

# Auxetic Behavior in Fibrous Soft Tissues

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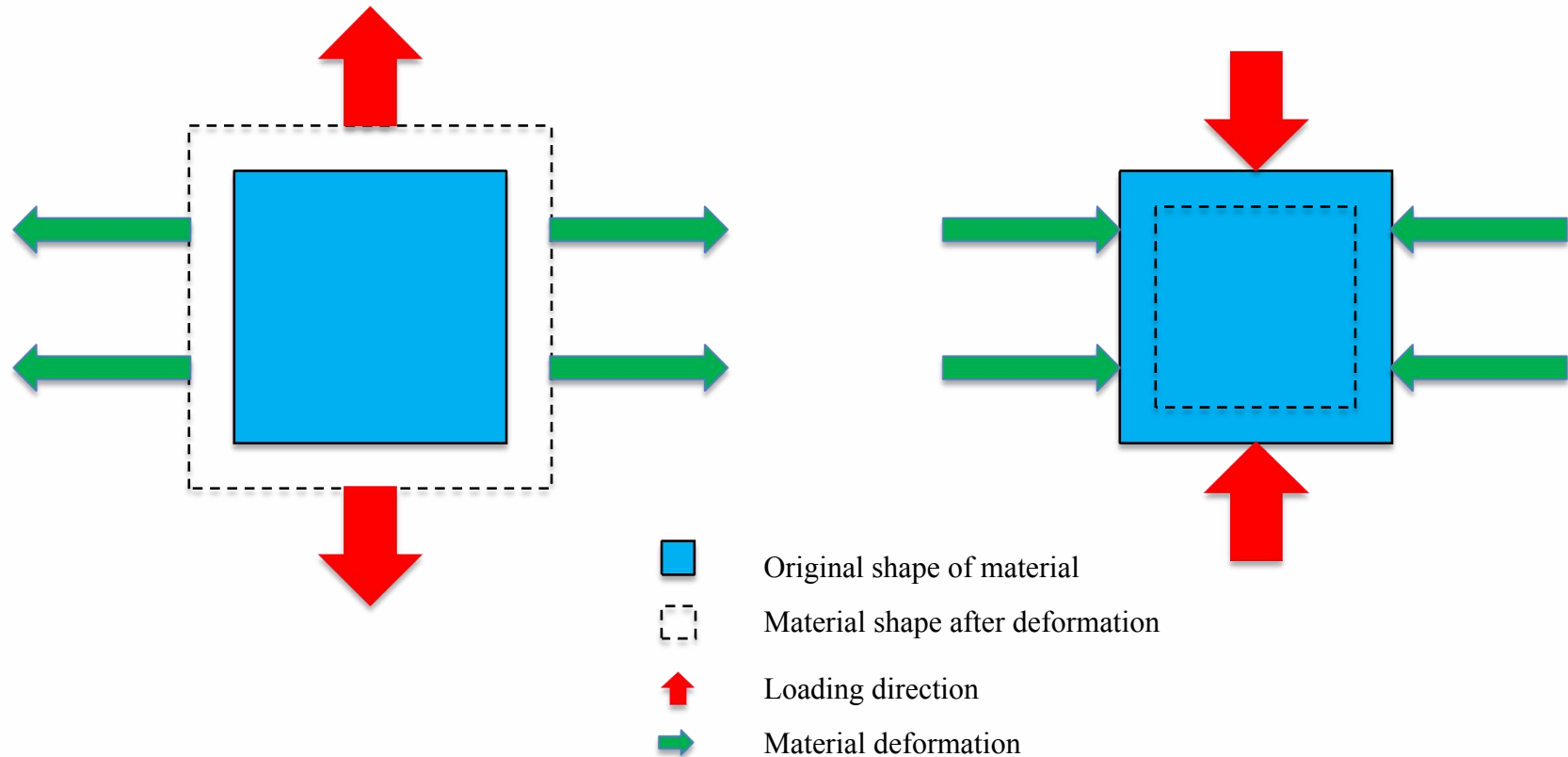
Laboratoire de Mécanique et Génie Civil (LMGC)  
Equipe BIOTIC - Biomécanique cellulaire et tissulaire



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LABORATOIRE DE MÉCANIQUE ET GÉNIE CIVIL - UM/CNRS

# Auxetic Materials



Auxetic materials have a negative Poisson's ratio. When stretched, they become thicker perpendicularly to the loading direction; and when compressed, they become thinner perpendicularly to the loading direction.

# Auxetic behavior in biological tissues reported in the literature

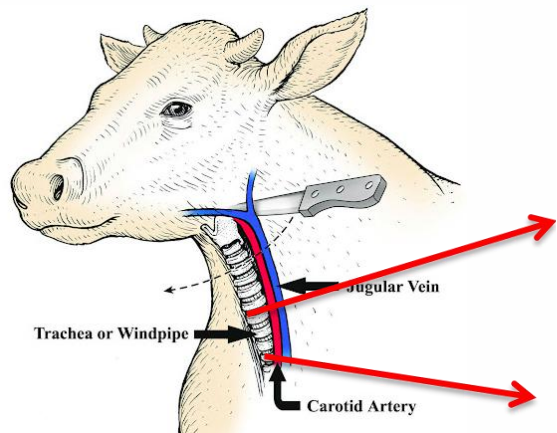
- **In skin tissue**
  - Cat skin - *Veronda et al. (1970)*
  - Cow teat skin - *Lee et al. (1991)*

The negative Poisson's ratio was found in the samples with a low aspect ratio (ratio of length to width).
- **In blood vessels**
  - Bovine common carotid arteries (Media) - *Timmings et al. (2010)*

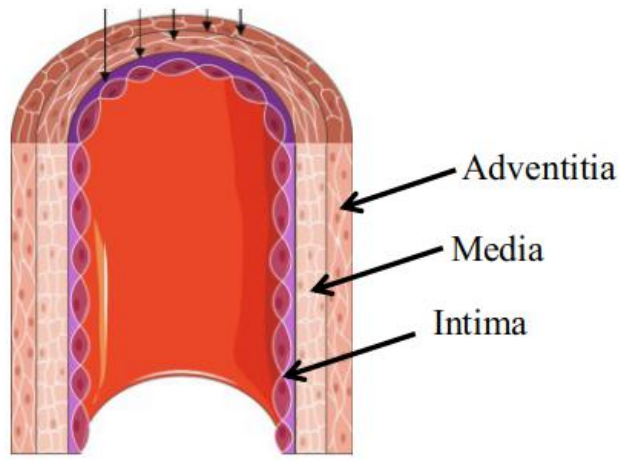
10% strain in the circumferential direction led to a tendency towards thickening to the radial direction.

  - Porcine aortic wall (Media) - *Skacel et al. (2016)*

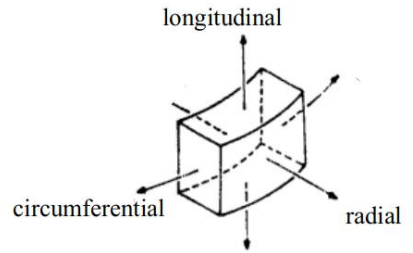
The negative Poisson's ratio is observed in some individual tests of multiple uniaxial tests, which are considered as an error by the authors.



Reproduced from Shearer et al. (2016)



Structure of the arterial wall.  
Reproduce from from Brown et al. (2017)

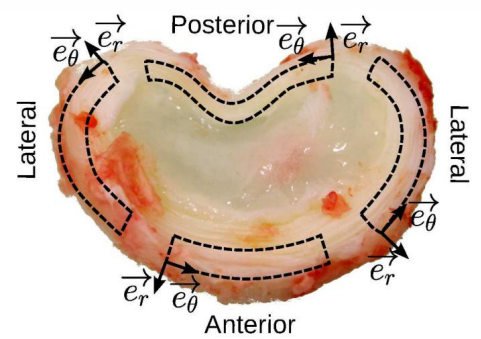


# Auxetic behavior in biological tissues reported in the literature

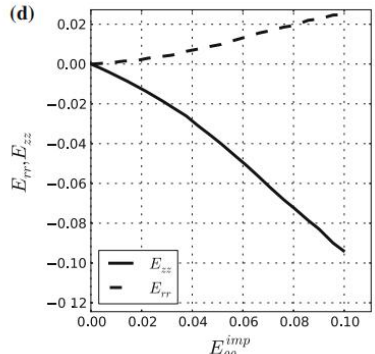
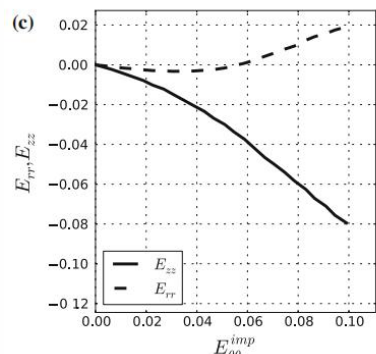
## In annulus fibrosus tissue

- Porcine intervertebral disc - *Baldit et al. (2013)*  
 Auxetic behavior in the radial direction is observed when the strain is applied in the circumferential direction in some tests of multiple uniaxial tests.

Storage time before test : 20 min  
 (in 0.15 mol/L NaCl solution)  
 Test strain rate: 0.001/s.



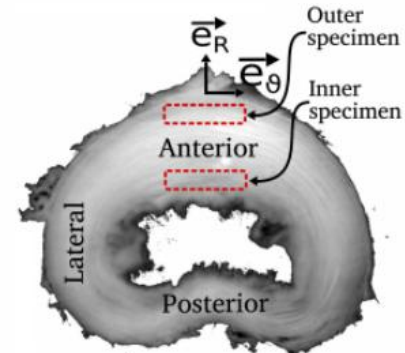
Specimen extraction



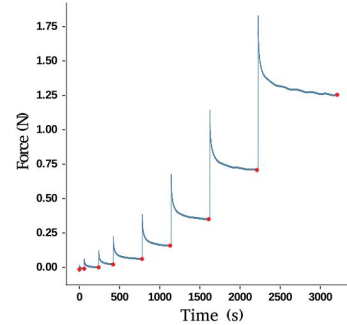
Logitudinal and radial transverse strains as functions of the circumferential strain.

- Porcine intervertebral disc - *Dusfour et al. (2020)*  
 Auxetic behavior is observed both in radial and longitudinal when the strain is applied in the circumferential direction.

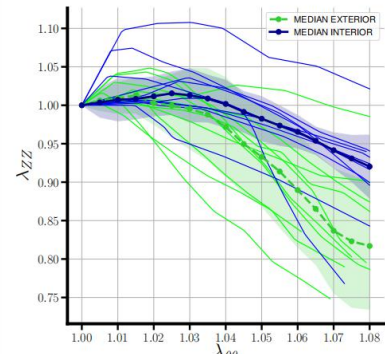
Storage time before test : 3 h  
 (in 0.15 mol/L NaCl solution)  
 Strain condition: multi-load-relax



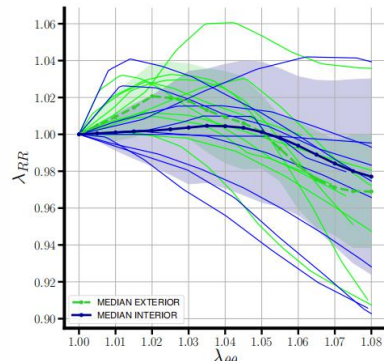
Specimen extraction



Multi-load-relax loading



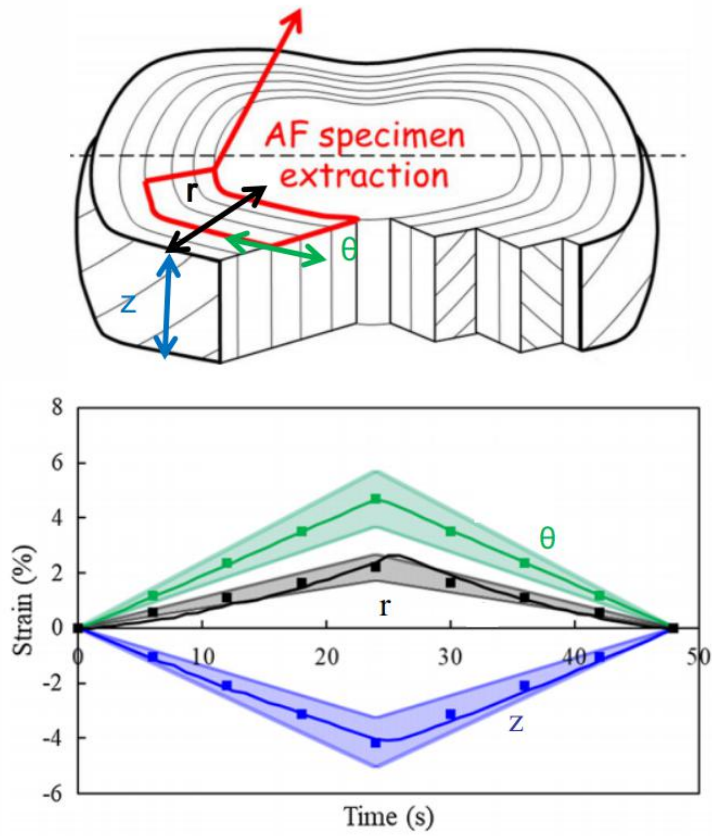
Vertical dilatation versus circumferential dilatation.



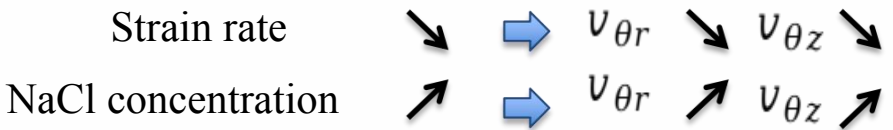
# Auxetic behavior in biological tissues reported in the literature

- **In annulus fibrosus tissue**
  - Bovine intervertebral disc - *Derrouiche et al. (2018)*

Auxetic behavior in radial direction is observed when the strain is applied in the circumferential direction.



Storage time before test : 100 min  
 (in different saline concentrations before and during the test)  
 Strain condition: Loading–unloading test



NaCl concentration (g/L)	Strain rate (s <sup>-1</sup> )	Poisson's ratio experiments	
		$\nu_{\theta z}$	$\nu_{\theta r}$
0	$2 \times 10^{-3}$	$0.887 \pm 0.19$	$-0.468 \pm 0.1$
	$2 \times 10^{-4}$	$0.74 \pm 0.16$	$-0.574 \pm 0.12$
9	$2 \times 10^{-3}$	$0.92 \pm 0.2$	$-0.2 \pm 0.04$
	$2 \times 10^{-4}$	$0.74 \pm 0.16$	$-0.387 \pm 0.08$
18	$2 \times 10^{-3}$	$0.963 \pm 0.21$	$-0.146 \pm 0.03$
	$2 \times 10^{-4}$	$0.811 \pm 0.17$	$-0.29 \pm 0.06$

Experimental Poisson's ratios for different saline concentrations and strain rates

Experimental circumferential and transversal strains for one of the 6 test.

# Auxetic behavior in biological tissues reported in the literature

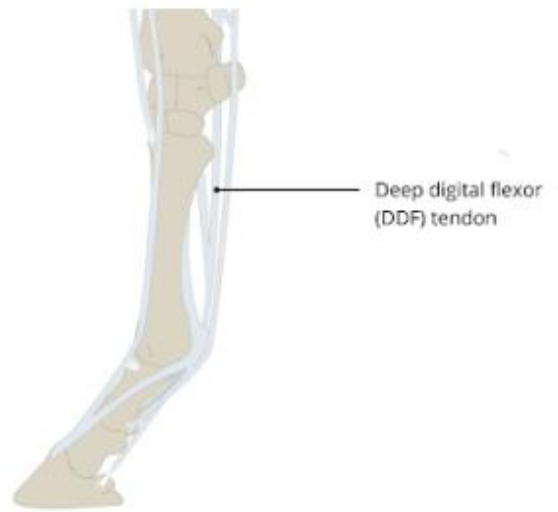
- In tendon - *Gatt et al. (2015)***

- Ex vivo

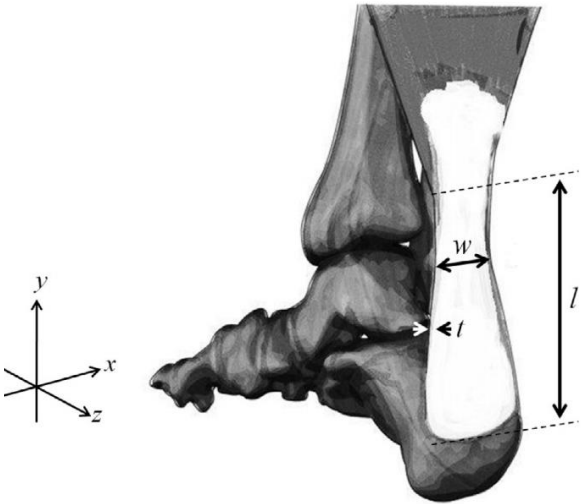
Uniaxial tests were carried out on human achilles, human peroneus brevis, porcine and ovine deep flexor tendons at a velocity 5 mm/min up to 3% strain.

- In vivo

The auxeticity of human Achilles tendon was also confirmed in vivo using magnetic resonance imaging.



Schematic of deep flexor tendons.  
Reproduced from *horseDVM*



Schematic of human achille tendon.

Tendon	Sample	Poisson's ratio
Achilles	HA1	-1.44
	HA2	-0.39
Peroneus brevis	HPB1	-3.81
	HPB2	-0.166
Deep flexor (sheep)	SDF1	-2.23
	SDF2	-1.14
	SDF3	-0.37
	SDF4	-3.56
	SDF5	-9.86
Deep flexor (pig)	PDF1	-0.56
	PDF2	-0.34
	PDF3	-3.11
	PDF4	-1.32
	PDF5	-1.32

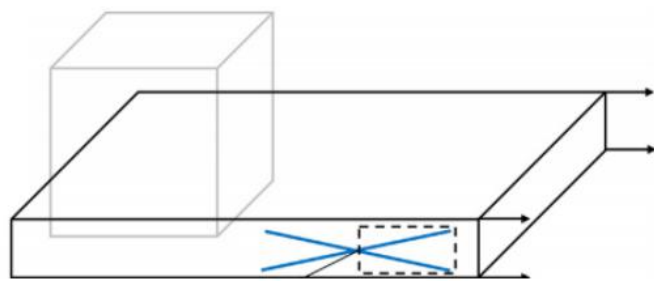
The negative Poisson's ratio measured in the plane  $xy$  for 3% strain of the tendons tested.

- In other tissue**

- Human tibia bone - *Williams et al. (1982)*
- Axoloti embryonic epithelia - *Wiebe & Brodland (2005)*
- Bovine eyes corneal at the interfibrillar level - *Patten et al. (2013)*

# Interpretation of auxetic behavior in soft tissues proposed in the literature

- Crimped fibre structure in tendon - Gatt *et al.* (2015)
- Crimped fibrous form in the skin tissue - Lee *et al.* (1991)
- Variable and inhomogeneous alignment of elastin and collagen fibres in arterial wall - Timmins *et al.* (2010)
- Strain rate of uniaxial test and osmolarity of the local environment in annulus fibrosus tissue - Derrouiche *et al.* (2018) (Chemo-mechanical approach for the intrinsic osmo-inelastic response.)
- Fibre-matrix stiffness ratio & fibres dispersion  
HGO (Gasser, Ogden and Holzapfel) model



Schematic of the uniaxial tension of a fibre-reinforced cube with two fibre families. Reproduce from Fereidoonzhad *et al.* (2020)

- HGO model to simulate annulus fibrosus tissue - Dusfour *et al.* (2020)

# Fibre arrangements reported in the literature

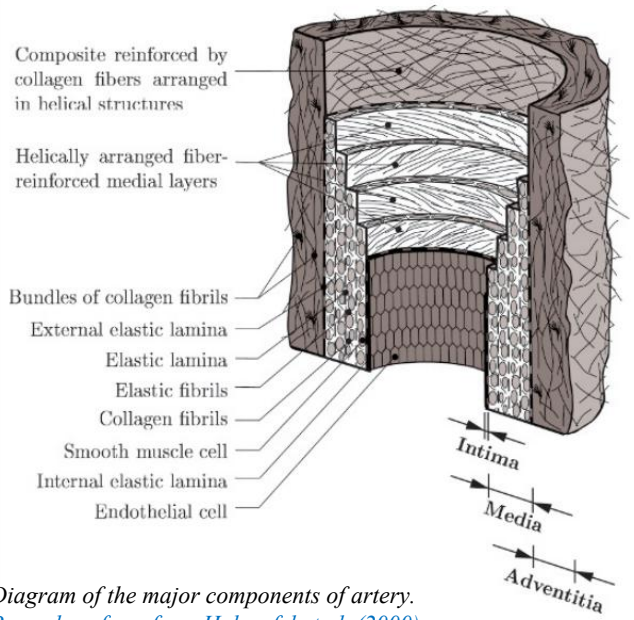
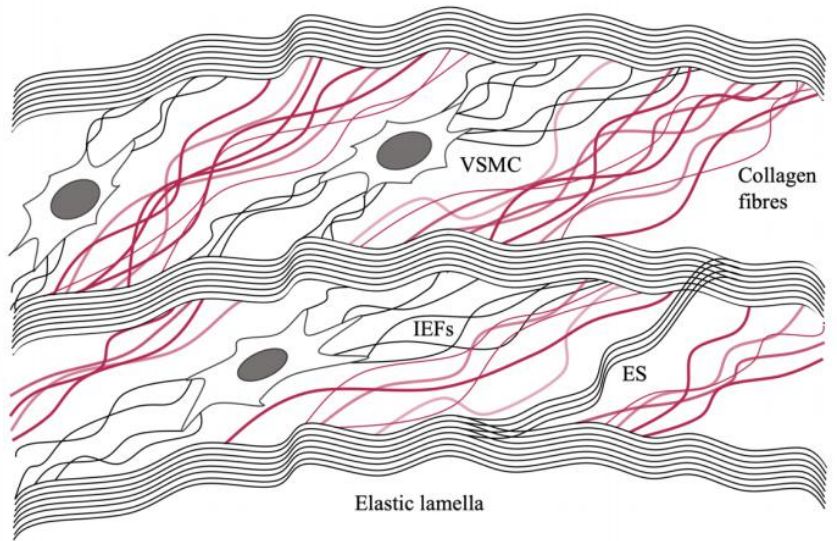


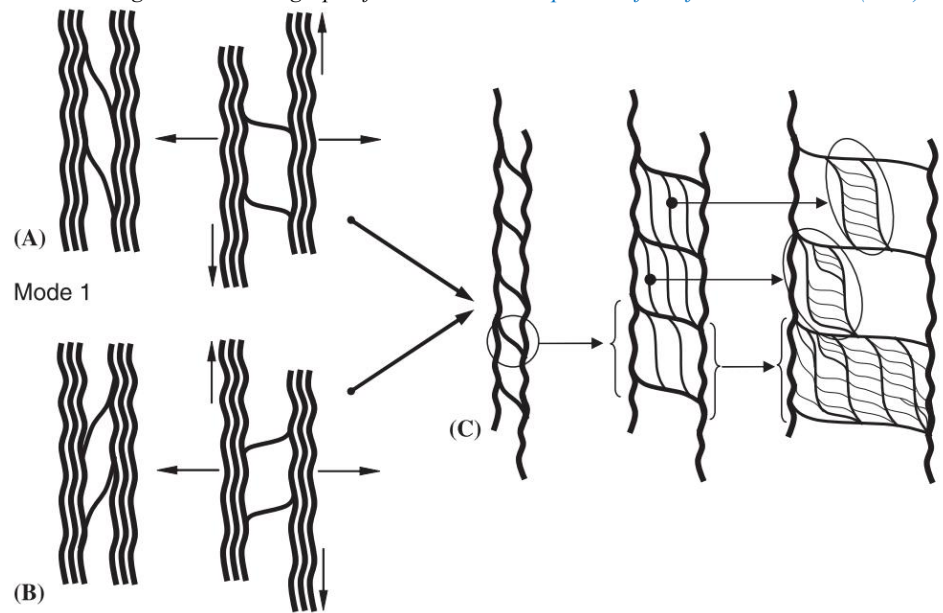
Diagram of the major components of artery. Reproduce from from Holzapfel et al. (2000)



Scanning electron micrograph of human tendon. Reproduce from from Evans et al. (1975)



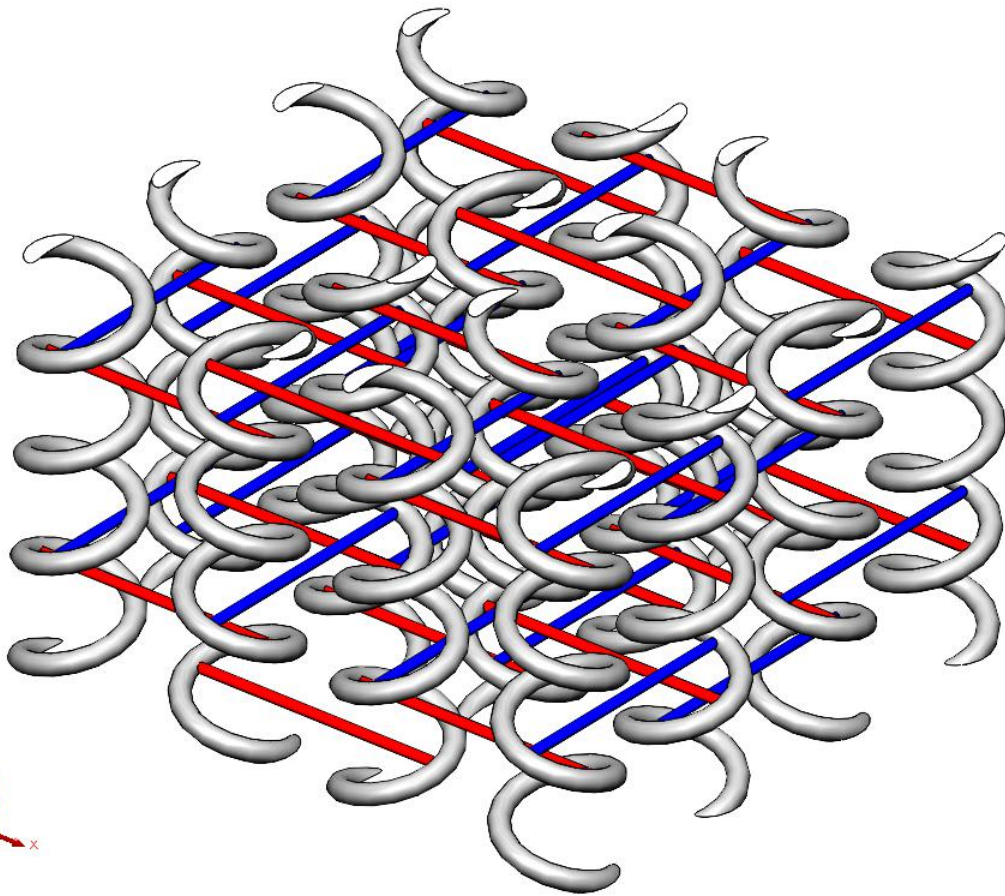
Schematic cross-sectional representation of the arterial media. Reproduced from Giudici et al. (2020)



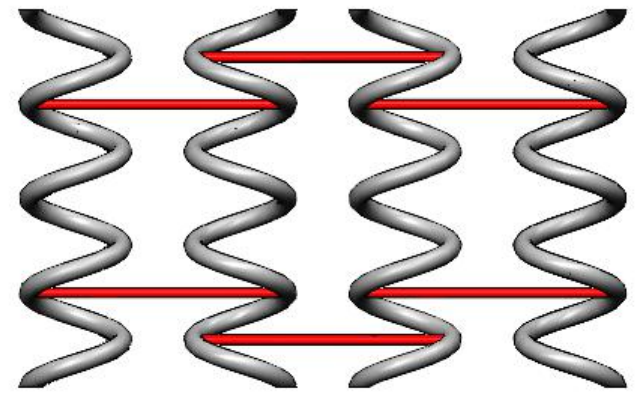
Schematic diagram of interconnectivities involving mono cross-over of collagen in the annulus fibrosus. Reproduced from Pezowicz et al. (2005)



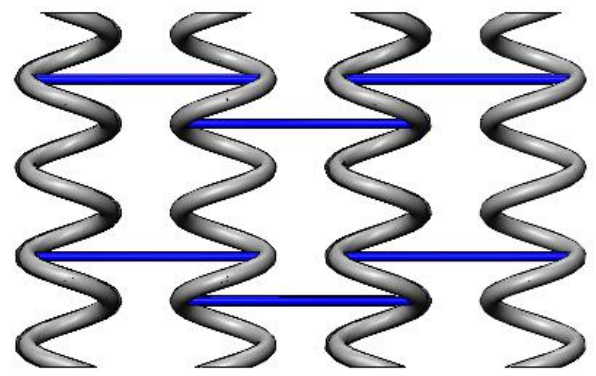
# Proposed collagen fibres structure



3D perspective of the fiber structure



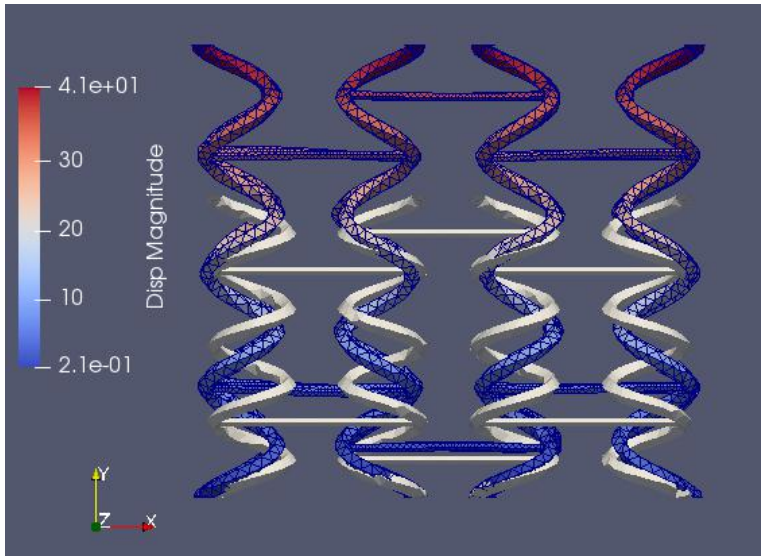
Fiber structure of the plan yx



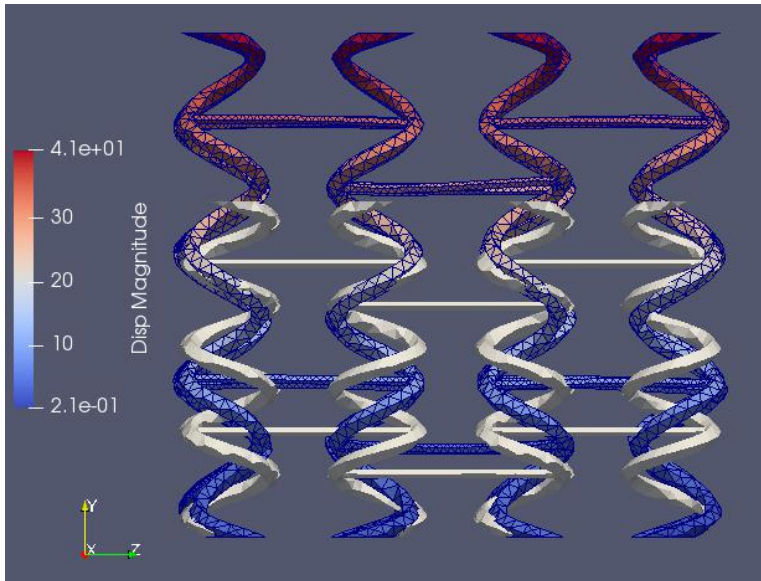
Fiber structure of the plan yz

Software: Solidworks, Freecad

# Tensile test simulation results

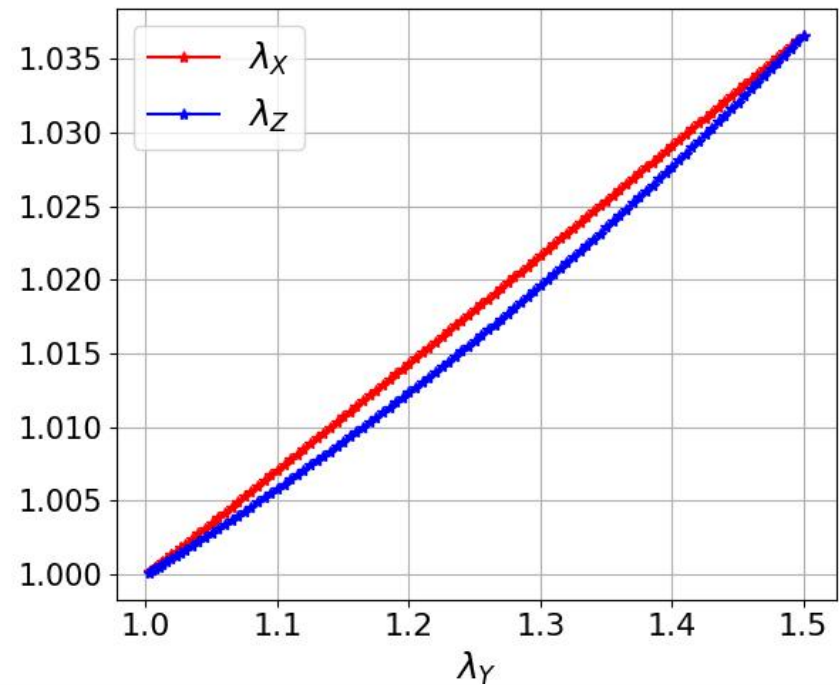


*Displacement field in plan  $xy$ .*

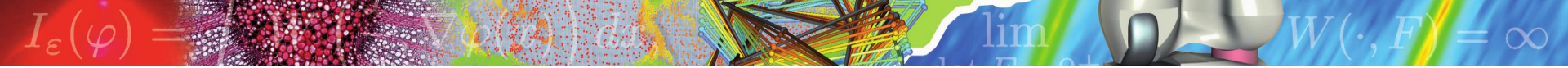


*Displacement field in plan  $yz$ .*

## Dilatation relation



Software: GMSH, LMGC90, Paraview



## Conclusions / Discussion

- Fibre corrugation and cross linking  $\longrightarrow$  Auxetic behavior of fibrous soft tissues
- The influence of the matrix has not been considered yet
- The auxetic response of fibrous soft tissues during tensile tests may not be an error
- Influenc of experimental conditions (storage time before test, strain rate and saline concentrations)

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