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The impact of flexion mechanical loading on the intervertebral disc metabolism

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1. Introduction

Intervertebral discs (IVD) are fibrocartilaginous organs that provide the linkage and mobility of the vertebrae of the spine. Healthy, they have a high-water content, nearly 80% by volume, which diminishes with age thus decreasing intervertebral mobility. IVDs allow the vertebrae to accommodate the mechanical loads supported by the spine. Naturally through aging IVDs undergo a process of degeneration that gradually alters their properties. Degeneration is a process in principle natural that continues throughout life but can, under the influence of various factors, such as mechanical factors, accelerate suddenly and leads to a pathological Disc Degeneration (DD). The DD, asymptomatic in its early stages, is hard to diagnose with conventional means of imaging such as CT scans or projection images (X-Ray and Discography). These images provide information on the general structure of the IVD such as disc height, surface area, and the volume of the disc in three-dimension. Nevertheless, they do not generally allow for the evaluation of quantitative parameters related to physiological quantities that are useful for making an early diagnosis. The detection of this pathology, at the first signs of back pain, is therefore of great interest to quickly establish effective treatments. The regulation of the water content of the IVD plays a central role in this pathology. It proceeds from a delicate balance between mechanical stresses exerted by the adjacent vertebrae, electrochemical phenomena within the extracellular matrix (ECM), and the performance of the nutritional transport processes throughout the ECM.

Previous work conducted by Ghiss et al. (2016), and Chetoui et al. (2019) made use of quantitative Magnetic Resonance Imaging (MRI) to assess the lumbar disc viability. Available Nuclear Magnetic Resonance (NMR) techniques in clinical practice allow access to intrinsic disc information such as the water content of the disc and its mechanical rigidity. Our research focuses on the biomechanical behavior model of lumbar IVDs when subjected to mechanical

loads, notably the bending in the coronal plane (flexion-extension). These solicitations generate high shear strain inside the disc and therefore present a high risk of injury Costi et al. (2007). One of the main aspects of this research work is the use of the real entire geometry of the lumbar IVD. This research study aims to implement a biphasic numerical model considering the biomechanical behavior of the IVD and then evaluate the impact of flexion-extension loads on disc metabolism.

2. Models and Methods

The experimental tests and the geometry reconstruction were detailed in Ghiss et al. (2016). As illustrated in figure 1, the 3D model of the IVD is reconstructed from the MRI images.

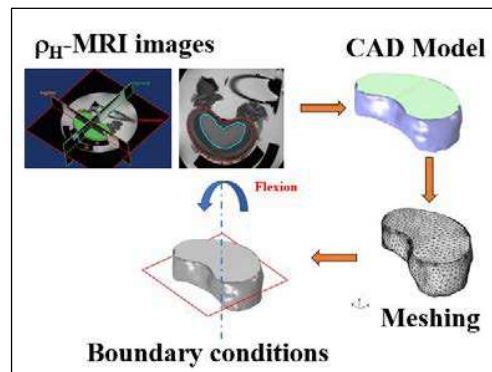


Figure 1. 3D IVD numerical model: reconstruction from MR images

An IVD biphasic FE model is used to characterize its mechanical behavior which is coupled with the metabolic transport model describing the transport of nutrients in the fluid phase via the porosity (ϕ). The problem is solved using Comsol Multiphysics® software.

Biphasic model for the IVD including nutrient transport

The IVD is modeled as a poroelastic biphasic media composed of an hyperelastic solid-phase filled by an intrinsically compressible fluid phase. The solid phase behavior is defined by a Mooney Rivlin model (Chetoui et al. 2019). Oxygen, lactate and glucose were included in the biphasic model and will henceforth be called nutrients (β).

- Momentum conservation: $\vec{\nabla}_X(\mathbf{FS}) = \vec{0}$
- Internal Pressure:

$$\nabla_X \cdot (Jk\vec{\nabla}_X(p)\mathbf{C}^{-1}) = \nabla_X \cdot (j\vec{v}^s(\mathbf{F}^{-1})^T)$$

where \mathbf{S} is the second Piola Kirchoff stress tensor, \mathbf{F} the deformation gradient tensor and J its determinant.

The tensor C represents the right Cauchy-Green strain tensor, v^s is the solid velocity, p is the intradiscal pressure and k is the permeability taken strain-dependant according to the relation of Argoubi and Shirazi-Adl, (1996).

- Diffusion of nutrients:

$$J\phi \frac{\partial C^\beta}{\partial t} - \nabla_X \cdot (J\phi D_A^\beta - \overline{\nabla}_X \cdot (C^\beta) C^{-1}) = JR^\beta$$

Where C^β is the nutrient concentration, D_A^β the apparent diffusion coefficient and R^β is the nutrient consumption rate (in nmol million cell⁻¹ h⁻¹). ($\nabla_X \cdot$) and $\overline{\nabla}_X$ are the divergence and gradient operators applied in the material referential (X, Y, Z). The Coupling equations by the porosity (water volume fraction) and the pressure:

- Evolution of porosity with deformation:

$$\phi = 1 - \frac{1 - \phi_0}{J}$$

- Second Piola Kirchoff Stress tensor:

$$S = S^s - J(p + \delta\pi)C^{-1}$$

- S^s is the second Piola–Kirchhoff effective stress tensor related to the solid phase and $\delta\pi$ is the osmotic pressure. Evolution of apparent diffusion with porosity:

$$D_A^\beta = D_{H_2O}^\beta \frac{\phi^2}{(2 - \phi)^2}$$

3. Results and discussion

In this research study, we computed the effect of a 5° flexion-extension loading ($\pm 5^\circ$ referred to the mid-coronal plane) in the diffusion of nutrients inside the disc. We predicted the pressure rise in the disc and calculated the glucose intake rate under both physiological equilibrium and flexion loading state. During the loading phase ($0 < t < 4s$), the absolute values of the osmotic stress and pressure of the disc increase rapidly to their maximum values. The curves then relax until they gradually reach a near-equilibrium state after about 60minutes. During the loading phase, the osmotic pressure increases very quickly up to its maximum value inducing a displacement of the external borders of the Annulus Fibrosus (AF) up to their maximum values. The results show that the pressure is low (0.35 MPa) in the anterior and posterior regions of the AF and seven times higher in the Nucleus Pulposus (NP).

At peak loading time ($t=4s$), the results, as shown in figure 2, reveal that the oxygen concentration is maximum on the boundary. This can be explained by the existence of more blood vessels in this region. In fact, the oxygen diffuses from peripheral vessels to the nucleus and is consumed by cells. Inversely, the concentration of lactate is minimal at the edges and

increases sharply as we approach areas of high cell density.

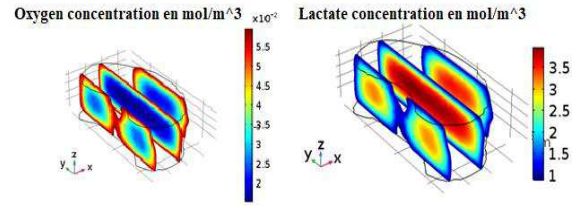


Figure 2. Distribution of the oxygen and lactate concentration (mol/m³)

4. Conclusions

This biphasic model combining disc osmo-mechanical behaviour and nutrient diffusion processes provides a reliable tool for investigating time-evolving osmotic pressure and nutrient concentration profiles in a flexion-loaded disc.

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