Computational Bioengineering: A Finite Element Method Approach to Biomechanics and Mechanobiology

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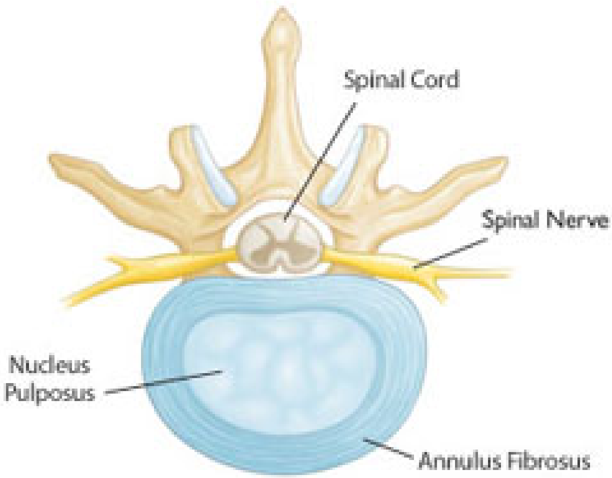
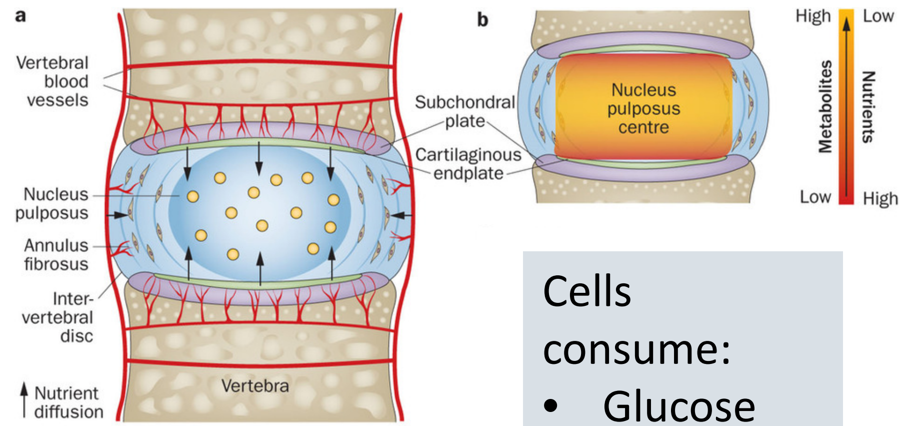
The anatomy of an intervertebral disc (IVD)

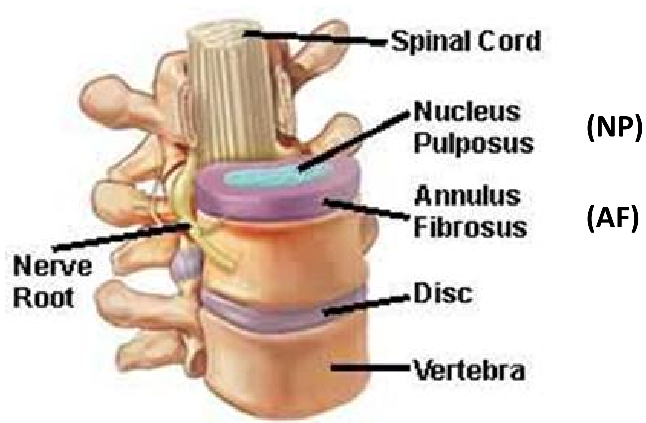




Huang et al., Nature Reviews Rheumatology (2014)

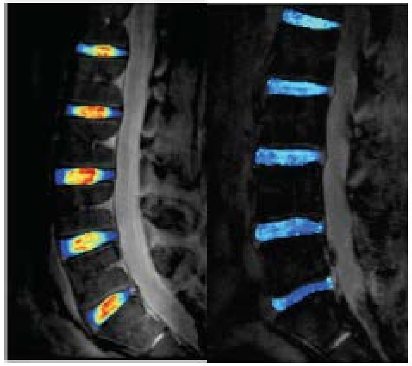
Cells consume:
- Glucose
- Oxygen

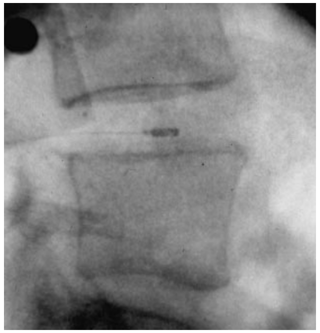
Cells produce:
- Lactate



Experimental Models

- *in vivo*
- *in vitro*
- *in silico*





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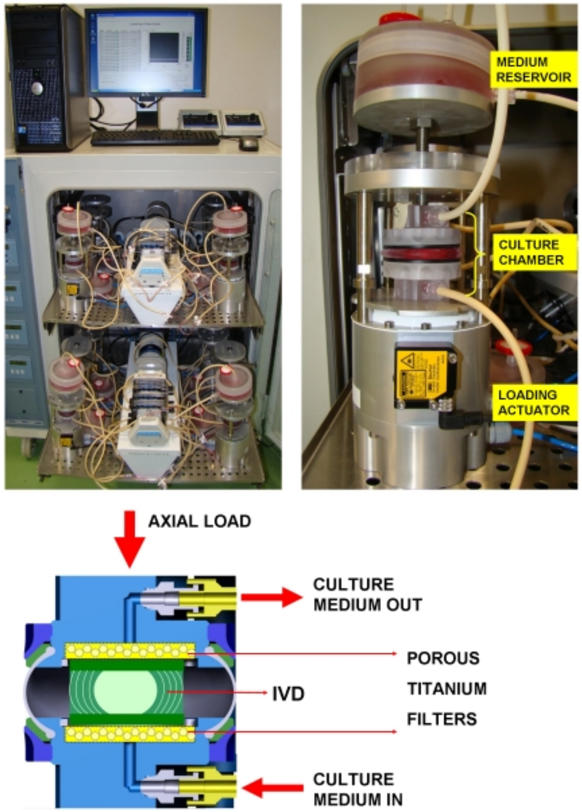
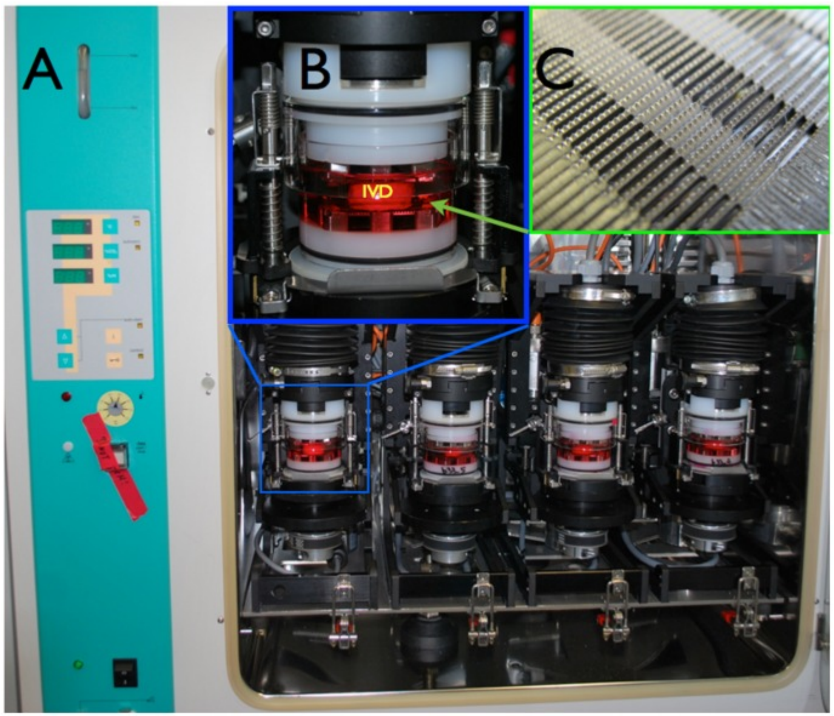
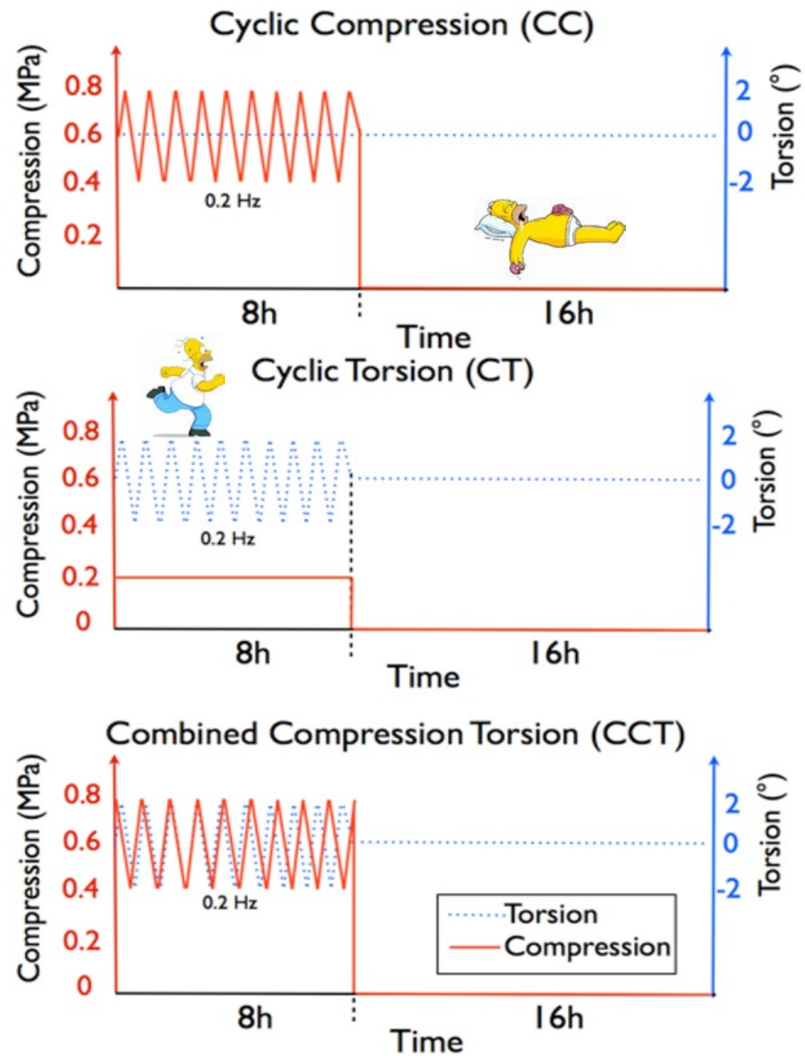


Paul et al., PLoS One (2012)

The *in vitro* study



Chan et al., Plos One (2013)



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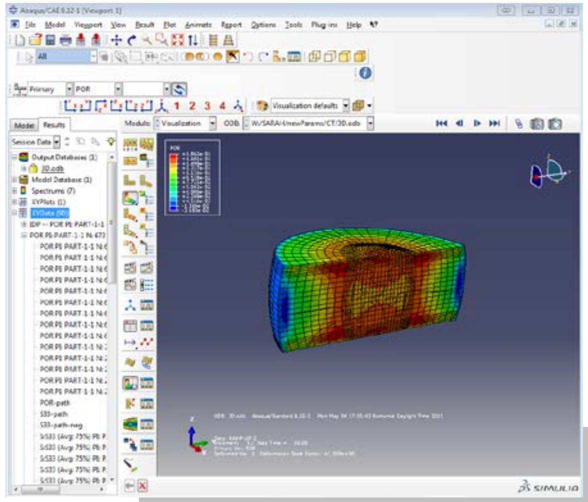
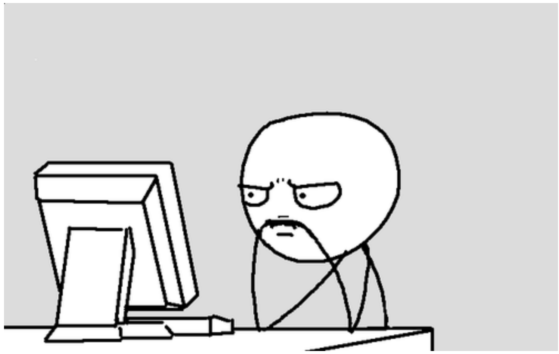
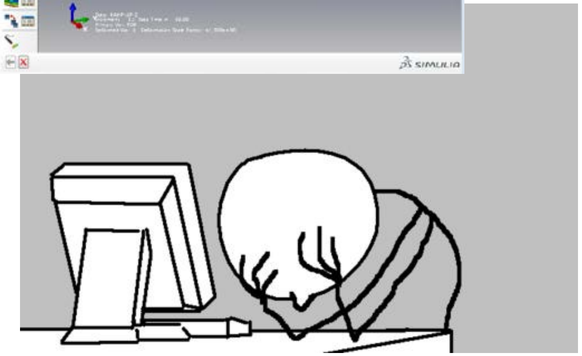
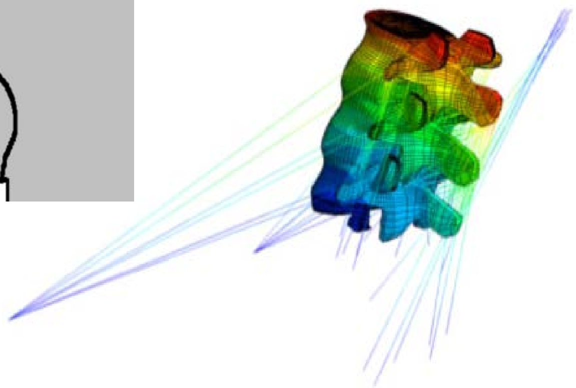
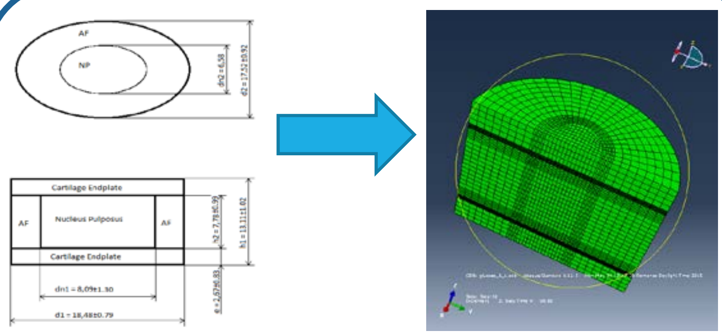





Finite element (FE) analysis workflow



modelling

$$W=\frac{G}{2}(I_1-3)+\frac{K}{2}(J-1)^2$$

$$\underline{\underline{\sigma}}=\frac{1}{J}\frac{\partial W}{\partial \underline{\underline{F}}}\underline{\underline{F}}^T-p\underline{\underline{I}}$$

$$\underline{u}_f\phi=\underline{\underline{k}}\nabla p$$

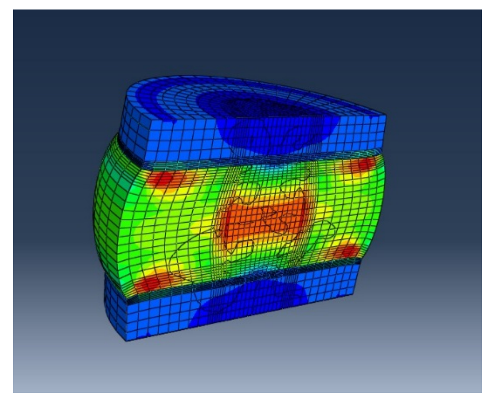
$$R^{O_2}_{tissue}=-\phi\frac{7.28\rho_{cell}}{S^{O_2}}\left(\frac{C_{[O_2]}(pH-4.95)}{1.46+C_{[O_2]}+4.03(pH-4.95)}\right)$$

$$pH=7.4-0.09C_{lact}$$

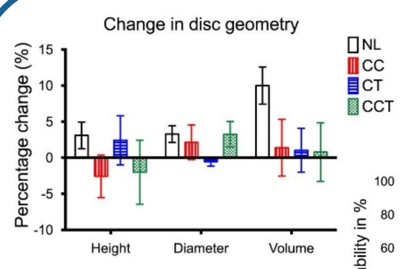
$$R^{lact}_{tissue}=\phi\rho_{cell}\exp(-2.47+0.93pH+0.16C_{[O_2]}-0.0058C^2_{[O_2]})$$

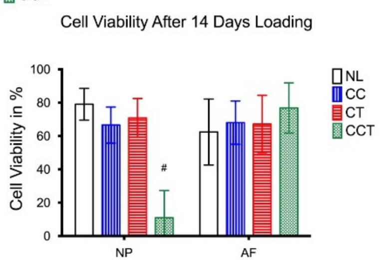
$$R^{gluc}_{tissue}=-\frac{1}{2}R^{lact}_{tissue}$$

constitutive equations and parameter selection



simulation





results analysis and model validation

Describing the mechanics of the IVD

Simulation uses a porohyperelastic formulation

Total stress

$$\sigma = \sigma_{eff} - pI$$

Effective stress

$$\sigma_{eff} = \frac{1}{J}\frac{\partial W}{\partial F}F^T$$

Pore pressure

$$p = u_w + \Delta\Pi$$

Strain energy

$$W = \frac{G}{2}(I_1 - 3) + \frac{K}{2}(J-1)^2$$ (NP)

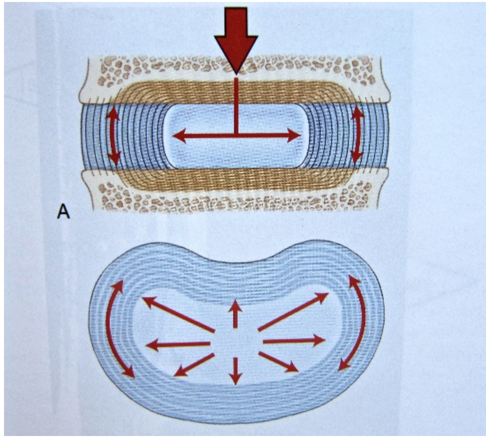
$$W_{AF} = \frac{G}{2}(I_1 - 3) + \frac{K}{2}(J-1)^2 + \frac{K_1}{K_2}\sum_{\alpha=1}^{2}\{\exp[K_2\langle\overline{E}_\alpha\rangle^2] - 1\}$$ (AF)

Darcy's Law

$$q = -\kappa\nabla p = v \times \varphi$$

Strain-dependent permeability

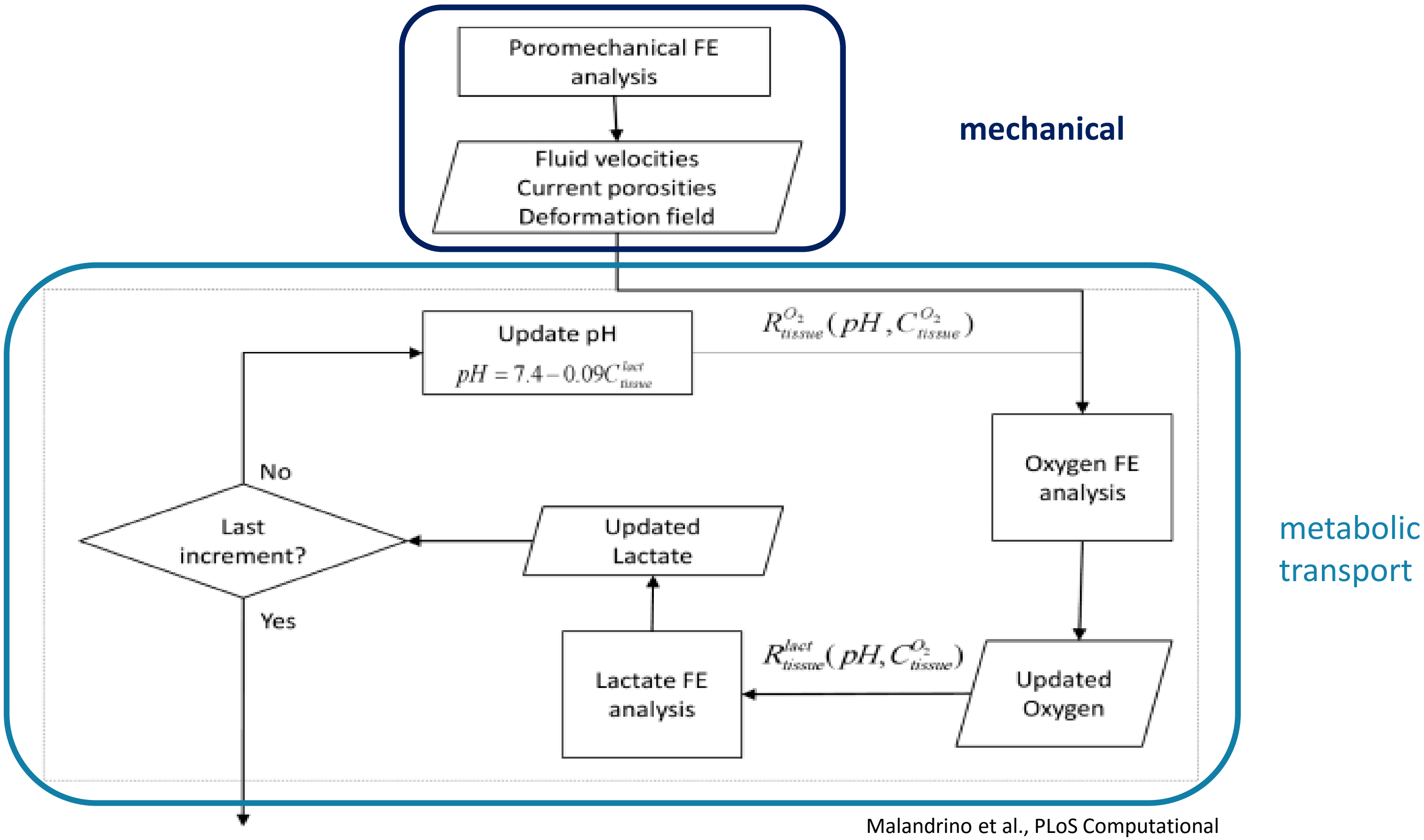
$$\underline{\underline{k}} = \left\{k_0\left(\frac{\phi}{\phi_0}\right)^2 \exp[M(J-1)]\right\}\underline{\underline{I}}$$



Neumann, 2010, page 331

Malandrino et al., PLoS Computational Biology (2011)

Mechano-transport coupling



Malandrino et al., PLoS Computational Biology (2011)

Transport

Cell death induced when :

- Glucose concentration < 0.5 nmol/ml
- pH < 6.8

Metabolic reactions:

$$R_{tissue}^{O_2} = -\phi \frac{7.28\rho_{cell}}{S^{O_2}} \left(\frac{C_{[O_2]}(pH - 4.95)}{1.46 + C_{[O_2]} + 4.03(pH - 4.95)} \right)$$

$$pH = 7.4 - 0.09C_{lact}$$

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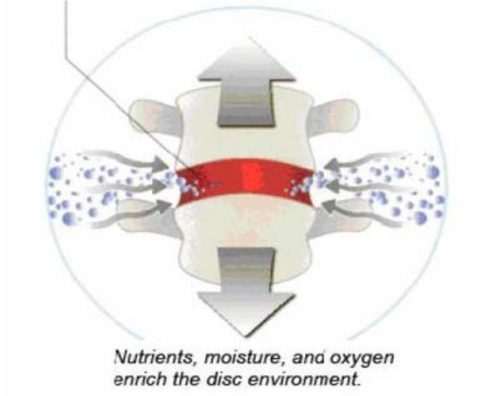
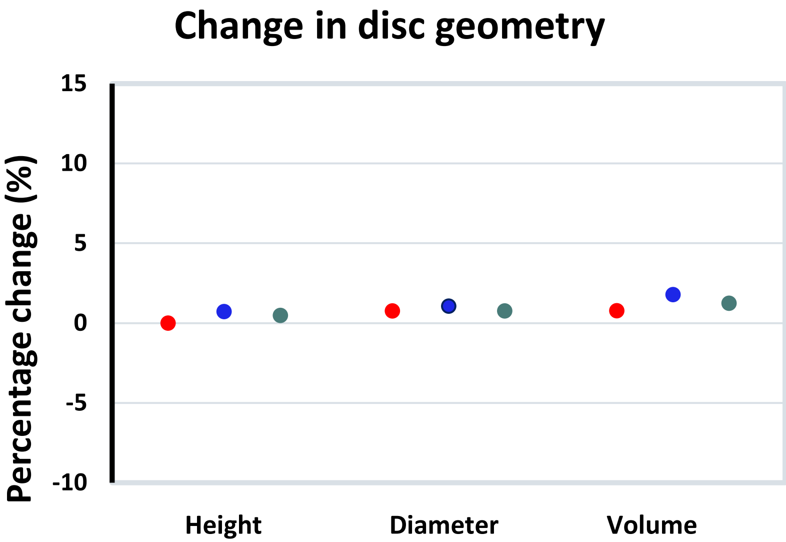
$$R_{tissue}^{gluc} = -\frac{1}{2} R_{tissue}^{lact}$$



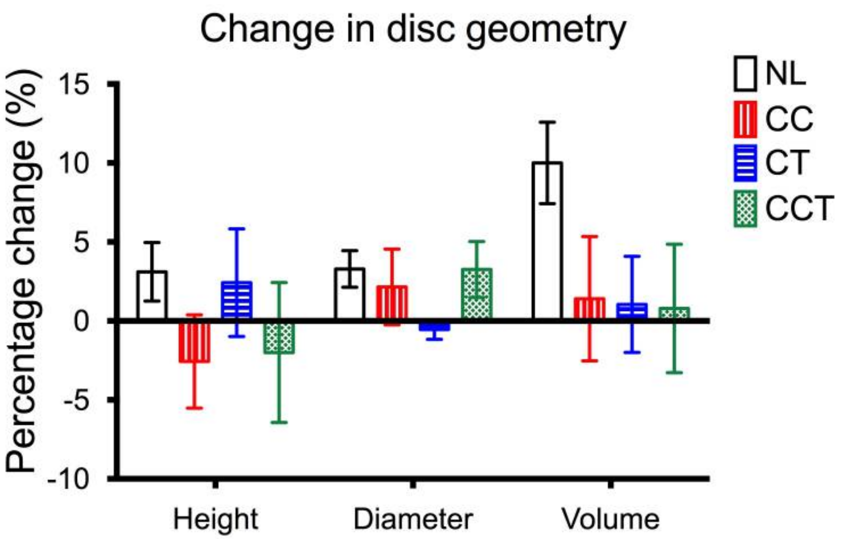
(Bibby et al., Spine (2005))

Disc deformations

In silico results:

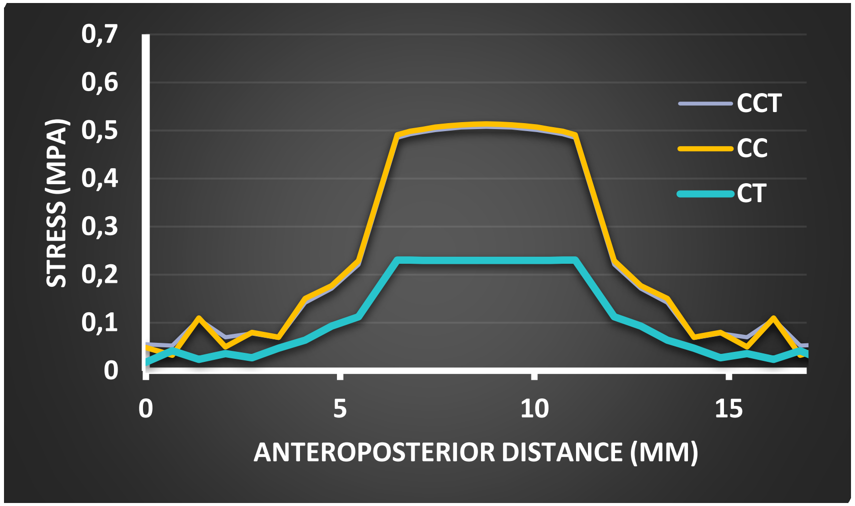


In vitro results:

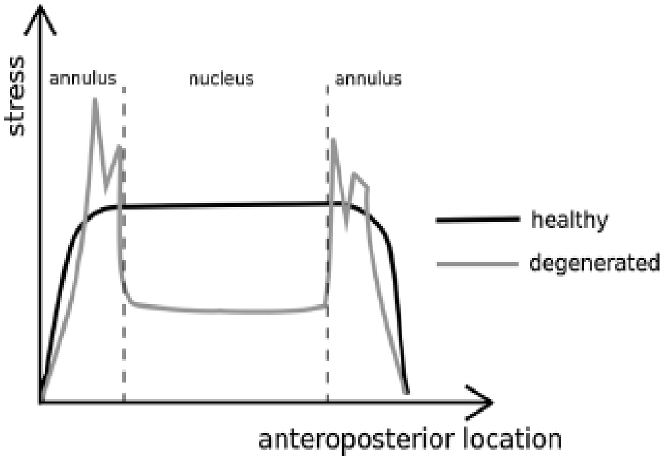


Chan et al., Plos One (2013)

Stress profiles in the IVD

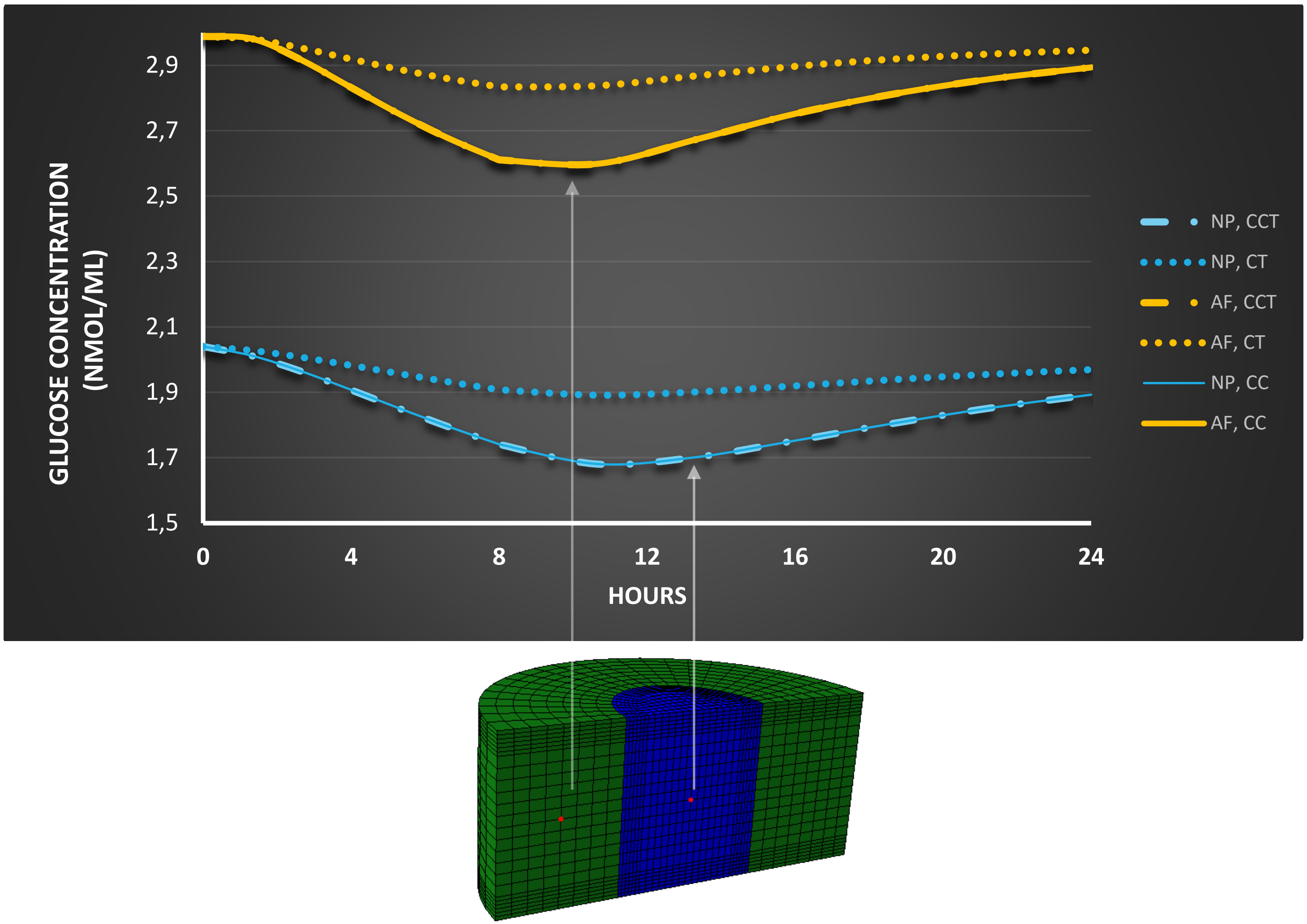


CCT= cyclic compression+torsion
CC= cyclic compression
CT = cyclic torsion

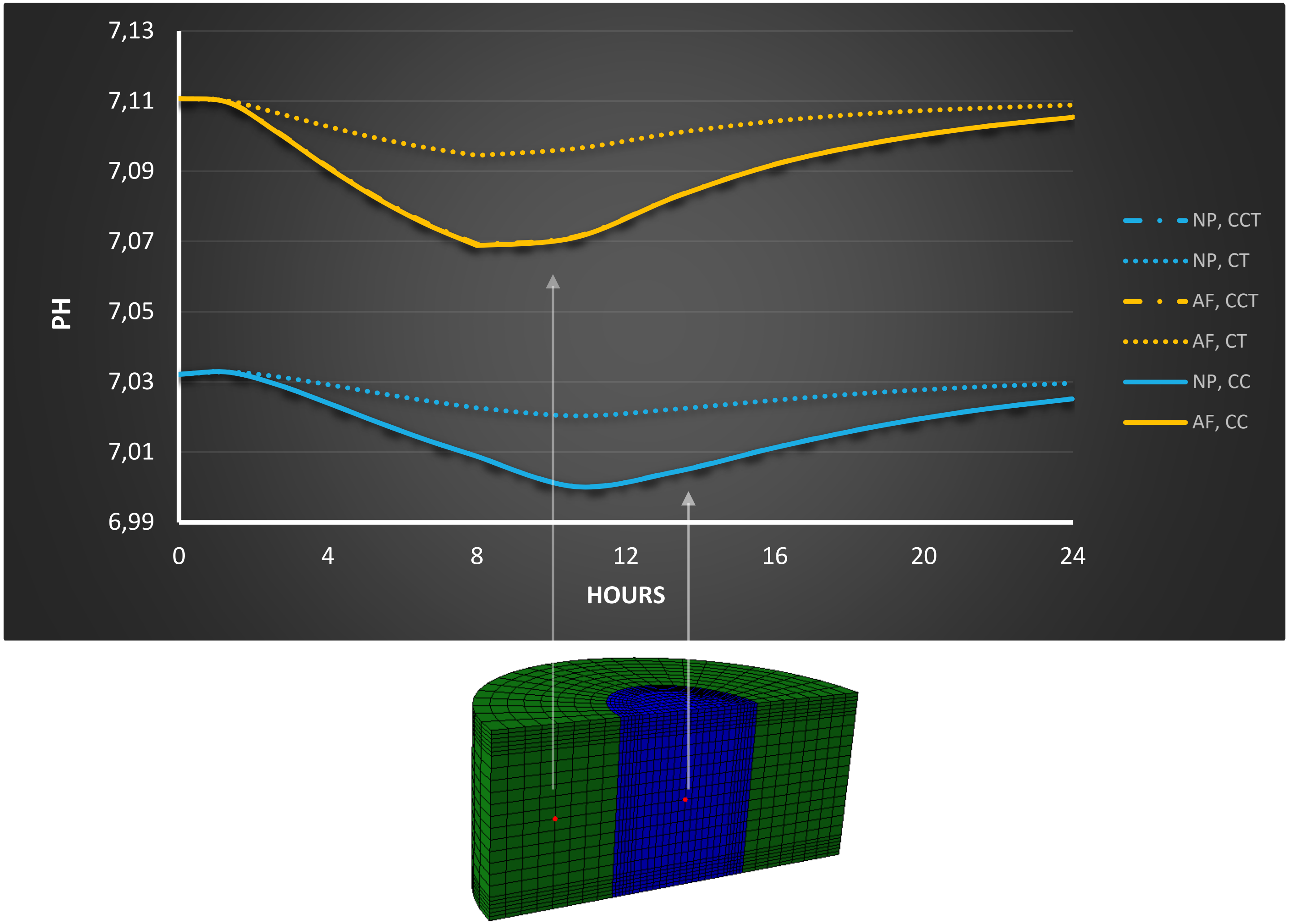


Niedlinger-Wilke, Eur Spine J (2014)

Glucose concentration in the IVD

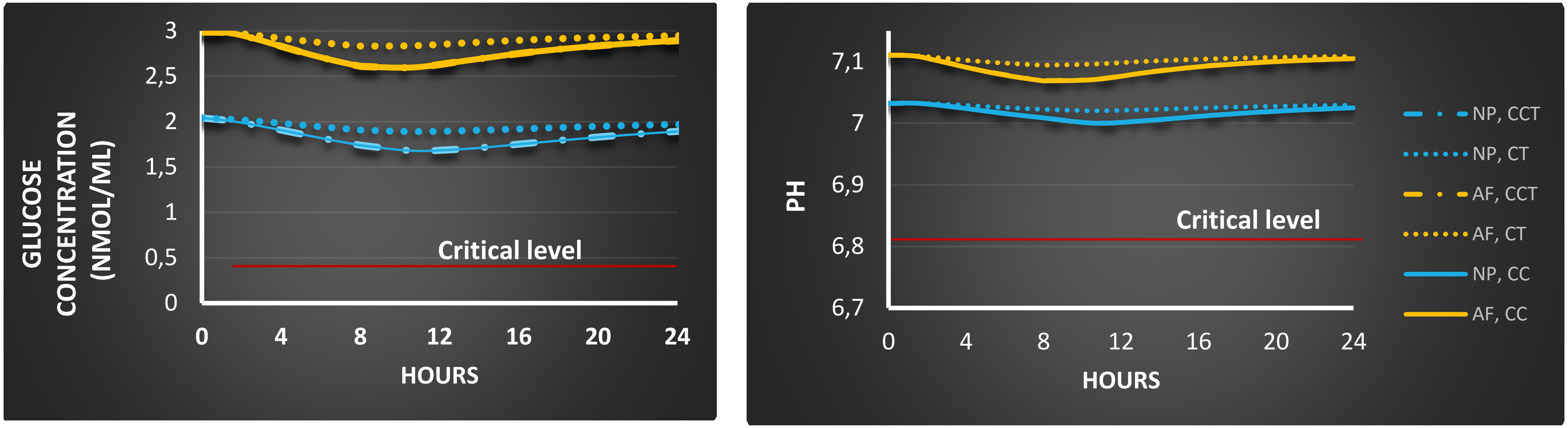


pH in the IVD



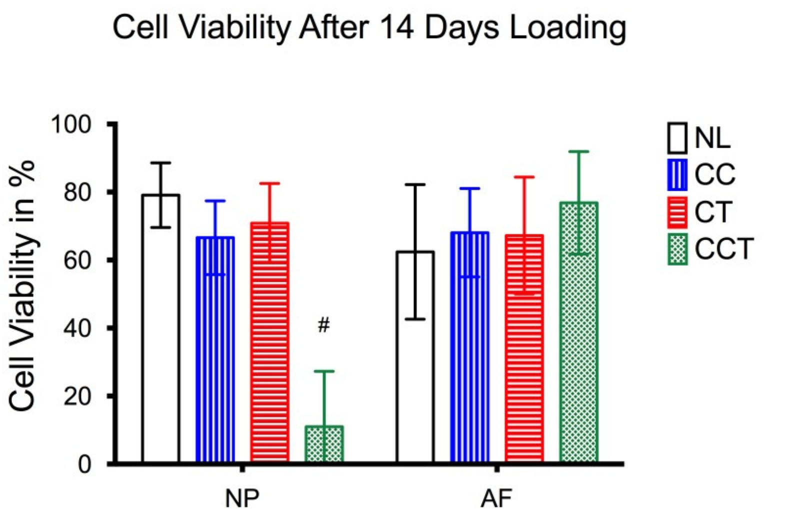
7,13
7,11
7,09
7,07
7,05
7,03
7,01
6,99
PH
0
4
8
12
16
20
24
HOURS
NP, CCT
NP, CT
AF, CCT
AF, CT
NP, CC
AF, CC

Solute concentrations and cell viability



- Cells will not die directly due to metabolic causes

VS.

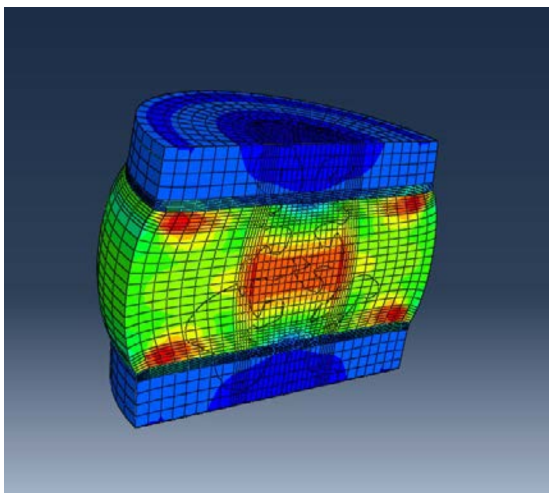


Chan et al., Plos One (2013)

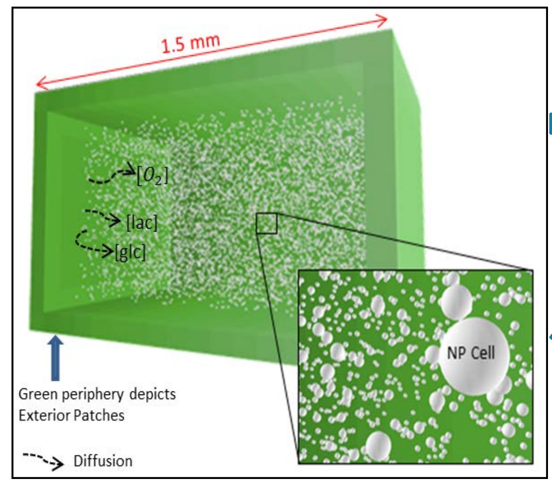
Future Work: Adding a Model on the Cellular Level

Porosity

Hydrostatic pressure



FEM



Agent Based Model (ABM)

Update cells' response to mechanical stimuli

Update relevant mechanical parameters

Using the FE method as a clinical tool

- Patient specific simulations
  - Diagnosis
  - Prognosis
  - Treatment evaluation

- Predictive tool

- Evaluating regenerative therapies

Smith et al. Dis Model Mech (2011)

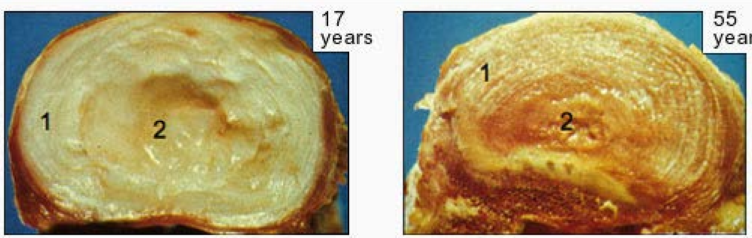
Conclusions:

- Compression effects appear stronger than torsion effects
- Necessary to further investigate reason for difference in results
- Important to make a model which is closer to physiological reality
- Computational simulations are powerful tools for the advancement of studies in biomedicine

Thank you

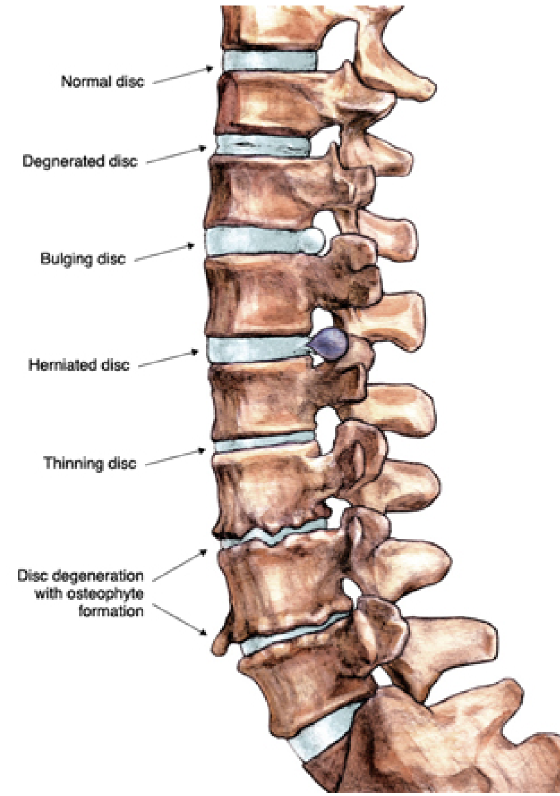
Disc degenerative disease

- Stiffening of AF
- Loss of liquid from NP
- Reduced disc height



Disc degeneration
Left: young healthy disc with annulus fibrosus (1) and nucleus pulosus (2)
Right: degenerative disc with loss of water content

http://www.eurospine.org/motion-preservation.htm



http://www.uvaspine.com/lumbar-degenerative-disc-disease.php

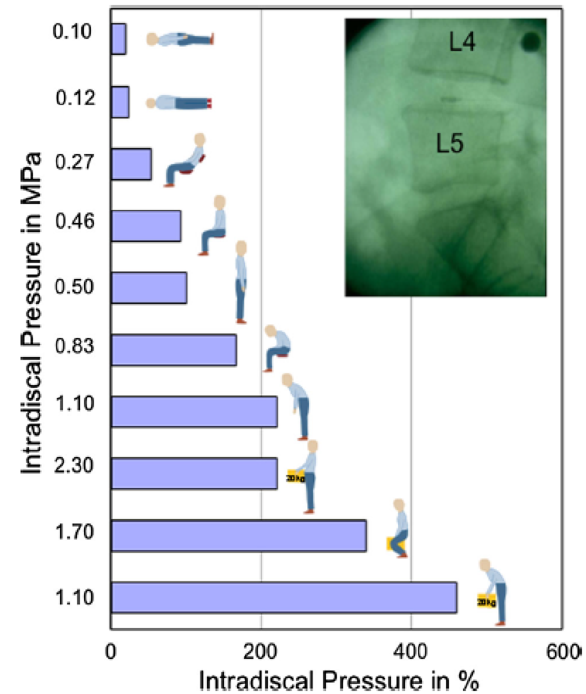
Effects of mechanical loading on IVDs

- Higher prevalence of disk degeneration in high level athletes than non-athletes
  - High risk sports:
    - Artistic gymnastics
    - Baseball
    - Golf
    - Swimming
    - Basketball
  - Loads:
    - Excessive, repetitive torsion
    - High impact
    - Excessive extension/flexion

Effects of mechanical loading on IVDs

With increasing loads:

- Water loss
- Reduction in disc height
- Increased hydrostatic pressure (NP)
- Reduction in porosity
- Increased tensile strain (AF)
- Activation of fibers (AF)



Neidlinger-Wilke et al., European Spine Journal (2014)