Effect Of Permeability Diminution In Nutrients Diffusion In The Intervertebral Disc

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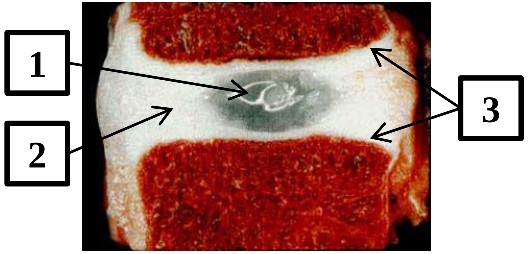
General context

Intervertebral disc



Intervertebral Disc

- Fibrocartilage
- Provides vertebrae joint flexibility= Ensure Spine motion
- Absorbs and distributes loads through the spine
- Saturated porous media
- Avascularised, non innervated

1-Nucleus Pulposus

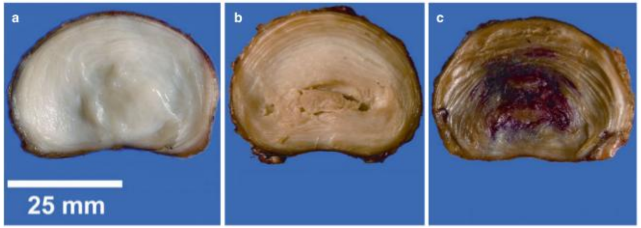
- Hydrogel (>80% of water)
- Fluid like behaviour

2-Annulus Fibrosis

- Lamellar
- Resists to tensile stress
- Viscoelastic behaviour

3-Endplates

- Bony structure
- Elastic behaviour



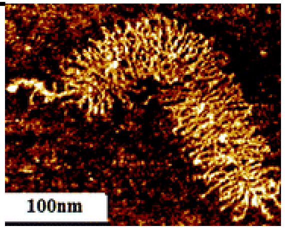
(Illien-Jünger et al. 2014)

Disc degeneration effects

- Morphological and biochemical changes (dessication, height diminution …)
- Loss of mechanical properties (stiffening, loss of tensile resistance, permeability diminution …)
- Pathologies associated (herniation, osteophytosis, ...)

IVD composition

ECM



Proteoglycans

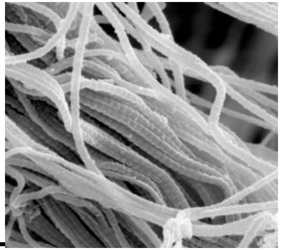
- Protein macromolecule
- Negatively charged
- provide swelling pressure

} hydration of IVD

→

After degeneration

- Loss of proteoglycans
- Fall in the swelling pressure



Collagen fibres

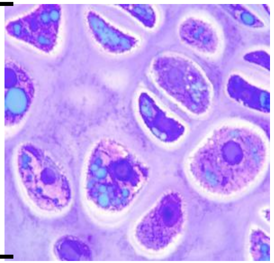
- Helicoidal shape
- Different types (mainly 1 in AF and 2 in NP)
- Provide IVD resistance to traction and swelling

→

After degeneration

- Loss of C2
- Modification of C1 properties

Cells



Cells

- Low concentration (≈10^4 mm^{-3})
- Synthesize extra-cellular matrix (ECM)
- ECM synthesis efficiency related to nutrient transport

→

After degeneration

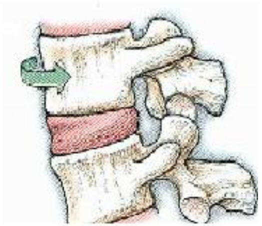
- Fall in cells viability
- Failure in nutrient supply to cells

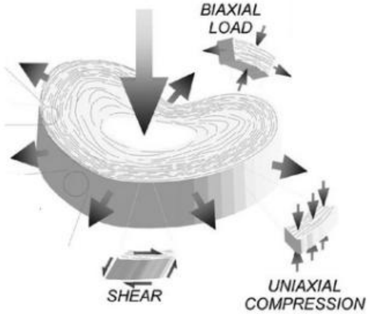
Goal

Mechanical loads

Mechanical loads
• Permanent • High loads (trunk motion, body weight) • Complex loads (torsion+ flexion+ traction)


Flexion


Torsion



Relation between mechanical loads and degeneration → Biomechanical model → FEM modelling

The aim of this study:
Role of the correlation between permeability and deformation in the nutrition process

Problem Formulation

ECM + water

Mechanical model

- Saturated pourous media $(\mathbf{V_t = V_s + V_f})$
- Incompressible phases
- Hyperelastic solid
- Osmotic pressure: $\Delta\boldsymbol{\pi}$

Swelling biphasic model

One way Coupled problems

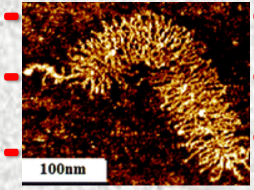
Cells

Nutrients transport model

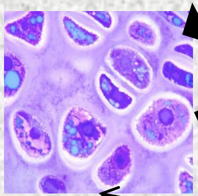
- Purely diffusive transfer
- Glycolysis pathway
- Glucose and oxygen consumption
- Lactate production

Diffusion of diluated species

- $\emptyset$: Porosity
- $\mathbf{c_{FC}}$:Fixed charge density (PG)
- k: Permeability
- p: Intradiscal pressure



$\Delta\boldsymbol{\pi}$



$\mathbf{O_2}$

Glucose

Lactate

- [Cell]: Cells density
- $\mathbf{c_\beta}$: Nutrients concentration

Problem Formulation

Swelling biphasic model+ nutrient diffusion model

biphasic model → Mooney-Rivlin solid; Incompressible fluid

Porous media+ Osmotic pressure →

Total stress:	Total pressure:
$\boldsymbol{\sigma} = \boldsymbol{\sigma}^e - p_{tot} . \mathbf{1}$	$p_{tot} = p + \Delta\pi$

Generalized Darcy law + Finite deformation (undeformed configuration)

$$\nabla.(k.\ J.\ \boldsymbol{F}^{-T}.\ \underline{\nabla} p) = \nabla.(J.\ \boldsymbol{F}^{-T}.\ \underline{v}^s)$$

diffusion of diluted species + Finite deformation (undeformed configuration)

$$J.\ \varnothing.\ (\partial c^\alpha / \partial t) + \nabla.(-J.\ \varnothing.\ D^\alpha.\ \boldsymbol{F}^{-T}.\ \underline{\nabla} c^\alpha) = J r^\alpha$$

The porosity depends on strain

$$\varnothing = 1 + (\varnothing_0 - 1)/J$$

$\boldsymbol{\sigma}^e$: Solid stress tensor
$\boldsymbol{\sigma}$: Total stress tensor
p: Intradiscal pressure
$\Delta\pi$: Osmotic pressure
p_{tot}: Total fluid pressure

$\varnothing$: Porosity (fluid fraction)
k: Permeability
$\underline{v}^s$: Solid skeleton velocity

J: Jacobian of transformation
$\boldsymbol{F}^{-T}$: Transpose of the inverse of gradient tensor

α: Nutrient (oxygen or lactate)
c^α: Nutrient concentration
D^α: Diffusion coefficient
r^α: Source term (related to cells density)

Problem Formulation

Permeability

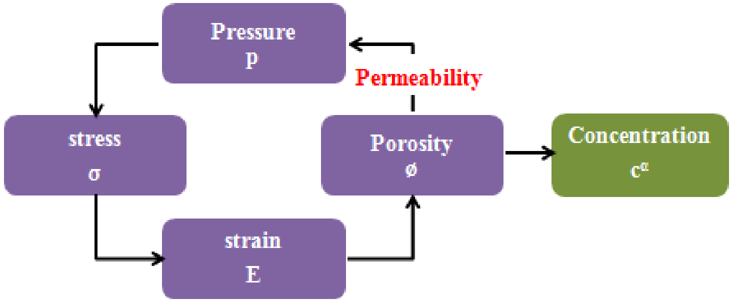
Constant	Variable
$k = k_0$	$k = k_0 \left(\frac{\phi}{\phi_0}\right)^2 e^{M\left(\frac{\phi-\phi_0}{1-\phi}\right)}$ Argoubi and Shirazi-Adl 1996 $\phi = \frac{\phi_0 - 1}{J} + 1$ $k = f(J)$

Comsol modelling

Physics

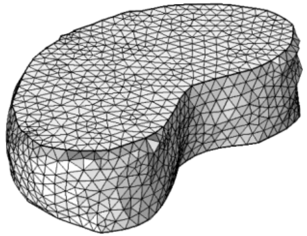
	Comsol physics	**Dependant variable**	**interpolation**	**referential**
Solid behaviour	Solid mechanics (Hyper-elastic solid , MR)	Solid displacement **(u,v,w)**	quadratic	
Fluid behaviour	PDE coefficient form	Pressure **(p)**		material
Diffusion of oxygen	PDE coefficient form	Oxygen concentration **(c^{O2})**	linear	
Diffusion of lactate		Lactate concentration **(c^{L})**		

Model coupling



Geometry (porcine IVD)

MRI
+ image processing → **STL file**



142605 DOF

Comsol modelling

1-Steady step

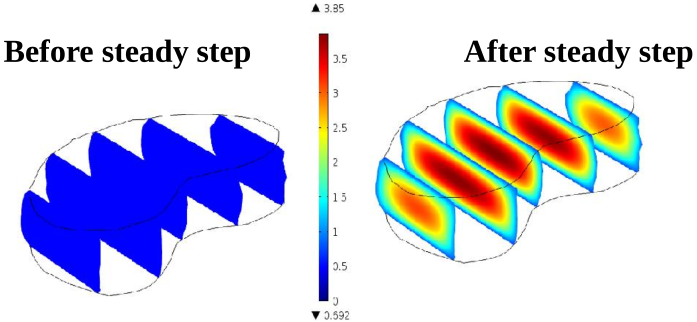
Stationary study

Fixed constraint in the upper and the lower sides

Dirichlet Boundary conditions
- Relative pressure
- Plasma nutrient concentration

Fully coupled

- IVD homeostasis
- Initial condition for the load step



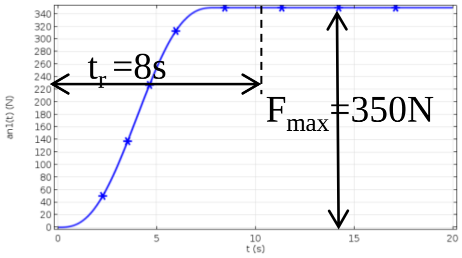
Lactate concentration

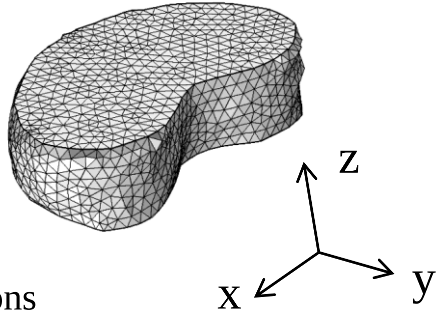
2-Unsteady step

Time dependant study

Uni-axial compression applied in the upper side
- Boundary load in z axis

Fixed constraint in the lower side



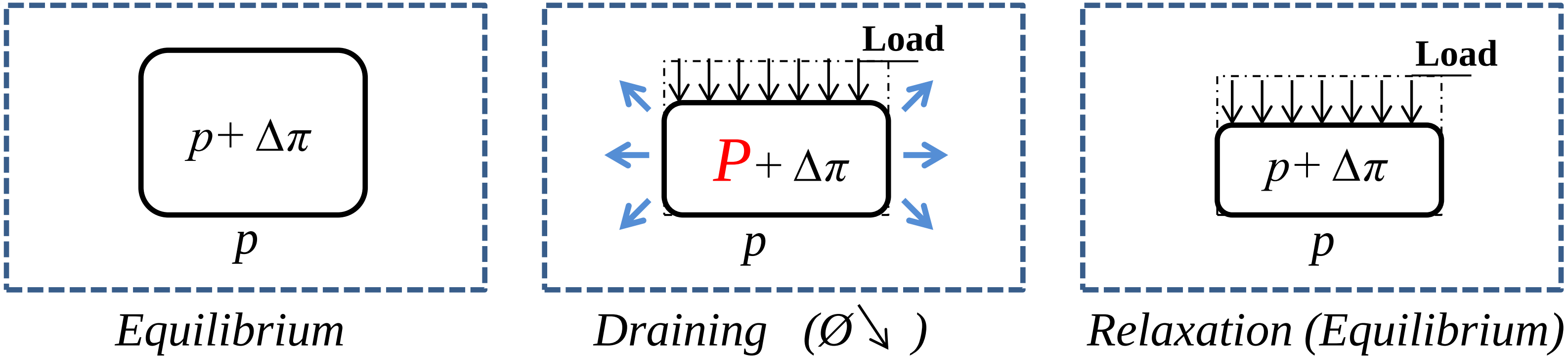


Dirichlet Boundary conditions
- Relative pressure
- Plasma nutrient concentration

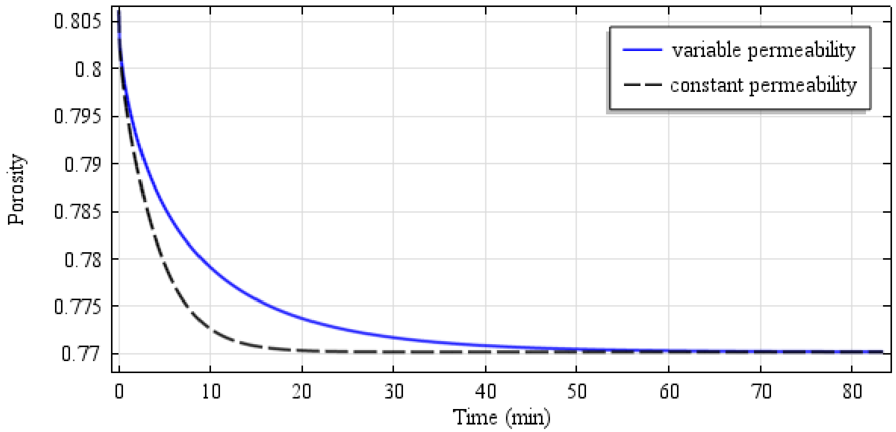
Fully coupled

Final results

Results



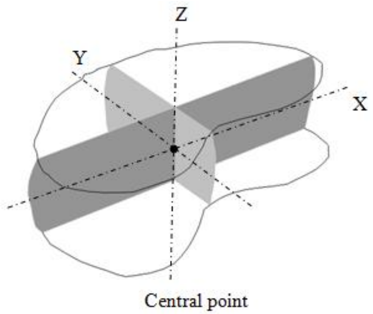
Porosity (volume integration)



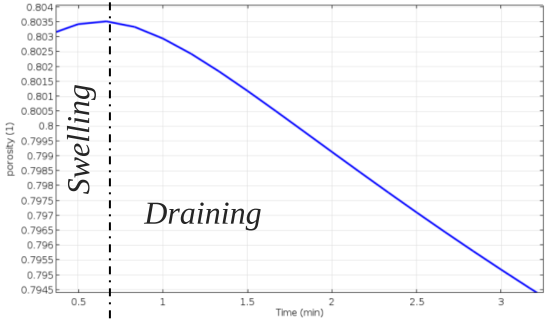
$$\phi = 1 - \frac{1-\phi_0}{J}$$

- A delay in relaxation with variable permeability 39.3% (relatively to the final time)
- Disc draining is slower with variable permeability

Results

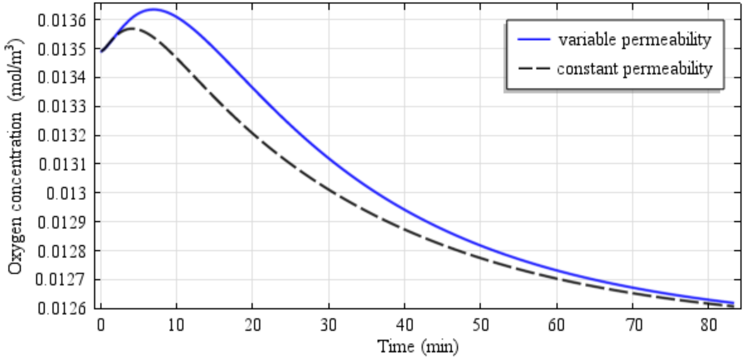


$$D_a^{\alpha} = \frac{\phi^2}{(2-\phi)^2} D_w^{\alpha}$$

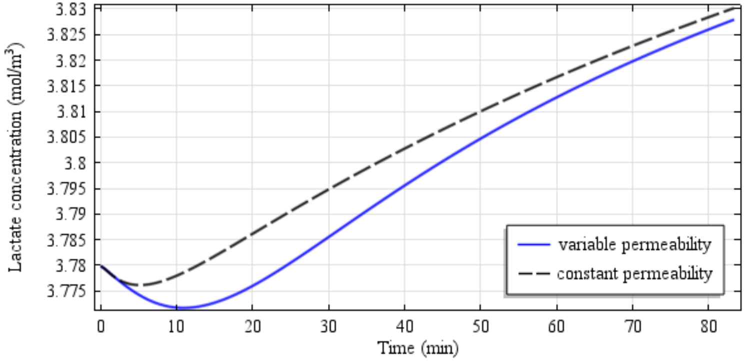


Porosity in the centre

Oxygen concentration

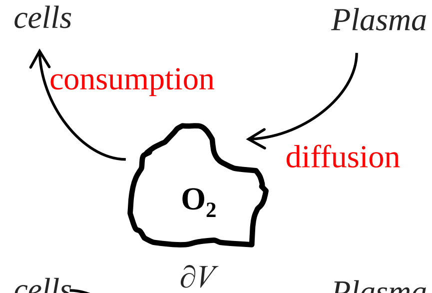


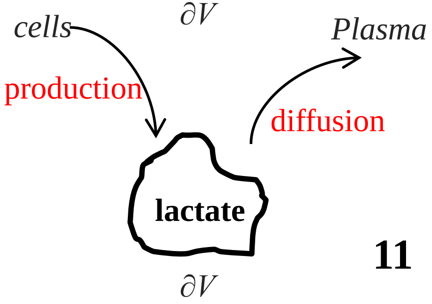
Lactate concentration



•Difference in nutrients concentration:
0.2% for O_2 and 0.7% for lactate

•Delay in diffusion:
3min for O_2 and 5 min for lactate





Conclusion

Considering the dependency of the permeability to strain:

- Makes a weak increase in O_2 concentration and a weak decrease in lactate concentration

  → *May be important because of the high sensibility of cells functions to nutrients concentration.*

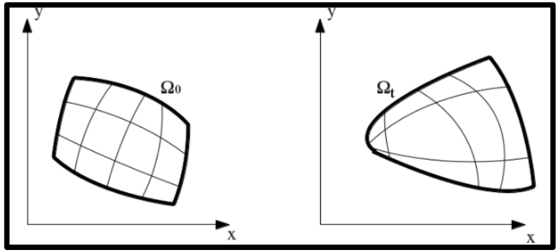
Increase in the lactate concentration → Medium acidification → Failure in cells functionality

- Affects the time of the nutrients diffusion and the relaxation time

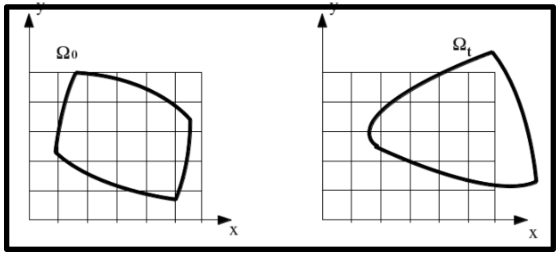
  → *Important in the case of successive loads (like in real life).*

Appendix A: finite deformations

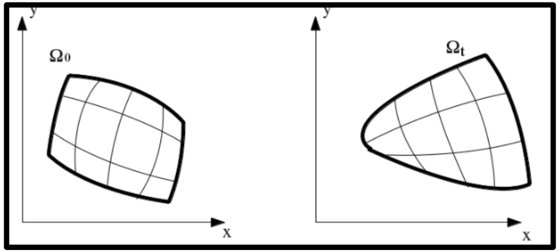
Lagrange description



Euler description



ALE description



Lagrange description

- Results in every geometric point
- Mesh quality degradation

Euler description

- Simple equations.
- Same quality of the mesh.
- Boundaries unfollowed by the mesh

ALE description

- Results in every geometric point
- Accepted quality of mesh
- More DOF
- Motion and BC of the mesh
- Remeshing of the domain

Lagrange description
+
Results in Ω_0
(To avoid mesh problems)

VS

ALE description

Appendix B: Variables and equations

Cauchy stress tensor: $\boldsymbol{\sigma} = \boldsymbol{\sigma}^e - p_{tot} . \mathbf{1}$

PK2 stress tensor: $\mathbf{S} = \mathbf{S}^e - J . p_{tot} . \mathbf{C}^{-1}$

- *$\mathbf{C}^{-1}$: defined as variable using **C***
- *The expression of **S** is modified*

Diffusion equation

$$J.\ \o.\ (\partial c^{\alpha}/\partial t) + \nabla.(-J.\ \o.\ D^{\alpha}.\ \mathbf{F}^{-T}.\ \underline{\nabla}\, c^{\alpha}) = Jr^{\alpha}$$

- *($J.\ \o.\ D^{\alpha}\, \mathbf{F}^{-T}$): defined as variable using **F***

  =>The diffusion coefficient is defined by a tensor
- *In the PDE interface we choose anisotropic diffusion coefficient*

Appendix C: Solvers

1-Steady step

Stationary study

- *Dependant variables scaled manually*
- *Fully coupled*
- *Newton method: automatic highly non linear*

2-Unsteady step

Time dependant study

- *Time step:* ***0 s to 10 s*** *by* ***0.1 s***
  10 s to 5000 s *by* ***10 s***
- *Method: BDF (orders max=2; min=1)*
- *Initial values resolved: Solution of the stationary study*
- *Dependant variables scaled manually*
- *Fully coupled*
- *Newton method: automatic*