Stress and strain analysis of a new design of cervical intervertebral disc under daily activity

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Abstract

Neck pain one of the most common diseases, with intervertebral disc degeneration being one of the main reasons for such pain. As part of developing a surgical procedure for intervertebral disc replacement (artificial intervertebral disc), a new design of intervertebral disc (cervical vertebra) was created using biomedical steel L 316, for the part fixed on the intervertebral disc, and polyethylene as the intermediate part between the two metals, which also biomedical material. This is designed to absorb and redistribute heavy loads from the vertebrae in a more equal way to reduce pressure; the symmetrical design offers many benefits where the intervertebral replacement is installed in an appropriate manner. Taking into account the different circumstances of surgery, three types of load were considered: the first was compressive, the condition when the neck is at rest and load is completely vertical without any moment; the second was extension, as the head moves upward and force and moment is applied; and the third was flexion, when the head moves downward and opposing force and moment is applied. By using Ansys 18.2, both stress and strain on the artificial intervertebral components were assessed, which showed that, under movement, the stress was much larger than when at rest due to the inflecting of moment on the artificial intervertebral disc. The soft polyethylene section suffered some degeneration and damage; however, the rounded shape of the parts allowed the load to be distributed more regularly, and the maximum value of the stress was seen at flexion at 256 mpa, as compared to 42 and 152 mpa for compression and extension, respectively. The maximum value of the strain at flexion was 0.076 as compared to 0.0689 and 0.00619 for compression and...
extension, respectively. Comparison between the new design and the currently used ProDisc implant showed that the strain on the former was lower, but that the stress in extension and flexion was higher.

1.1 Introduction

Many people will suffer from neck pain some time in their life, whether due to disc, bone, muscle, or other vertebral issues. The weight of the head and its fast movement means that the improper positioning is frequently the main reason for intervertebral damage which can lead to neck pain and disease.

Disc degeneration one of the most dangerous of these, and it may require surgical intervention, despite multiple non-surgical attempts to reduce or eliminate pain.

The history of the ProDisc device began in the late 1980s, when Marnay developed the initial prototypes. The current ProDisc implant relies on a single articulating interface between the superior metallic endplate and the superior surface of the polyethylene core. It is a semi constrained device, with the polyethylene core (bearing surface) being fixed to the inferior endplate but not to the superior endplate, as shown in figure 1 [1].

The range of movement of the segment of the spine is often a standard clinical measure, as noted in literature [1-4], but by using CAD, further biomechanics analysis can be undertaken. Finite element methods (FEM), a new computer technology, has also helped by developing advanced numerical analysis models that can be used not only for the spine [1] but also use in dental prostheses [2], dentinal microtubules [4], and hip and knee joints [3-5]. The combination of medical and engineering knowledge offers an excellent basis for the analysis of
biomedical factors to assist rehabilitation or optimal condition of spinal treatment. The development of engineering simulation models and analysis of biomechanical motion can also be easily amended to fit the patient’s needs, with biomechanical engineering tailoring solutions to patients’ conditions.

Some biomedical problems can be solved by using CT micro-computed tomography [5-8] to develop an image of the human spine from CT scans, helping to identify the area that must be treated by implanting an intervertebral artificial disc more accurately.

A wide type of biomaterials can be used for such implant applications [1, 3, 9-13], and the finite element method simulator can thus be used to select the proper material.

The aim of this study is to determine the effects of using a 316L stainless steel alloys and polyethylene implant on the cervical vertebral section by analysing both stress and strain using Ansys 18.2 under three motions (compression, extension, flexion).

### 2.1 Structure of the spine

The human spine supports the body, and its vertebrae is divided into groups formed of seven cervical vertebrae, twelve thoracic vertebrae, five lumbar vertebrae, five sacrum vertebrae, and four coccyx vertebrae.

The movable vertebrae are found in the cervical, thoracic, and lumber regions.

There are generally twenty- three vertebrae in the human spine, connected by discs between the vertebrae [15-16].

An example connection between vertebrae is shown in fig 2.

![Figure 2 Connection of two vertebrae, lateral view [17.](image)]
An example cervical vertebra [18] is shown in Fig. 3.

The intervertebral disc consists of atherosclerotic nuclei, a boundary plate, and dozens of layers of fibrous rings of a different material.

The major jobs of the disc are to ensure the stability of the human spine, to link the vertebrae, and to perform vibration damping [20, 21].

3 Materials and methods

Due to the large loads carried by cervical vertebra while a person is moving or sitting, CT micro-computed tomography was used to measure patient vertebra, so that these could be modelled using solid edge ST8 (CAD Software) in order to design an artificial disc that fits the patient’s needs, with upper and lower pads made of stainless steel 316L, and a polyethylene layer. The size of the artificial intervertebral disc must match the patient’s vertebrae as shown in figure 4.

Two materials were used for this study: stainless steel 316L and ultra-high-molecular-weight polyethylene. The mechanical properties of the materials are given in table 1.
Table 1. Mechanical properties of tested materials.

| Material                        | Element                        | Young’s modulus [MPa] | Poisson’s ratio | Density g/cm³ |
|--------------------------------|--------------------------------|-----------------------|-----------------|---------------|
| Stainless Steel 316L           | Upper, bottom pad              | 190000                | 0.32            | 8.00          |
| Ultra-high-molecular-weight polyethylene | Insert                        | 1070                  | 0.41            | 0.95          |

Figure 4. Model of the artificial intervertebral disc with dimensions corresponding to CT results [8]

The finite element method model was adopted using the Ansys 18.2 simulator.

The lower pad of the artificial intervertebral disc was fixed as rigid and the load was applied to the upper pads so that an investigation of the material effect could be undertaken. The upper and lower plate pads were made of stainless steel 316L, with a polyethylene insert.

The element type for Ansys analysis was thus Solid 95.

The artificial intervertebral disc was analysed using the finite element method based on the position of the load and moment applied to the upper pads and the lower pads being fixed, assuming the body weight of a human to be about 100 kg.
The movement of the vertebrae modelled were extension, flexion, and compression [22].

The mesh was generated using 16,533 nodes and 10,082 elements as shown in fig 5; the load and fixed disc are shown in fig 6.

Figure 5. Disc Mesh

Figure 6 a) Disc load                                             b) Disc support

4. Result and Discussion

The load and moment were chosen to replicate daily activity and maximum load on the distribution of an artificial intervertebral disc.
The distribution on the artificial vertebral disc of stress and strain was determined by using finite element method analysis, as shown in Figs 7 to 9. The load and moment applied to each pad are listed in Table 2, with the maximum stress and strain values dependent on the von Mises theory of failure.

The result showed that the maximum stress and strain were found in the polyethylene insert layer, with concentrated loading in the tip of the inset and less modulus of elasticity compared with that seen in the stainless steel 316L alloys.

The corrosion resistance of the polyethylene is much higher than that of stainless steel 316L due to the modulus of elasticity and dynamic motion of the insert layer. The taper of the pads also affects this, which may require modification of the insert layer or the selection of another material for this design.

| Movement | Force (N) | Moment (Nm) |
|----------|-----------|-------------|
| Compression | 92        | 0           |
| Extension   | 40        | 1           |
| Flexion    | 91.2      | 1.3         |

Table 2. Disc load

Figure 7 a) Stress Compression b) Strain Compression
As a comparison, a ProDisc stress and strain analysis is shown in figures 10 to 12.
Figure 10 a) Stress Compression  

b) Strain Compression

Figure 11 a) Stress Extension  

b) Strain Extension
A comparison of the new design and the ProDisc design is seen in table 3

| Movement | New design (stress) Mpa | ProDisc (stress) Mpa | New design (strain) | ProDisc (strain) |
|----------|-------------------------|----------------------|---------------------|------------------|
| Compression | 42                     | 25.6                 | 0.00619            | 0.0109           |
| extension  | 156                    | 114                 | 0.0689             | 0.064            |
| flexion    | 256                    | 95                  | 0.0766             | 0.07             |

**5.1 Conclusions**

The main target of this study was to determine the effect of stainless steel 316L and polyethylene insert implants in cervical vertebrae and to compare the new design and the existing ProDisc design.

Using Ansys 18.2, a stress and strain analysis of the artificial intervertebral discs was undertaken using three different positions: extension, flexion, and compression.

The model was generated using CT micro-computed tomography scans of the patient spine.

Using the finite element method, the major stress was found to be in the polyethylene insert, which may become damaged more rapidly than the stainless steel pads; two tapered metal edged implants...
were found to be better than a single edge model in terms of vertebral distribution of stress and strain and thus to offer more stability to the artificial intervertebral disc.

The strain on the new design of disc is lower than that on the ProDisc design due to the more regular distribution of forces and moment in the new design; however, stress in extension and flexion are lower in the ProDisc due to its thin upper plate layer.

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