Mechanical Vulnerability of L3-L4 Spinal Segment after Fusion Surgery Utilizing Dynamic Stress Analysis

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Introduction: Pedicle screw-based spine fusion has been employed as a felicitous approach for treatment of degenerative lumbar spinal diseases. Although the pedicle screw designs and fixation techniques have progressed, many clinical studies have reported the adjacent segment degeneration (ASD) and several other adverse effects after surgery. In the case of fixation techniques, the use of semi-rigid rods such as Polyarylether ether ketone (PEEK) rods can be an appropriate substitute for rigid fusion instrumentation. However, the biomechanical effects of using viscoelastic PEEK rods for use in clinical studies are still unclear. **Materials and Methods:** In this study, the effects of using two pedicle screw-based stabilization systems, i.e. viscoelastic PEEK rods and elastic Titanium rods, on the stress distribution in L3-L4 intervertebral disc and the surrounding osseous tissue were investigated. An L1-L5 lumbar region was modeled. Subsequently, a mild degenerative disc disease was simulated in the L3-L4 lumbar level. Next, an axial cyclic torque was applied to the model. **Results:** The results showed that, at the end of the loading cycle, the maximum von-Mises stress in the L3-L4 intervertebral disc as well as the overall value of stress in the surrounding osseous tissue were slightly greater in the viscoelastic model as compared to the elastic one. Nonetheless, the stress distribution contours and the location of maximum stress were different in the two models. **Conclusion:** It can be postulated that the vulnerable areas of lumbar bone are different in two models.

Keywords: Dynamic Stress; Fusion Surgery; Finite Element Analysis; Mechanical Vulnerability

Introduction

One of the most common reasons of back pain is the degenerative disk disease (DDD), which produces adverse effects on the patients' quality of life (1). Pedicle-based rigid fixation surgery is a standard therapeutic approach to strengthen the position of the spine and restore its stability. However, the adjacent segment degeneration (ASD) causes several problems after surgery including pain increase, herniation of the nucleus pulposus, acquired spondylolysis, spinal stenosis of the posterior facet joints and redo spinal surgery (2). Therefore, the problem has remained as an important complication in fusion surgery. To overcome this problem, different implants were examined in terms of material properties and structural design (3). Such implants can be exerted into spines through either semi-rigid instrumentation or dynamic stabilization. With the aim of providing flexibility for different segments and improving the load applied to them, these systems can control abnormal motion, limit unwanted effects on spinal functional segments and lessen the negative effects on the adjacent segments (3). However, the biomechanical effects of these two types of systems have not yet been well understood. The previous studies investigated the effects of material types on the implant performance *in silico* and *in vivo*.

Polyarylether ether ketone (PEEK) implants have shown promising potentials in biomedical applications. PEEK is a semi-crystalline linear polymer with favorable mechanical properties which has been utilized in various medical applications including fusion and orthopedic surgery. In the degenerated disk replacement surgery using cages, PEEK cages have shown desirable outcomes in maintaining intervertebral height and yielded more favorable clinical results than those of titanium cages in a long-term follow-up study (4, 5).

Clinical data regarding utilization of PEEK rod in spinal fusion surgery are limited and there is a lack of consistency between studies in this area. Furthermore, strong evidence is not yet available even on the short-term performance of PEEK rods after fusion surgery. Further studies are required for investigation the effects of using PEEK rods as a feasible instrumented fusion (6).

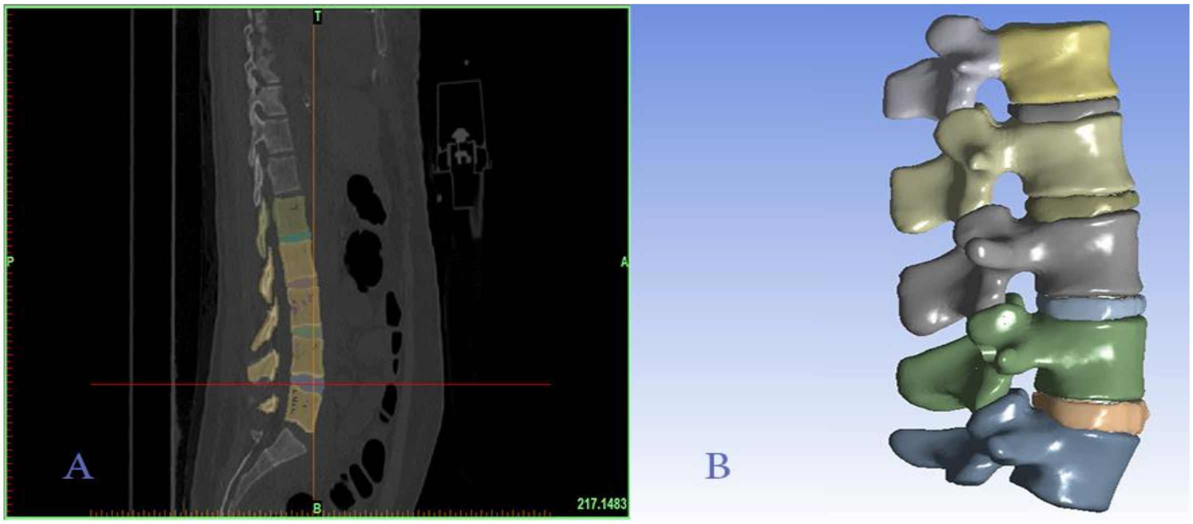

Figure1. Constitution of CAD model of lumbar spine. A) Sagittal section of CT images; B) The 3D model of the lumbar spine including nucleus pulposus and annulus ground substance

It has been reported that the use of elastic PEEK rod in fusion surgery allows more range of motion in the model compared to the elastic Titanium Rod, which in turn can reduce negative clinical outcomes; however, clinical and follow-up studies are in demand to validate these results (7). In another study, the biomechanical effects of fixation rod on the adjacent spinal segments of L3-L4 were investigated in fusion surgery. The findings suggested that the use of elastic CFR-PEEK rods can lessen the risk of pedicle screw failure as compared to the rods fabricated from other material types (8).

However, the effect of considering viscoelastic properties for PEEK rods on the adjacent segment levels is not yet well understood, mainly due to the fact that most studies in this area have only modeled the PEEK rods as an elastic material. A viscoelastic material such as PEEK shows time-dependent behavior in response to mechanical stimuli. Our previous studies indicated that the viscoelastic properties of biological tissues can affect dynamic stress distribution within tissue when subjected to external mechanical forces (9)-(10). In this study, finite element analysis was employed to investigate the stress distribution in L3-L4 spinal segment when the segment was fixed with viscoelastic PEEK rods and elastic titanium ones in fusion surgery.

Materials and Methods

3-D design of the vertebrae, lumbar disc, pedicle screw and rods

CT images of L1-L5 lumbar bone for a 25-year-old individual without any pathologies , 672 slices at the thickness of 1.25 mm, were imported to the Mimics 19 software and a 3-d model of the vertebrae and discs (L1-L5) was made as shells. Then, the model was imported into the 3-Matic software to smoothen the surfaces and solid (volumes) (Figure 1). Next, the developed model was imported to the ANYSY Workbench18.2 software for finite element analysis. According to the previous published studies, the intervertebral disk was modeled as an annulus ground substance with fiber layers and nucleus pulpous (11), (12). The cancellous bone was also modeled for each vertebrates in which it was enclosed with a cortical shell with the thickness of 0.7 mm (13).

Pedicle and radial screws were designed using CATIA V5.21software, 3D computer-aided design (CAD) software. A type of spinal pedicle screw, called cylindrical and solid design (Cy-SD), with the dimension of 20 mm in diameter and a screw with the length of 45 mm were designed as descried previously (14). The screw threads of the pedicle were removed and simplified, and the screw was considered as a nail, assuming that the screw was firmly fixed to the vertebrate as it generally happens in successful surgical operations (8). A rod with the diameter of 6 mm was also designed (15) (Figure 2C). To simulate L3-L4 spinal segment due to fusion surgery, pedicle-screws were inserted inside the L3 and L4 vertebrae, and the two rods were fixed to the screws.

FE Simulation and boundary conditions

After exertion of each of the pedicle screws in the L3-L4 spinal segment, two different models with geometric shapes and identical boundary conditions with different mechanical properties were modeled. In the elastic model, the bones, pedicle screws and rods

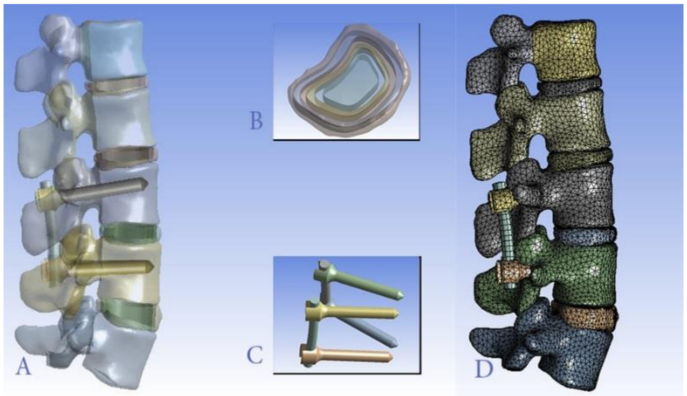

Figure 2. Assembly of lumbar spine. Pedicle screws and rods (B); Designing of annulus fibers; (C) Designing of pedicle screws and rods; (D) The finite element model of the whole lumbar spine L1-L5, pedicle screws, and rods after fusion surgery

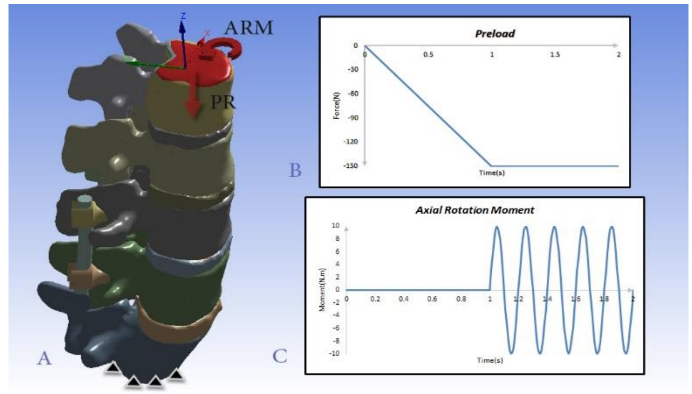

Figure 3. A) The applied loading and boundary conditions of the developed finite element model; B) A 150 N preload was applied to the superior surface of the L1 vertebral body; C) The cyclic torque with the amplitude of 10 N.m and frequency of 5 Hz was applied to the superior surface of the L1 vertebral body.

were considered to be homogeneous and isotropic solid. A healthy disk was also modeled as a hyperplastic Mooney-Rivlin material (16). For the degenerative disk, the material behavior of annulus ground substance and nucleus pulpous were assumed to be hyperplastic Mooney-Rivlinand elastic respectively. It should be noted that the grade for the degenerative disk was considered as Mild , a mild degenerative disc disease at the L3-L54 lumbar level (17). On the other hand, the rods and the PEEK pedicle screw were assumed to be linear viscoelastic solid. Prony series were used to represent the viscoelastic characteristics of PEEK as it has been widely utilized to describe viscoelastic response of various polymeric materials (18).

The obtained geometry was meshed using ANSYS workbench 18.2. The Vertebrae bone, pedicle screws, and intervertebral discs were filled with 3-D 10-Node Tetrahedral Structural & 3-D 20-Node homogeneous Structural Solid element. The final models were comprised of 123203 and 197928 nodes (Figure 2D).

The stimulation process was divided into two steps. In the first step, to simulate the weight of the upper body and the contractions of the abdominal muscles, a compressive load with the magnitude of 150 was applied to the upper level of the L1 vertebrate (19), (20) (Figure 3B). After the model was stabilized with this preload, after the first loading second, this stage was used as the initial condition for the next step. Then, a cyclic vertical torque with the magnitude of 10 N.m and the frequency of 5 Hz was applied to the upper surface of the L1 vertebrate for 1 second. Transient dynamic analysis by ANSYS workbench 18.2 was performed for both elastic and viscoelastic models to evaluate the dynamic stress distribution in the degenerative disk and the surrounding osseous tissue.

The contact surfaces of the vertebrae with the intervertebral discs as well as the pedicle screws were considered as tie. The bottom surface of the L5 vertebral body was held rigidly fixed for all models.

Results

The numerical results obtained from dynamic analysis at the L3-L4 level were investigated, which included the stress distribution in the degenerative intervertebral disk and the surrounding osseous tissue. Figure 4 shows the distribution of dynamic stress at the final stage of loading in the superior surface of L4 as well as the inferior surface of L3 vertebrae. Figure 4A, B and Figure 4C,D illustrate the von-Mises stress for the viscoelastic PEEK and elastic titanium models respectively. As can be observed, at the end of loading stage, the maximum value of stress in the viscoelastic model is 0.49397 MPa whereas this maximum value for the elastic model is 0.44304 MPa.

Figure 4B and D show the distribution of dynamic stress at the final loading time (second seconds) in the superior surface of L4 vertebrate. In the viscoelastic model, the maximum value of stress is detected to be 0.53925 MPa, while this value in the elastic model is 0.44897 MPa. In addition, for both models, the regions that stress concentration occurs were the same. In Figure 5, the distribution of dynamic stress in the L3-L4 intervertebral dick at the end of the loading cycle is shown. As can be noticed, the dynamic response shows a slight increase in the magnitude of stress for the viscoelastic model. The magnitudes of stress for the viscoelastic and elastic models are 1.0243 MPa and 0.90118 MPa, respectively.

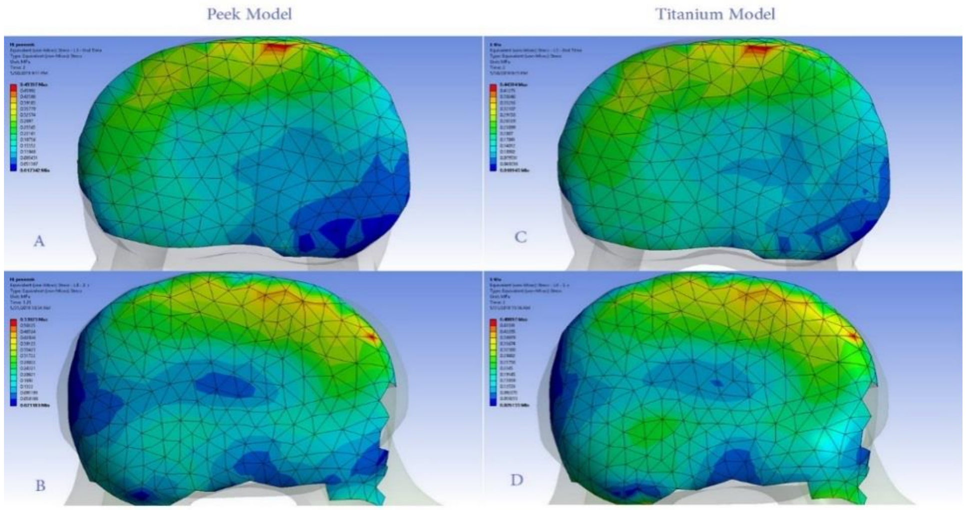

Figure 4. The stress contour at the inferior surface of L3 vertebrate bone at 2s in (A) PEEK and (C) Titanium models. The tress contour at the superior surface of L4 vertebrate body at 2s in (B) PEEK and (D) Titanium models

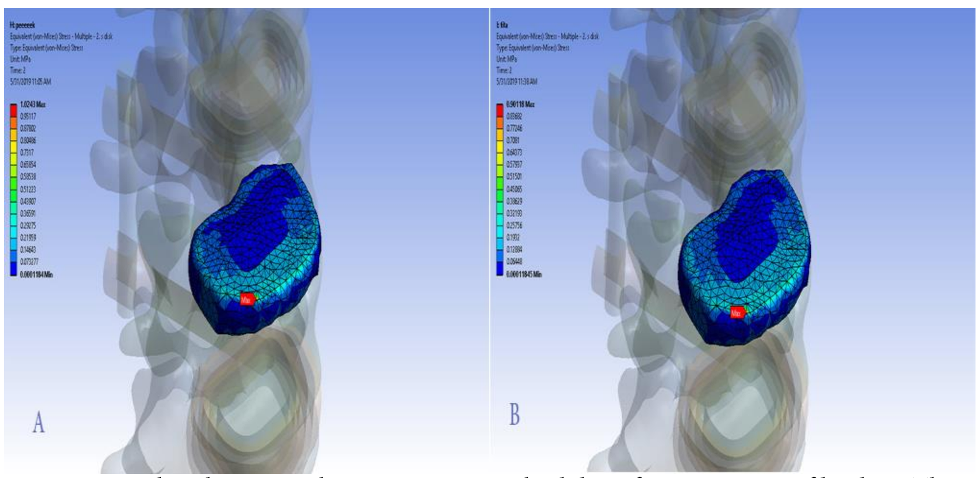

Figure 5. The von-Mises stress distribution in the L3-L4 intervertebral disc after passing 2S of loading. The corresponding stress contour in the (A) viscoelastic PEEK rod model and (B) elastic Titanium rod model.

Discussion

Pedicle-screw-based spine fusion using fixation rods is a widely-utilized technique in the field of spinal surgery. This standard surgical technique with the aim of improving lumbar spine stability yields desirable clinical results. However, several important complications of spinal fusion, i.e. high rate of ASD, have been reported (6). The finite element method in the field of biomechanical studies has long been used to bridge between clinical outcomes and predicted biomechanical results. Several studies have investigated the biomechanical response of using PEEK pedicle-screws for fusion surgery. It was reported that PEEK rods for semi-rigid fusions provided similar stiffness and stability as compared to Titanium ones, while it improved the stress distribution within different segments and reduced the likelihood of mechanical failure. It has also been shown that, in comparison to the titanium rods, utilization of PEEK rods can reduce the negative effects of disk and facet degeneration in the adjacent segments (6), (7). But, to the best of our knowledge, the long-term effects of using PEEK rods in fusion surgery have not yet been investigated. In the finite element studies, representing the proper mechanical properties of a material can markedly improve accuracy of the results. Mostly, PEEK rods have been considered as elastic materials in the previous studies and their viscoelastic behavior have been neglected (21), (22), (7), (23). Herein, we investigated the effect of viscoelastic properties of PEEK rods on the dynamic stress distribution in the adjacent segment levels in comparison to the Titanium rods with elastic properties. In was found that, at the end of loading cycle, the dynamic stresses in the viscoelastic model are greater than those of the elastic model. The stress in the inferior surface of L3 vertebrate and also the superior level of the L4 vertebrate are slightly greater in the viscoelastic model as compared to the elastic model.

Conclusion

According to the results, the stress distribution and the location of maximum stress differ in the models, thereby concluding that the two models can experience different mechanical damages.

Conflict of Interest: 'None declared'.

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