Special Issue of the 6th International Congress & Exhibition (APMAS2016), Maslak, Istanbul, Turkey, June 1–3, 2016

Parametric and Structural Analysis of Dynamic Anterior Cervical Biomaterial Plate Implant by Computer Aided Virtual Engineering

Ö. Karaçali*

Istanbul University, Faculty of Engineering, Department of Mechanical Engineering, Avcılar, Istanbul, 34320 Turkey

The main objective of this study was to examine the convenience of an accurate model of placement of dynamic anterior cervical plate, made of poly (methl-methacrylate) biomaterial, for testing spinal implants, and to determine the maximum fatigue values of differently surfaced Ti-5Al-2.55n spinal screw-rods, by finite element modeling. Anterior cervical biomaterial plates reduce the hazard for spinal cord injury and provide outstanding fixation for the anterior column to stop the relocation and slackening of screws-rods, using a cross-split screw crown that may be fastened into the biomaterial plate. This article reports about the hollow Ti-5Al-2.55n screw and cervical biomaterial plate system. The flexion movement of the spine implant was modeled, using finite elements method, to control the stresses and strains of the bone and screw interfaces to external forces, as well as motion of the vertebras. This computational engineering analysis was aimed to support patients suffering anterior cervical arthrodesis after a degenerative disease or trauma. The obtained data from this research may provide an essential base to estimate the stabilization quality and mechanical properties of biomaterial selection. Model of the region between C4 and C6 segments of vertebrae of cervical spine was produced to correct the stabilization of implant with non-linear material properties. Study of the cervical biomaterial implant has provided instantaneous virtual experiment of secure fixation with minimal complications before a real implant surgery, using computer aided virtual engineering.

DOI: 10.12693/APhysPolA.131.588

PACS/topics: 87.10.Kn, 81.70.Bt, 87.15.La

1. Introduction and background

Anterior cervical plate is a mechanical device of spinal fixation used to decrease the risk for spinal neck-cord injury and to provide outstanding fixation for the anterior column, to stop the relocation and slackening of rod-screws, using a cross-split screw head that can be fastened into the biomaterial plate [1–2]. Vertebral compression in the back of the body causes 1.4 million fractures in the musculoskeletal system worldwide [3].

In this study, a most negative scenario of vertebrectomy situation was considered, where the implant insert is embedded in vertebral body-like pieces and needs to bear presso-flexion. The quality of the spine bone determines the characteristics of the fixation screws and stabilizer plate implants [4]. Spinal implant systems for posterior fixation must be made of biomaterial with a good biological response and must have biomechanical stability [5].

In previous research, biomechanical computational models of the spine implants had not included the developed accurate nonlinear stresses and viscoelastic properties of the biomaterial, although spine implantation is a vital procedure [5–7]. Therefore, current research of dynamic anterior cervical biomaterial plate (DACBP) placement was performed for computation of strain and stresses generated within the cervical spine area during several back motions, for natural spine, using structural analysis method. The methods used for testing spinal instrumentation require a relatively long time for valid results of the new or improved implants [8]. Hence, the aim of the study is to determine the fatigue life of available commercial devices. The simulation of cyclic fatigue test reduces considerably the time used for testing the biomechanical properties of the spinal rods [9].

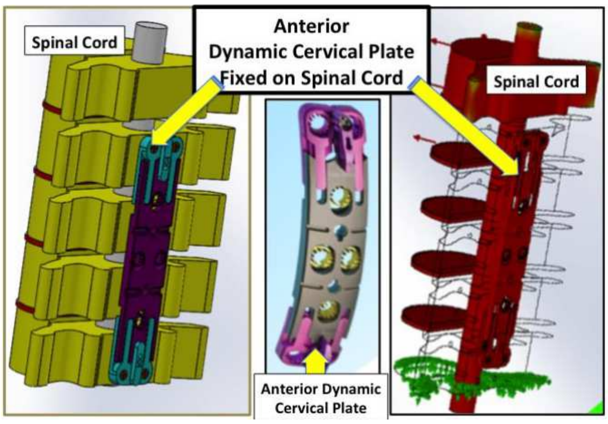

Fig. 1. Dynamic anterior cervical biomaterial plate and spinal cord.

A virtual implant was developed for the finite element modeling (FEM) of a spinal implant design. The implant under research was made from poly (methl-methacrylate)

*e-mail: ozdogank@istanbul.edu.tr

(PMMA) biomaterial. The implant disc is of symmetrical design with screwable attachments on its top and bottom surface. The disc is thus sandwiched between rigid plates. The goal of the analysis was the accurate simulation of flexion, extension, torsion and bending deformation modes. Heightening of anterior cervical plates, containing units that turn under compression and, on the other hand, maintain their place under pressure, was modeled using virtually constructed non-clinical experimental testing model shown in Fig. 1.

2. Analysis of dynamic anterior cervical biomaterial plate

Multi-step analysis was carried out by first simulating the pre-compression and then, simulating the extension, flexion, in the second step. The this research (a) the non-linear biomaterial properties of the PMMA had to be taken into account and (b) large expansion deformation along with multi-step analysis procedure had to be carried out. The parametric constrained part model of DACBP-back spinal (neck) fixation insert was designed according to ASTM F1717 standards. The experimental static test was employed for spinal rod-screw to validate the occurring strains.

The spine implant was examined for failure mechanisms and distortions. The FEM model had included representative topology with cervical spine features that consists of important motion and stiffness model with biomaterial non-linearity. The validation of model was made by estimation of the number of cycles to breakdown for 3.0 mm diameter thread.

3. Results

Load forces in range between 25 N and 400 N were applied during simulation according to the (ISO) 18192 and ASTM standards. Outcomes of the simulation test have shown that those unidirectional plates, clinched alongside flexion-extension, shown in Fig. 2, needed less movement. An additional reliable graft load was also observed when contrasted with bidirectional configuration.

Unidirectional movement of the DACBP has permitted pivotal load distribution between the implant and the vertebra plate, which permits unidirectional translation up to 2 mm for every level. Unidirectional development gives a constant compressive load between the end of plate and the bone implant in light of nonclinical testing. 4500 N mm flexion moment, 350 N compressive load, 350 N tension load were applied to predict the behaviour of the model. In Fig. 3, the equivalent stresses during loading of DACBP are presented. The moment and forces were applied to surfaces of vertebra C4 and C6. This loading of the segments was accomplished by solution using iteration method in ANSYS, version 17.2.

Then, a precise parametric analysis of the insert (screw head, rod) was carried out using Von Mises stress expansion. Maximal stress level was over 24 MPa in flexion situation. During simulation, the maximum stress level has occurred in the implant rod-screw zone, as shown in Fig. 3.

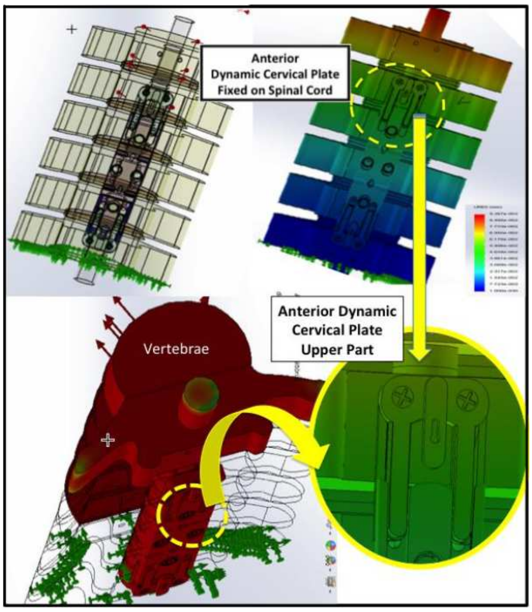

Fig. 2. DACBP system assembly used for spinal cord analysis.

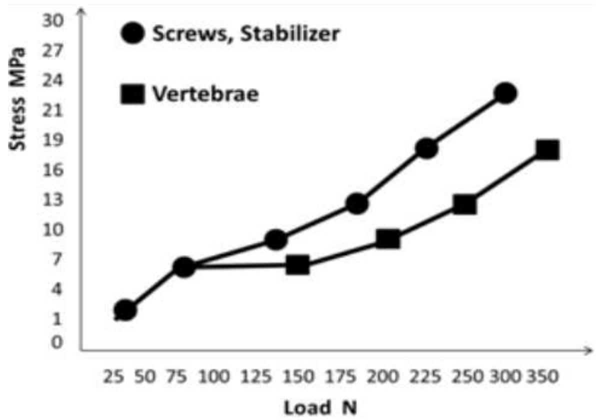

Fig. 3. Stresses during loading of DACBP.

In this research, equivalent Von Mises yield criterion [10] for elastic stress Eq. (1) and strain Eq. (2) were computed for the integrated screw and bone area. Computational simulation software has employed the effective Poisson's ratio v'. The bone and thread strain were evaluated to control the strain action distribution and to determine whether the bone was strong enough to cope with the loading stresses. The behaviour of C4 and C6 vertebra, corresponding to the equivalent stresses occurring during loading to DACBP, is presented in Fig. 3.

$$\sigma_{\text{Von Mises}} = \left(\frac{1}{2} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \right)^{1/2}, \tag{1}$$

$$\sigma_{\text{Von Mises}} = \frac{1}{1+v'} \left(\frac{1}{2} \left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2 \right] \right)^{1/2}. \tag{2}$$

The parametric analysis of screw head shows that the unsupported screw length and the cantilever arm parameters are the most stressed regions. Cyclic fatigue life testing simulation was applied at 290 and 440 N force levels. During experiment the displacements of biomaterial stabilizer and metallic parts of Ti-5Al-2.55n were 0.009 mm. Displacements for the biomaterials did not exceed the value of 0.12 mm. This analysis shows that the stiffness and stability of DACBP system within the loading limits is acceptable. The stabilizer and screws maximum equivalent stress levels were evaluated as 24 MPa. The C4-C6 segments were subjected to 2000 N load by stabilizer. On the other hand the applied stress induced in the vertebral parts has exceeded 180 MPa.

The computational analyses were carried out using the up-to-date modeling ANSYS software. The compressive testing, static tensile and cyclic fatigue testing were accomplished in the experimental work. ASTM F451-99a standards were used for static tensile and compressive testing, while ASTM standard F1717 was used for cyclic fatigue testing in 13–25 MPa stress ranges. As a finding of this research, the biomaterial strength of the DACBP was assessed by investigation of static mechanical properties and fatigue life.

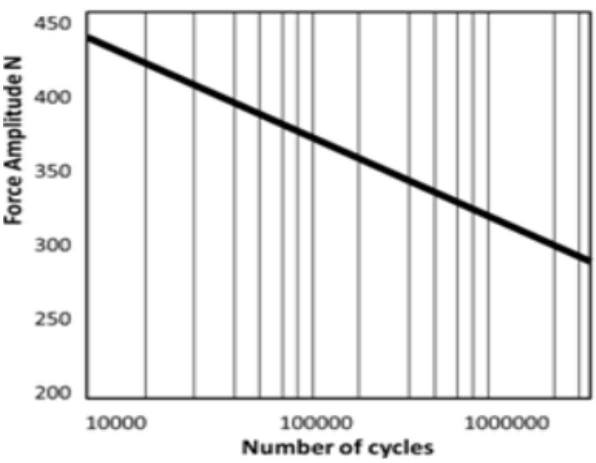

Fig. 4. The DACBP S-N cyclic fatigue test.

In this research, the static testing has shown the overall mechanical profile at in vivo loading conditions. The DACBP cyclic fatigue test simulation was run by loading for up to 1 M cycles, to define the Whöler's diagram in agreement with the existing standard, as shown in Fig. 4.

4. Discussion

The main outcome of this research was the excessive motion at the lower-end vertebra-screw junction in the DACBP model, caused by stresses, strain and fatigue. A method was developed and implemented for analysis of dynamic cervical plate during rapid flexural movements, which can be used to validate predictions of finite element model of the response of biomaterial implant to mechanical loading.

Morcher has initially stated the utilization of the securing plate in the cervical spine in 1986 [11]. After that, problems of plating, particularly releasing of the screws and the plates have diminished extraordinarily [12].

In the study of Lazennec et al. [13], the fusion rate was higher with dynamic plates. To be able to compare the results, the presented system has used a similar fusion rate for extendable wings. Previous studies of spinal implants did not consider the extendable parts that influence the results of the forces, according to their sites, number and shapes [14].

The link between spinal DACBP implant and the rod was the only link between extensions as mechanical joint. The simulations were more precise and reproducible than those in cadaver models [15]. Nevertheless, the experiment outcomes cannot predict the actual situation of in vivo application of the modified DACBP system. In the literature, the complications concerning the front cervical plate are restricted to releasing or breaking of the equipment and tracheoesophageal or neurovascular auxiliary wounds [16]. Different sorts of complications that may prompt to clinical indications are overlooked, and the emphasis is fundamentally made on unconstrained plates [17]. Furthermore, there are few reports concerning an extensive example estimate [5, 12, 13]. A great amount of difficulties experienced with cervical bolting plates are considered whereas only flexural and tensile mechanical phenomena are studied in these investigations. The DACBP system was implemented according to the ASTM F1717 testing standard to imitate standardized dynamic anterior cervical plate to analyze its biomechanical properties [17].

The DACBP system has provided positive results and it is seen that using dynamic plates is so advantageous, that it can be later used in the clinical settings. One significant limitation of this study is that the calculation of applied moments is prone to error given the large loads and small moments imposed in these virtual experiments.

In summary, his research shows promising results of the virtual application of expandable biomaterial parts for reconstruction of the cervical spine. Additional studies are necessary to examine the contradictory data concerning biomechanical efficiency of the expandable parts of the DACBP.

5. Conclusions

Computer aided virtual engineering shows that DACBP-anterior cervical fixation provides instant strengthening of the cervical spine, permitting preliminary restoration. In this research, mathematical modeling of biomechanical anterior cervical plate was applied to determine the stresses, strains and displacements during applied loading using FEM. The simulated loading was applied in experimental investigation of C4-C6 vertebrae units, the essential constraint for flexibility in neck spinal part.

The ASTM F1717 standards were used for DACBP experimental system to realize the biomaterial and procedures of static and cyclic fatigue testing in virtual environment. A new model was developed by design variables analysis and fatigue behaviour. The cyclic fatigue life of DACBP system was computed by S-N fatigue curve after FEM analysis. The results have revealed that with the increase of the load applied to the system, the fatigue life decreases. The outcomes of the research of spine implant between C4-C6 vertebral parts are very valuable for resolving the characteristics of the DACBP stabilizer and cervical PMMA plate and for choosing the metallic biomaterial.

Acknowledgments

This research is funded by Istanbul University, Turkey, project No: 24431 (The Scientific Research Foundation). Such support is greatly acknowledged.

References

[1] T.L. Johnston, E.E.K. Karaikovic, E.P. Lautenschlager, D. Marcu, *Spine J.* **6**, 667 (2006).

[2] M.A. Davies, S.C. Bryant, S.P. Larsen, D.B. Murrey, D.S. Nussman, E.B. Laxer, B.V. Darden, *J. Biomech. Eng.* **128**, 481 (2006).

[3] L.L. Barbera, F. Galbusera, T. Villa, F. Costa, H.-J. Wilke, *Proc. IMech E. Part H: J. Eng. Med.* **228**, 1014 (2014).

[4] S. Kurtz, M. Villarraga, K. Zhao, A. Edidin, *Biomaterials* **26**, 3699 (2005).

[5] P. Schleicher, R. Gerlach, B. Schar, C.M.J. Cain, W. Achatz, R. Pflugmacher, N.P. Haas, F. Kandziora, *Eur. Spine J.* **17**, 1757 (2008).

[6] J.A. Beltran-Fernández, L.H. Hernández-Gómez, G. Urriolagoitia-Calderón, A. González-Rebatú, G. Urriolagoitia-Sosa, *Appl. Mech. Mater.* **24–25**, 287 (2010).

[7] C.M. DuBoi, P.M. Bolt, A.G. Todd, P. Gupta, F.T. Wetzel, F.M. Phillips, *Spine J.* **7**, 188 (2007).

[8] D.S. Korres, I.S. Benetos, D.S. Evangelopoulos, M. Athanasssacopoulos, P. Gratsias, O. Papamichos, G.C. Babis, *Eur. J. Orthop. Surg. Traumatol.* **17**, 521 (2007).

[9] R.R. Campos, R.V. Botelho, *Eur. Spine J.* **23**, 298 (2014).

[10] T. Brandt, M. Morcher, I. Hausser, *Cerebral Artery Dissection* **20**, 16 (2005).

[11] D. Korres, V.S. Nikolaou, M. Kaseta, D. Evangelopoulos, K. Markatos, J. Lazarettos, N. Efstathopoulos *Eur. J. Orthop. Surg. Traumatol.* **24**, 125 (2014).

[12] J.Y. Lazennec, A. Aaron, O. Ricart, J.P. Rakover, *Eur. J. Orthop. Surg. Traumatol.* **26**, 9 (2016).

[13] M.J. Fagan, S. Julian, A.M. Mohsen, *Proc. Instn. Mech. Engrs.* **216**, 291 (2002).

[14] C.P. Yen, T.Y. Hwang, C.J. Wang, S.L. Howng, *Acta Neurochir.* **147**, 665 (2005).

[15] M. Driscoll, J.-M.M. Thiong, H. Labelle, S. Parent, *Bio. Med. Res. Int.* **2013**, 931741 (2013).

[16] L.L. Barbera, F. Galbusera, T. Villa, F. Costa, H.-J. Wilke, *Proc IMechE Part H: J. Eng. Med.* **228**, 1014 (2014).

[17] J.-B. Park, Y.-S. Cho, K.D. Riew, *J. Bone Joint Surg. Am.* **87**, 558 (2005).