Stress analysis of different types of cages in cervical vertebrae: a finite element study

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Abstract. To facilitate cervical fusion, cervical cages filled with bone or bone substitute are inserted between the vertebrae. To improve the subsidence of the cage and to avoid its post-surgical migration, design optimization concept is being employed in the present work. In this study, finite element method is being used to design several cervical cages with varying shapes and sizes. The cages are designed using Solid modeling software. Finite element analysis (FEA) optimization is done by varying the material properties as well as shapes and sizes of the cage. Stress analysis has been performed using FEA in the cervical vertebrae C3-C4 for the different types of cages.

1. Introduction
The human spinal cord comprises of cervical, thoracic, lumbar, sacral and coccyx. The cervical portion comprises of 7 vertebral columns. Due to ageing the vertebrae shrinks and as a result of which various cervical diseases, like cervical stenosis, occur in cervical portion. This leads to severe neck pain, clumsiness and many other complications in human body. Depending on the severity of the decaying cervical disc, the option of surgical treatment is employed. One of the surgical treatment options is replacement of the intervertebral disc by artificial disc. The other option is called anterior cervical discectomy and fusion. In this type of surgery in cervical spine, a cage is inserted between two vertebrae filled with bone or bone substitute which facilitates this fusion. The main limitations of this process are subsidence of the cage and possibility of the post-surgical migration of the cage. These two aspects depend on the material property and the design of the cage.

The factors that cause subsidence include (a) geometry of cages (b) different moment loadings (c) material used in cages (d) bone material density. It has been found that subsidence occurs due to extension, flexion, lateral bending and torsion as a result of the movement of the cervical spine [1]. After the removal of the compressive structures autogenous graft is employed to achieve fusion. Though the medical procedure has been standardized, there are scope for improvement of the clinical rate including rate of fusion can be improved through modifications in the design of implant of the cervical cage and the materials of the same [2],[3]. The cage materials can be ceramic, polymeric and metallic materials (mostly titanium alloys), though polymer materials are being preferred nowadays for its radio-transparency. Poly-ether-ether-ketone (PEEK) is the polymeric materials being mostly used [4],[5] and in the present work we have considered PEEK and its composites as the cage materials. Among the in threaded and non-threaded designs, nowadays more weightage is being provided non-threaded cages having wedge shaped profile.
To maintain foraminal height anterior cervical discectomy and fusion (ACDF) an intervertebral fusion cage is combined with anterior plate fixation [6]. The normal height of cervical disc could vary to restore the natural status of the cervical spine. When the height of the implant model is ≥2 mm then the overall range of motion (ROM) reduces by 19.2% in flexion, 19.4% in extension, 18.4% in lateral bending and 19.0% in axial rotation [7]. Due to increase in age the vertebral column collapses and as a result, various problems like rupture of bone, bone loss, fusion failure arise. To overcome these problems various biomechanical spine testing process are developed [8]. Finite element analysis (FEA) is an integral part of design of medical devices which includes various decompression and stabilization procedures simulated in FEA. It validates the model by applying various test load to find stress, strain and shear [9]. In this work the effect of cage design and the materials property (elastic modulus) on the distribution of stresses on the cage is studied. The moduli of the material, for five different design of the cervical cage are varied within the range achievable by using PEEK or its composites. FEA is done to assess the distribution of stresses in the cage for achieving better subsidence as well as lesser migration of the cage.

2. Methodology

2.1. 3-D Modelling

2.1.1. Image Processing. In the present study, cervical vertebrae (C3-C7) is selected and a 3D geometry is developed (Figure 1). A 45-year-old male is selected, and the preliminary data are collected from axial computed tomography (CT images). A designing software MIMICS is used to process the CT data and axial 2D slices were imported as a DICOM format. With respect to disc height, vertebral height and orientation, endplate thickness, facet shape and size and orientation various relevant geometric parameters are examined. By combined effort of automatic segmentation and manual trials bone tissues are separated from the entire CT scan volume. By using the topological smoothing algorithm embedded inside MIMICS software a 3D model is generated by segregating the segmented tissue followed by surface smoothing. With proper measurement of intervertebral space from CT data, the cages are manually created and are inserted into the solid model with the help of CAD software like Solid work. The curvature of the cervical spine is carefully maintained during the assembly process of the cage into the vertebrae model (Figure 1). After that the whole assembly is exported to IGES format for further processing.

Figure 1. Dicom images of CT scan data of cervical region.
2.1.2. Solid Modelling. Solid work is modeling software. Using solid works various 2D surfaces can be transformed into 3D surfaces. It uses various topological as well as geometrical information to complete a model. At first 2D model is being prepared by using the geometrical data. Extrude is used to convert it into 3D model by giving the thickness. Fillet is used to draw the curves between two planes. Various patterns can be used in Solid works. Multiple planes can be selected to draw the mirror images of any 2D as well as 3D drawings. Cut extrude is used to draw the holes in the extruded model.

![Diagram of a cervical cage model](image)

**Figure 2.** A representative model of cervical cage.

A representative 3-D solid modelled cervical cage is shown in Figure 2. The data has been collected from various literature surveys and solid modeled have been developed according to the geometric dimensions. Cervical cages with varied dimensions and Young’s modulus of the material are modeled according to L25 Orthogonal Array of Taguchi Design of Experiments. The details of the twenty-five models are described in Table 1.

### Table 1. Dimensions and moduli of the cage models.

| Design | Wall thickness (mm) | Partition thickness (mm) | Length (mm) | Width (mm) | Young’s modulus (GPa) | Height (mm) |
|--------|---------------------|--------------------------|-------------|------------|-----------------------|-------------|
| Cage 1 | 1.8                 | 1.8                      | 12          | 12         | 4                     | 5           |
| Cage 2 | 1.8                 | 1.9                      | 13          | 13         | 5.5                   | 5           |
| Cage 3 | 1.8                 | 2                        | 14          | 14         | 7                     | 5           |
| Cage 4 | 1.8                 | 2.1                      | 15          | 15         | 8.5                   | 5           |
| Cage 5 | 1.8                 | 2.2                      | 16          | 16         | 10                    | 5           |
| Cage 6 | 1.9                 | 1.8                      | 13          | 14         | 8.5                   | 5           |
| Cage 7 | 1.9                 | 1.9                      | 14          | 15         | 10                    | 5           |
| Cage 8 | 1.9                 | 2                        | 15          | 16         | 4                     | 5           |
| Cage 9 | 1.9                 | 2.1                      | 16          | 12         | 5.5                   | 5           |
| Cage 10| 1.9                 | 2.2                      | 12          | 13         | 7                     | 5           |
2.1.3. Finite Element Analysis. The finite element software (ANSYS 18.1) has been used to mesh the cervical model for the analysis purpose. For solutions of vertebral bones and cage, the higher order tetrahedral elements (SOLID187) are being used. In the analysis mesh convergence has been performed to 0.3 to 0.5 mm and the difference was achieved up to 4%. As a result, 0.3 mm was selected as global mesh size. In the present study boundary conditions are used as bonded between bone and cage material. The friction coefficient of the sliding contact is considered as 0.3. A compressive load of 50 N is applied on the top surface of the cervical vertebrae. The cervical cage model is kept in such a way to simulate finite element model which is nearer to the in vivo behavior of the cage implant. The materials properties used for the stress analyses are given in Table 2 and the cage Young’s modulus has been varied for five different levels between 4 to 10 GPa.

| Component  | Young’s Modulus(MPa) | Poisson’s Ratio |
|------------|----------------------|-----------------|
| Cortical bone | 20000                | 0.3             |
| Cage       | 4000-10000           | 0.4             |
| Ligament   | 4-10                 | 0.3             |

3. Results and discussions
One of the commonly used cervical cage shapes are used with varying dimensions and modelled using solid works. Twenty-five different dimensions of the cage are modeled as described in Table 1. In those five models, the cage materials Young’s modulus (E) are varied as 4 GPa, 5.5 GPa, 7 GPa, 8.5 GPa and 10 GPa. The values are chosen within a range which can be achieved by using PEEK with suitable reinforcement as the cage material. Figure 3 shows the representative images of the assembly of the cage within the cervical vertebrae, with stress, strain and shear stress analyses using FEA for a particular cage model.
Figure 3. FE models of (a) cervical cage with vertebrae, (b) stress at cervical cage, (c) strain at cervical cage and (d) shear stress at cervical cage.

The above analyses showed that the stress distribution varied with the size/dimensions of the cages as well as the modulus of the cage materials. As it is already mentioned that the foremost problems of the cervical cages are the subsidence and migration. Better the distribution of the normal stress the possibility of subsidence will decrease, and similarly better shear stress distribution will reduce the possibility of migration. In order to find the above, the maximum stress, maximum strain and maximum shear stress generated are measured from the FEA for all twenty-five cage models. Lower the generated maximum normal and shear stresses and strains, better will be stress distribution in the cage, and thus possibility of subsidence and migration will reduce. The maximum stresses and strain recorded are shown in Figure 4. Figure 4a shows the results of normal stress generated in the cage. Here the values varied from around one megapascal to three megapascals. Similarly the resulted strain also varied within a long range (Figure 4b). The shear stress generated varied between 0.1 MPa to 0.7 MPa. These results show that for different material property different cage model performs better (Figure 4c). Further it could be noted that the models having higher normal stress generally have lower shear stress generated and vice versa. As the target of the present work is to reduce both the stresses, these two conflicting objectives need to be addressed in a different way. To find the optimum model with optimum materials property to achieve highest stress distribution, further in-depth studies are required. A few results, where lower values of both the stresses could be achieved are shown in table 3.
Figure 4. FEA analyses results for all cages (a) Stress, (b) Strain and (c) Shear stress.
### Table 3. A few better results achieved from all the models.

| Wall thickness (mm) | Partition Thickness (mm) | Length (mm) | Width (mm) | E (MPa) | Stress (MPa) | Strain | Shear stress (MPa) |
|---------------------|-------------------------|-------------|------------|---------|-------------|--------|------------------|
| 2.2                 | 1.9                     | 12          | 16         | 8.5     | 0.928482    | 0.00011| 0.210842         |
| 2.2                 | 2.1                     | 14          | 13         | 4       | 0.932034    | 0.000237| 0.095385         |
| 2.1                 | 1.9                     | 16          | 14         | 4       | 1.03518     | 0.000262| 0.194393         |
| 2.2                 | 2                       | 13          | 12         | 10      | 1.04172     | 0.000105| 0.170193         |
| 2                   | 2                       | 16          | 13         | 8.5     | 1.1068      | 0.000134| 0.149625         |

### 4. Conclusion

The present work provides some initial studies on the role of materials property and cage dimension for achieving the better stress distributions. The results show that different dimensions are suitable for different material property (Young’s modulus). Thus, it is not possible to choose any particular dimension of the cage or a particular material for the best stress distribution. Further in-depth study is required to achieve the optimum design of the cage. The present study can be used to get some preliminary idea about the suitable dimensions of the cage for a particular material.

### 5. References

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