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# Intervertebral disc mechanical response to axial rotation: the consequences of a mobile centre of rotation on the anisotropic component

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## 1. Introduction

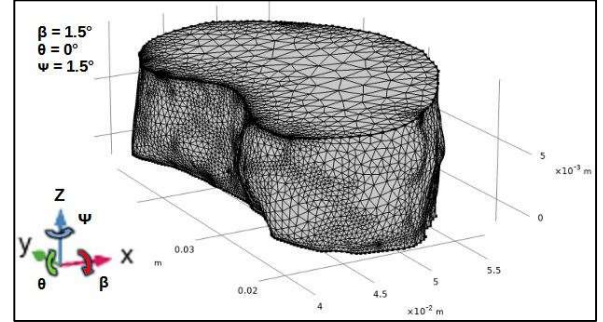
The intervertebral discs (IVDs) are essential to the mobility of the spine as they ensure the mechanical stresses transmission between vertebral bodies and play an important role in shock absorption. In everyday life, the discs are mechanically solicited in compression, flexion (either in the sagittal or transverse plane) and in axial rotation (Figure 1). For these last two movements, the literature highlights complex kinematics that cannot be reduced to a pure rotation but rather to a set of compound movements and, more importantly, to non-static instantaneous centres of rotation (ICR). In our ongoing works, we are investigating the biomechanical impacts of the ICR mobility and we hypothesize it would yield lower average stress. As these organs are heterogeneous, we detail in this study the behaviour of the various constitutive parts of the IVDs. This work sheds light on the consequences of the ICR mobility on the collagen fibres.

## 2. Methods

### 2.1 Model

We used a 3-dimensional finite element model of a porcine IVD (Figure 1) in which a poroelastic biphasic swelling formulation (Mow *et al.*, 1980) for the IVD mechanical behaviour is coupled with a nutrients transport model. The two phases are incompressible, the extracellular matrix (ECM) is assumed to be hyperelastic and a fibre reinforced model is used to account for the anisotropy of the collagen network in the *annulus fibrosus*. The mesh chosen after a mesh convergence analysis was made up of 56 568 elements and 342 699 degrees of freedom. A preliminary stationary simulation was run to put the IVD at an unloaded physiological state and initialize the osmotic

pressure and the nutrients concentration fields. We define two fibre families characterized by their mean orientation ( $e_1$  and  $e_2$ ) with respect to the transverse plane. Two orientation invariants,  $I_4$  and  $I_6$ , are computed using the family directions and fed in a  $\rho$ -model as defined by Gasser *et al.*, 2006. Hence our medium is defined by a strain energy density which can be split into three parts: a volumetric component ( $W_{\text{volumetric}}$ ), an isochoric isotropic component ( $W_{\text{isotropic}}$ ) and an isochoric anisotropic component ( $W_{\text{aniso1}} + W_{\text{aniso2}}$ ), as expressed below.



**Figure 1:** 3D finite element model of an IVD. X axis points anteriorly, y points left and z points superiorly.

$$\begin{aligned} A_i &= e_i \otimes e_i ; I_{2i+2} = \bar{C} : A_i \\ W &= W_{\text{isochoric}} + W_{\text{volumetric}} \\ W_{\text{volumetric}} &= \frac{\kappa}{2} (J - 1)^2 \\ W_{\text{isochoric}} &= W_{\text{isotropic}} + W_{\text{ani}} + W_{\text{aniso2}} \\ W_{\text{isotropic}} &= \frac{\mu}{2} (\bar{I}_1 - 3) \\ W_{\text{aniso}(i)} &= \frac{a}{2b} \left( e^{b(\rho(\bar{I}_{2i+2} - 1)^2 + (1-\rho)(\bar{I}_1 - 3)^2)} - 1 \right) \end{aligned}$$

Which yields through differentiation to:

$$PK_{\text{aniso}(i)} = 2a e^{b(\rho(\bar{I}_{2i+2} - 1)^2 + (1-\rho)(\bar{I}_1 - 3)^2)} \left( (1-\rho)(\bar{I}_1 - 3) \left( J^{-\frac{2}{3}} Id - \frac{\bar{I}_1}{3} C^{-1} \right) + \rho(\bar{I}_{2i+2} - 1) \left( J^{-\frac{2}{3}} A_i - \frac{\bar{I}_4}{3} C^{-1} \right) \right)$$

$$PK_{\text{isotropic}} = \mu C^{-1} \text{dev}(\bar{C}) + \kappa J (J - 1) C^{-1}$$

With  $\kappa$  and  $\mu$  the coefficient of compressibility and shear modulus of the ECM,  $J$  the Jacobian of the transformation,  $C$  the right Cauchy-Green deformation tensor,  $I_1$  its first invariant,  $\bar{C}$  the isochoric Cauchy-Green tensor,  $\bar{I}_1$  its first invariant,  $a$ ,  $b$  and  $\rho$  parameters defining the fibres behaviour and PK referring to the second Piola-Kirchhoff stress tensor.

### 2.2 Kinematics

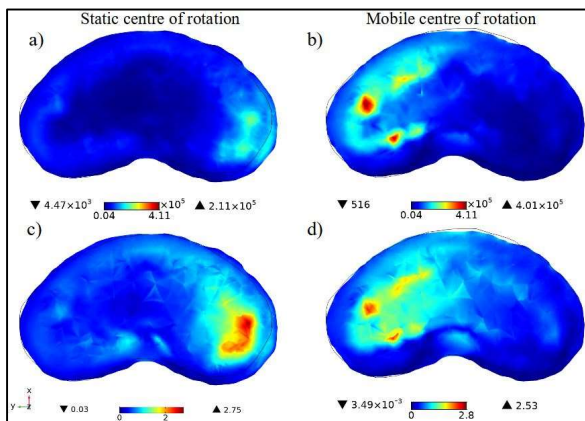
As reported in several studies, axial rotation of the spine is a compound motion. We chose the range of motion of Percy and Tibrewal (1984) for a L4/L5 spinal unit and we modelled the motion as a 2-second prescribed displacement of the superior endplate, the

inferior endplate being rigidly fixed and the lateral face free to swell. As the location of the ICR is a controversial topic, we implemented two different definitions reported in the literature: a static centre of rotation at the IVD barycentre and a mobile one, moving posteriorly in the opposite side of the rotation as described in Schmidt *et al*, 2008. All the numerical simulations were performed on *COMSOL Multiphysics 5.5* on a workstation with an Intel(R) Xeon(R) W-11955M CPU and 64GB of RAM.

### 3. Results and discussion

The aims of this work were to analyse the consequences of a mobile ICR on the stress tensors associated with the strain energy densities and to quantify the contribution of the anisotropic component of the solid phase during axial rotation. Our results show that the assumption made on the ICR kinematics considerably influences the fibres sollicitation. A static ICR at the IVD barycentre creates higher stress (up to 0.21MPa) in the right side of the IVD for a left axial rotation while the simulation with a moving ICR gives higher stress (up to 0.40MPa) in the left posterior side, as illustrated on Figure 2 (a, b). These results are of particular interest as they can bring new insights on the origin of some injuries related to the IVD.

Regarding the contribution of the anisotropic component with respect to the isotropic one, Figure 2 (c, d) displays the ratio of the first anisotropic eigenvalue (i.e.  $\max(Sp\{PK_{anis} + PK_{anis}\})$ ) over the first isotropic eigenvalue ( $\max(Sp\{PK_{isotropic}\})$ ). Although the anisotropic stress is up to two times higher when considering a mobile ICR, its proportion with respect to the isotropic stress stays similar, with the maximal values reached in the inner annulus.



**Figure 2:** (a, b) First anisotropic eigenvalue (in Pa) in the median transverse plane. (c, d) Ratio of the first anisotropic eigenvalue over the first isotropic eigenvalue in the median transverse plane.

It indicates that in the areas of higher deformation, most of the stress is due to the anisotropic component of the solid phase.

### 4. Conclusions

ICR mobility is known to increase along with IVD degeneration (Gertzbein *et al*, 1985). Our results can help to precise this relationship as it appears that even though a mobile ICR might globally reduce joint reaction forces (Senteler *et al*, 2018), it also tends to locally put more stress on the fibres which could subsequently fuel the degeneration process or ease the apparition of acute injuries. Future work could focus on how physical therapy or muscle reinforcement might slow down the degeneration by restraining the ICR mobility and reducing the amount of stress put on the fibres.

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