 doi:10.20944/preprints202112.0003.v1

Investigation into cervical spine biomechanics following single, multilevel and hybrid disc replacement surgery with dynamic cervical implant and fusion: a finite element study

1. Muzammil Mumtaz, M.Sc.

Engineering Center for Orthopaedic Research Excellence (ECORE), Departments of Bioengineering and Orthopaedic Surgery, Colleges of Engineering and Medicine, The University of Toledo, Toledo, OH, USA

2. Iman Zafarparandeh, Ph.D.

Department of Biomedical Engineering, Medipol University, Istanbul, Turkey

3. Deniz Ufuk Erbulut, Ph.D.

Herston Biofabrication Institute, Metro North Hospital and Health Service, Brisbane, Queensland, Australia

Corresponding author: Deniz U. Erbulut, Herston Biofabrication Institute, Metro North Hospital and Health Service, Brisbane, Queensland, Australia.

Email: erbulut.deniz@gmail.com

Conflict of Interest: The authors have no conflict of interest to declare.

Abstract

Cervical fusion has been a standard procedure for treating the abnormalities associated with the cervical spine. However, the reliability of anterior cervical discectomy and fusion (ACDF) has become arguable due to its adverse effects on the biomechanics of adjacent segments. One of the drawbacks associated with ACDF is adjacent segment degeneration (ASD) which has served as the base for the development of dynamic stabilization systems (DSS) and total disc replacement (TDR) devices for cervical spine. However, the hybrid surgical technique has also gained popularity recently but their effect on the biomechanics of cervical spine is not well researched. Thus, the objective of this FE study was to draw the comparison among single, bi-level and hybrid surgery with DCI implant with traditional fusion. Reduction in range of motion (ROM) for all the implanted models was observed for all the motions except extension, compared to intact model. The maximum increase in ROM of 42% was observed at C5-C6 level in Hybrid-DCI model. The maximum increase in adjacent segment's ROM of 8.7% was observed in multilevel fusion model. The maximum von Mises stress in the implant was highest for the multilevel DCI model. Our study also showed that the shape of DCI implant permits flexion/extension relatively more compared to lateral bending and axial rotation.

Keywords: cervical spine, finite element, dynamic cervical implant, multi-level fusion, hybrid surgery, disc replacement.

1. Introduction

The cervical disc degenerative diseases are often treated with traditional anterior cervical discectomy and fusion (ACDF). However, ACDF leads to the loss of motion at the index segment which is compensated by the adjacent segments [1]. Thus, traditional cervical fusion procedure has been under question in recent decades as studies have reported high rate of adjacent segment degeneration (ASD) following fusion surgery [2]. Hence, motion preserving devices are being explored by clinicians that may restore motion at index segment and reduce the chances of developing ASD [2–6]. The dynamic stabilization systems (DSS) and total disc replacement (TDR) implants are commonly used as motion preserving devices [7–9].

Single level disc replacement has become one of the most common procedure for treating abnormalities associated with the intervertebral disc and its effect on cervical spine biomechanics has been reported in literature [1,10,11]. On the other hand, bi-level dynamic stabilization systems have also gained attention in the past decades but very few devices are approved by FDA for multilevel usage. The dynamic cervical implant (DCI) is one of the FDA approved implant for multilevel usage. However, dynamic cervical implant is less researched compared to other TDR implants. Also, DCI implant is relatively less mobile compared to ball-socket TDR designs. The effect of single level disc replacement DCI was present in our conference proceedings [12]. In this study, the scope of our work has been extended to evaluate the biomechanics of single, multilevel and hybrid disc replacement surgery with dynamic cervical implant and fusion.

Thus, the aim of our present study was to use FE analysis to evaluate the effect of DCI implant on adjacent segment ROM. For that purpose, five different configurations of cervical FE model were developed; 1) single level disc replacement (C5-C6 DCI), 2) bi-level disc replacement (C4-C6 DCI), 3) hybrid surgery (Hybrid-DCI); C4-C5 fusion and C5-C6 DCI, 4) single level fusion (C5-C6 Fused), 5) bi-level fusion (C4-C6 Fused). The range of motion (ROM in all

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2021 doi:10.20944/preprints202112.0003.v1

models was calculated and compared with the intact model. Moreover, maximum von Mises stress in the implant was also measured and compared for all cases.

2. Materials and Methods

A previously validated C2-T1 FE model was used in this study [12–14]. In summary, the model was developed based on the computed tomography (CT) scan data of a 35-year-old male. Ethical approval was given by the Institutional Ethics Board committee of the Koc University. The number of protocol was 2012.019.IRB2.009. The CT scan data were processed in medical image processing software (Mimics® Version 14.1; Materialise, Inc., Leuven, Belgium) to obtain the three-dimensional (3D) geometry of the vertebrae. The space between the 3D geometry of vertebrae were filled to represent the intervertebral discs. The 3D geometry of the vertebrae and intervertebral discs was meshed with hexahedral elements in IA-FE Mesh software (University of Iowa, IA). The meshed vertebrae and intervertebral discs were exported to Abaqus software for FE analysis. To model the behavior of ligaments, 3D truss elements were in Abaqus software were used to simulate nonlinear behavior of ligaments under tensile forces [15,16]. The 3D tension only truss elements were used to model the five cervical ligaments: the anterior longitudinal ligament (ALL), the posterior longitudinal ligament (PLL), the capsular ligament (CL), the ligamentum flavum (LF), and the interspinous ligament (ISL). The facets joints were modeled via three-dimensional gap contact elements (GAPUNI) in the Abaqus software.

FE Model of Instrumented Cervical Spine

To simulate the DCI surgery, intervertebral disc at the index at the index was completely removed along with the ALL and PLL ligaments. The DCI implant was then inserted into the cavity at the index segment. The upper and lower surface of the implant was attached to the respective vertebra via “TIE” constraint in ABAQUS. The DCI implant was assigned material property of a Titanium Alloy (Ti6Al4V) with a poisson's ratio of 0.35 and elastic modulus of 114,000MPa. The material properties for all the soft and hard tissues in the FE model are summarized in Table-1.

Table 1:Material properties for different components of the cervical spine FE model [17].

Component				
Bony Structure	Element Type	Young's Modulus (MPa)	Poisson's Ratio	Cross-Sectional Area (mm^2)
Vertebral Cortical Bone	Isotropic, elastic hex element	10,000	0.30	-
Vertebral Cancellous Bone	Isotropic, elastic hex element	450	0.25	-
Ligaments				
Transverse, Tectorial Membrane	Isotropic, elastic hex element	80	0.3	-
Apical-Alar	Tension only, truss elements	20	0.3	-
Anterior Longitudinal	Tension only, truss elements	15 (<12%) 30 (>12%)	0.3	11.1
Posterior Longitudinal	Tension only, truss elements	10 (<12%) 20 (>12%)	0.3	11.3
Ligamentum Flavum	Tension only, truss elements	5 (<25%) 10 (>25%)	0.3	46.0
Capsular	Tension only, truss elements	7 (<30%) 30 (>12%)	0.3	42.2
Joint				
Facet (Apophyseal Joint)	Nonlinear soft contact, GAPUNI	-	-	-

To simulate the single level disc replacement, disc between the segment C5-C6 was removed Similarly, bi-level disc replacement was simulated by removing the discs and ligaments between segments C4-C6. To simulate hybrid surgery (HS), disc between the C5-C6 segment was replaced by implant whereas C4-C5 segment was fused by removing the ALL and PLL whereas disc C45 was assigned the material property of cancellous bone. Similarly, single and bi-level fusion was simulated by fusing C5-C6 segment and C4-C6 segments by assigning cancellous bone property to the discs C5-C6 and C4-C6 respectively.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2021 doi:10.20944/preprints202112.0003.v1

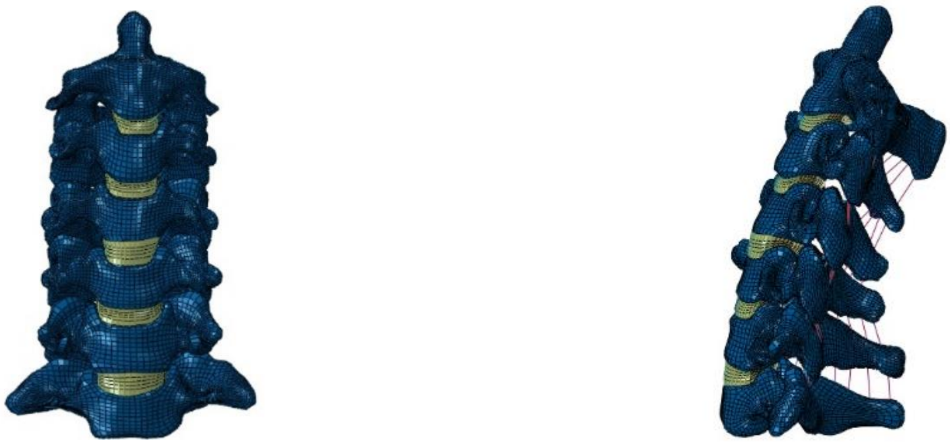
Loads and Boundary Conditions

A pure moment of 2Nm was applied at C2 in three planes sagittal, coronal and axial to simulate of flexion-extension, lateral bending (LB) and axial rotation (AR). The T1 bottom surface was fixed under all loading conditions.

Data Analysis

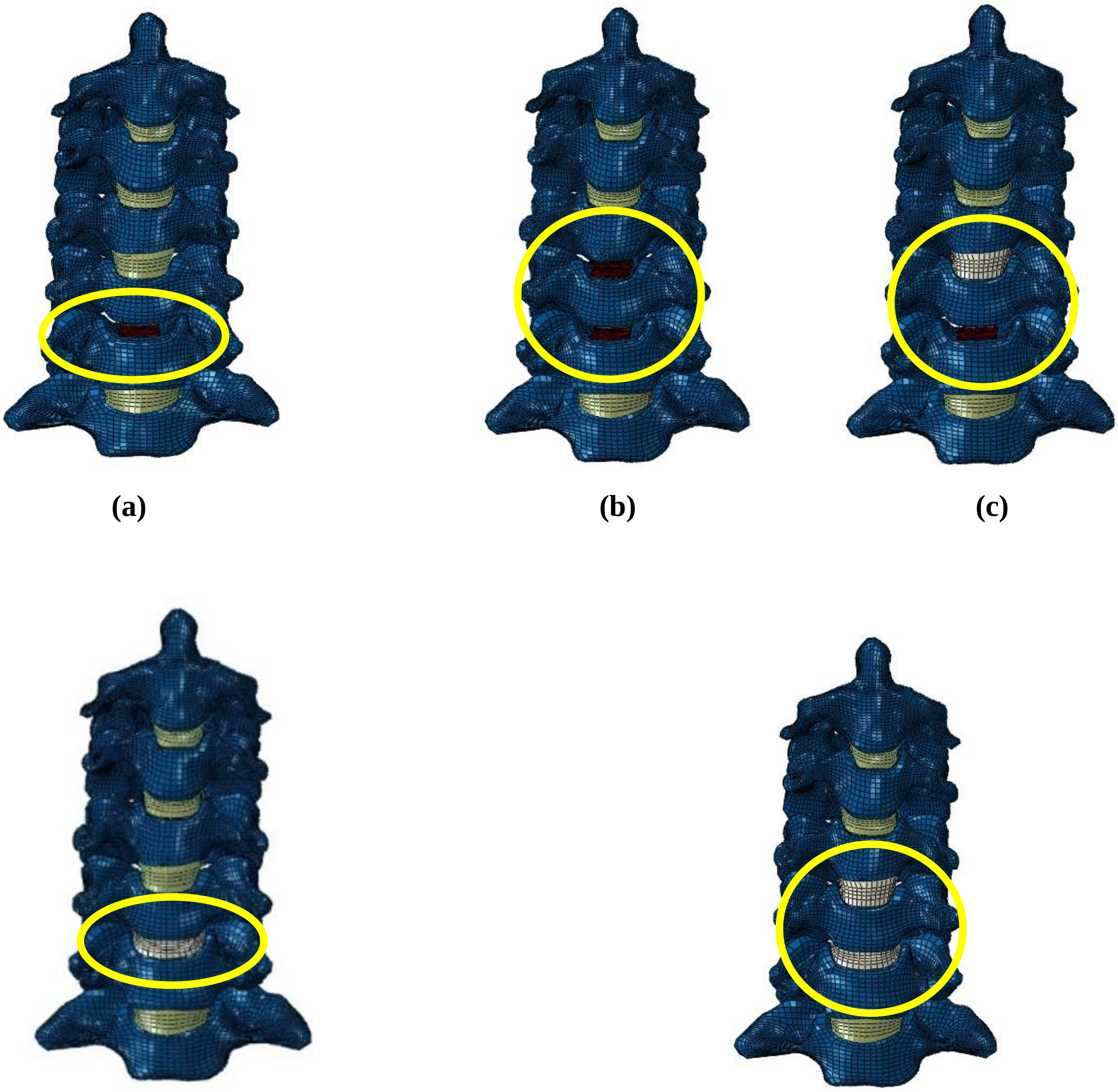
The post processing of data obtained from FE simulations was done in MATLAB via custom scripts. The ROM for each segment was calculated and compared with the ROM of intact cervical spine. The percentage difference between intact and implanted models was calculated with the following formula:

$$Percentage\ Difference = \frac{Implanted_{Data} - Intact_{Data}}{Intact_{Data}} * 100$$



(a) (b)

Fig 1. Finite element (FE) model of intact C2-C7 cervical spine. a) Coronal View, b) sagittal view



(a) (b) (c)

(d) (e)

Fig 2. a) C5-C6 DCI model, b) C4-C6 DCI model, c) hybrid surgery model, d) C5-C6 fused model, e) C4-C6 fused model.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2021 doi:10.20944/preprints202112.0003.v1

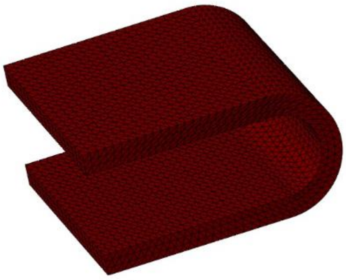


Fig 3. Dynamic cervical implant.

3. Results

3.1 Range of Motion

Under flexion, The ROM was reduced about 38% at C5-C6 segment in C5-C6 DCI, C4-C6 DCI and Hybrid-DCI models compared to intact model. The ROM was reduced about 5.9% at C4-C5 segment in C4-C6 DCI model compared to intact model. The change in adjacent segments ROM was less than 1% for all the surgery models compared to intact model.

Under extension, the maximum increase in ROM of 42% was observed at C5-C6 level in Hybrid-DCI model and about 39.7% increase in ROM was observed at C5-C6 DCI and C4-C6 DCI. The maximum increase in adjacent segments ROM of about 8.71% was observed in C4-C6-Fused model at the superior segment. The Hybrid-DCI model had 2.56% increase in ROM at the superior segment compared to intact model. Conversely, reduction of 1.35% and 3.87% was observed at superior adjacent segment in C5-C6 DCI and C4-C6 DCI models respectively, compared to the intact model.

Under lateral bending, the C4-C6 DCI model had 66.6% and 83.70% reduction in ROM at C4-C5 and C5-C6 segment respectively, compared to intact model. The ROM reduction of about 84.25% and 85.39% was observed at C5-C6 segment in C5-C6 DCI and Hybrid-DCI models respectively, compared to intact model. The maximum increase in adjacent segments ROM was observed at the superior adjacent segment of C4-C6-Fused model i.e., 11.35%, compared

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2021 doi:10.20944/preprints202112.0003.v1

to intact model. Moreover, 10.28% increase in ROM at the superior adjacent segment in Hybrid-DCI model was observed, compared to intact model.

Under axial rotation, about 89% reduction in ROM was observed in all the implanted models at C5-C6 segment, whereas C4-C5 segment in C4-C6 DCI model had 79.42% reduction, compared to intact model. Conversely, increase in ROM was observed at the adjacent segments of all the models, compared to intact model. The superior adjacent segment in C5-C6 DCI and C5-C6 Fused models showed an increase in ROM of 5.92% and 6.34% respectively, compared to intact model. The adjacent segments ROM for other implanted models was increased less than 4%, compared to intact model.

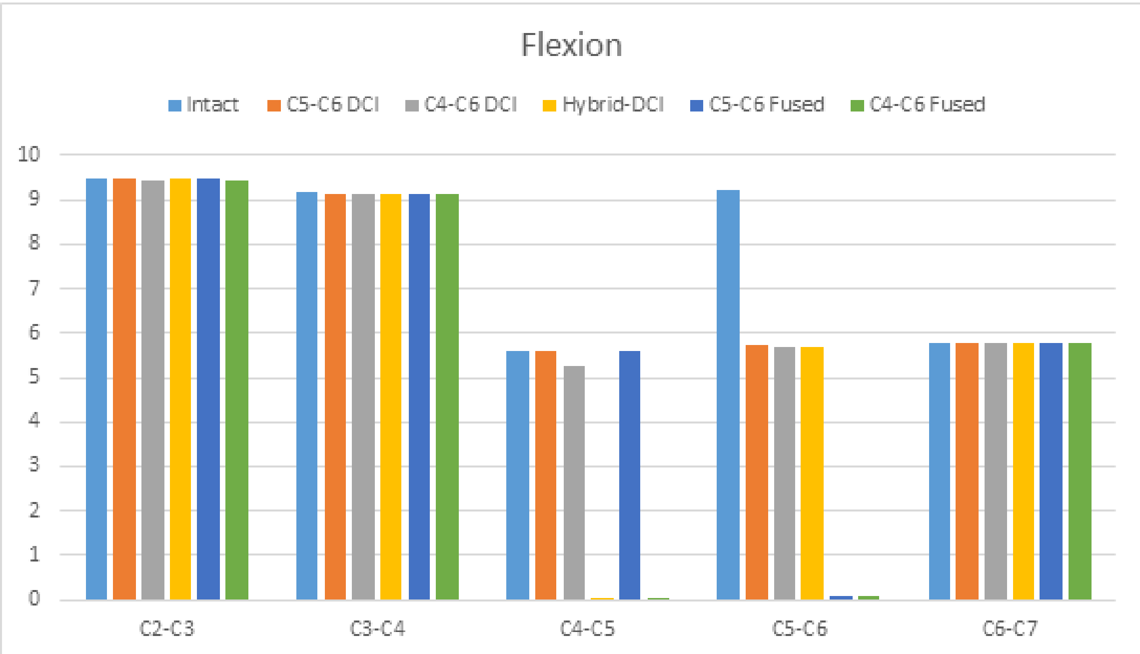


Fig 4. The comparison of ROM during flexion among C5-C6 DCI, C4-C6 DCI, Hybrid DCI, C5-C6 fused and C4-C6 fused. The vertical axis shows ROM in degrees.

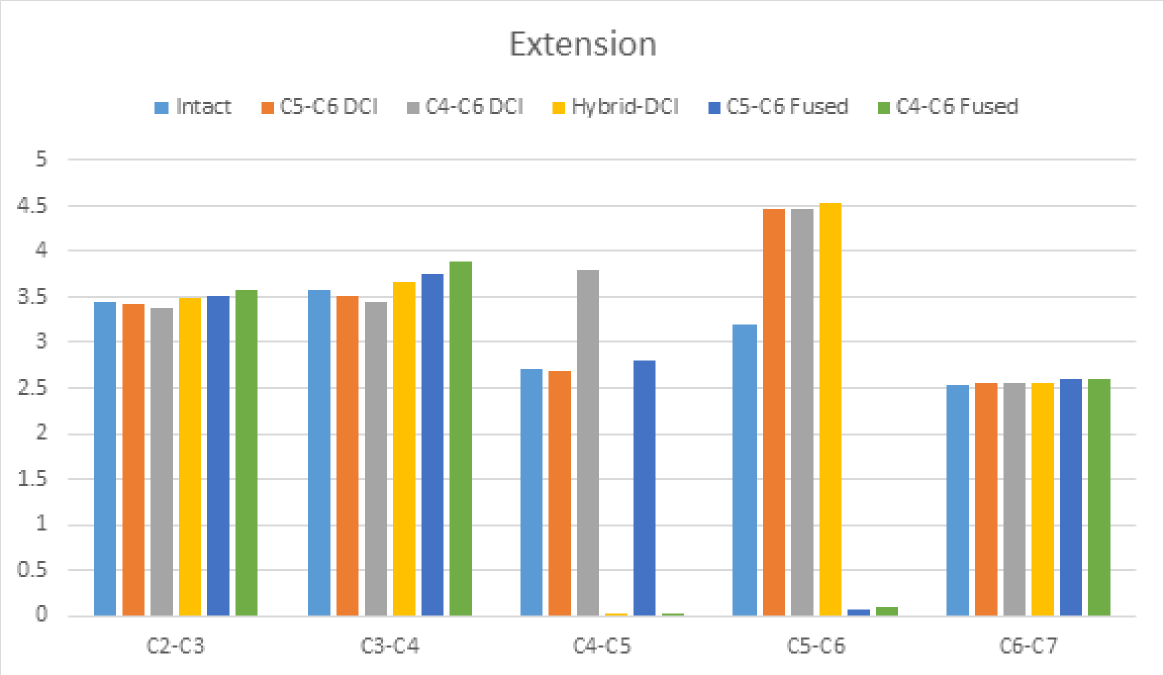


Fig 5. The comparison of ROM during extension among C5-C6 DCI, C4-C6 DCI, Hybrid DCI, C5-C6 fused and C4-C6 fused. The vertical axis shows ROM in degrees.

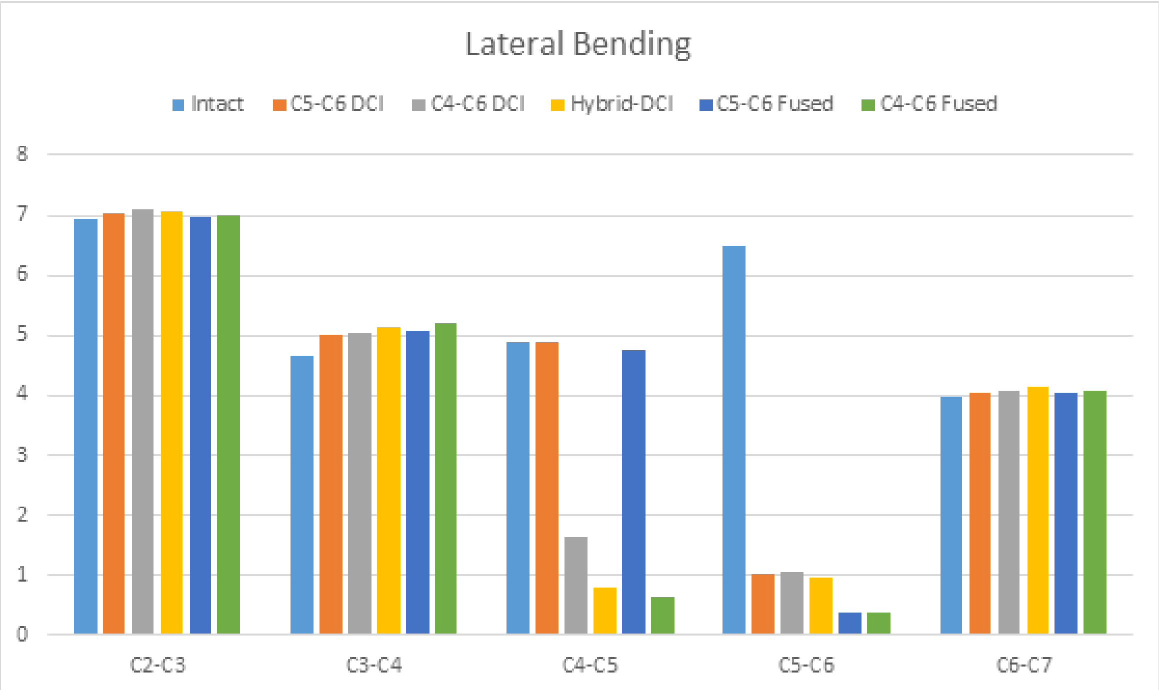


Fig 6. The comparison of ROM during lateral bending among C5-C6 DCI, C4-C6 DCI, Hybrid DCI, C5-C6 fused and C4-C6 fused. The vertical axis shows ROM in degrees.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2021 doi:10.20944/preprints202112.0003.v1

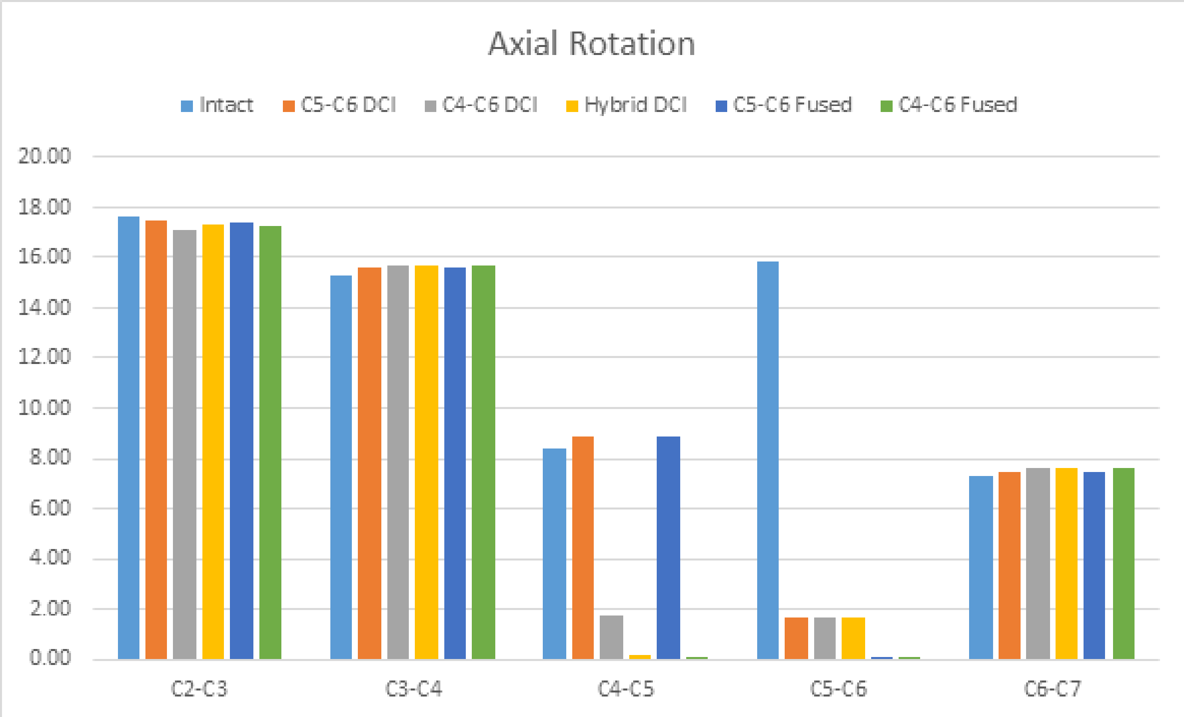


Fig 7. The comparison of ROM during axial rotation among C5-C6 DCI, C4-C6 DCI, Hybrid DCI, C5-C6 fused and C4-C6 fused. The vertical axis shows ROM in degrees.

3.2 Stress Distribution in Implant

The maximum von Mises stress predicted in the implant for different models are summarized in Figure-8. The maximum von Mises stress was observed during flexion in all the models, it was highest in C4-C6 DCI i.e., 765.85 MPa at C5-C6 segment. During extension, maximum stress of 633.64 MPa was predicted in Hybrid-DCI model. Under lateral bending, the maximum stress of 575.62 MPa was predicted during the right lateral bending (RLB) at C4-C5 segment of C4-C6 DCI model. Under axial rotation, the maximum stress observed was about 648.5 MPa at C5-C6 and C4-C6 segments of C5-C6 DCI and C4-C6 DCI models respectively.

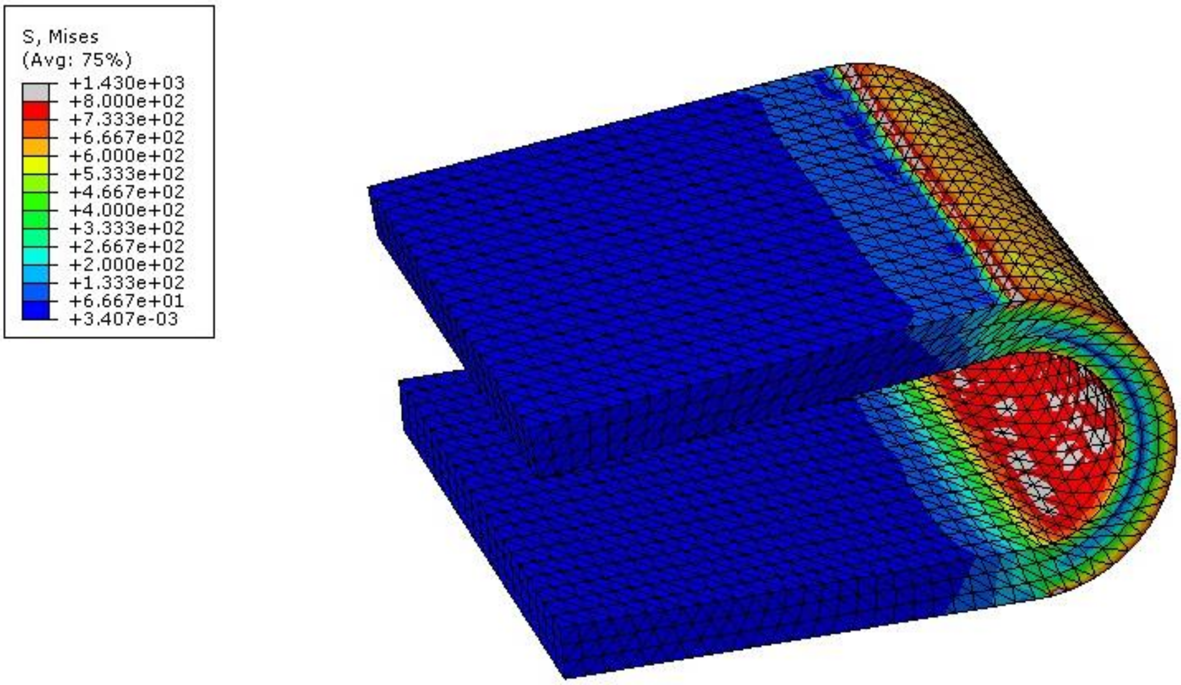


Fig 8. Maximum stress distribution in U-Shaped Implant (DCI) during flexion in C4-C6 DCI model.

4 Discussion

Dynamic stabilization systems and TDR implants have gained popularity in the recent decades as they tend to reduce the radiographic adjacent segment degeneration by preserving motion at the index segment. These motion preserving implants employ different mechanisms for preserving the motion at the operated segment. However, some of the TDR devices tend to increase the ROM more than the natural ROM at the index segment as reported by Chang et al. and Kotani et al. [11,18]]. Besides this, some studies have also reported that the use of TDR may lead to excessive loading at the facet joints [19,20]. For such reasons, DCI implant has drawn significant attention of medical professionals as an alternate to traditional TDR devices. However, the literature on biomechanics of cervical spine following DCI surgery is sparse per the author's knowledge. Hence, the aim of this finite element analysis was to study the effect of DCI implant on cervical spine biomechanics and compare with the traditional fusion surgery.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 1 December 2021 doi:10.20944/preprints202112.0003.v1

Our FE results showed that the DCI implant in all the models causes reduction of ROM at the index segment during flexion and increases the ROM during extension, similar trend was observed by Li et al. [21]. The increase in adjacent segments ROM was less in DCI implant models compared to fusion model. In C4-C6 Fused model, adjacent segment's ROM increased up to 8.7% compared to intact model. During LB, the increase in ROM of C3-C4 segment of C5-C6 DCI model was up to 7.5% whereas the increase in ROM of adjacent segments was less than 2%, similar trend was observed by Zhong et al. [22]. However, in AR, reduction in ROM for DCI implant models was higher compared to flexion/extension and lateral bending, our findings were consistent with the prospective case study of Mohamed [23] [30]. Since, the shape of DCI implant permits flexion/extension moment. Therefore, maximum von Mises stress was also predicted during flexion in all the implanted models and our finding was also in agreement with the studies of Fogel et al. and Mo et al. [21,22]. The highest maximum von Mises stress predicted in the DCI implant was predicted for the C4-C6 DCI model and it was higher than the endurance limit of Ti6Al4V (500 MPa), suggesting implant failure may occur relatively earlier than other DCI implant configurations.

4.2 Limitations

This FE study had limitations due to the nature of mathematical modeling technique. Simplified material properties, interactions, boundary conditions and loads very used in the model. The effect of neck musculature was also not simulated. These limitation may alter the biomechanics of cervical spine and stress on the implants. However, the general trend for ROM and implant stress may remain the same.

4.3 Conclusion

In summary, this study used computational analysis to draw comparison among single level DCI, bi-level DCI, hybrid-DCI implant configurations with single and bi-level fusion. Our biomechanical FE study suggests that the DCI implant may be a good alternate to ACDF, but

 doi:10.20944/preprints202112.0003.v1

it has its own limitations. The DCI implant preserves ROM reasonably for flexion/extension but the stress in implant was also maximum during flexion. The ROM of adjacent segments is least affected in C5-C6 DCI model. Besides this DCI implant tends to experience high stress in bi-level (C4-C6 DCI) model suggesting that failure may occur sooner in patients with multi-level DCI implantation compared to patients with single level or hybrid DCI implantation.

References

[1] A.E. Dmitriev, B.W. Cunningham, N. Hu, G. Sell, F. Vigna, P.C. McAfee, Adjacent Level Intradiscal Pressure and Segmental Kinematics Following A Cervical Total Disc Arthroplasty: An: In Vitro: Human Cadaveric Model, Spine (Phila. Pa. 1976). 30 (2005) 1165–1172.

[2] R.J. Hacker, J.C. Cauthen, T.J. Gilbert, S.L. Griffith, A prospective randomized multicenter clinical evaluation of an anterior cervical fusion cage, Spine (Phila. Pa. 1976). 25 (2000) 2646–2655.

[3] F. Kandziora, R. Pflugmacher, J. Schaefer, M. Scholz, K. Ludwig, P. Schleicher, N.P. Haas, Biomechanical comparison of expandable cages for vertebral body replacement in the cervical spine, J. Neurosurg. Spine. 99 (2003) 91–97.

[4] C. Brenke, S. Fischer, A. Carolus, K. Schmieder, G. Ening, Complications associated with cervical vertebral body replacement with expandable titanium cages, J. Clin. Neurosci. 32 (2016) 35–40.

[5] S. Hartmann, C. Thomé, A. Tschugg, J. Paesold, P. Kavakebi, W. Schmölz, Cement-augmented screws in a cervical two-level corpectomy with anterior titanium mesh cage reconstruction: a biomechanical study, Eur. Spine J. 26 (2017) 1047–1057.

[6] Z. Li, Y. Zhao, J. Tang, D. Ren, J. Guo, H. Wang, L. Li, S. Hou, A comparison of a new zero-profile, stand-alone Fidji cervical cage and anterior cervical plate for single and multilevel ACDF: a minimum 2-year follow-up study, Eur. Spine J. 26 (2017) 1129–1139.

[7] M. Bydon, R. Xu, M. Macki, R. De la Garza-Ramos, D.M. Sciubba, J.-P. Wolinsky, T.F. Witham, Z.L. Gokaslan, A. Bydon, Adjacent segment disease after anterior cervical discectomy and fusion in a large series, Neurosurgery. 74 (2014) 139–146.

[8] A.A. Gandhi, S. Kode, N.A. DeVries, N.M. Grosland, J.D. Smucker, D.C. Fredericks, Biomechanical analysis of cervical disc replacement and fusion using single level, two level, and hybrid constructs, Spine (Phila. Pa. 1976). 40 (2015) 1578–1585.

[9] B.W. Cunningham, N. Hu, C.M. Zorn, P.C. McAfee, Biomechanical comparison of single-and two-level cervical arthroplasty versus arthrodesis: effect on adjacent-level spinal kinematics, Spine J. 10 (2010) 341–349.

[10] C.M. Puttlitz, D.J. DiAngelo, Cervical spine arthroplasty biomechanics, Neurosurg. Clin. 16 (2005) 589–594.

[11] U.-K. Chang, D.H. Kim, M.C. Lee, R. Willenberg, S.-H. Kim, J. Lim, Range of motion change after cervical arthroplasty with ProDisc-C and prestige artificial discs compared with anterior cervical discectomy and fusion, J. Neurosurg. Spine. 7 (2007) 40–46.

[12] M. Mumtaz, I. Zafarparandeh, P. Taherzadeh, S.Z. Akıncı, D.U. Erbulut, Effect of U-shaped implant on the biomechanics of the cervical spine, in: 2016 20th Natl. Biomed. Eng. Meet., IEEE, 2016: pp. 1–3.

[13] D.U. Erbulut, I. Zafarparandeh, I. Lazoglu, A.F. Ozer, Application of an asymmetric finite element model of the C2-T1 cervical spine for evaluating the role of soft tissues in stability, Med. Eng. Phys. 36 (2014) 915–921.

[14] M. Mumtaz, Finite element analysis of cervical spine & finite element modeling of knee joint, (2017).

[15] N. Nishida, M. Mumtaz, S. Tripathi, A. Kelkar, T. Sakai, V.K. Goel, Biomechanical Analysis of Posterior Ligaments of Cervical Spine and Laminoplasty, Appl. Sci. 11 (2021) 7645. https://doi.org/10.3390/app11167645.

[16] M. Mumtaz, J. Mendoza, A.S. Vosoughi, A.S. Unger, V.K. Goel, A Comparative Biomechanical Analysis of Various Rod Configurations Following Anterior Column Realignment and Pedicle Subtraction Osteotomy, Neurospine. 18 (2021) 587–596. https://doi.org/10.14245/ns.2142450.225.

[17] D.U. Erbulut, I. Zafarparandeh, I. Lazoglu, A.F. Ozer, Application of an asymmetric finite element model of the C2-T1 cervical spine for evaluating the role of soft tissues in stability, Med. Eng. Phys. 36 (2014) 915–921. https://doi.org/10.1016/j.medengphy.2014.02.020.

[18] Y. Kotani, B.W. Cunningham, K. Abumi, A.E. Dmitriev, N. Hu, M. Ito, Y. Shikinami, P.C. McAfee, A. Minami, Multidirectional flexibility analysis of anterior and posterior lumbar artificial disc reconstruction: in vitro human cadaveric spine model, Eur. Spine J. 15 (2006) 1511–1520.

[19] H. Kang, P. Park, F. La Marca, S.J. Hollister, C.-Y. Lin, Analysis of load sharing on uncovertebral and facet joints at the C5–6 level with implantation of the Bryan, Prestige LP, or ProDisc-C cervical disc prosthesis: an in vivo image-based finite element study, Neurosurg. Focus. 28 (2010) E9.

[20] F. Galbusera, F. Anasetti, C.M. Bellini, F. Costa, M. Fornari, The influence of the axial, antero-posterior and lateral positions of the center of rotation of a ball-and-socket disc prosthesis on the cervical spine biomechanics, Clin. Biomech. 25 (2010) 397–401.

[21] Y. Li, G.R. Fogel, Z. Liao, R. Tyagi, G. Zhang, W. Liu, Biomechanical analysis of two-level cervical disc replacement with a stand-alone U-shaped disc implant, Spine (Phila. Pa. 1976). 42 (2017) E1173–E1181.

[22] Z.J. Mo, Y. Bin Zhao, L.Z. Wang, Y. Sun, M. Zhang, Y.B. Fan, Biomechanical effects of cervical arthroplasty with U-shaped disc implant on segmental range of motion and loading of surrounding soft tissue, Eur. Spine J. 23 (2014) 613–621. https://doi.org/10.1007/s00586-013-3070-4.

[23] M.M. Mohi Eldin, Dynamic cervical implant (DCI) in single level cervical disc disease, Open Spine J. 6 (2014).