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COMPRESSION MODELING OF BIOMEDICAL POLYURETHANES

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Abstract. Lower back pain is one of the most common medical problems, and in the 80% of cases it is associated to lumbar disc degeneration. Nucleus replacement appears as a good alternative to current surgical procedures since it is less invasive and can restore normal biomechanics. In the present work, the compressive mechanical behavior of specially designed polyurethane elastomeric foams was studied. A constitutive model capable of describing highly compressible elastomer mechanics was adopted. In order to characterize the implant response in an elastic confinement configuration, the following extreme cases were studied: uniaxial and confined compression. Previous studies revealed that the constitutive model had to predict the material response in different stress states simultaneously. In this case the problem becomes incompletely defined and is of an inverse type, so the computational implementation became mandatory. Consequently, an inverse program was developed. By successive finite element simulations, the program adjusts the model parameters using a trust-region algorithm. Finally, a simple finite element model of an intervertebral disc was constructed to simulate disc biomechanics in intact, denucleated and implanted conditions.

1 OBJECTIVE

The aim of this work is to characterize the compressive mechanics of polyurethane foam designed to replace nucleus pulposus of the intervertebral disc. Once the mechanical response is properly described, a finite element study will be carried out in order to analyze the disc biomechanics.

2 INTRODUCTION

2.1 Anatomy

The intervertebral disc is the largest avascular tissue in the human body. Each disc transmits and distributes large loads on the spine, while allowing for the necessary flexibility of the structure (Figure 1). The intervertebral disc is mainly composed of three different tissues: the central core, the nucleus pulposus, surrounded by the outer annulus fibrosus, and the upper and lower cartilaginous end plates.

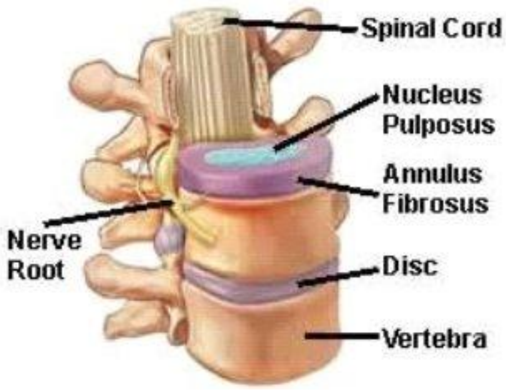

Figure 1: Vertebraes and intervertebral discs.

2.2 Biomechanics

The spine is mainly subjected to compressive loads. In this condition, the nucleus transfers axial loads to the annulus by creating an intradiscal pressure and tensing the annulus fibers (Kapandji, 1998). The load is transmitted approximately 75% by the nucleus and the remainder 25% by the annulus.

With age degeneration, nucleus becomes more fibrous than fluid-like and the internal pressure decreases. Additionally, damage on annulus fibrosus may cause leakage of nucleus substance. These factors contribute to disc degeneration and alter the natural load transfer phenomenon.

2.3 Constitutive Model

The Ogden-Storakers model (Storakers, 1986), or Hyperfoam, was specially designed to describe highly compressive materials, as the case of the polyurethane foam studied in this work. Considering a first order model and neglecting thermal effects, the strain energy density has the form given by Eq. (1).

$$W = \frac{2\mu}{\alpha^2}\left[\hat{\lambda}_1^{\alpha} + \hat{\lambda}_2^{\alpha} + \hat{\lambda}_3^{\alpha} - 3 + \frac{1}{\beta}\left(J_{el}^{-\alpha\beta} - 1\right)\right] \tag{1}$$

Where μ, α and β are the constitutive parameters. β is related to the effective Poisson's ratio by Eq. (2).

$$\beta = \frac{\upsilon}{1 - 2\upsilon} \tag{2}$$

The nominal stress, *Tj*, given by Eq. (3), is obtained by taking the derivative of the strain energy density (Eq. (1)) with respect to the corresponding elongation.

$$T_j = \frac{\partial U}{\partial \lambda_j} = \frac{2\,\mu}{\lambda_j\,\alpha}\left(\lambda_j{}^{\alpha} - J^{-\alpha\beta}\right) \tag{3}$$

The three main reasons for choosing Hyperfoam model were: availability in commercial finite element codes, ability to model highly compressible elastomers and because it was widely used to describe mechanical response of polyurethanes (Mills, 2006) and other similar foams (Li et al., 2009).

3 METHODS

3.1 Mechanical Characterization

In service, the implant is elastically confined by the annulus fibrosus. The present work studied the extreme confinement configurations: uniaxial compression (no lateral restriction) and confined compression (complete lateral restriction).

The tests were performed using a universal testing machine Instron 4467 at crosshead speed of 1mm/min. Specimens of 15.90 mm diameter and 9.80mm height were employed.

Confined compression test was carried out using specially designed equipment (Figure 2). This equipment consists in a bronze barrel (1), which acts as the confinement chamber, of 15.90mm internal diameter and 44mm external diameter bolted to an inferior stainless steel plate (2). A superior stainless steel plate (3) and a piston (4) of 15.90mm diameter complete the equipment.

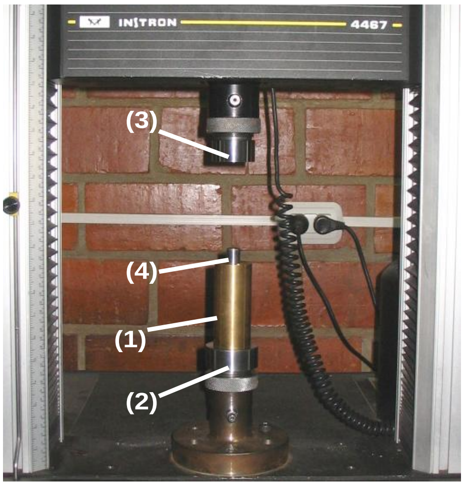

Figure 2: Confined compression equipment (Sachetti, 2008).

The specimen is placed into the chamber and the superior plate pushes down the piston, applying the axial force on the material sample. Since the chamber stiffness is orders of magnitude greater than foam stiffness it is reasonable to assume there is no lateral expansion.

3.2 Finite Element Modeling

Axisymmetric models were employed to simulate mechanical tests and intervertebral disc biomechanics. The mechanical properties of cortical and cancellous bone are well established and were taken from literature (Goel et al., 1995). The literature is more varied for the experimentally reported nucleus and annulus material properties (Ferguson et al., 2004; Nagy and Gentle, 2001). The non linear anisotropic behavior of fibrosus annulus was simplified and it was modeled as a linearly elastic solid. This consideration is a reasonable assumption because only uniaxial compression loading was analyzed in this study. The anisotropic nature of the annulus becomes relevant to mechanical behavior in other loading modes such as torsion and bending. The Young moduli and Poisson's ratio were obtained from values of porcine cartilages reported by Jin y Lewis, 2010.

Since even degenerated nucleus still has fluidic components, adult nucleus is better modeled as a linearly elastic solid with a high Poisson's ratio. To simulate the natural load transfer phenomenon effectively, the highest possible Poisson's ratio was used for the nucleus. Regarding the cortical and cancellous bone, previous work can be found considering both as linearly elastic solids (Massey, 2009). The material property definitions used in the model for cortical bone, cancellous bone, nucleus pulposus and annulus fibrosus are given in Table 1.

	E [MPa]	**ν**
Cortical Bone	12000	0.3
Cancellous Bone	100	0.2
Nucleus Pulposus	1	0.5
Annulus Fibrosus	0.45	0.46

Table 1: Elastic properties employed in finite element modeling.

The nucleus implant was modeled as Hyperfoam material using the constitutive parameters obtained from the inverse program (Table 2).

3.3 Inverse Modeling

The inverse modeling approach process is shown in Figure 3. It consists of three main parts: experimental tests, finite element modeling and inverse program.

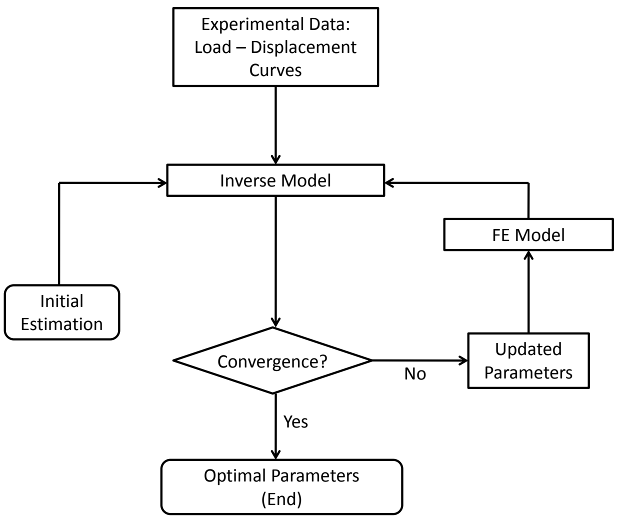

Figure 3: Flow chart showing the inverse modeling.

4 RESULTS AND DISCUSSION

4.1 Model Calibration

The inverse program converges to the solution showed in Table 2. The inverse modeling from experimental data of one test configuration was not satisfactory. Using uniaxial data, the model predicted lower loads than those obtained in the confined configuration. In case of confined data calibration, loads much higher than those of the uniaxial test were observed. The axial load that the cell senses is affected by the different boundary conditions corresponding to each test. Since the Hyperfoam is a phenomenological model, it is not capable of capturing the dependence of material volumetric response with boundary conditions, and consequently it fails predicting a different stress states.

μ [MPa]	α	ν
0,60	0,01	0,39

Table 2: Parameters obtained from uniaxial and confined compression tests.

When both test configurations data were considered, the inverse program achieved parameters capable of capturing the material mechanical response with an acceptable error for both stress states. The results are presented in Figure 4.

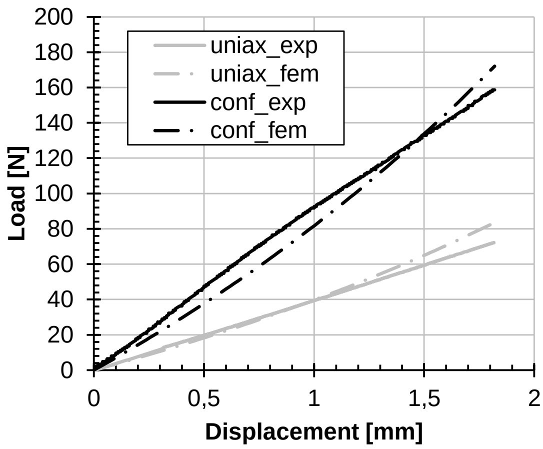

Figure 4: Fitting of experimental data with Table 2 parameters.

4.2 Finite Element Study of Intervertebral Disc

Figure 5 shows Von Mises stress distributions for the three simulated conditions: intact, denucleated and implanted disc. Peak values of Von Mises stress in nucleus corners are observed in both cases because of the geometrical restriction of adjacent vertebraes and inner annulus layers. There are some differences between intact and denucleated condition stress profiles in the annulus, while the implanted condition is more comparable to the intact condition for the stress distribution in the annulus. Also, it is interesting to note that the implant presents a more uniform and higher stress distribution than the natural nucleus.

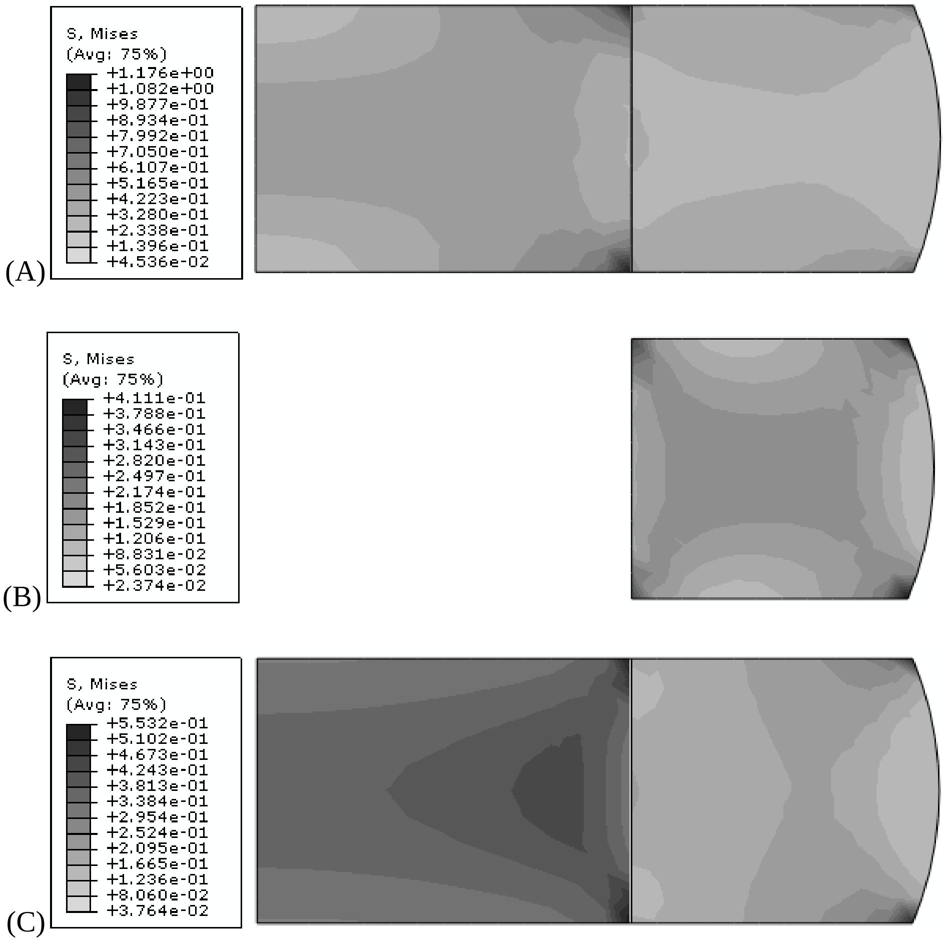

Figure 5: Von Mises stress distributions for (A) intact, (B) denucleated and (C) implanted model. All values in MPa.

The radial displacements along the disc equator were analyzed in detail (Figure 6). The intact and implanted model show positive displacements. Denucleated condition exhibits negative displacements at about a 70% of the distance from the axis of symmetry, corresponding to an inward bulging of the annulus. At greater distances, the displacements become gradually positive but still below the other two condition displacements.

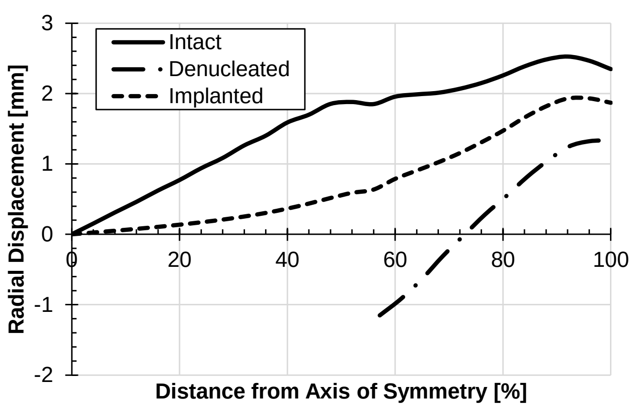

Figure 6: Radial displacements of three models.

5 CONCLUSIONS

A numerical tool capable of applying the inverse method to calibrate constitutive models was developed. The inverse program presented obtains, assisted by commercial finite element software, constitutive parameters from experimental data corresponding to different mechanical tests. Using the Ogden-Storakers constitutive model it was possible to capture the material behavior in mainly compressive multiaxial stress states. The model calibration had to be done using simultaneously uniaxial and confined compression data. Only in this way, a solution able to describe the mechanical response in both stress states for the strain ranges studied could be found.

Finally, a finite element study of disc biomechanics was carried out by employing a simple finite element model. The intact, denucleated and implanted conditions were analyzed. The implant made of the proposed material exerts an action on inner annulus layers equivalent to the natural intradiscal pressure in the case of a healthy disc. The proposed implant partially restores the natural load transference mechanism so its mechanical fitness to be used as nucleus pulposus replacement in the spine arthroplasty would be reliable.

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