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Experimental measurements versus model predictions of fiber rotations in soft tissues

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(2) LTDS, CNRS UMR 5513, Université de Lyon, Ecole Centrale Lyon, France

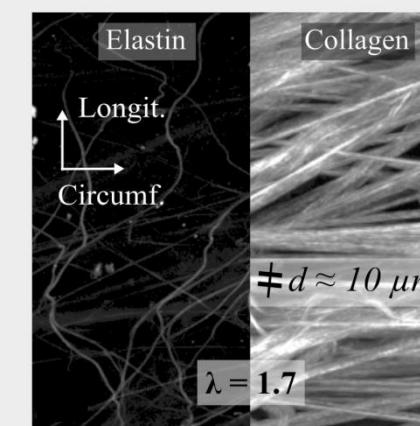


Context

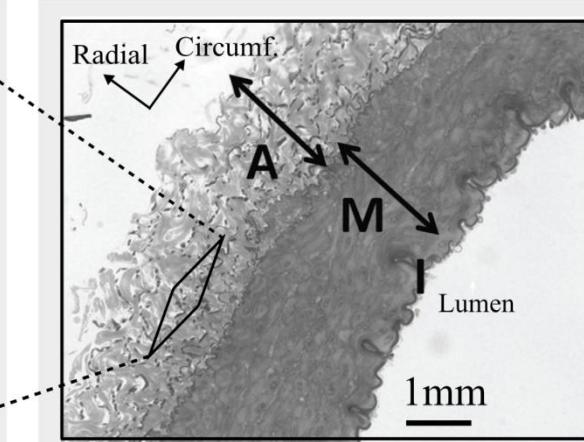
> Multiscale approaches to vascular biomechanics



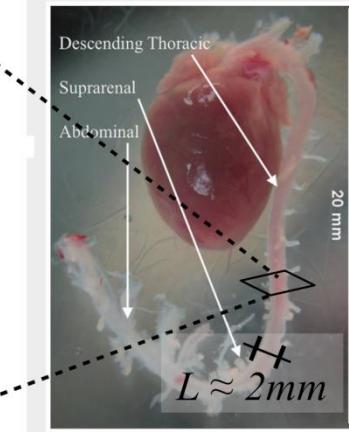
Rearranging,
remodeling
microstructure



Prediction

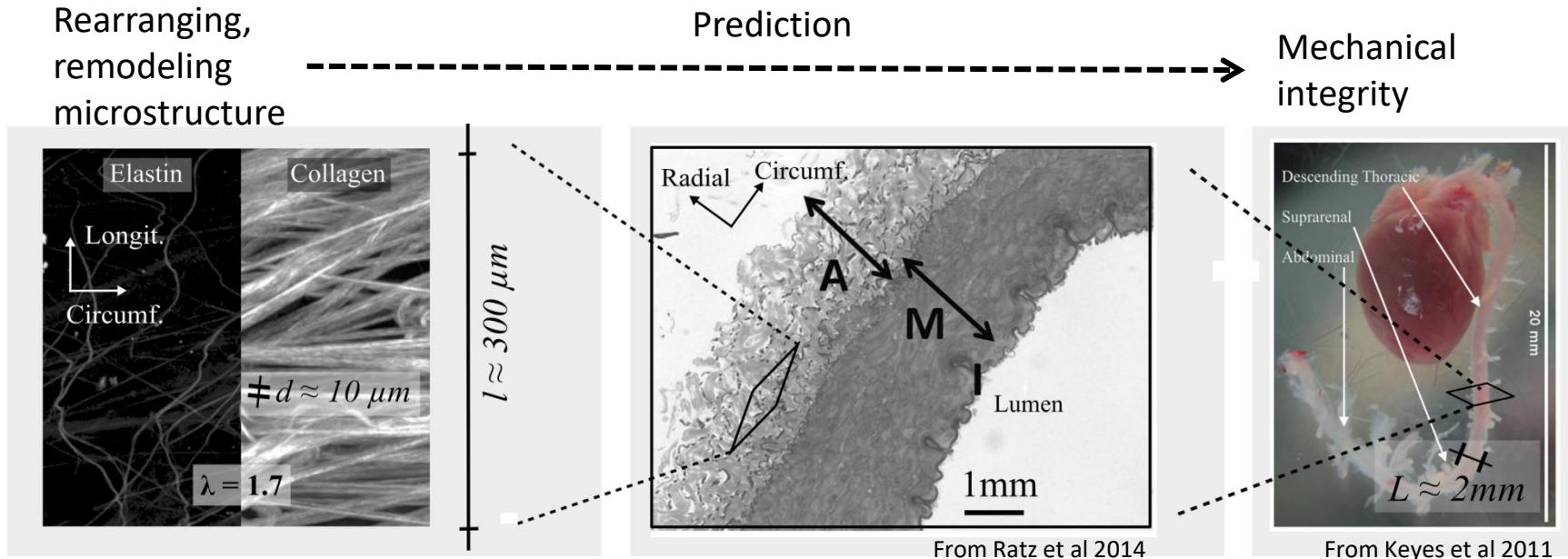


Mechanical
integrity



Context

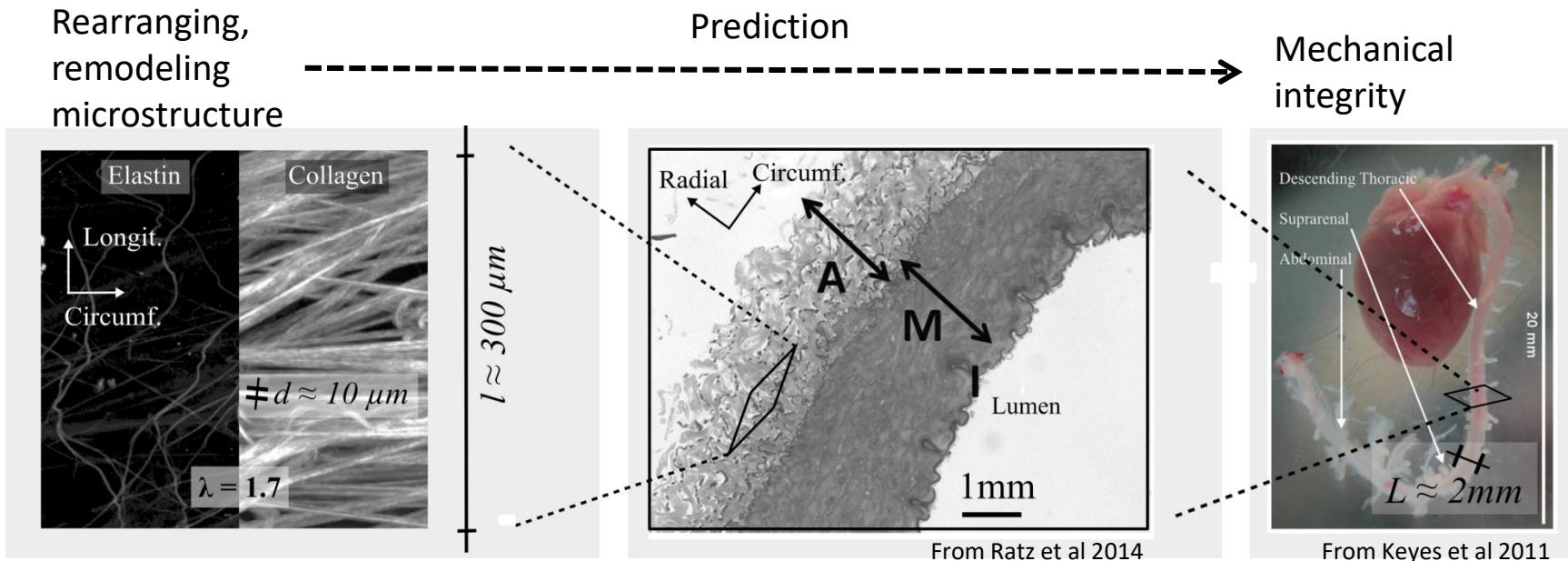
> Multiscale approaches to vascular biomechanics



- > Treatment of vascular diseases: overcome the **limits of phenomenological models**
- > Existing models provide interesting results: [Stylianopoulos et al \(2007\)](#), [Zhang et al \(2013\)](#), [Marino et al \(2013\)](#), [Lee et al \(2015\)](#)

Context

> Multiscale approaches to vascular biomechanics



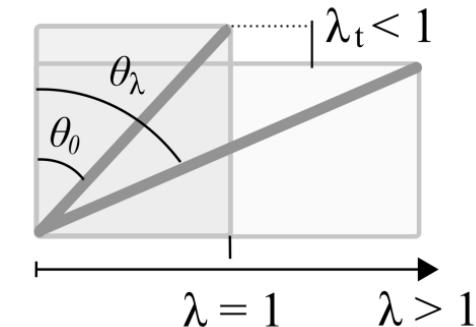
- > Treatment of vascular diseases: overcome the **limits of phenomenological models**
- > Existing multiscale models provide interesting results: [Stylianopoulos et al \(2007\)](#), [Zhang et al \(2013\)](#), [Marino et al \(2013\)](#), [Lee et al \(2015\)](#)
- > The challenge remains open: uncertainty about **underlying mechanisms** that govern load-induced **microstructure rearrangements**

New questions are raised...

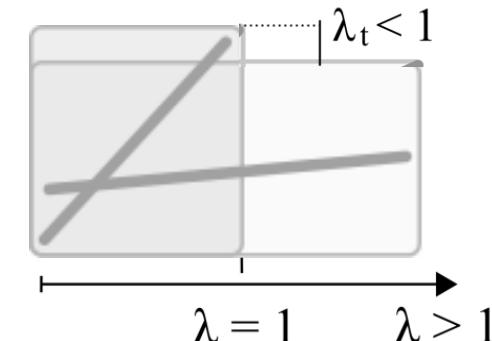
> Evidenced **non affine kinematics** of collagen fibers: Billiar et al (1997), Chandran et al (2003), Lake et al (2012)

Representative Volume
Element of a fibrous material
under biaxial deformation

Affine fiber motion:



Non affine fiber motion:

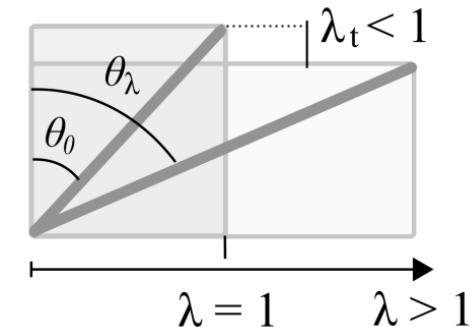


New questions are raised...

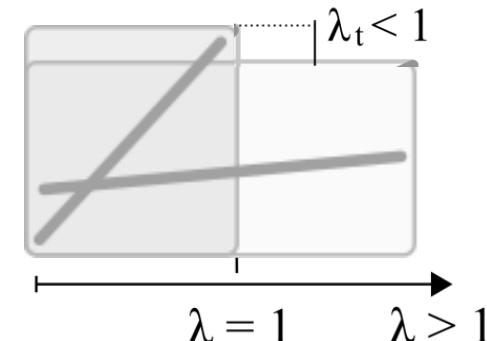
- > Evidenced **non affine kinematics** of collagen fibers: Billiar et al (1997), Chandran et al (2003), Lake et al (2012)
- > Do particular deformation scenarii or conditions **challenge affinity** of fiber motion?
- > If so, may this complex kinematics suggest **unknown structural properties or mechanisms** in the artery?

Representative Volume
Element of a fibrous material
under biaxial deformation

Affine fiber motion:



Non affine fiber motion:



Previous results

Krasny, W., Morin, C., Magoariec, H., & Avril, S. (2017). A comprehensive study of layer-specific morphological changes in the microstructure of carotid arteries under uniaxial load. *Acta Biomaterialia*.

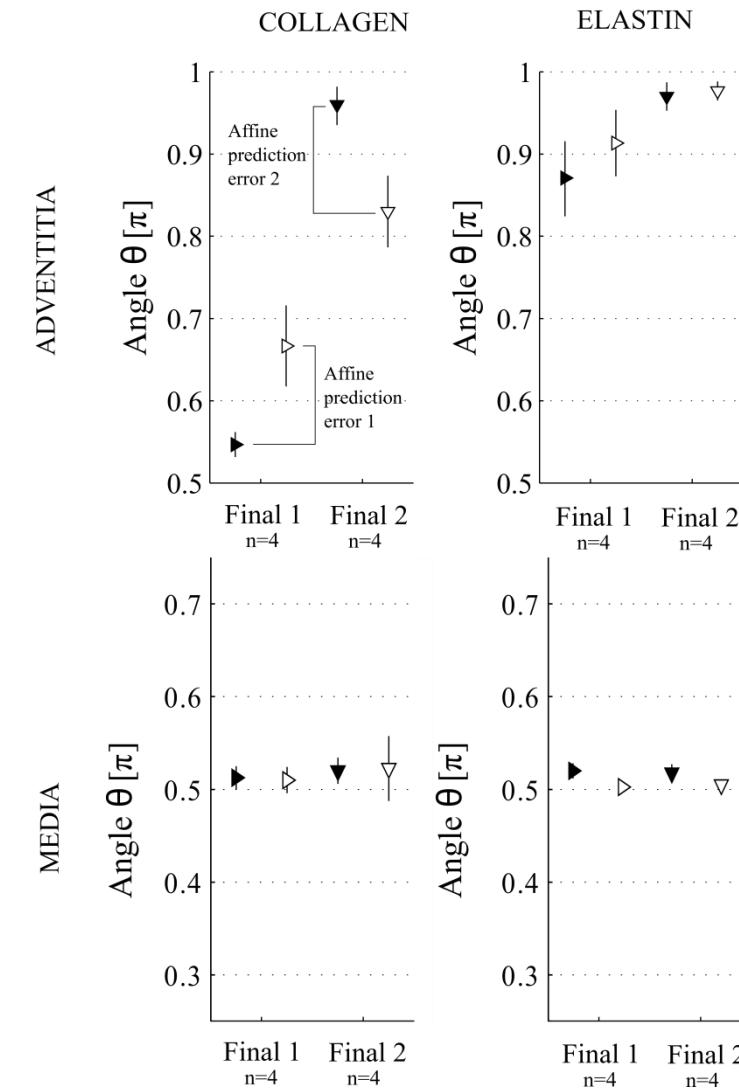
#1

The affine transformation rule **predicts well** the limited realignment of

- medial collagen
- medial elastin
- adventitial elastin

#2

The affine transformation rule **underestimates the realignment** potential of adventitial collagen fibers



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#1

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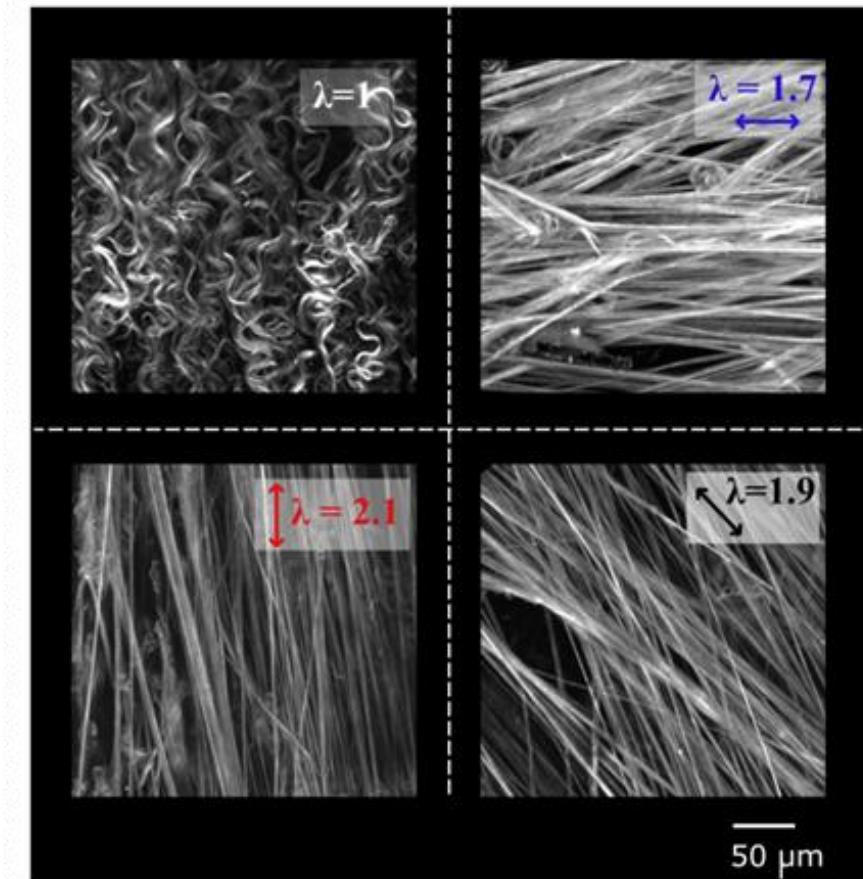
- medial collagen
- medial elastin
- adventitial elastin

#2

The affine transformation rule **underestimates the realignment** potential of adventitial collagen fibers

> We analyze **adventitial collagen** kinematics under **tension - inflation** loadings

Adventitial collagen under variously oriented uniaxial tension

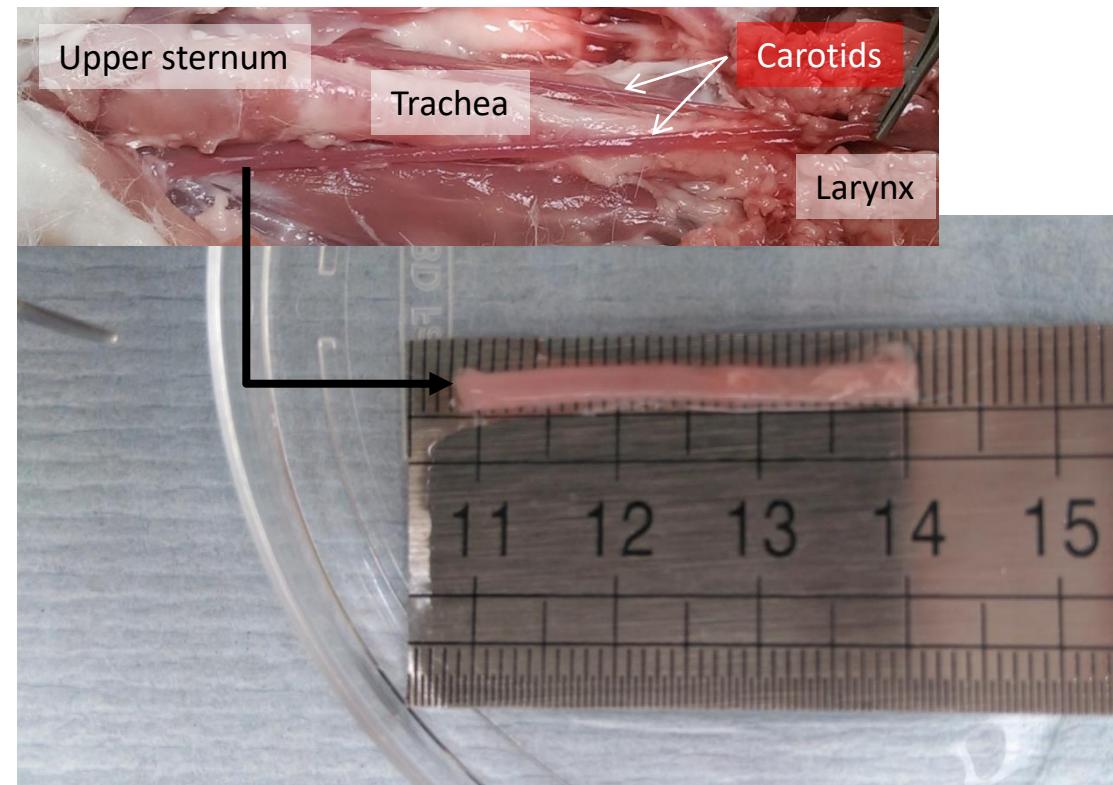


Excision of carotid arteries

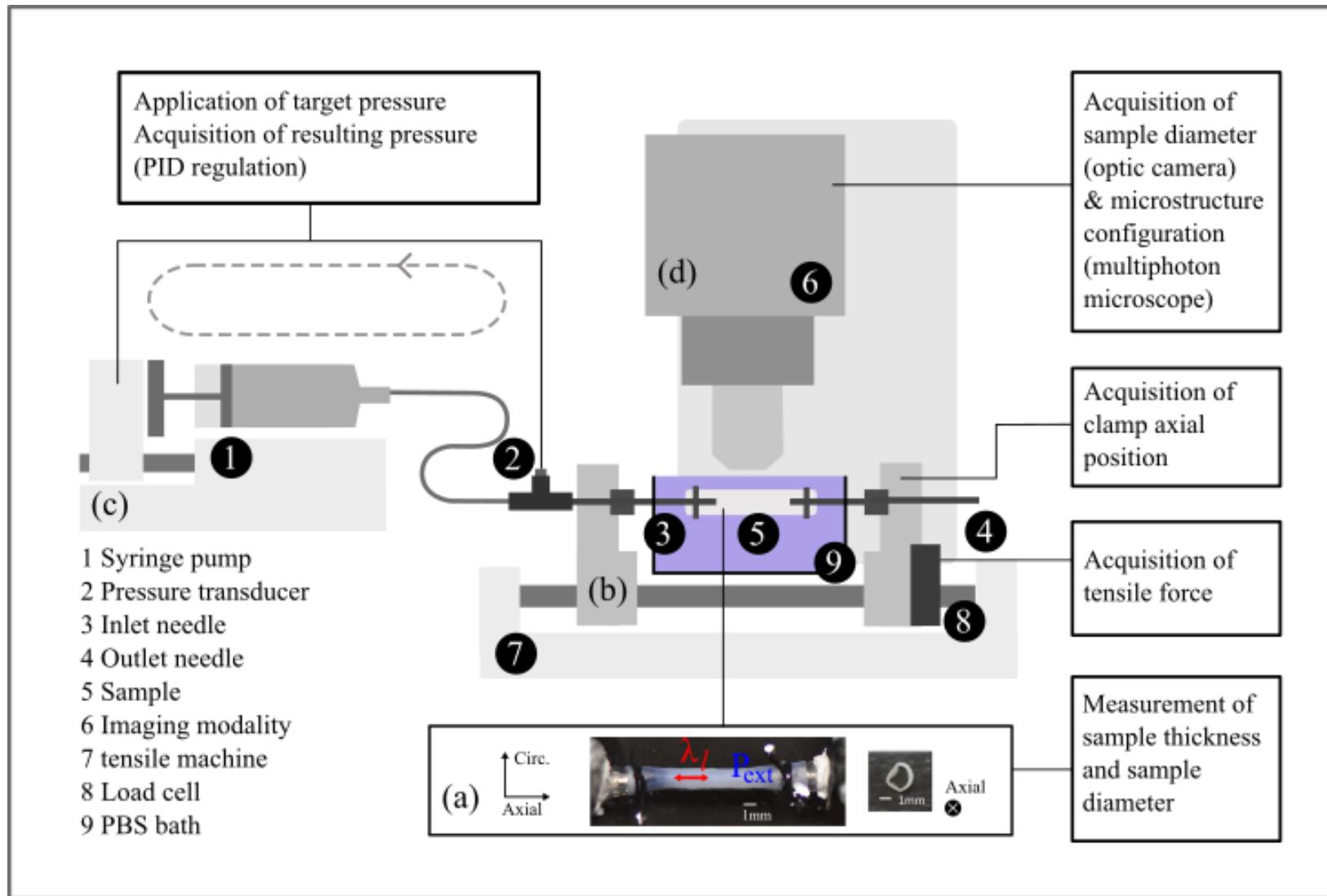
New Zealand
White rabbits

3kg males

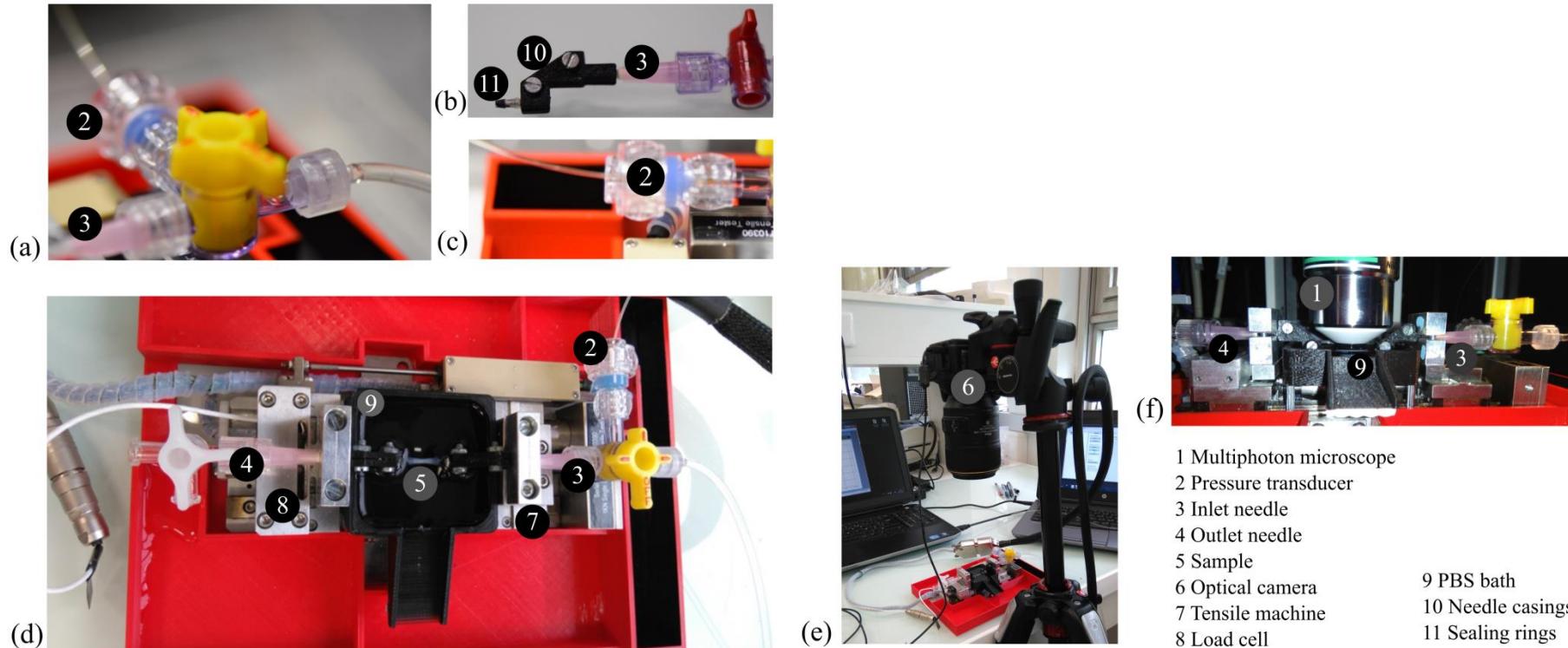
Excision @ VetAgro
Sup, Marcy l'Etoile (FR)



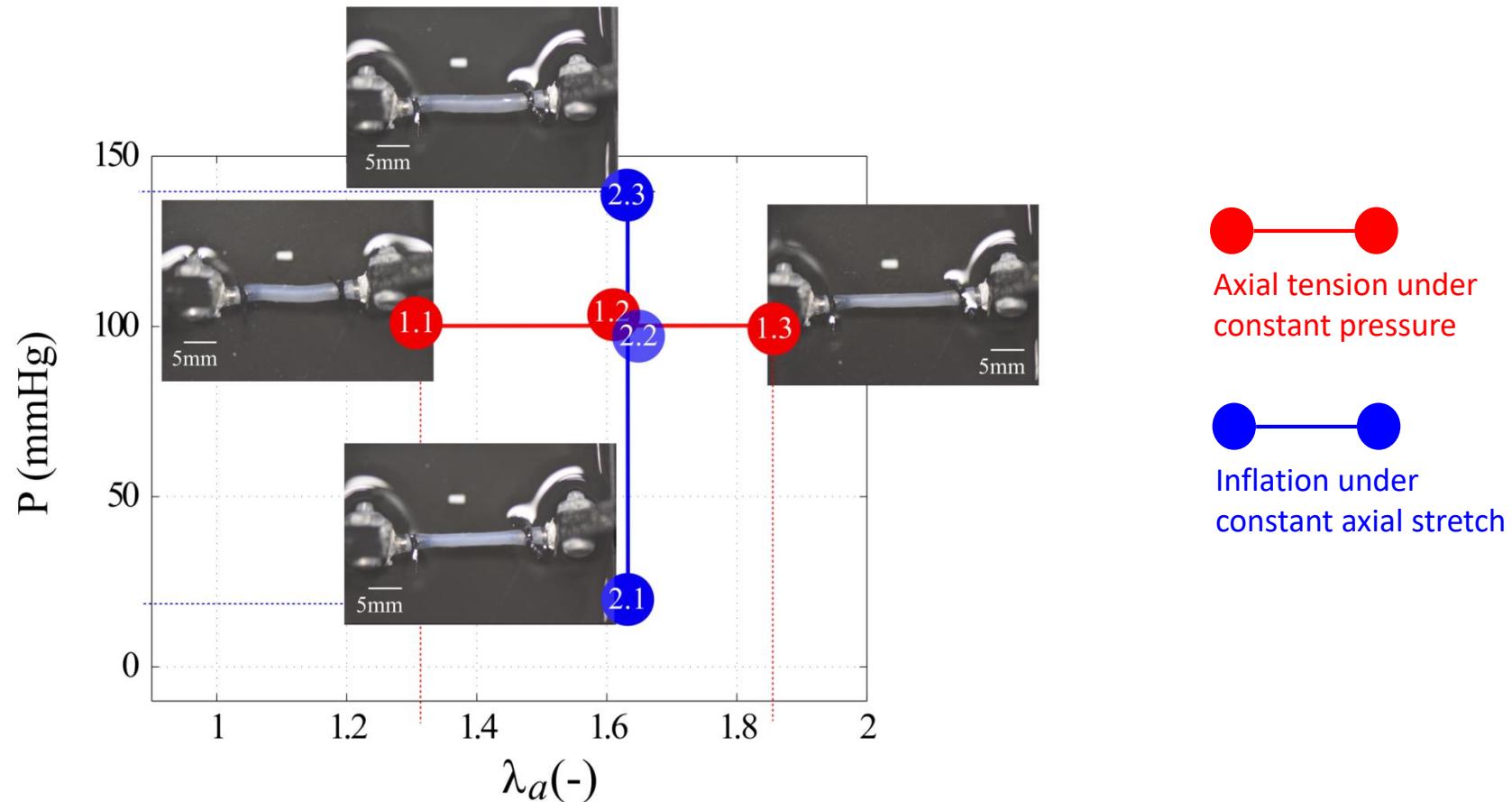
Experimental tension-inflation setup



Experimental tension-inflation setup

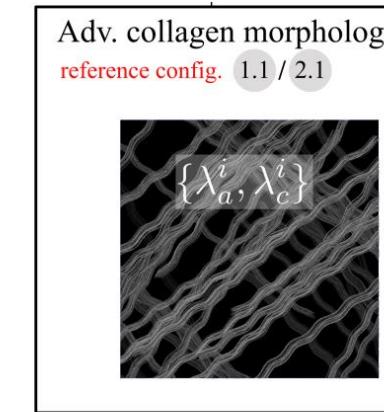
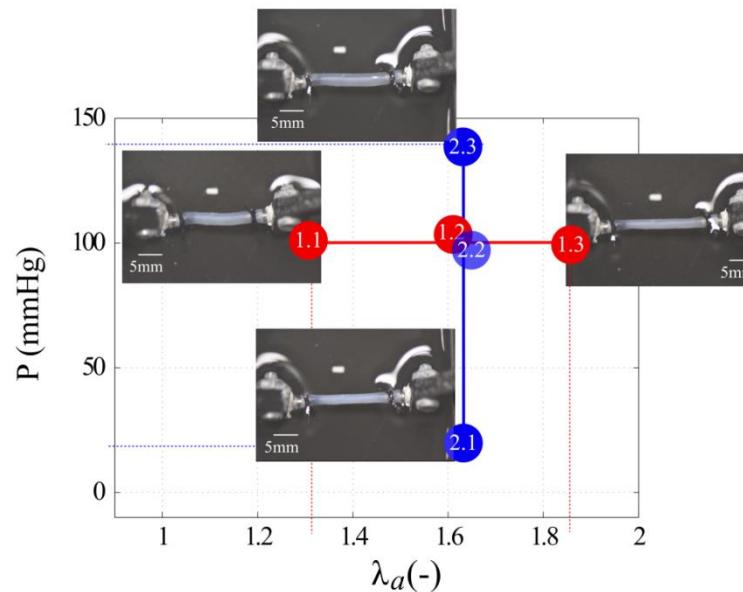


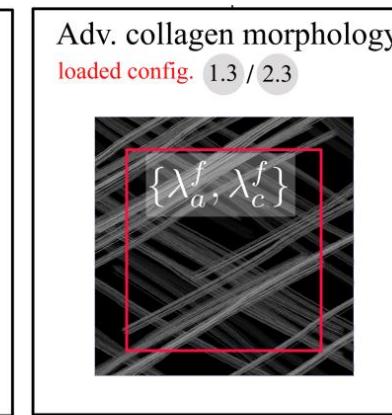
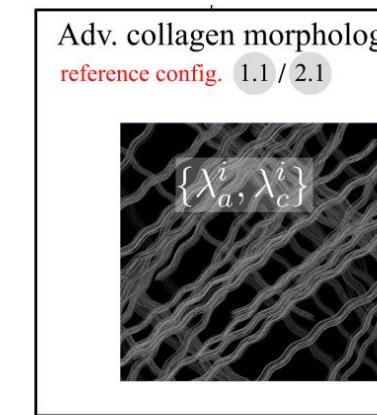
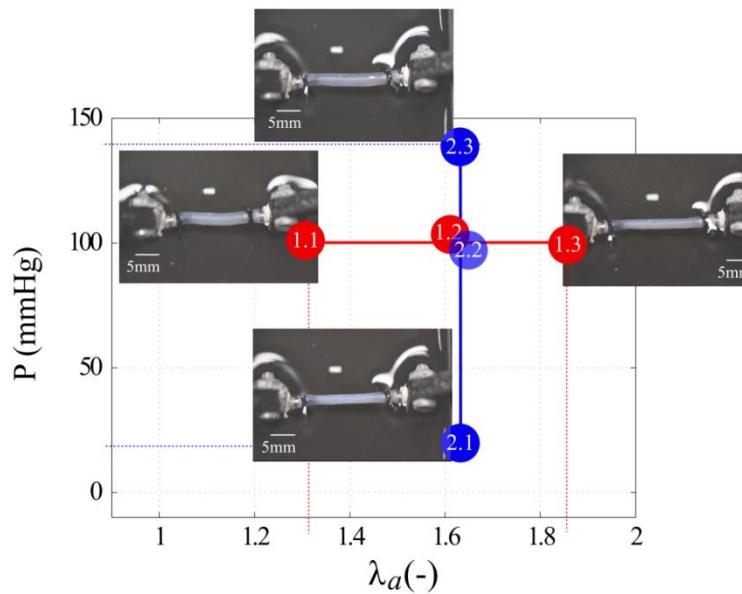
Tension-inflation loading protocol



Axial tension under constant pressure

Inflation under constant axial stretch





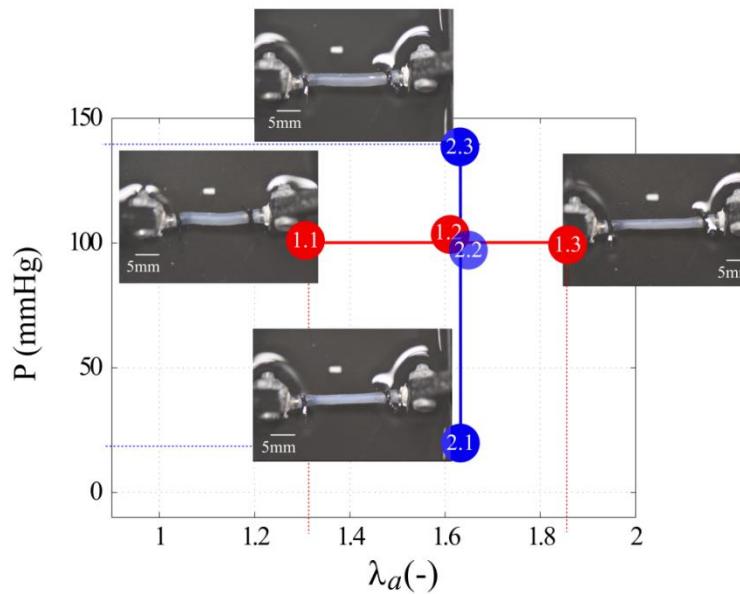
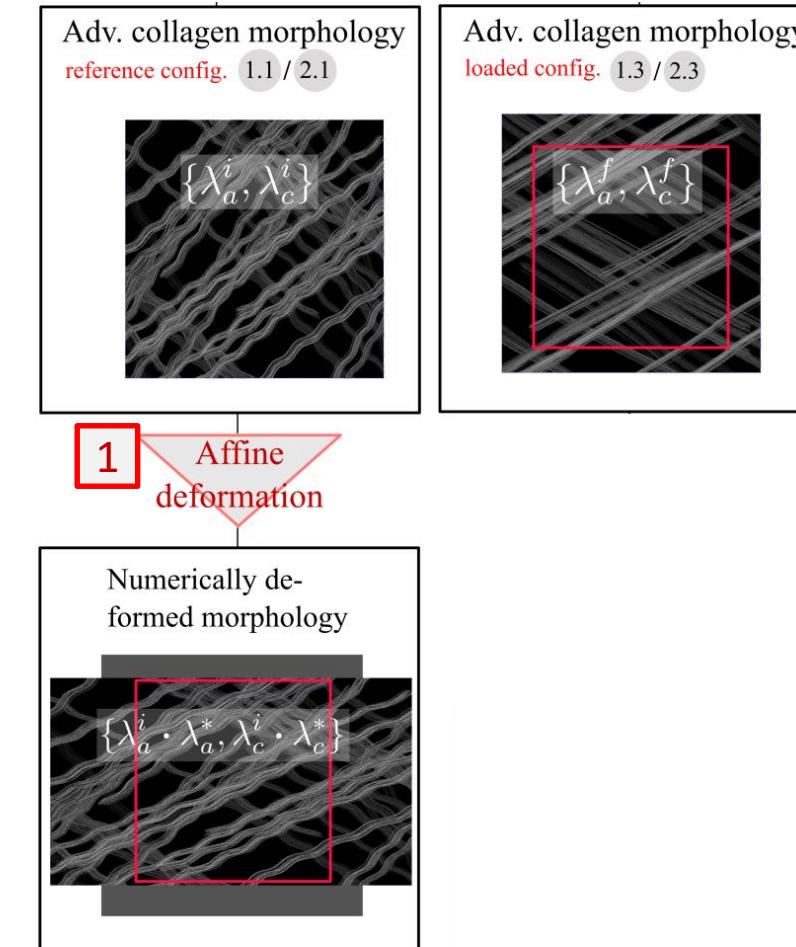


Image analysis and characterization of fiber kinematics



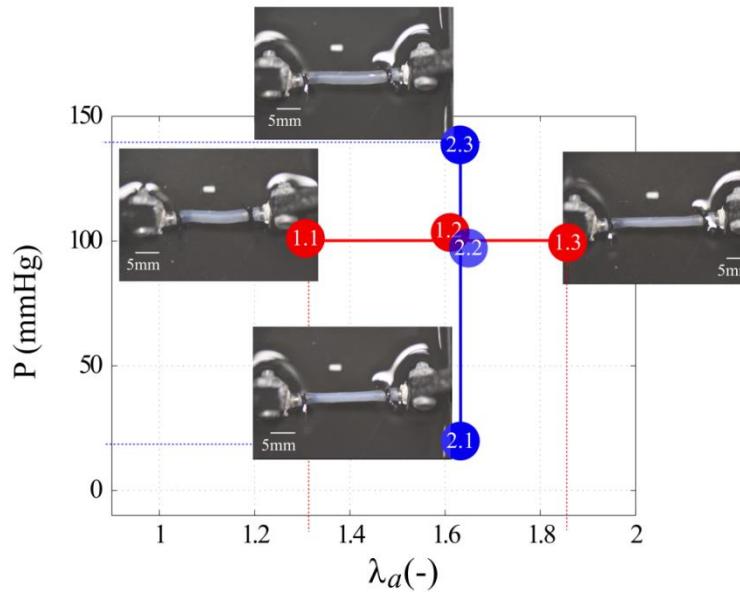
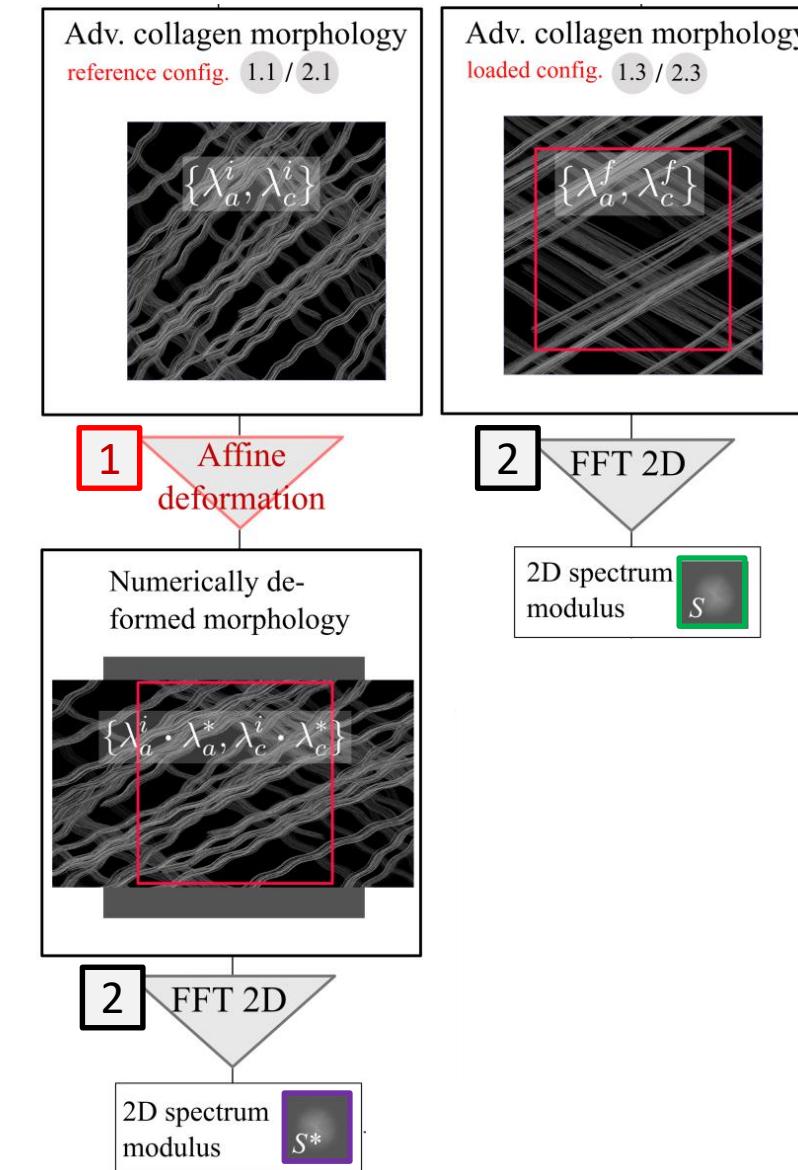


Image analysis and characterization of fiber kinematics



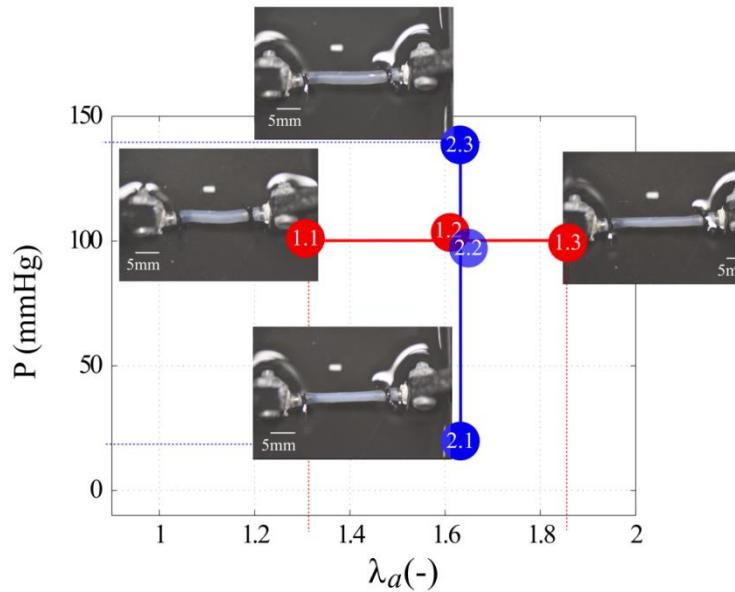
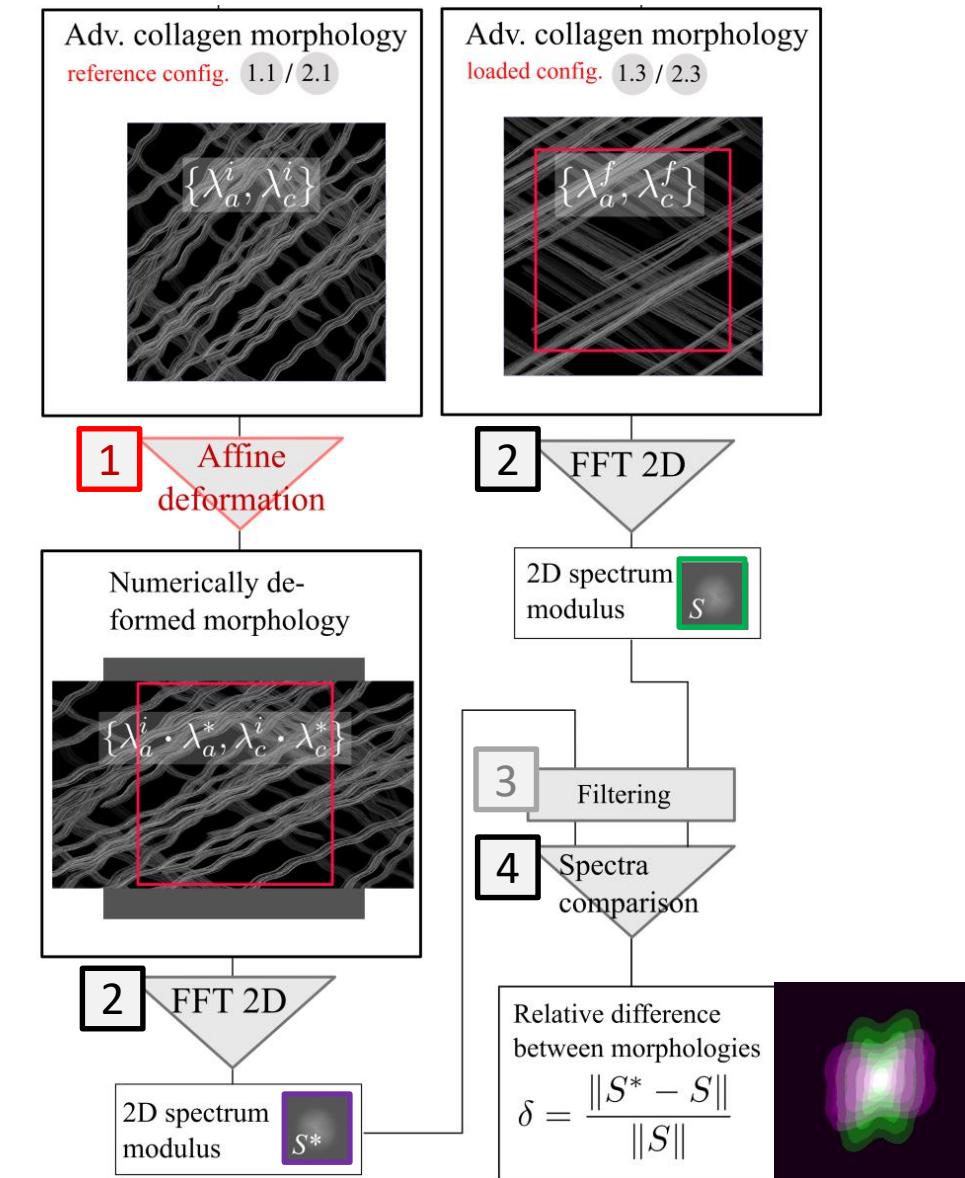
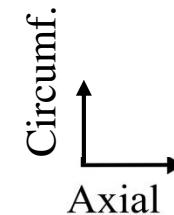
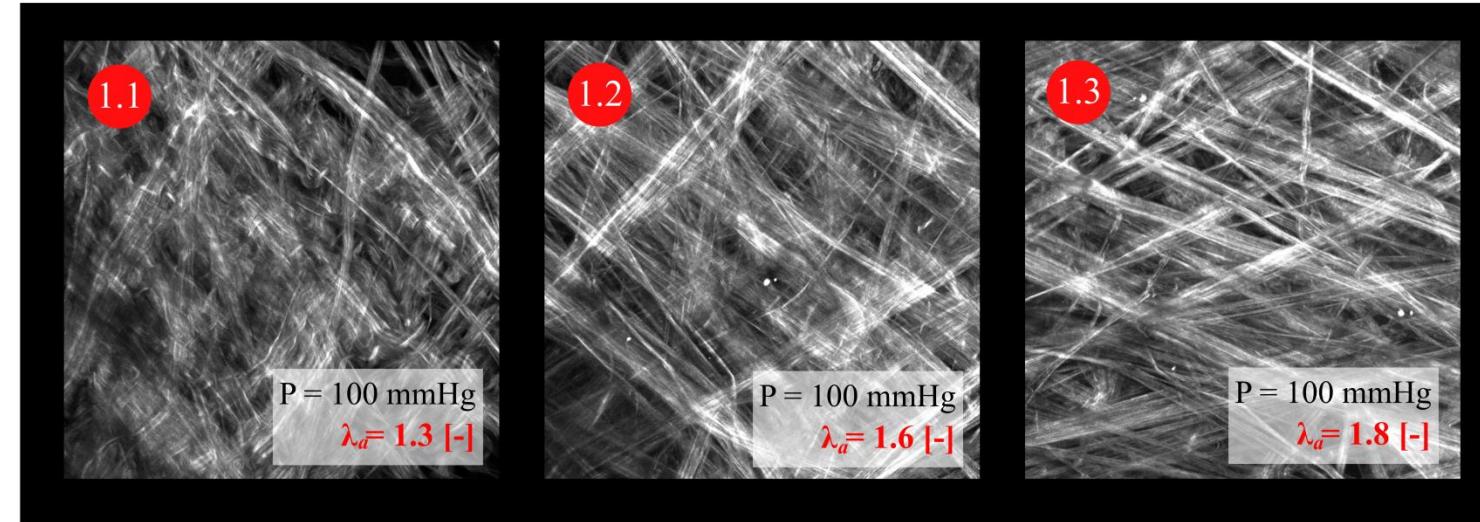


Image analysis and characterization of fiber kinematics



Adventitial collagen morphology under both loading scenarii

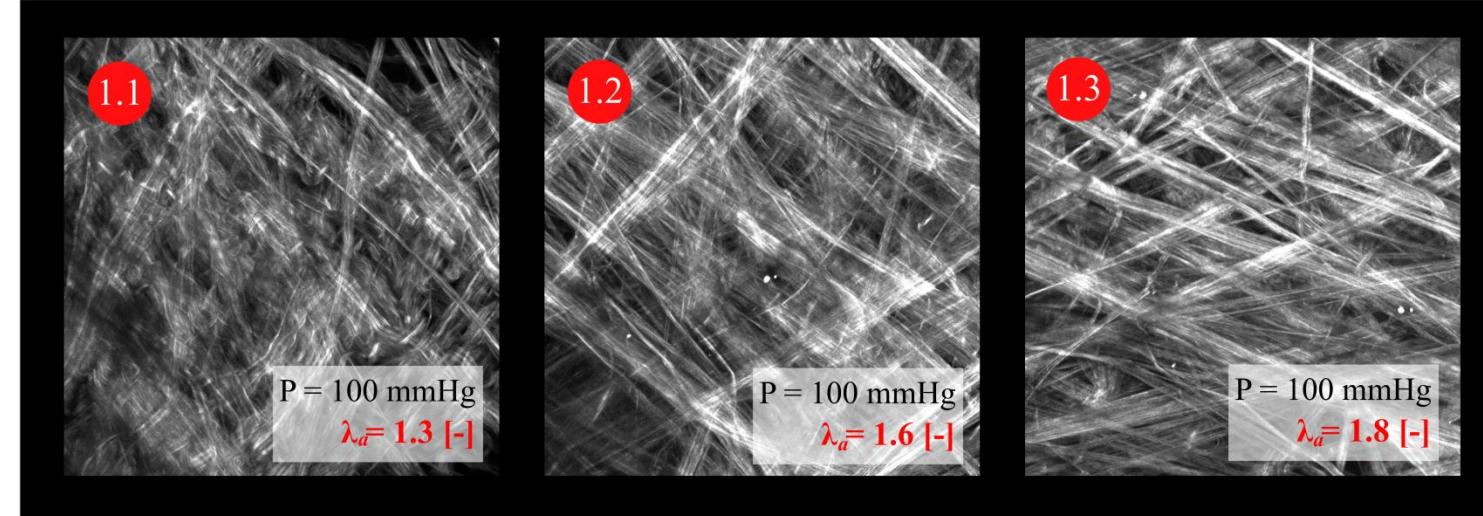
Tension under
imposed
constant
pressure



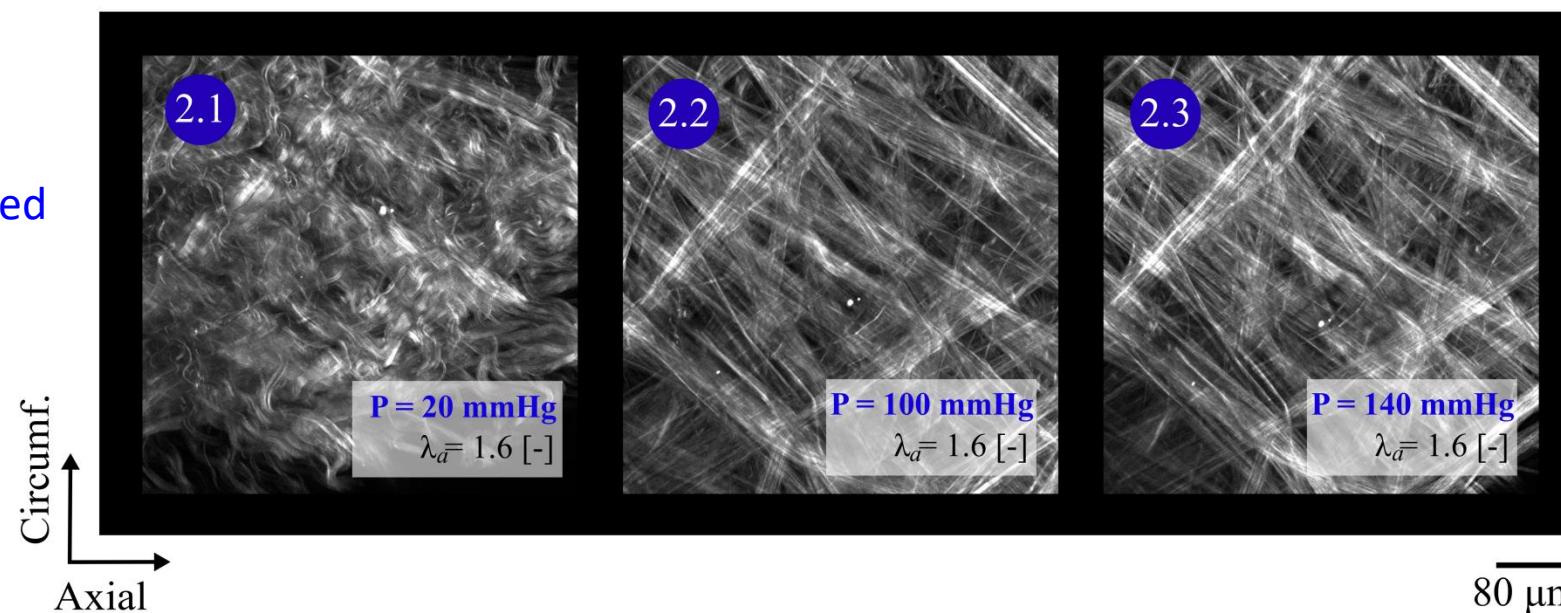
80 μm

Adventitial collagen morphology under both loading scenarii

Tension under imposed constant pressure



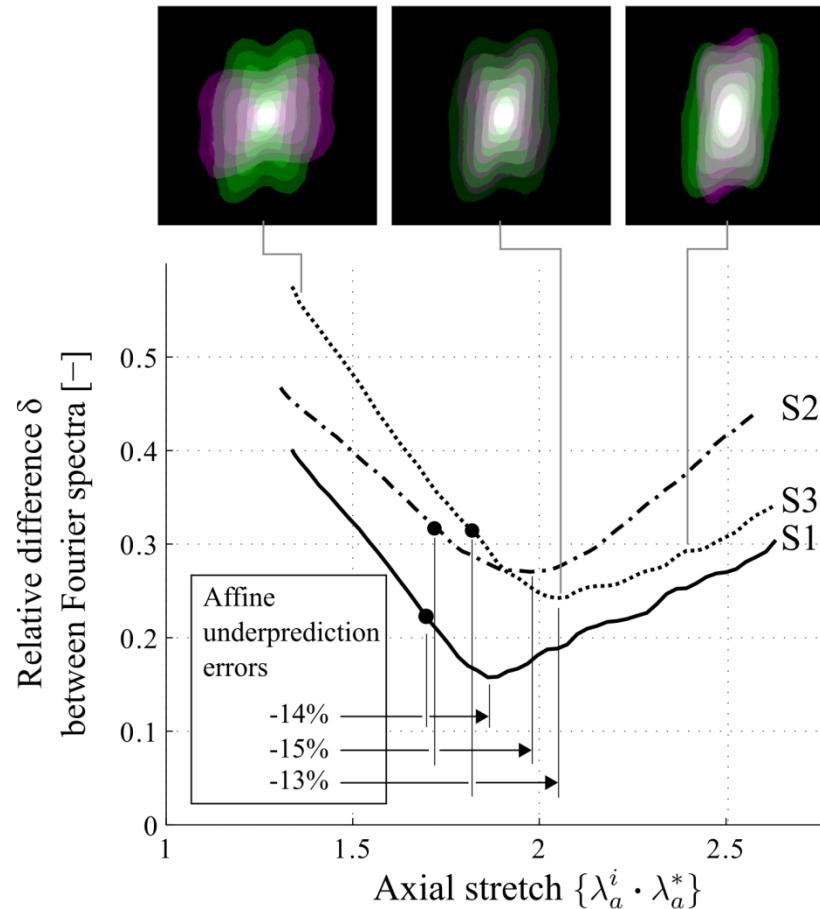
Inflation under imposed constant axial stretch



Evolution of the relative difference δ between spectra

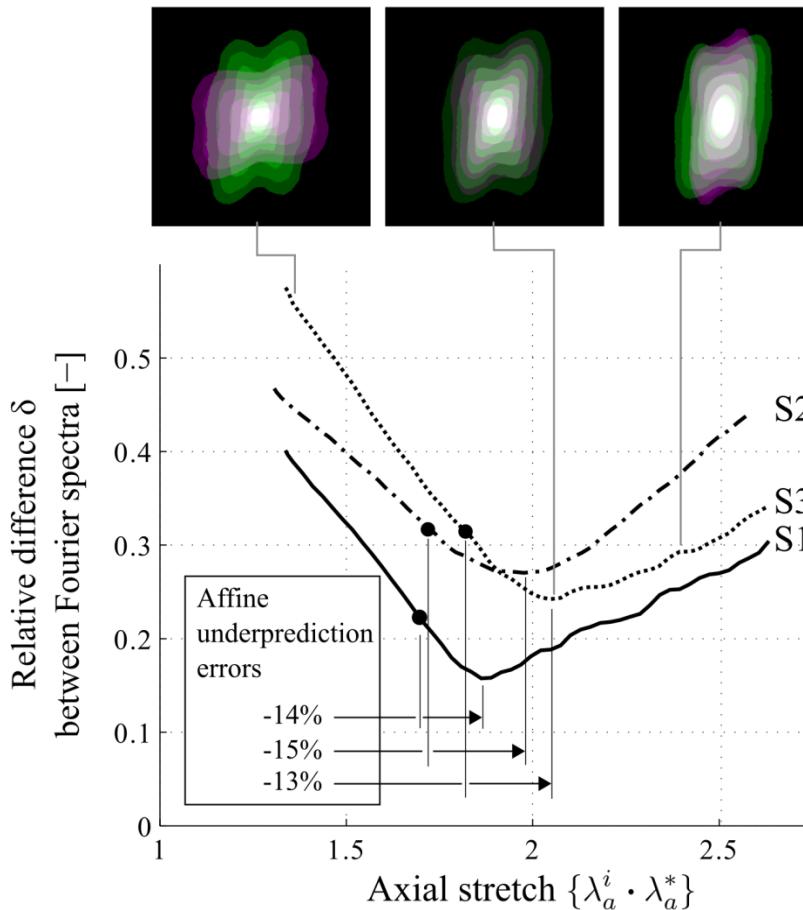


Tension under imposed constant pressure

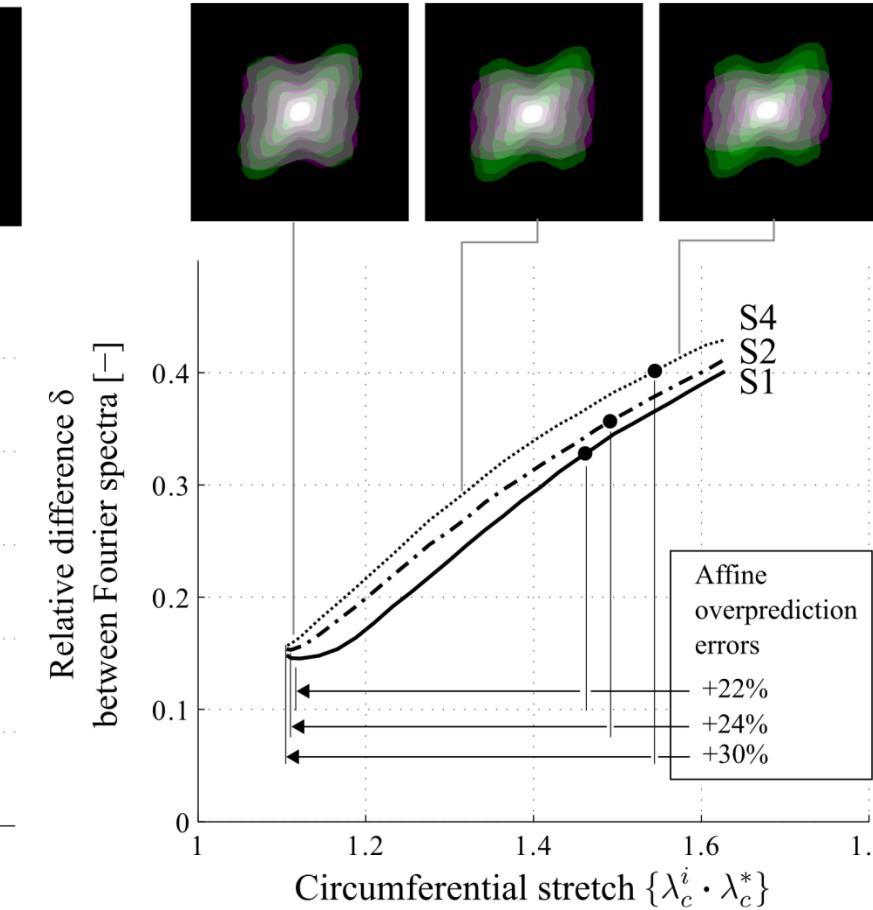


Evolution of the relative difference δ between spectra

Tension under imposed constant pressure



Inflation under imposed constant axial stretch



Discussion : interpretation of fiber kinematics

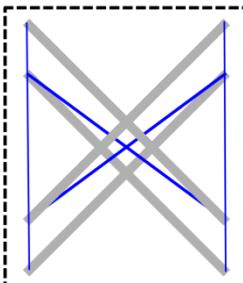
Lanir et al (1979), Chow et al (2014) :

- #1 mechanobiological **interactions between elastin and collagen** are important for properly functioning arteries
- #2 elastic fibers are under **tension** and impart an intrinsic **compressive stress** on the collagen

Wenger et al (2005)

- #1 the **elastic modulus of collagen fibers is greater** than the elastic modulus of elastic fibers by a factor 10^3

Schematic representation of adventitial microstructure inspired from the tensegrity structure of [Dejager et al \(2004\)](#), [Luo et al \(2008\)](#)



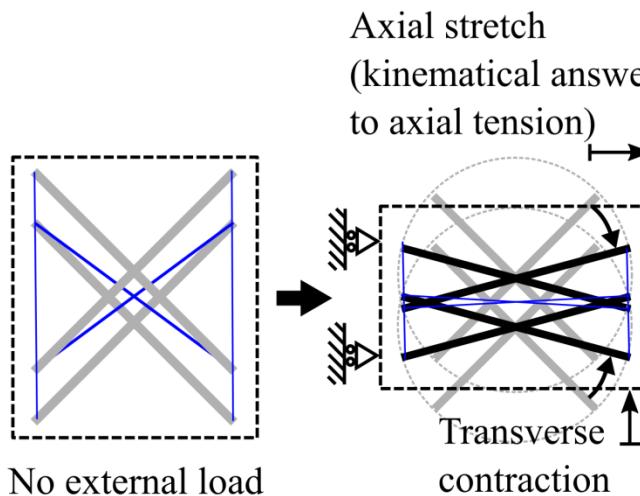
No external load

- > Grey segments represent here low-compliant collagen bundles
- > Blue segments represent high-compliant bonding fibers which exert compressive forces on the collagen bundles under zero stretch (presumably elastin)

Discussion : interpretation of fiber kinematics

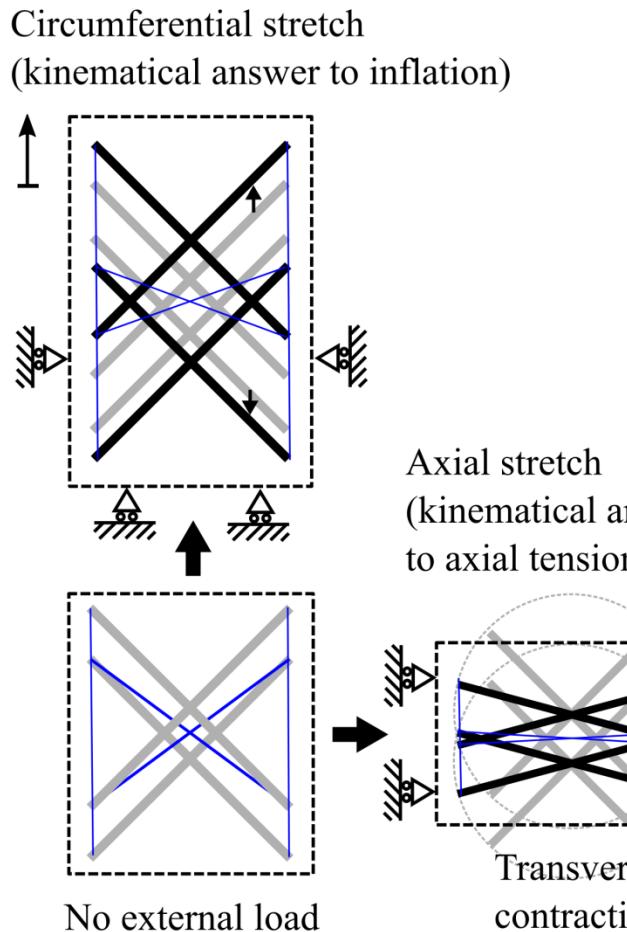
Schematic representation of adventitial microstructure inspired from the tensegrity structure of Dejager et al (2004), Luo et al 2008

> Under axial tension at a constant inner pressure, **fiber rotation is the best way to allow the extension** without stretching the fibers



Discussion : interpretation of fiber kinematics

Schematic representation of adventitial microstructure inspired from the tensegrity structure of Dejager et al (2004), Luo et al 2008



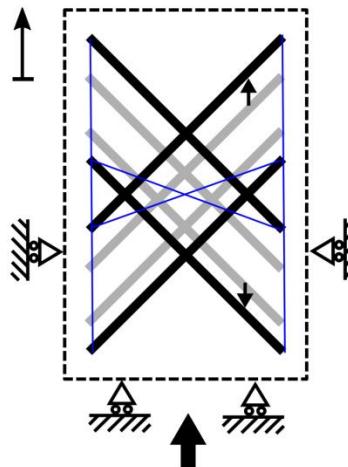
> Under axial tension at a constant inner pressure, **fiber rotation is the best way to allow the extension** without stretching the fibers

> Under inflation loading at a constant axial stretch, **rotation is impossible**, as it would imply a transverse strain, the fibers being rigid

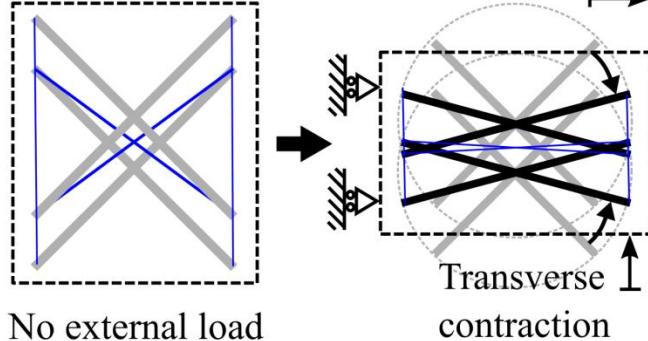
Discussion

Schematic representation of adventitial microstructure inspired from the tensegrity structure of Dejager et al (2004), Luo et al 2008

Circumferential stretch
(kinematical answer to inflation)



Axial stretch
(kinematical answer to axial tension)



Transverse contraction

#1

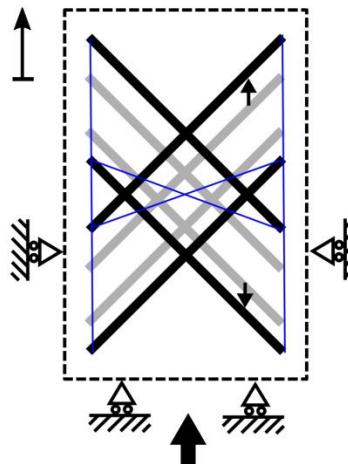
Adventitial collagen fibers **cannot be considered as firmly embedded in their surrounding matrix**

→ High degree of kinematical freedom

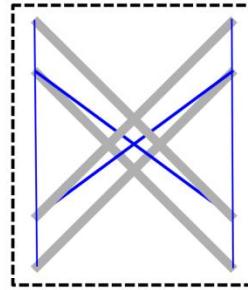
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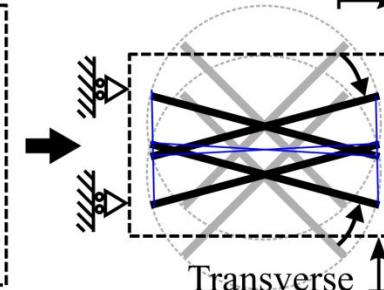
Circumferential stretch
(kinematical answer to inflation)



Axial stretch
(kinematical answer to axial tension)



No external load



Transverse contraction

#1

Adventitial collagen fibers **cannot be considered as firmly embedded** in their surrounding matrix

→ High degree of kinematical freedom

#2

Boundary conditions play a major role in the complex* kinematics of collagen fibers in the arterial adventitia!

* non-affine & load-dependent

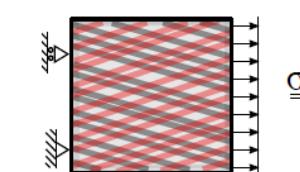
Future directions

#1 Experimental :
 Characterize **interactions / bindings**
 between collagen and other load bearing
 proteins such as
 (i) elastin
 (ii) proteoglycans

#2 Modelling (initialization):
 Further test the **applicability of**
tensegrity models at the tissue level
 with collagen and elastin as principal
 components (force equilibrium)

#3 Modelling (ongoing work):
 Multiscale model based on continuum
 micromechanics ([Morin et al \(2015\)](#))
> load dependence of fiber kinematics
currently under investigation

Axial tension under constant
 pressure (cylindrical sample)

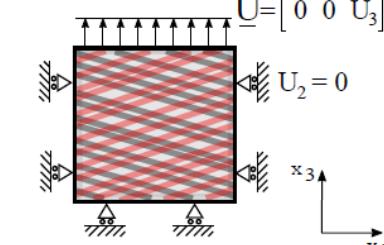


$$\underline{\sigma} \cdot \underline{n} = p \underline{x}_3$$

$$\underline{\sigma} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sigma_{22} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

1) $\underline{\sigma} \cdot \underline{n} = p \underline{x}_3$

Inflation under constant axial
 stretch (cylindrical sample)



$$\underline{U} = [0 \ 0 \ U_3]^T$$

$$U_2 = 0$$

2) $\underline{U} = [0 \ 0 \ U_3]^T$
 $U_2 = 0$

Acknowledgements

- > Research contributors & PhD supervision: Dr Witold Krasny, Dr. Claire Morin, Dr. Hélène Magoariec
Multiscale modelling of the Cardiovascular System: Disease development, progression, and clinical intervention,
Jul 10th 18, 16:00 - 16:10, Location: Liffey B
- > This material is based upon work supported by the ARC2 program of the Auvergne-Rhône-Alpes region (FR)
- > Provision of biological samples and training for excision
 - Prof. Eric Viguier, Vet Agro Sup, Université de Lyon (FR)
 - Dr. Caroline Boulocher, Vet Agro Sup, Université de Lyon (FR)
 - Fabrice Desplanches, Centre Lago, Vonnas (FR)
- > Technical assistance in experimental setup
 - Ophélie Pollet, IVTV Platform, Ecole Centrale Lyon (FR)
 - Lionel Charles, Ecole Centrale de Lyon (FR)

