Change of Mobility and Stress Morphology due to Different Types of Artificial Cervical Spine Implementation: a Finite Element Analysis

S.W. Yang, Y.Y. Chien, and M.H..Chen

Abstract—**The purpose of this study was to analyze the mobility and stress morphology of different implants, in order to provide a clinical reference for individual needs. Three types of commercial cervical implants namely Bryan Disc, Prodics-C, and Prestige were reconstructed according to the product information. A displacement controlled non-linear FEM was analyzed and compared. All models were subjected to a sequential rotation in flexion-extension, lateral bending, and axial torsion using the LS-DYNA prescribed motion analysis. The range of segmental motion (ROM), facet joint force, tension on major ligaments, and stresses on the cores were analyzed.**

Unlike the spinal fusion, the stress level and the mobility in adjacent levels didn't increase significantly for all types of disc arthroplasties but ROM at C5 level did increase particularly in the fixed core design of Prodisc-C. The metal-on-metal design (Prestige) limited the ROM which resulted in stiffening the spinal column structure. The instantaneous center of rotation moved to near facet joints after cervical arthroplasties. The multi-articulation design of the Bryan Disc would induce overall better biomechanical benefits for the cervical spinal disc replacement than other designs.

Different design characteristics result in different kinematics and kinetics. A multi-articular metal-on-polymer mobile core provides better functions than other implants.

Key Words: Artificial cervical disc replacement, finite element method, Spinal Fusion, Range of Motion Displacement Control

I. INTRODUCTION

SPINAL FUSION surgery for various disc disorder treatments has been clinical concluded to accelerate the adjacent segment degeneration and results in either treatment failure or further multiple-segment fusion. The mechanism of progressing degeneration of adjacent level particular the one above the fusion segments is mainly due to increase the range of motion (ROM)of the adjacent non-fusion levels which results in abnormal high pressures on discs and facet joints [1,2]. Various designs of artificial cervical or lumbar spinal disc prostheses have been developed for years in order to reduce adverse effects of segmental fusions. The design concept of mobile prosthesis is to provide the spinal column ROM as well as weight bearing of each motion segment similar to that of the normal spine. The long-term follow-up as well as biomechanical studies have shown the efficacy of mobile spinal prostheses to be super than the segment fusion procedures [3,4,5].

However, recent long-term follow-up of post-cervical arthroplasty showed an adverse result. A four year prospective study revealed that 94 subjects who underwent the total cervical disc replacement by using the Bryan and Prestige LP cervical disc devices; the rate of adjacent disc degeneration was similar between the traditional fusion treatment and total disc replacement. In addition, five patients who were treated with arthroplasty, returned for evaluation of neck and arm symptoms between 48 and 72 months after surgery. Four patients had peridevice vertebral body bone loss. One patient had posterior device migration and presented with myelopathy. Three required revision surgery and 2 were observed. The survey concluded that the delayed device-related complication may occur after years of surgery [6].

Few studies have investigated the changes in kinematics as well as kinetics after three different design concepts of cervical spinal replacements. The purpose of this study was to analyze the mobility and stress morphology of different implants, in order to provide a clinical reference for individual needs. .

II. MATERIALS AND METHODS

A. *Finite Element Modelling*

A validated ligamentous head-neck finite element model was modified from the previously published FE model. The original neck model was established based on the CT data of a 29-year-old man with height of 1.74 m and weight of 75 kg. [7,8]. An advanced general-purpose multiphasic software was used for the simulation (LS-DYNA, Livermore Software USA). Head-brain, eight vertebrae (C1toT1) and corresponded intervertebral discs were represented by elastic-solid elements. The nucleus of spinal disc were represented as an solid elastic fluid element, the annuals as well as associated ligaments were modelled as either tension only beam-cable or tension-only shell-fabric elements according to the real dimensions of ligaments. The facet joint articulations were simulated as frictionless surface-to-surface contacts. The atlanto-occipital membrane was modelled as beam-cable elements. The intact head-neck model (Fig. 1) consisted of 13780 elements and 18217 elements for head and neck-ligaments, respectively. The detail of element types and mechanical properties is shown on Table I.

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B. Prostheses modelling

Three types of commercial cervical spinal prostheses: mobile core implant- with metal-on-multi-polymers design- Bryan Disc, mobile-core of metal-on-metal design- Prestige, and fixed-core implant with metal-on- polymer- Prodisc-C were integrated at the C5-C6 segment into the validated FE model (Table II). The geometry and dimensions of prostheses were obtained by inversed engineering modeling by using the published data and samples (Fig. 2).

C. Boundary and loading conditions

Intact spinal cervical column, fusion at the C5-6 intervertebral space, and three types of prostheses were implanted at the C5-6 were simulated and analyzed. The bottom elements of the T1 vertebra were fixed in all directions. All models were subjected to a sequential rotation in 30 degrees of flexion-extension, 30 degrees of lateral bending, and 30 degrees of axial torsion related to the fixed T1 vertebra by using LS-DYNA prescribe motion analysis. A local coordinate system was constructed on the geometrical center of each vertebra; the Eulerian angle of segmental motion was calculated. The range of segmental motion (ROM), facet joint force, tension on major ligaments, and stress on the cores were analyzed.

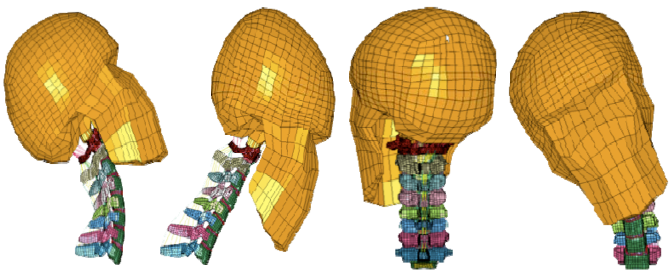

Fig. 1. Intact Head-Neck FEM *in 30 degrees of flexion-extension, 30 degrees of lateral bending, and 30 degrees of axial torsion related to the fixed T1 vertebra* .

TABLE I
Element types and Material Properties

Substructure	E(MPa)	Poisson's Ratio	Density (ton/mm^3)
Bain(Solid/Rigid)	2.07E+05	0.28	7.83E-09
Posterior (Solid/elastic)	3.50E+04	0.25	1.41E-09
Cortical (Solid/elastic)	1.20E+04	0.3	1.85E-09
Cancellous (Solid/elstic)	10	0.2	9.00E-10
Endplate (Solid/elastic)	5.00E+02	0.4	1.42E-09
Nucleus (Solid/elastic fluid)	2.07E+05	0.499	1.30E-09
Annulus fiber (beam/cable)	1.50E+02	0.4	1.30E-09
Substance (Solid/elastic)	2	0.45	1.30E-09
ALL(C2~T1) (shell/fabric)	11.4	0.4	1.10E-09
AL(C1~C2) (beam/cable)	11.4	0.39	1.10E-09
PLL (shell/fbric)	9.12	0.4	1.10E-09
SSL (beam/cable)	9	0.39	1.10E-09
ISL (beam/cable)	4.56	0.39	1.10E-09
LF(beam/cable)	5.7	0.39	1.10E-09
Vertical cruciate ligament(beam/cable)	38	0.39	1.10E+09
TL(shell/fabric)	1.71E+02	0.4	1.10E-09
CL(beam/cable)	2.28E+01	0.39	1.10E-09
Apical ligament (beam/cable)	80	0.39	1.10E-09
Anterior atlantoocipital membrane(beam/cable)	1.50E+01	0.39	1.10E-09
Posterior atlantoocipital membrane (beam/cable)	4	0.39	1.10E-09
Tectorial membrane (beam/cable)	7	0.39	1.10E-09

Fig. 2. Three types of cervical disc prostheses, Bryan disc, Prestige, Prodisc-C (from left- right)

TABLE II
Prosthesis types and Mechanical Properties

Prosthesis	Bearing Surface	Articula-tion Surf.	Center of Rotation	Material Properties
Bryan	Metal on polymer	2-surface Unconstr-ained	Mobile	End plate -Titanium 110Gpa, υ=0.3 Core-PU-Curve dependent Mooney Rivlyn Rubber
Prestige	Metal on metal	1-surface Semicon-strained	Mobile	CoCrMo StainlessSteel -220Gpa υ=0.3
Prodisc-C	Metal on polymer	1-surface Semicon -strained	Fixed	End Plate-Ti-110Gpa Core-UHMWPE-0.75Gpa

III. RESULTS

The instantaneous center of rotation (ICR) of an intact normal cervical column in flexion stably locates at the superior-posterior of the vertebral body [9]. When fusion, it moved superior and anteriorly. All types of prostheses presented unstable ICR at the adjacent segment as shown in Fig. 3.The total ROMs of each simulation were about the same. Fig. 4 shows the ROM at each motion segment in intact and three disc replacement conditions and Fig. 5 is the stress distribution in 30 degrees of flexion. The fusion procedure limited the ROM at the C5-6 while increased the ROM (degree) the stress (von-Mises, Mpa) at the adjacent intervertebral discs. Three designed prostheses had about the same stress values at the adjacent discs, but the metal-on-metal core design of Prestige showed the least ROM at the implanted segment, and metal-on polymer core design-Prodics-C had the largest ROM at the implanted segment.

In the extension simulation, all prostheses presented hyperextension than the intact condition(Fig. 6); the stresses were about similar in comparison with the intact one (Fig. 7). In the lateral bending condition, the ROM of each condition at each segment was very small; the mobile core designs showed adverse motion, and the fixed core design had similar ROM to the intact spinal column. In the axial rotation simulation, the prosthetic segment had almost twice ROM than the normal one for all types, although the ROMs were small in compared with the flexion motion.

In extension, the force on the facet joints were much higher in Prodisc-C and Prestige (Fig. 8).

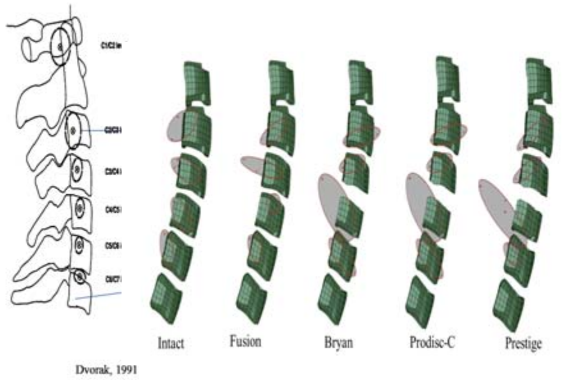

Fig.3. The instantaneous center of rotation in each simulation.

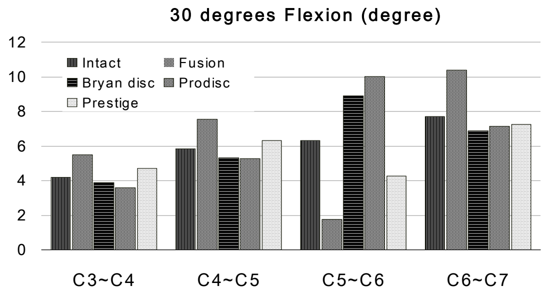

Fig. 4. The range of motion (degrees) at each functional segment in 30 degrees flexion.

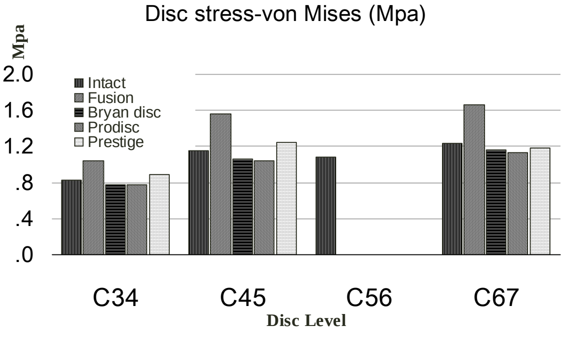

Fig 5: The von-Mises stresses at each intervertebral disc in 30 degrees flexion

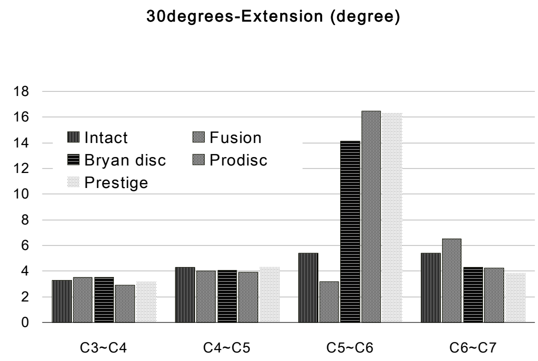

Fig. 6. The range of motion (degrees) at each functional segment in 30 degrees extension

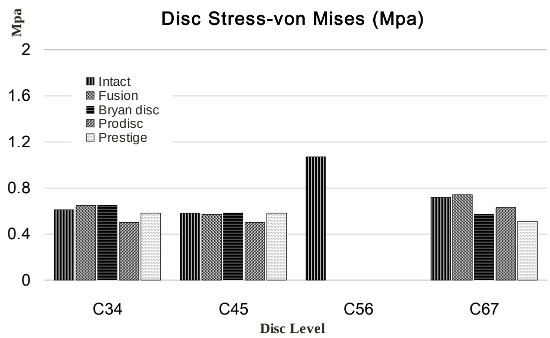

Fig 7: The von-Mises stresses at each intervertebral disc in 30 degree extension

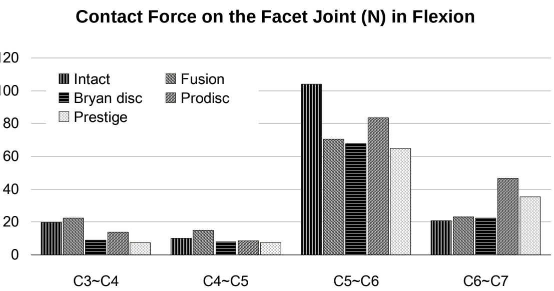

Fig. 8. Force acted on the facet joints in the conidion of 30 degrees extension.

IV. DISCUSSION and CONCLUSION

Unlike the spinal fusion, the stress level and the mobility in adjacent level didn't increase significantly for all types of disc arthroplasties but the ROM at C45 level did increase particularly in the fixed core design of Prodisc-C. The metal-on-metal design-Prestige limited the stress distribution and then resulted in stiffening the spinal column structure. The instantaneous center of rotation moved to near facet joints after cervical arthroplasties. The multi-articulation design of the Bryan Disc would induce better biomechanical effects for cervical spine than other designs.

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Theoretically, the motion at the fused functional segment of C56 should be zero degree, however, this study had the elastic modulus of endplate (500Mpa) much softer than the titanium cage (120Gpa) which might produce a micro deformation of bone and result in very small motion.

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