE model of cervical vertebrae C4 to C6 was produced using Solid works premium 2016 X64 edition software in the present study. The assembled models of vertebrae and cervical discs were transferred then to Abaqus/CAE 2016 software for meshing and FEM analysis. As the cervical spine is weaker against the rotational loading than normal loading<sup>18</sup>, three common rotational head movements – axial rotation, flexion and extension – were simulated in this study for a normal subject and a subject with cervical artificial disc and the biomechanical parameters of both subjects were compared with each other. Most of the cervical spine injuries lead to replacement of the C5/C6 disc<sup>14,19</sup>, therefore a subject who had an artificial disc between the vertebrae C5 and C6 was recruited for the present study.

It is noteworthy that the best type of artificial disc according to previous study is the Bryan artificial disc made of titanium<sup>6</sup> and the subject of this study had also

**Table 1.** Mechanical properties of vertebrae, discs and artificial disc in the finite element models.

Component	Module of elasticity (MPa)	Poison ratio
Vertebrae	10000	0.3
Disc	4.2	0.3
Bryan artificial disc	110000	0.3

an artificial disc of this type. Vertebrae and discs were considered as linearly elastic materials. Table 1 presents the mechanical details regarding the materials of discs, vertebrae and artificial disc<sup>20,21</sup>. In the present study similar to the study by Teo et al., the vertebrae were considered to be homogenous and completely cortical and the nucleus pulposus part was ignored in the disc model<sup>22</sup>.

### Boundary conditions and loadings

The end plate of C6 was constrained in all directions<sup>23</sup> and the disc-vertebra interface was considered as a hard contact with a friction coefficient of 0.2<sup>24</sup>. A distributed normal load of 73.6 N was exerted on the upper surface of C4 to simulate the head weight during the rotational movements of head and moment of 1.8 N.m was exerted over the top surface of C4 vertebra to simulate the axial rotation, flexion and extension. The axes of moments for axial rotation, flexion and extension were along the vertebral column, clavicle bone and clavicle bone, respectively<sup>25,26</sup>.

### Grid independence study

The convergence conditions of responses and the independence of results from meshing conditions are investigated in this section. The elements used for meshing healthy discs, artificial disc and vertebrae in subjects were hexdominant, tetrahedral and hexdominant, respectively. The results were calculated at a time step of 0.01. The maximum error between medium and fine meshes was 0.8% according to figure 1. Ultimately, the results of the medium mesh as the original mesh were used. The number of elements used for cervical discs and vertebrae in the original mesh was 22800 and 79920, respectively. So the independence of results from the size and number of elements and the convergence of results were ensured in a favorable manner.

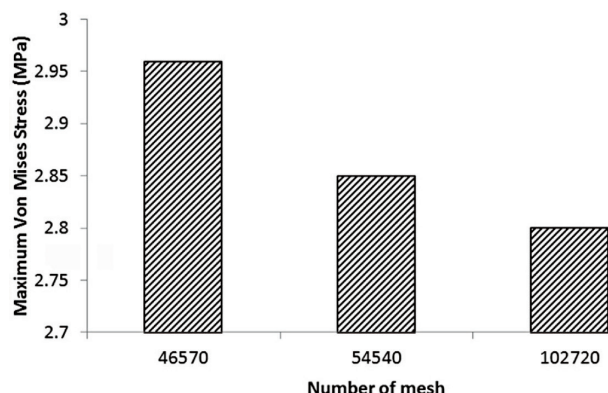


Figure 1. Panel shows the mesh independence study of subject with artificial disc.

## RESULTS

The maximum stress and the maximum deformation were considered as biomechanical indices for analysis of the cervical spine in this research. These two parameters were calculated and compared in the normal subject and the one with artificial disc for three types of head rotation: axial rotation, flexion and extension. The von Mises stress was used as criterion for expressing the maximum stress in discs and vertebrae.

### Axial rotation of neck

The results of maximum stress and deformation in standing position when the subject rotates his head around the spine axis were calculated for the normal subject and the subject with artificial disc and were compared with each other. In addition to the moment, the head weight should also be considered in calculations during neck rotation. As the head weight is distributed over the cervical spine, a distributed compressive load of 73.6 N was exerted in the simulation as the head weight and the axial rotation was simulated with a moment of 1.8 N.m about the spine axis.

### Stress evaluation

According to figure 2, the maximum stress in the normal subject occurs in C5/C6 intervertebral disc while in the subject with artificial disc, it occurs in the first vertebra above the artificial disc, i.e. C5. The values of maximum stress in the subject with artificial disc and the normal subject are 6.64 and 5.34 MPa, respectively. The maximum stress in the subject with artificial disc is 24.3% greater than that in the normal subject indicating that the artificial disc has caused the maximum stress in cervical spine to increase.

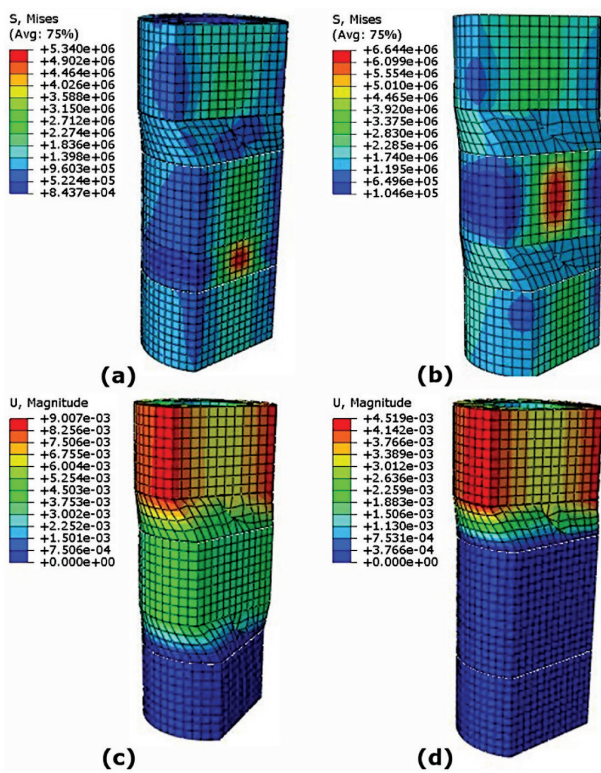
### Deformation evaluation

According to figure 2, the maximum deformation occurs in C4 in both subjects, however its value is 9mm in the normal subject and 4.5 mm in the subject with artificial disc. In the normal subject, there is even a significant amount of deformation (4 mm) in the C5/C6 intervertebral disc and deformation value is ultimately tempered in the vertebra C6, while in the subject with artificial disc, the maximum deformation is completely tempered in vertebra C5. As seen, the deformation in the normal subject is two times the value in the subject with artificial disc and the artificial disc has adjusted the deformation in the cervical spine.

### Flexion of neck

The results of maximum stress and deformation in



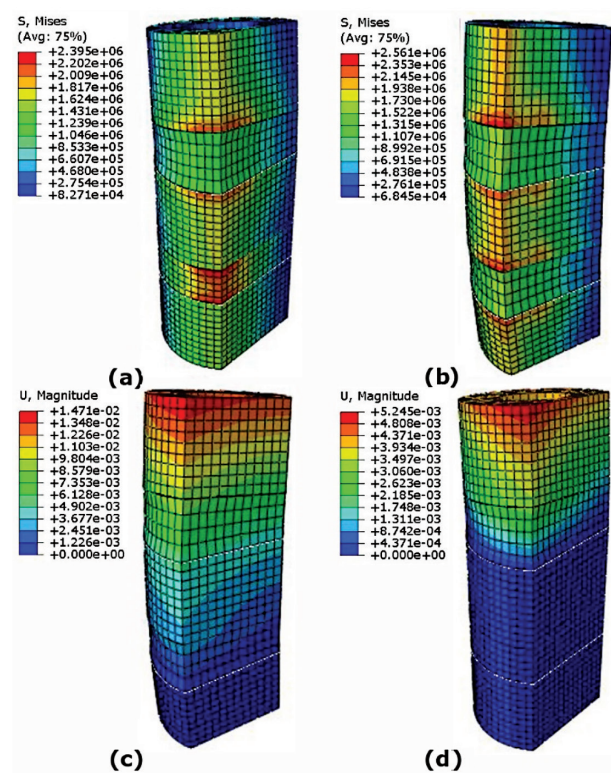


**Figure 2.** Panels (a) and (b) show stress distribution in the cervical spine for normal subject and subject with artificial disc during axial rotation, respectively. Panels (c) and (d) show same data for deformation in the cervical spine.

standing position when the subject bends his head forward with flexion were calculated for the normal subject and the subject with artificial disc and were compared with each other. The flexion was simulated with a moment of 1.8 N.m about the clavicle bone. The head weight should be added to the moment during bending the head. As the head weight is distributed over the cervical spine, a distributed compressive load of 73.6 N was exerted in the simulation as the head weight.

### Stress evaluation

According to figure 3, the maximum stress in both subjects occurs in all vertebrae (at the location where the vertebrae connect to the discs). A significant stress is also produced in the C5/C6 intervertebral disc of the normal subject; after disc replacement, however, the amount of stress at this location reduces intensely. The values of maximum stress in the subject with artificial disc and the normal subject are 2.56 and 2.39 MPa, respectively. The maximum stress in the subject with artificial disc is 6.9% greater than that in the normal subject indicating the stress increase in the subject with artificial disc.



**Figure 3.** Panels (a) and (b) show stress distribution in the cervical spine for normal subject and subject with artificial disc during flexion, respectively. Panels (c) and (d) show same data for deformation in the cervical spine.

### Deformation evaluation

According to figure 3, the maximum deformation occurs in both subjects in C4, the location of the input load application. In the normal subject, there is also some deformation in the vertebra C5 and the C5/C6 intervertebral disc, while in the subject with artificial disc, there is no significant deformation in the artificial disc and the vertebra above it. The values of the maximum deformation in the subject with artificial disc and the normal subject are 5.24 mm and 14.7 mm, respectively. As seen, the maximum deformation in the normal subject is 2.8 times the value in the subject with artificial disc and the artificial disc has reduced the deformation intensely.

### Extension of neck

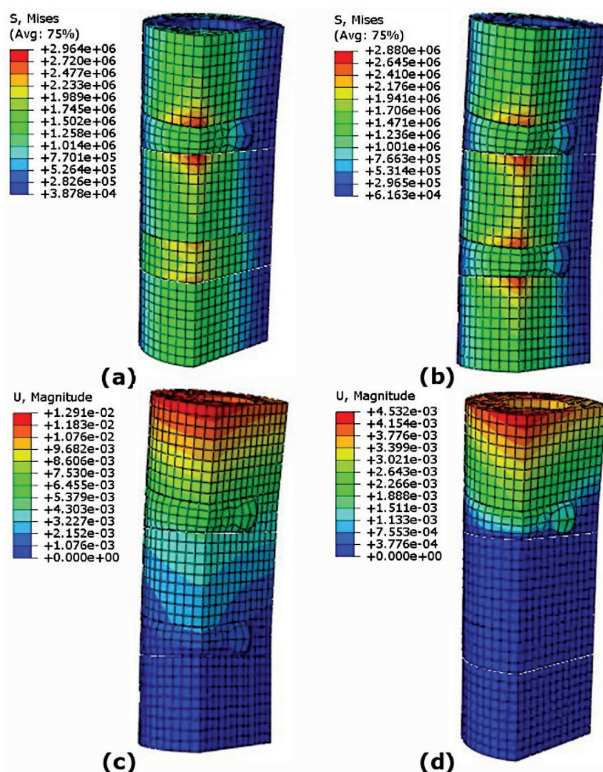
The results of maximum stress and deformation in standing position when the subject bends his head backwards with extension were calculated for the normal subject and the subject with artificial disc and were compared with each other. The loading manner is similar to that in section 3.2 with the only difference that the extension moment is applied in the reverse direction to the flexion moment.

### Stress evaluation

According to figure 4, the maximum stress in the normal subject occurs at locations where vertebrae C4 and C5 connect to the intervertebral disc between them and also in the C5/C6 intervertebral disc while in the subject with artificial disc, no significant stress is produced in the artificial disc and the maximum stress occurs in the vertebrae (especially at the location where vertebrae connect to disc). The values of maximum stress in the subject with artificial disc and the normal subject are 2.88 and 2.96 MPa, respectively. The maximum stress in the subject with artificial disc is 2.7% less than that in the normal subject indicating the stress decrease in the cervical spine after disc replacement.

### Deformation evaluation

According to figure 4, the location of the maximum deformation in the normal subject is completely similar to that in section 3.2.2. The values of the maximum deformation in the subject with artificial disc and the normal subject are 4.53 mm and 12.9 mm, respectively. As seen, the maximum deformation in the normal subject is 2.8 times the value in the subject with artificial disc



**Figure 4.** Panels (a) and (b) show stress distribution in the cervical spine for normal subject and subject with artificial disc during extension, respectively. Panels (c) and (d) show same data for deformation in the cervical spine.

and the artificial disc has reduced the deformation. The location of the maximum deformation in the subject with artificial disc is limited to the vertebra C4 and the C4/C5 intervertebral disc and doesn't transfer to the lower discs and vertebrae.

### DISCUSSION

There are several biomedical parameters for comparison of samples conditions in the numerical analysis of biological samples; the most important point, however, is to find the critical point in the model of each sample. Critical point is the weakest point of the model, in which the von Mises stress has its maximum value<sup>27</sup>. Therefore the damage to the model starts from this point and grows. According to the results of section 3.3, the cervical spine strength against extension has improved by almost 2.7% after artificial disc replacement. So the artificial disc replacement is effective for this movement. However according to the results of sections 3.1 and 3.2, the cervical spine strength against the axial rotation and flexion has decreased by 24.3% and 6.9% respectively after replacement of the injured disc with artificial disc and this indicates that the subject is more vulnerable to injury after disc replacement. As seen, the cervical spine strength against axial rotation has decreased intensely. The investigation of the stress amounts produced in the cervical spine of the normal subject during various movements reveals the cause of strength reduction after disc replacement. According to table 2, the maximum von Mises stress in the normal subject during axial rotation is 2.2 and 1.8 times the values of maximum stress during flexion and extension, respectively. So the axial rotation is the most dangerous movement causing damage to the cervical spine of the normal subject. Therefore after artificial disc replacement, the greatest stress difference between the subject with artificial disc and the normal subject appears in the axial rotation (24.3%). In general after artificial disc replacement, the cervical spine strength increases a little only against the extension but decreases in the other two movements especially axial rotation.

According to figures 3 and 4, the maximum stress in the normal subject during flexion and extension occurs both in vertebrae (at the location where the vertebrae connect to the discs) and the C5/C6 intervertebral disc. Therefore this disc is more vulnerable to injury. This result agrees with those of the studies by Coelho et al. and Lin et al.<sup>14,19</sup>. So in addition to the C5/C6 intervertebral disc, the edges of all vertebrae at locations where they connect to the discs are at the risk of injury during flexion and extension. After replacement of the C5/C6

**Table 2.** Maximum stress and deformation in the normal subject and subject with artificial disc during axial rotation, flexion and extension.

Parameters	Movements					
	Axial rotational (patient)	Axial rotational (normal)	Flexion (patient)	Flexion (normal)	Extension (patient)	Extension (normal)
Stress (MPa)	6.64	5.34	2.56	2.39	2.88	2.96
Deformation (mm)	4.52	9.00	5.24	14.7	4.53	12.9

intervertebral disc with an artificial disc, however, the stress reduces intensely since the module of elasticity of the artificial disc is much more than that of the natural disc as seen in table 1. According to figure 2, only the C5/C6 intervertebral disc of the normal subject is at the risk of injury during axial rotation but after artificial disc replacement, the vulnerable location moves to the first vertebra above the artificial disc. It means the vertebra C5 is at the risk of injury. The reason of this change is again the module of elasticity of the artificial disc which is 11 times the module of the elasticity of vertebra (Table 1). This causes the vertebra to hurt sooner than the artificial disc. Although all vertebrae and the C5/C6 intervertebral disc during flexion and extension and only the C5/C6 intervertebral disc during axial rotation are exposed to the injury, the axial rotation is a more dangerous movement than the flexion and extension regarding the damages they may cause in the C5/C6 intervertebral disc. It should be noted that even after artificial disc replacement, the maximum von Mises stress during axial rotation is 2.6 and 2.3 times the maximum stress during flexion and extension, respectively (Table 2). There is generally a much greater probability of injury during axial rotation.

As the axial rotation is the most dangerous movement for creating damage to the C5/C6 intervertebral disc, the models of the normal subject and the subject with artificial disc when they were in the lying position and made the axial rotation were also investigated. The difference between the lying and standing positions is the head weight since the 73.6-N compressive load due to the head weight is omitted in the lying position. The results show that the differences of the maximum stress and deformation between lying and positions under axial rotation in the normal subject and the subject with artificial disc are less than 0.3%. It can therefore be concluded that the head weight doesn't have any significant effect on the cervical spine and artificial disc injuries.

According to table 2, the maximum deformation values in the normal subject during flexion, extension and axial rotation are respectively 2.8, 2.8 and 2 times the values in the subject with artificial disc during similar movement. Although the stress in cervical spine increases after artificial disc replacement (except for the case of

extension), the deformation of vertebrae and discs after artificial disc replacement decreases significantly and more favorable conditions are created.

According to figures 2, 3 and 4, the location of the maximum deformation during all three movements of axial rotation, flexion and extension has a similar trend in both subjects so that the maximum deformation occurs in vertebra C4 in both subjects. The reason of this phenomenon can be explained with the help of buckling effect in columns. With a kind of simplification, the cervical spine can be assumed as a column with a fixed and a free end with pressure force and moment. Based on the Euler's formula in columns, the maximum vertical deflection should occur in the upper part of the column, i.e. the vertebra C4<sup>28</sup>. Furthermore due to the high value of the module of elasticity in the artificial disc, deformation in the C5/C6 intervertebral disc is tempered completely. In the normal subject, however, the deformation continues up to the C5/C6 intervertebral disc based on the Euler's formula in columns.

## CONCLUSION

Comparison of the maximum stress and deformation in the cervical spine of a normal subject and a subject with artificial disc showed that the cervical spine strength during extension increased a little after artificial disc replacement but the cervical spine strength in flexion and axial rotation decreased. After artificial disc replacement, the probability of damage to the first vertebra above the artificial disc during axial rotation is higher comparing to other parts but during flexion and extension the risk of damage is transferred to the cervical vertebrae. In general, the probability of damage is greater during axial rotation than other movements.

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