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Determination of the hyperelastic material properties of the intervertebral disk under dynamic compressive loads

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1 Introduction

In the last decade, many finite element (FE) models of the spine were used as surrogate experiments to provide relevant knowledge on the biomechanics of spinal trauma [1-2]. One of the major concerns in the development of such model is the modeling and validation of the spinal components' mechanical behavior in dynamic loading conditions. For instance, very few FE models have considered the strain rate dependency shown by the intervertebral disk (IVD) when submitted to high strain rates [3], thus limiting their ability to represent traumatic conditions. Such limitations arise from the lack of appropriate material properties available in the literature. Thus, the purpose of the current study was to determine suitable material properties of the IVD for its FE modeling under dynamic compressive loads.

2 Methods

Material properties of the IVD were assessed using a combined experimental-numerical approach. A FE model of the L2-L3 spinal unit (figure 1) that includes a detailed modeling of the IVD described in [4] was used to simulate the experiments of Kemper et al. [3] which consist in the characterization of the axial compressive stiffness of post-mortem human IVDs at different strain rates: 6.8, 13.5 and 72.7 s⁻¹. In the FE model, the fluid-like behavior of the nucleus and

the hyperelastic properties of the annulus ground substance were both modeled using an isotropic and hyperelastic material law based on a first order Mooney-Rivlin formulation described by the following strain energy function W :

$$W = c_{10}(I_1 - 3) + c_{01}(I_2 - 3) + (J - 1)^2 / d \quad (1)$$

with C_{10} , C_{01} = material constants ; I_1 , I_2 = first and second strain invariants ; $J = V/V_0$ = local volume ratio; $d = 2/K$ = incompressibility factor computed from the material constants and the Poisson ratio.

By setting the nucleus as an incompressible material (Poisson ratio $\nu = 0.5$), and the annulus as a slightly compressible material (Poisson ratio = 0.45), and by using the relationship $C_{01} \approx 0.25 C_{10}$ [5], only two constants (C_{10} -Annulus; C_{10} -Nucleus) need to be defined in order to model the mechanical behavior of both components.

To select those constants according to the experimental results of Kemper et al. [3], a reliability study based on a Monte-Carlo simulation approach was conducted. It consisted in the random-selection of 35 pairs of discrete values for C_{10} -Annulus and C_{10} -Nucleus using an Optimal Latin Hypercube sampling method, thus providing an efficient spread over the design space which was bounded by values taken from literature [5]. For each pair of values, a simulation was launched in order to compress axially and dynamically the IVD at the three

reference strain rates. Compressive stiffness values were extracted from each simulation using points located at approximately 25% and 50% of the load-displacement curves, as performed experimentally. A surface response was then interpolated and a mathematical relationship was computed between the simulated compressive stiffness and the material constants $C_{10}\text{-Annulus}$ and $C_{10}\text{-Nucleus}$. A corridor of candidate values that adequately simulate the mechanical behavior of the IVD at a given strain rate was finally obtained by combining the mathematical relationship with the range of stiffness measured experimentally.

3 Results and Discussion

Figure 2 presents the surface response and the corridor of candidate values for $C_{10}\text{-Annulus}$ and $C_{10}\text{-Nucleus}$ computed from the mathematical relationship and the experimental stiffness obtained at 72.7 s^{-1} ($K_{\min} = 4534.1 \text{ N/m}$; $K_{\max} = 8568.1 \text{ N/m}$). Similar results were obtained at 6.8 and 13.5 s^{-1} . The use of a hyperelastic material law was appropriate since the study focused on the IVD's mechanical response to high strain rates, as opposed to long-term gravitational loads which may induce a poroelastic response over a timeframe of hours.

The wide range of candidate values defining $C_{10}\text{-Annulus}$ and $C_{10}\text{-Nucleus}$ suggests that additional experimental data such as the intradiscal pressure (IDP) could be measured and exploited as a physiologic criterion to also discriminate values that simulate too high or too low IDPs. Verification of the incompressibility hypothesis adopted for the nucleus, by comparing the initial and final volumes of the nucleus after simulation, is another alternative currently under investigation. Finally, to implement strain-rate dependency in a unique IVD model, a mathematical relationship between the material constants $C_{10}\text{-Annulus}/C_{10}\text{-Nucleus}$ and the strain rate need to be implemented in the simulation software, as opposed to manually adjust these constants according to the strain rate.

4 Conclusions

This study presents a new innovative method to identify appropriate material properties for the FE modeling of the IVD in dynamic loading conditions. This is of particular interest since most FE models dedicated to the study of spinal trauma use inappropriate material properties derived from quasi-static loading conditions.

References

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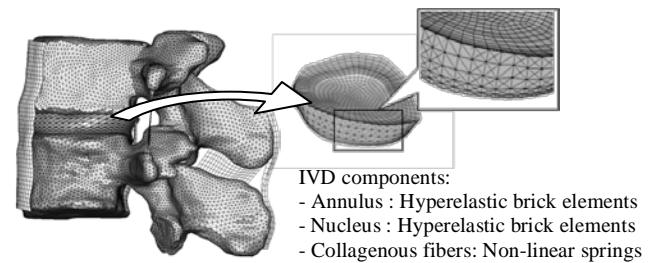


Figure 1: FE model of the L2-L3 spinal unit and detailed modeling of the IVD (adapted from [4])

$$K_{\text{IVD}} = -272 + 7260 * C_{10\text{-ANN}} + 15548 * C_{10\text{-NUC}} + 5400 * C_{10\text{-ANN}} * C_{10\text{-NUC}} - 308 * C_{10\text{-ANN}}^2 - 2190 * C_{10\text{-NUC}}^2 \quad (r\text{-sqr} = 0.996)$$

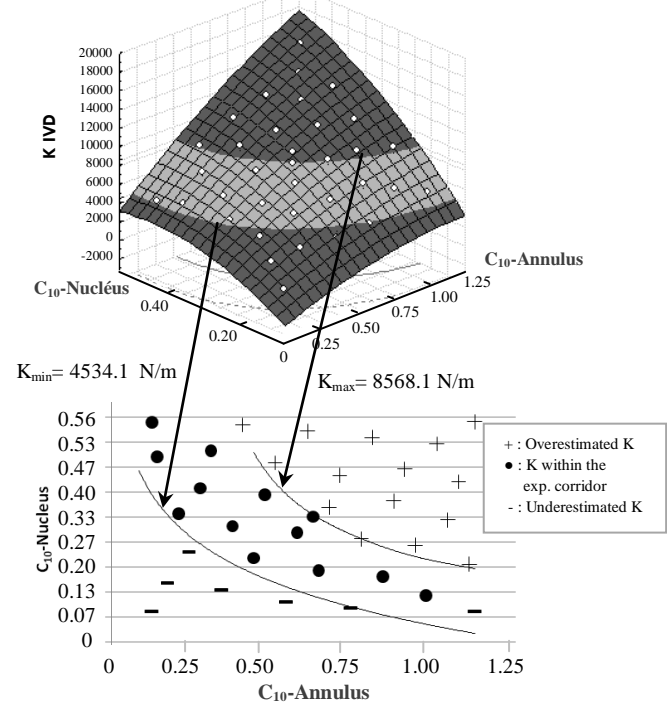


Figure 2: Surface response and corridor of candidate values for $C_{10}\text{-Annulus}$ and $C_{10}\text{-Nucleus}$ at a strain rate of 72.7 s^{-1}