

Journée thématique du GDR TACT

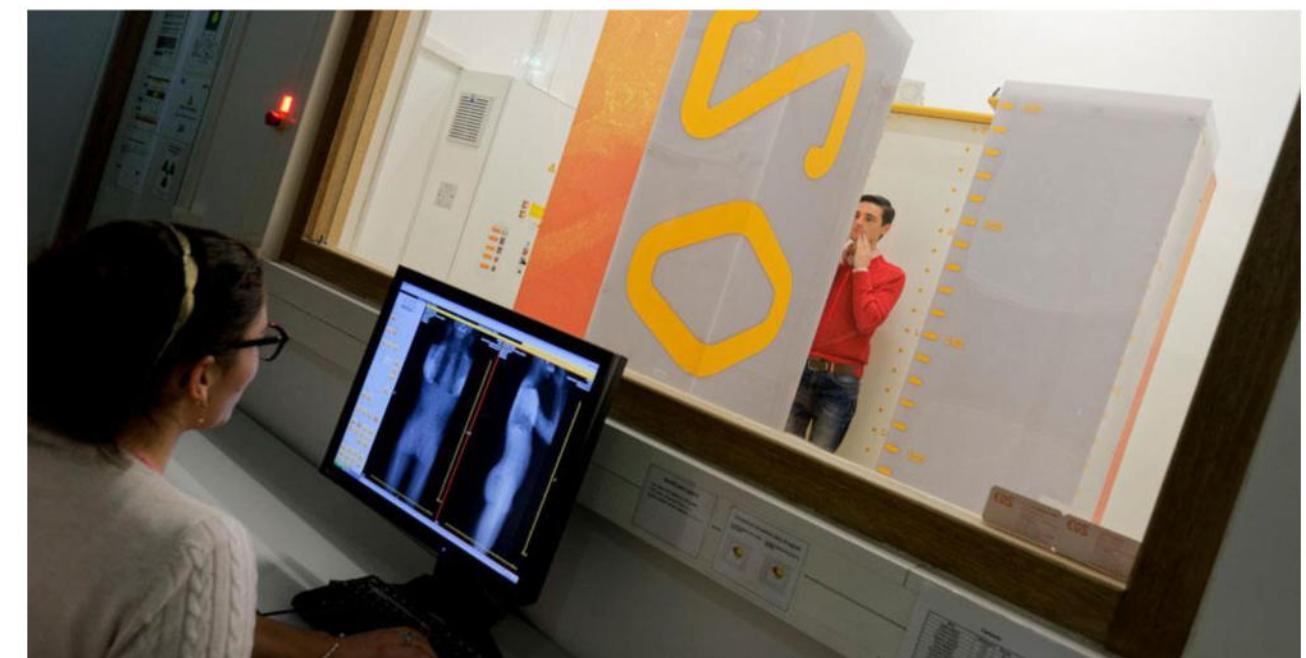
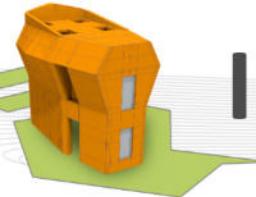
« Propriétés mécaniques de la peau, du doigt »

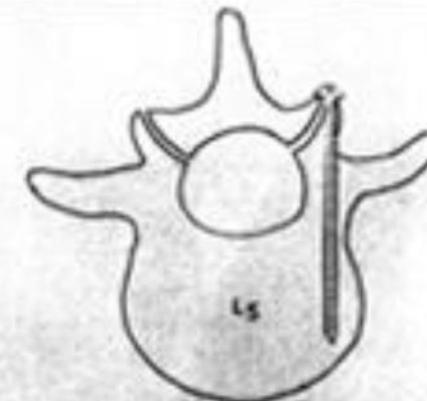
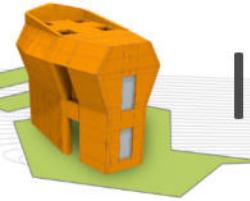
24 novembre 2023, ISIR Sorbonne Université

Modélisation mécanique de la peau

Pierre-Yves ROHAN

Institut de Biomécanique Humaine Georges Charpak



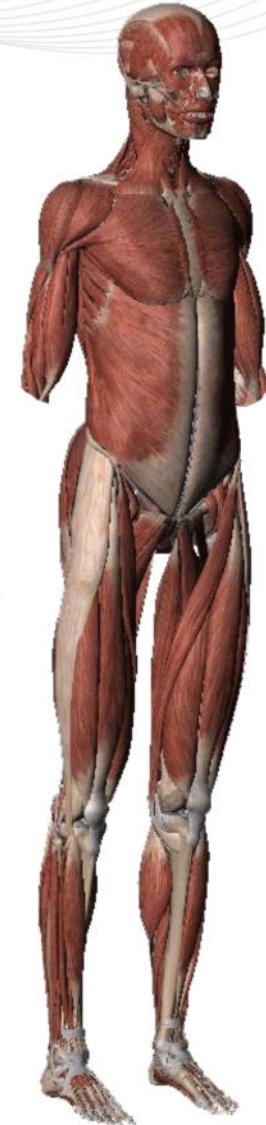


Collaboration entre le Pr. Raymond Roy Camille et Pr. François Lavaste

1979

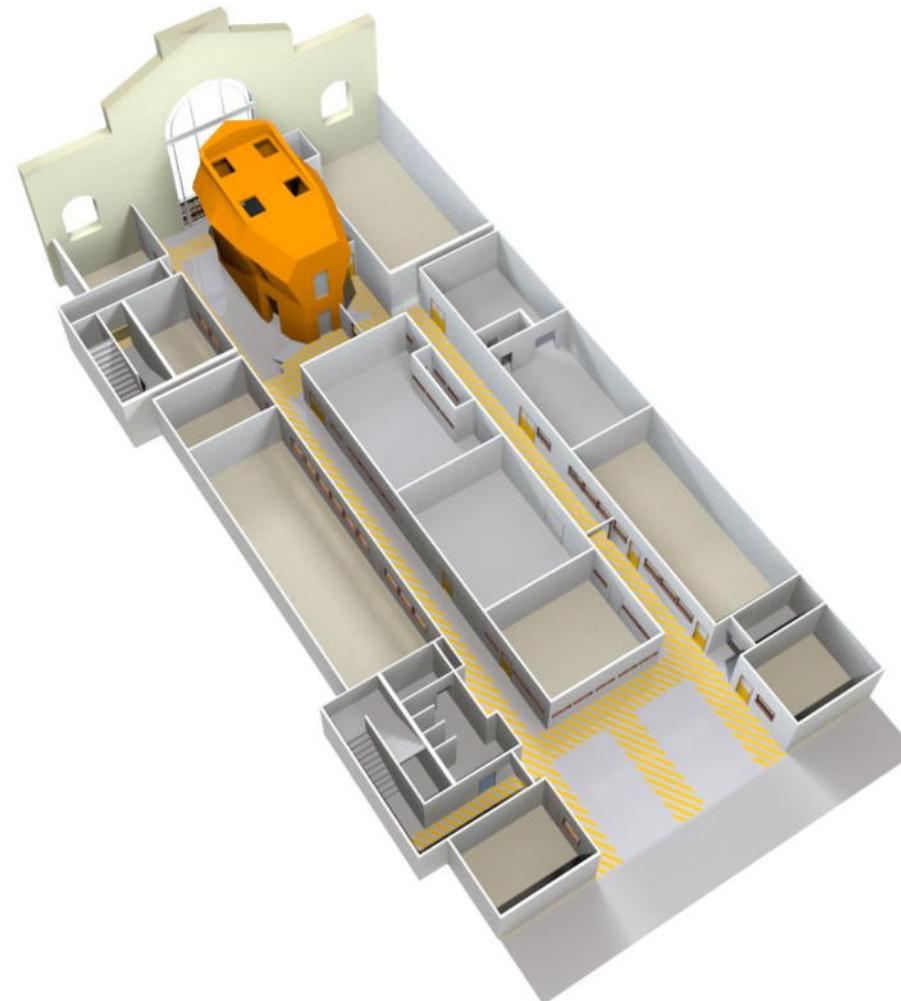
Objectifs

- ✓ Étudier et modéliser le système neuro-musculo-squelettique
- ✓ les recherches menées doivent déboucher sur des outils utilisables en routine clinique au service du patient

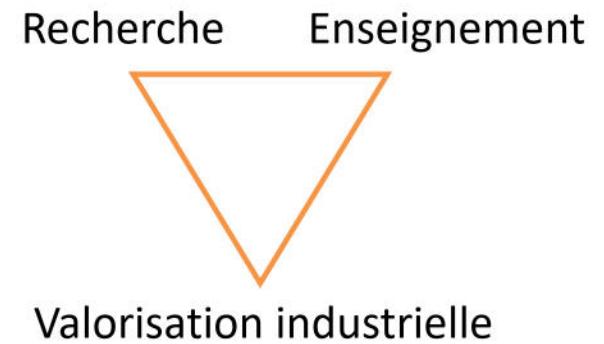




Plateforme expérimentale



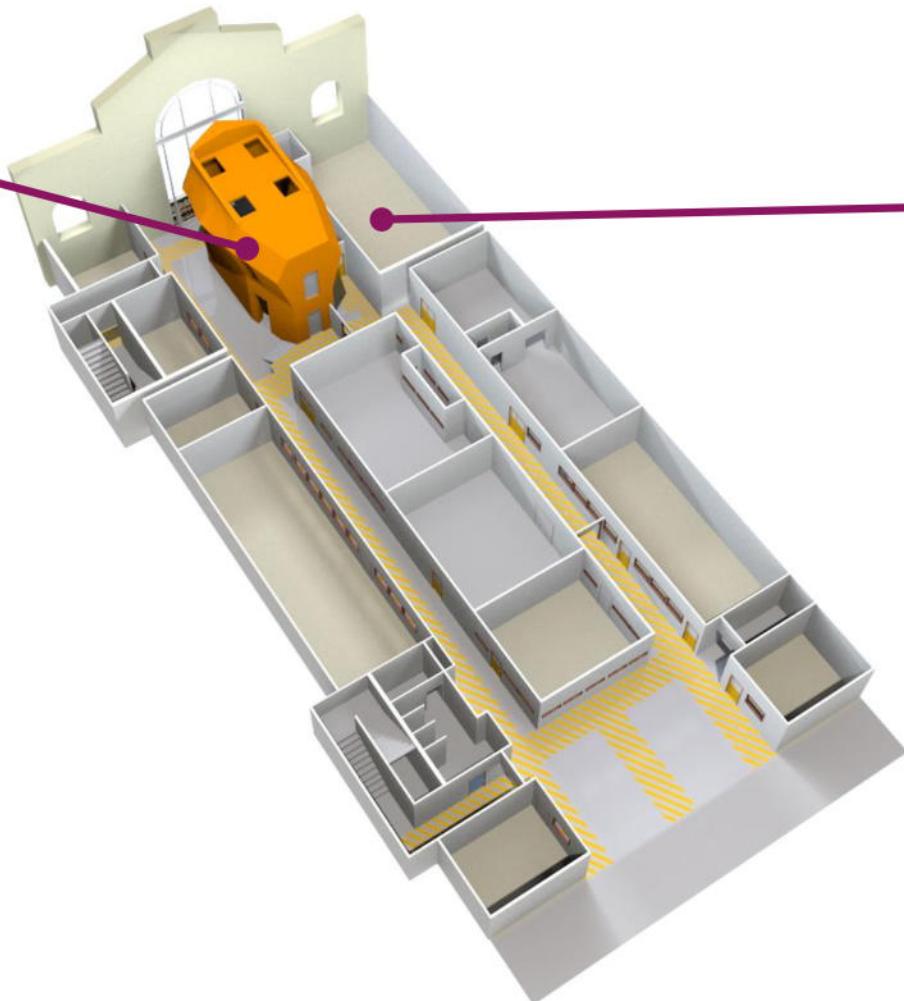
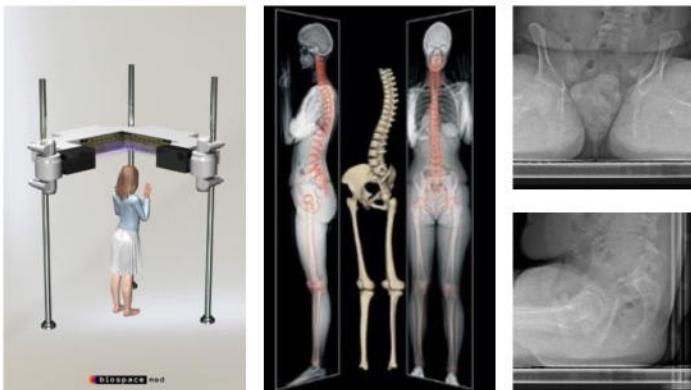
**1000 m², ~ 50 chercheurs, cliniciens
and ingénieurs**



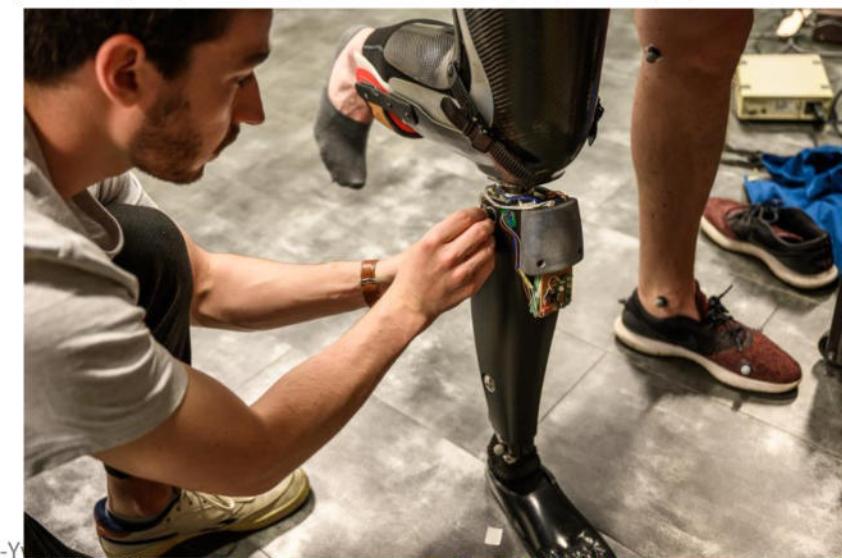
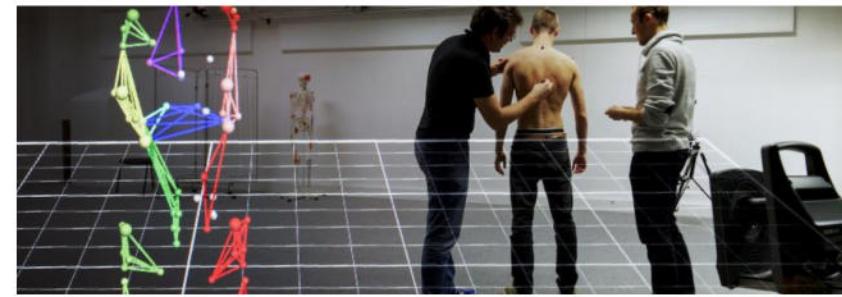


Plateforme expérimentale

Système EOS



Salle d'analyse du mouvement





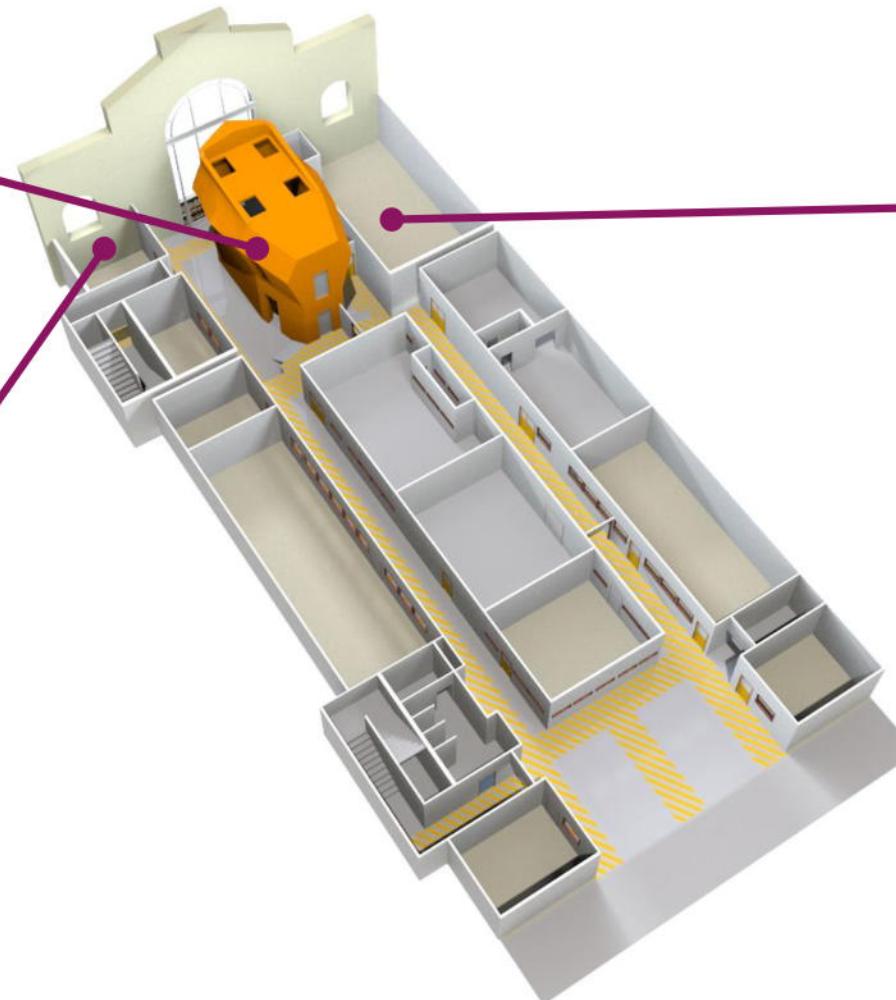
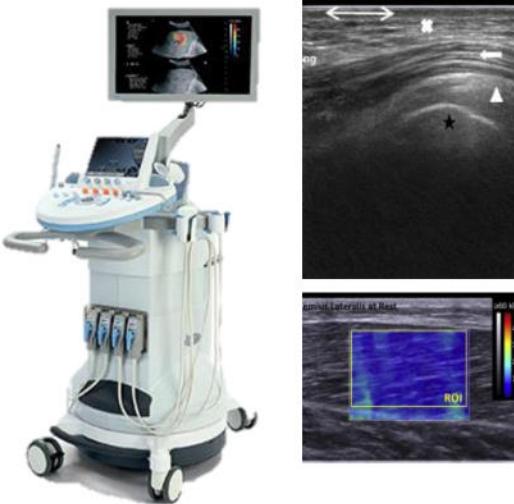
Plateforme expérimentale

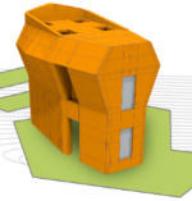
1000 m², ~ 50 chercheurs, cliniciens
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Système EOS

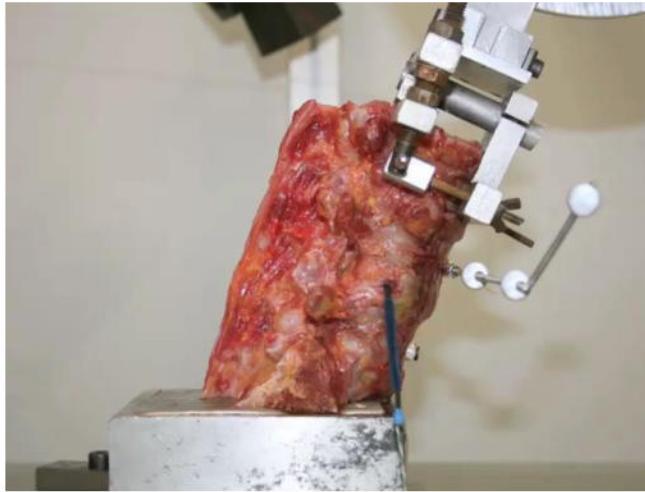
Salle d'analyse du
mouvement

Echographie
Elastographie

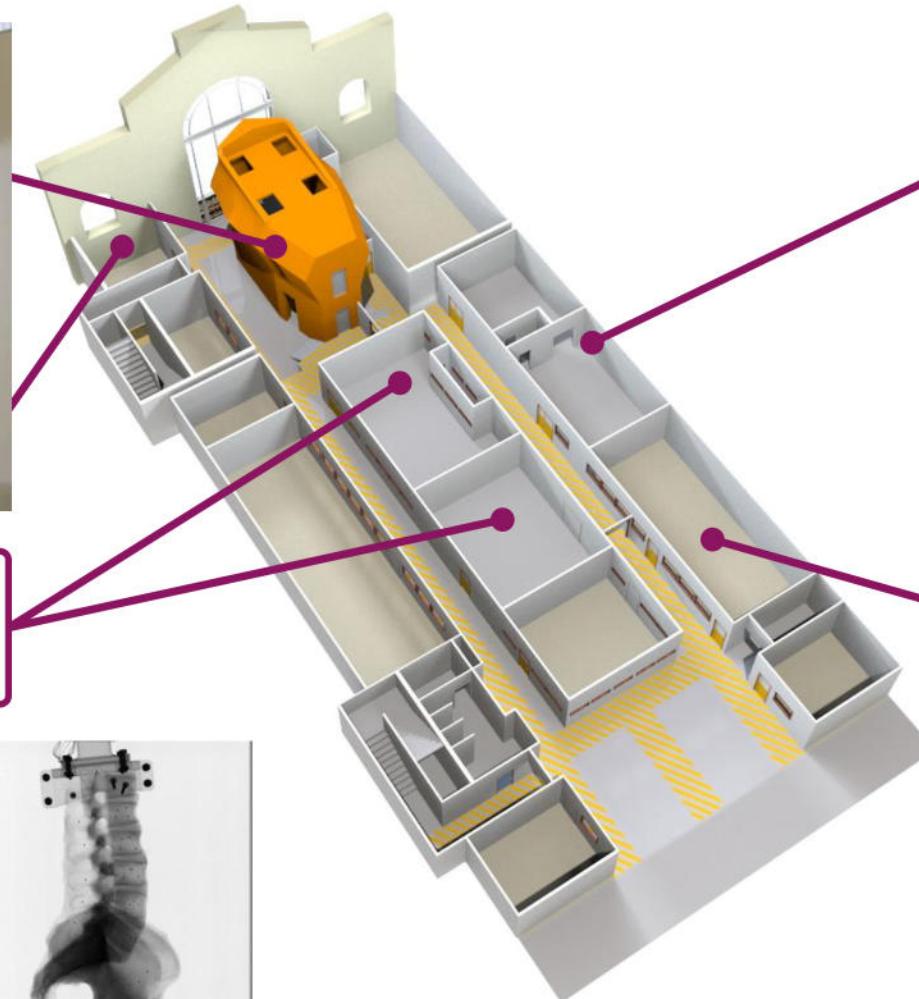
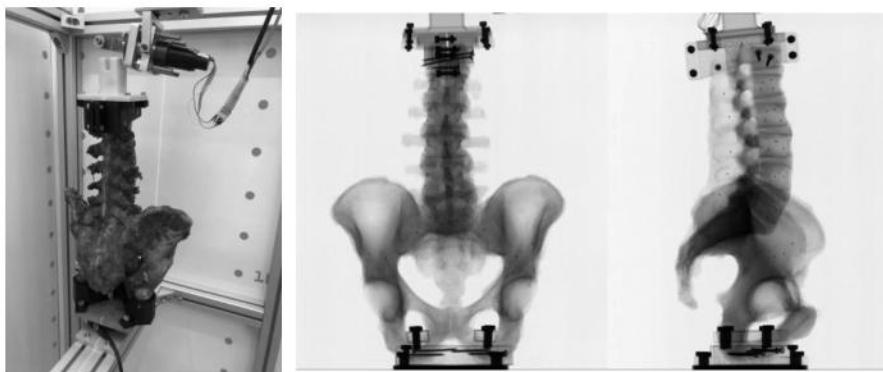




Plateforme expérimentale



**Essais mécaniques in vitro
(statique et dynamique)**

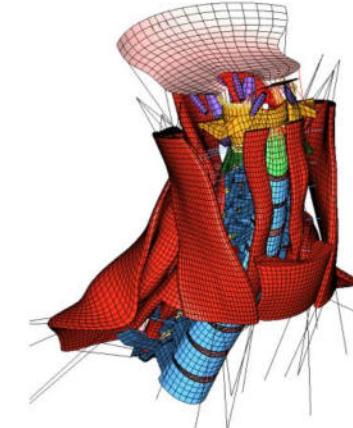


**1000 m², ~ 50 chercheurs,
cliniciens and ingénieurs**

chirurgie expérimentale

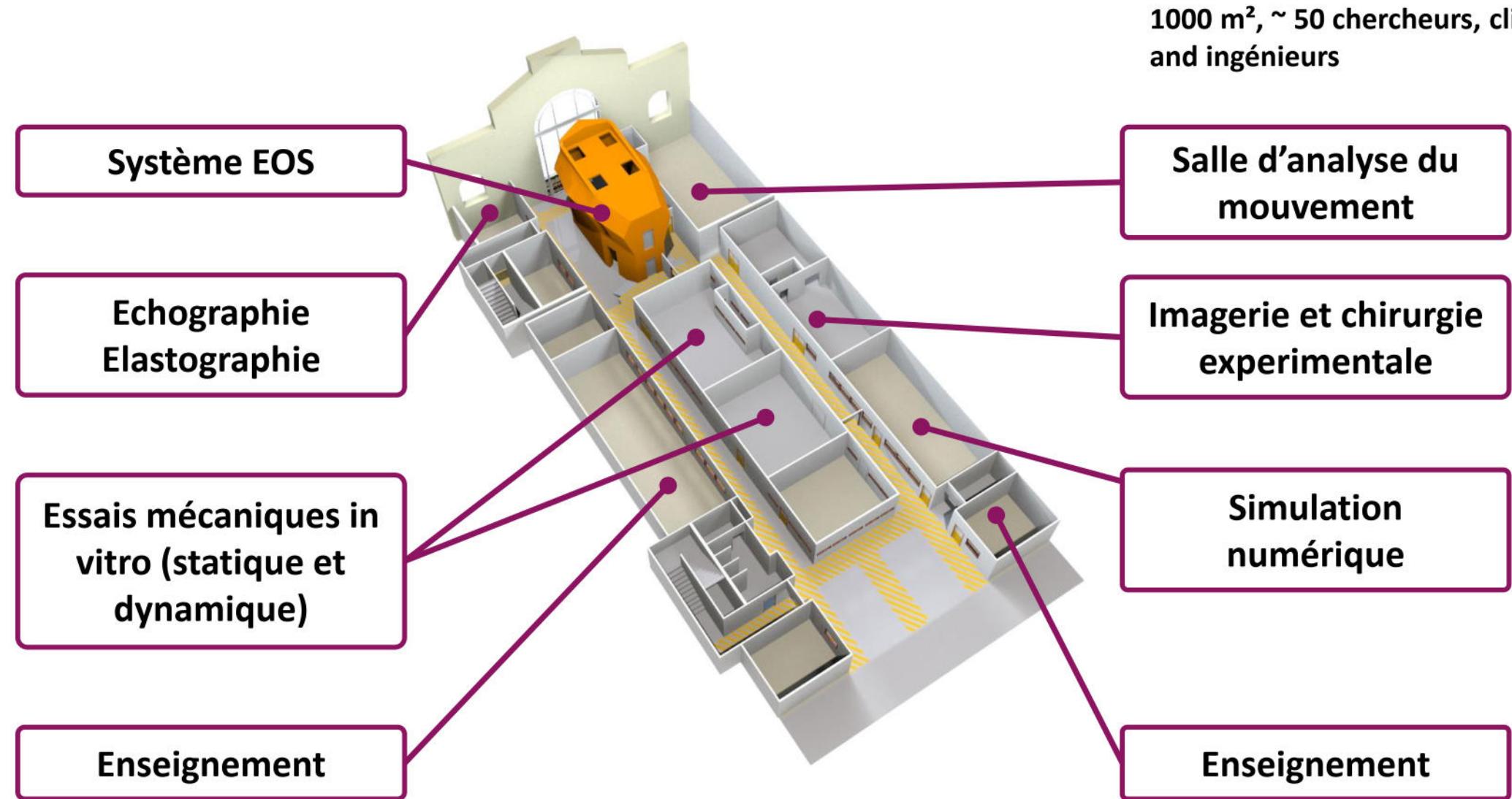


Simulation numérique





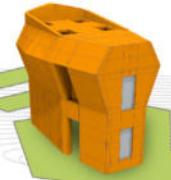
Plateforme expérimentale



1

Boite à outils

Mécanique du solide déformable



C'est quoi la mécanique?



$$\sum \underline{f} = m \underline{a}$$

Cause Mouvement



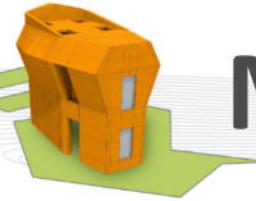
Mécanique du solide rigide

Problématiques cliniques/industrielles, Performance sportive

$$\sum \underline{f} = m \underline{a}$$



Philippe ROUCH
Christophe SAURET
Maxime BOURGAIN
Laura VALDES



Mécanique du solide déformable

Problématiques cliniques, Performance sportive, Questions industrielles





Notion de déformation 1D

Analyse de d'adduction de hanche :

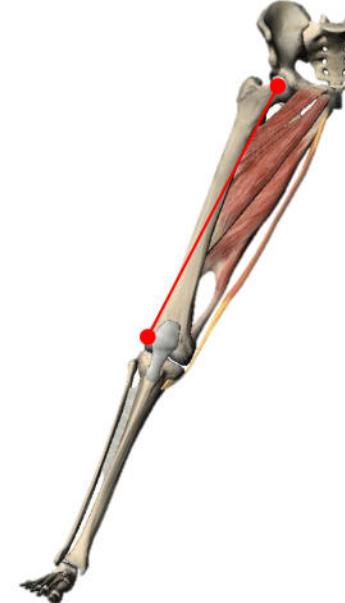
- Certaines structures gardent leur longueur (os)
- Certaines structures ont des longueurs variables (muscles)



Exemple du fémur



Configuration initiale



Configuration actuelle

pas de variation
de longueur = mouvement de
solide rigide



Notion de déformation 1D

Analyse de d'adduction de hanche :

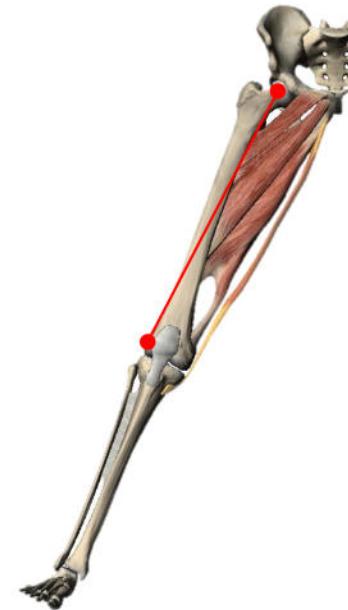
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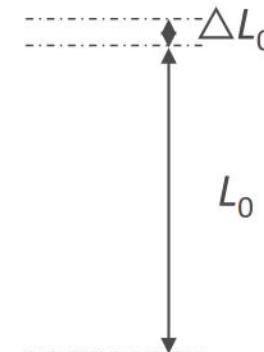
Exemple du fémur



Configuration initiale



Configuration actuelle



variation
de longueur = déformations

$$\varepsilon = \frac{\Delta L_0}{L_0} \quad \sum \underline{f}_{int} \# \underline{m} \underline{f}_{ext} = \underline{Q}$$

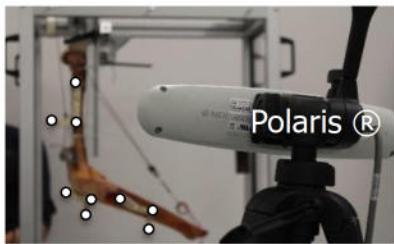


Notion de déformation 1D

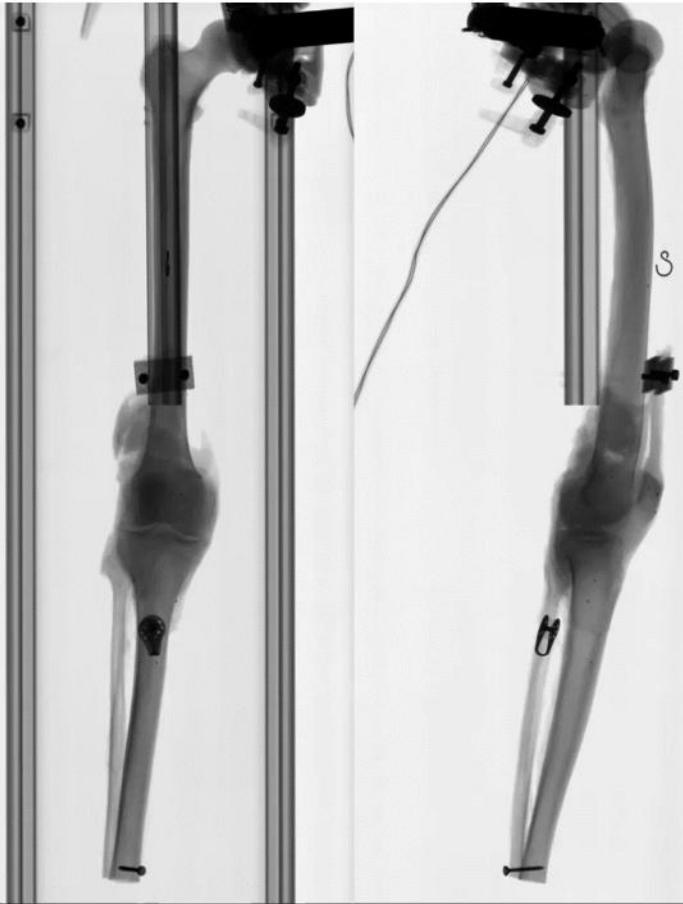
Application aux ligaments du genou



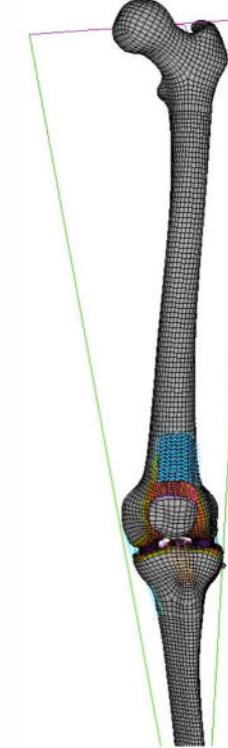
Azmy et al. 2010



Polaris ®



Cinématique 3D personnalisée



Modélisation EF personnalisée



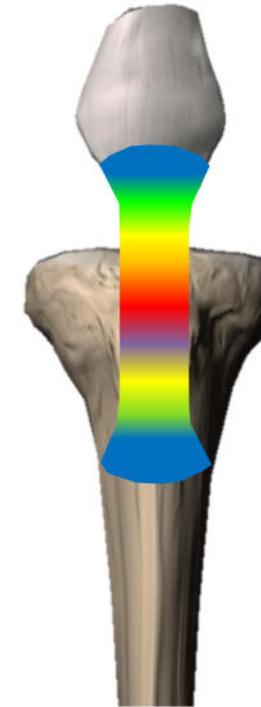
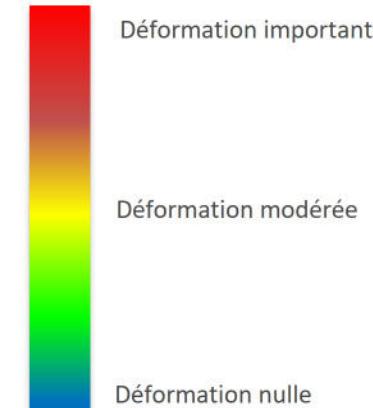
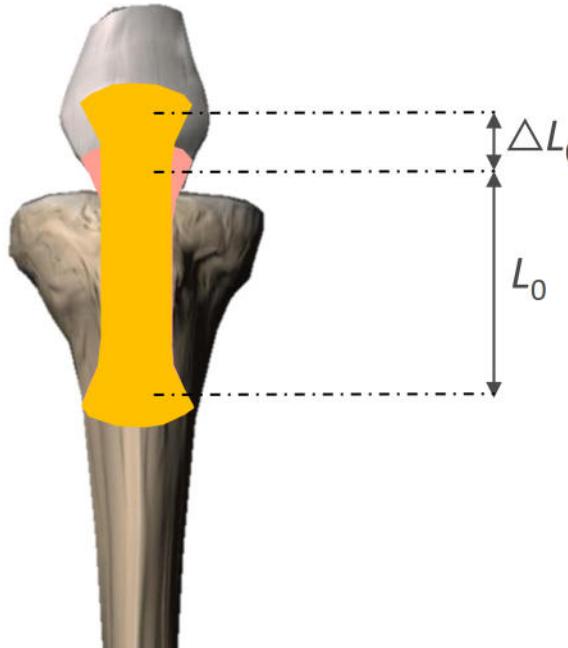


Notion de déformation 1D

Une vision locale de la déformation

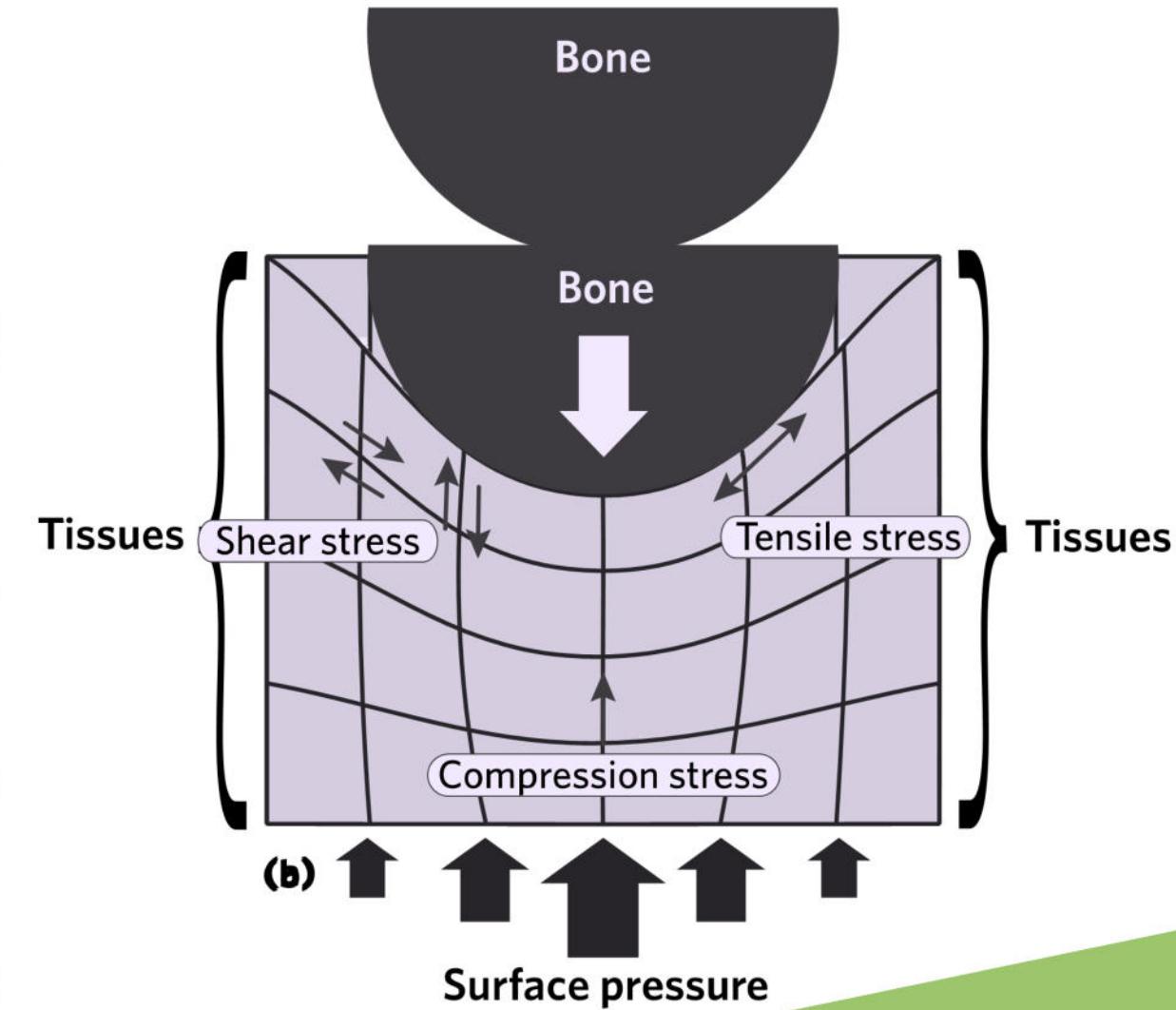
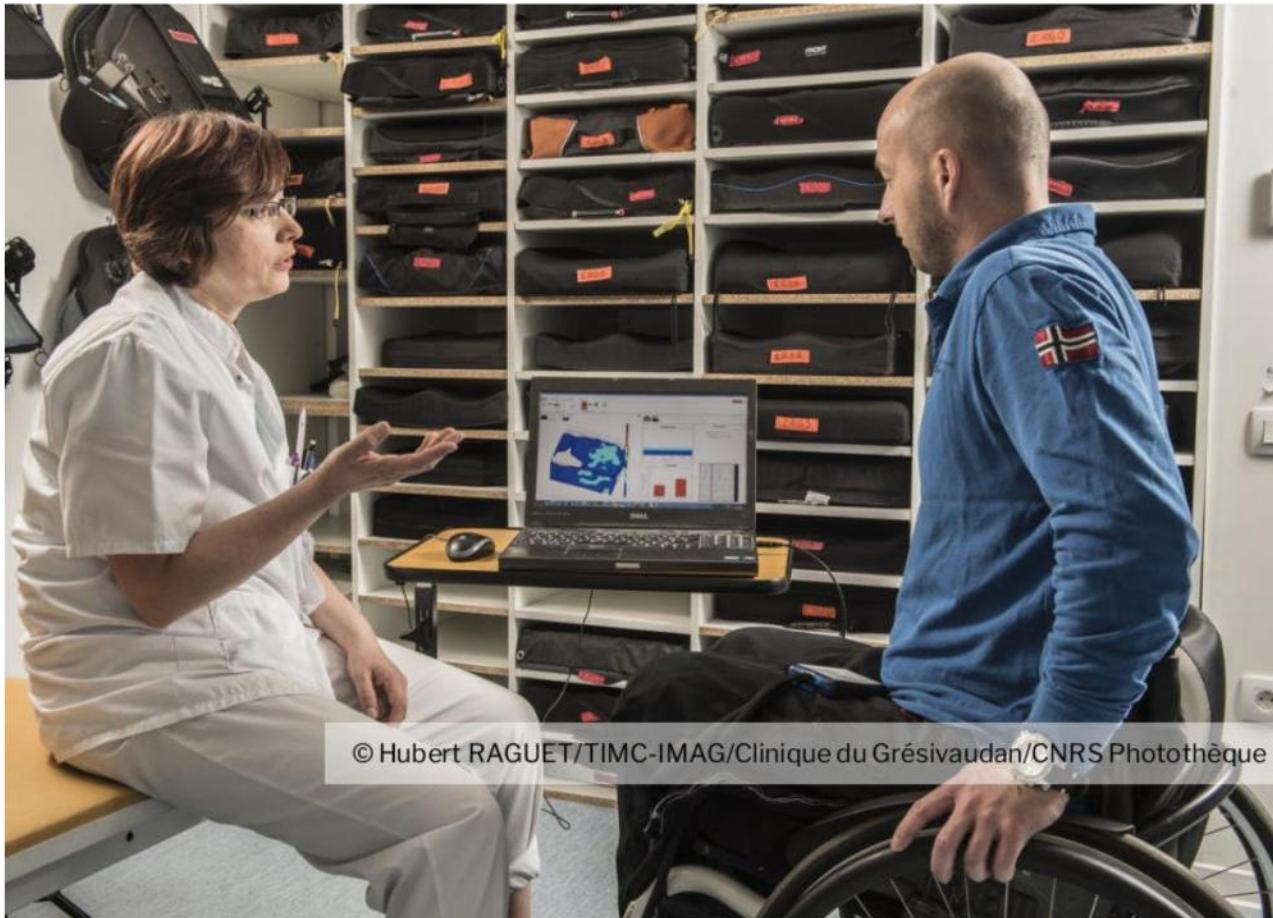
La formule simplifiée a ses limites

$$\varepsilon = \frac{\Delta L_0}{L_0}$$



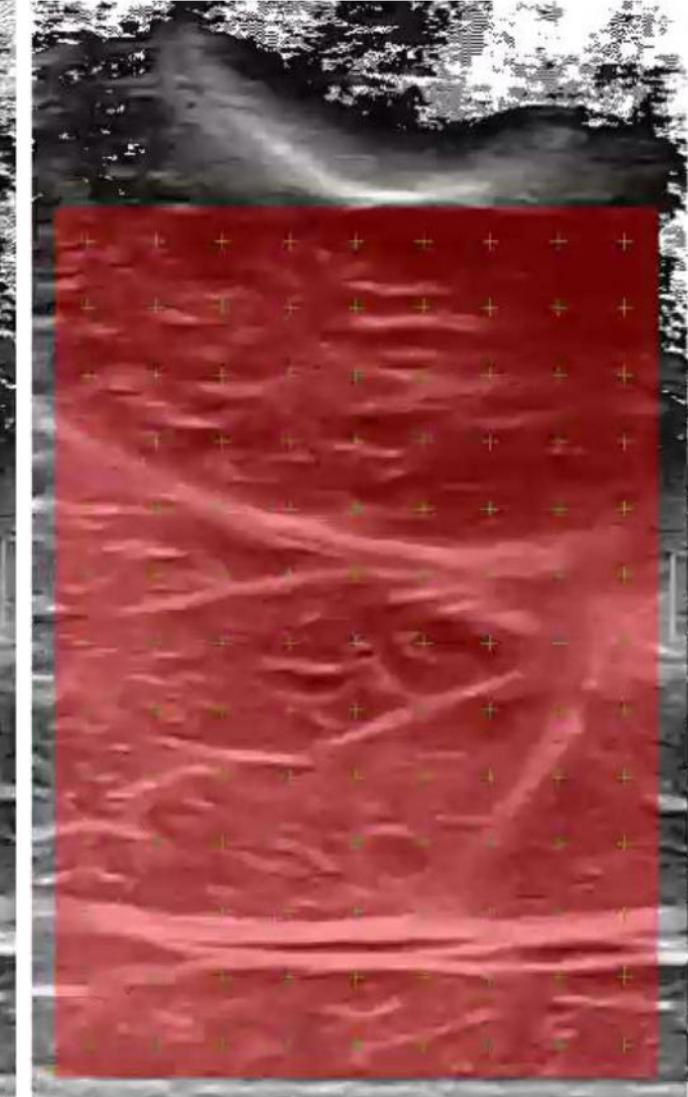
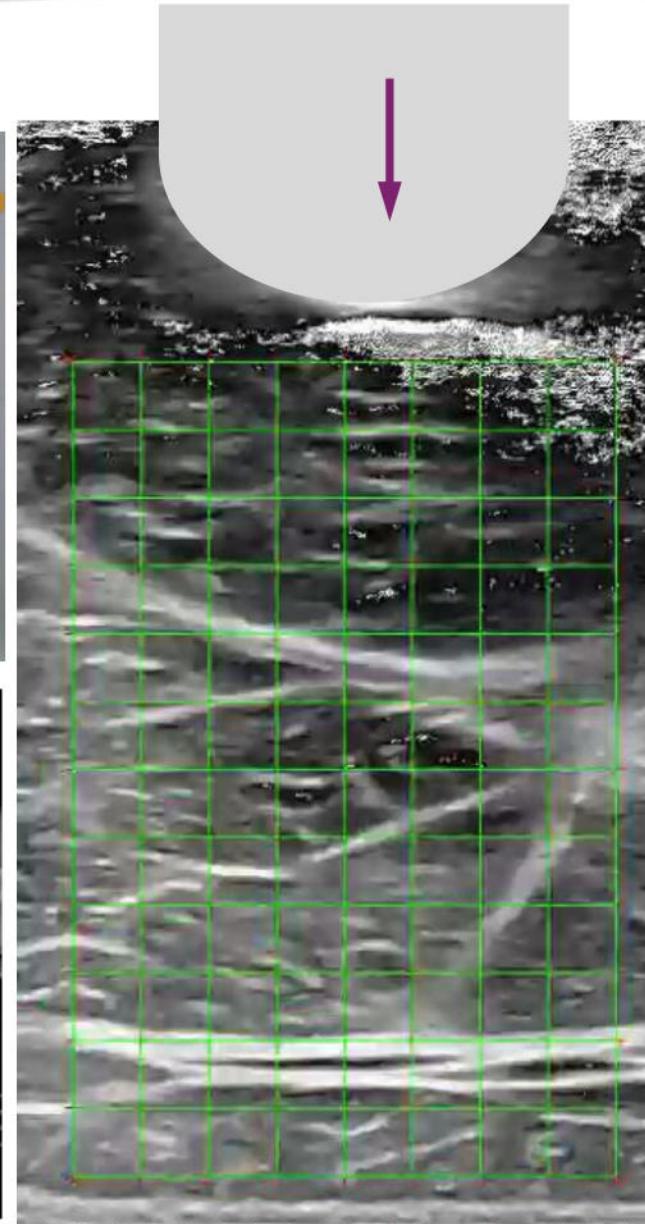
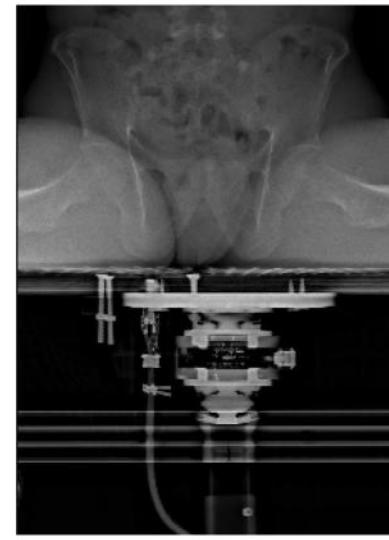
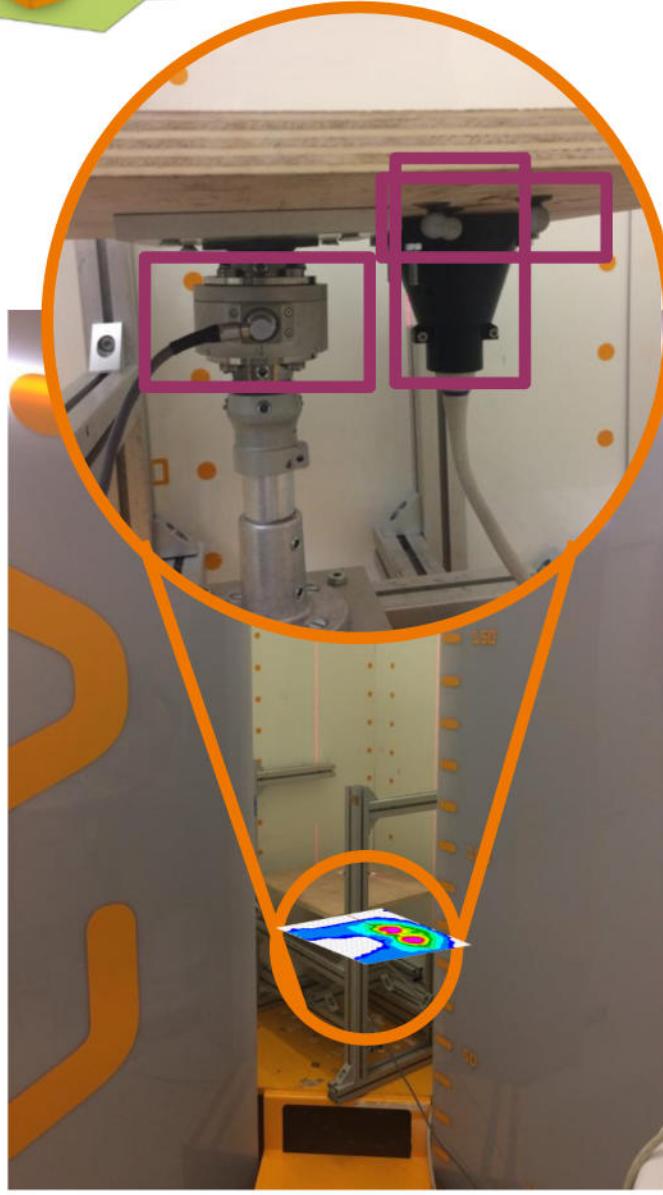


Notion de déformation 2D



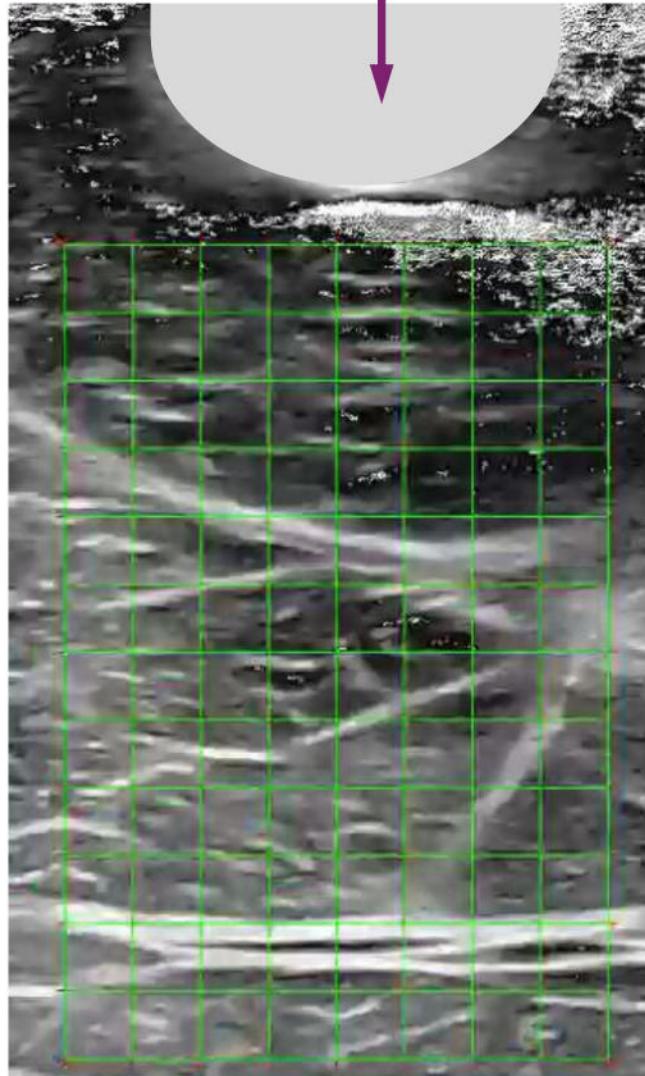


Notion de déformation 2D





Notion de déformation 2D



Formulation du problème (EDP) :

At each frame, find the displacement field \underline{u} such that :

$$\operatorname{div}(\underline{\sigma}) + \underline{f} = \underline{0} \text{ on } \Omega$$

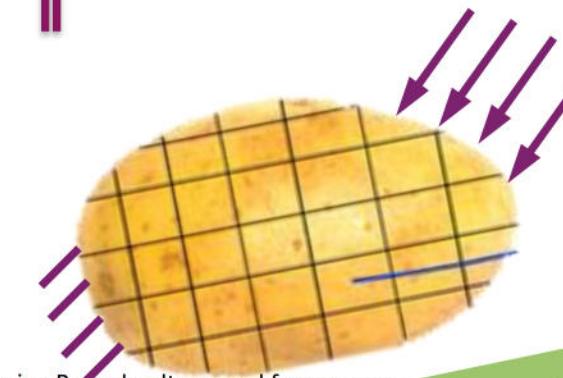
With BC :

$$\underline{u} = \underline{u}_0 \text{ on } \Gamma_u$$

$$\underline{t} = \underline{\sigma} \cdot \underline{n} = \underline{t}_0 \text{ on } \Gamma_t$$

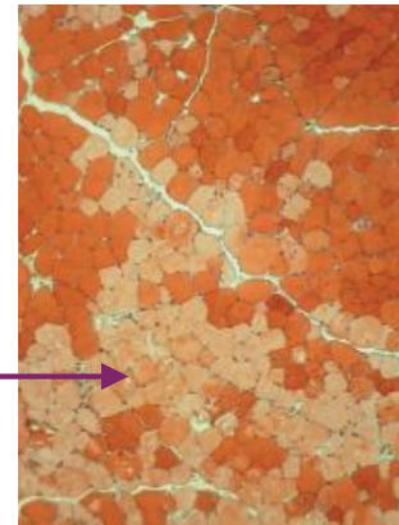
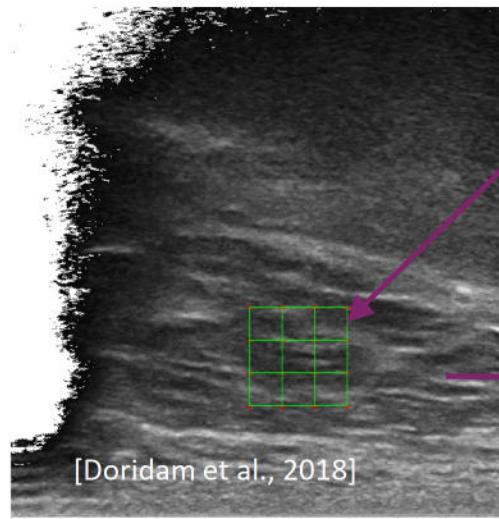
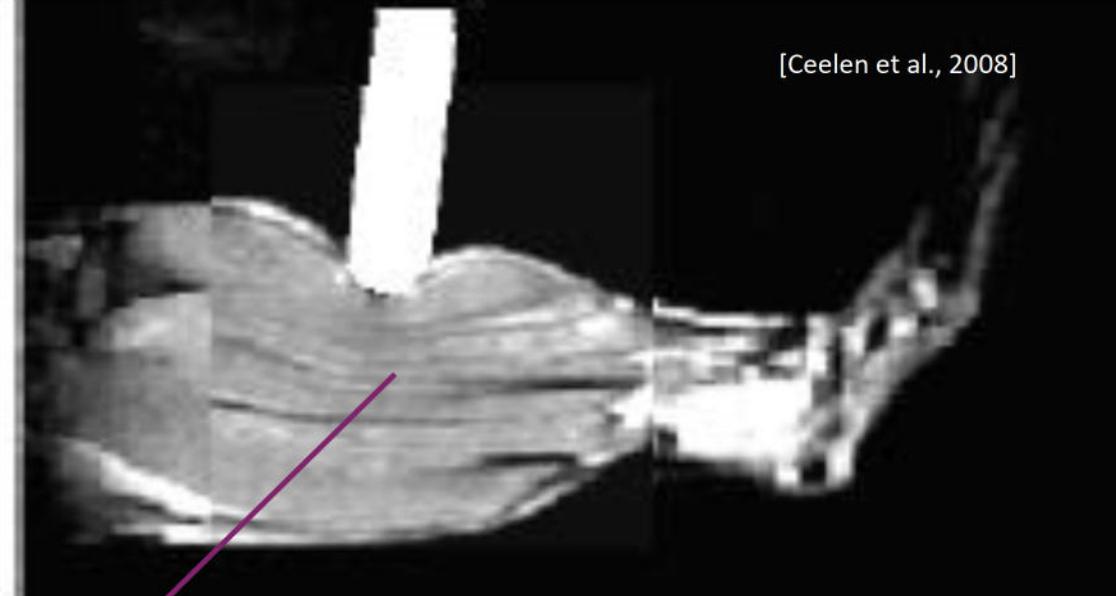
Material behaviour law :

$$\underline{\sigma} = \underline{C} \cdot \underline{\epsilon}$$





Biomechanical indices correlates with injury



[Bosboom et al., 2001] N=11
[Stekelenburg et al., 2006] N=10
[Ceelen et al., 2008] N=8
[Stekelenburg et al., 2008] N=11
[van Nierop et al., 2010] N=6
[Loerakker et al., 2011] N=16
[Traa et al., 2019] N=39



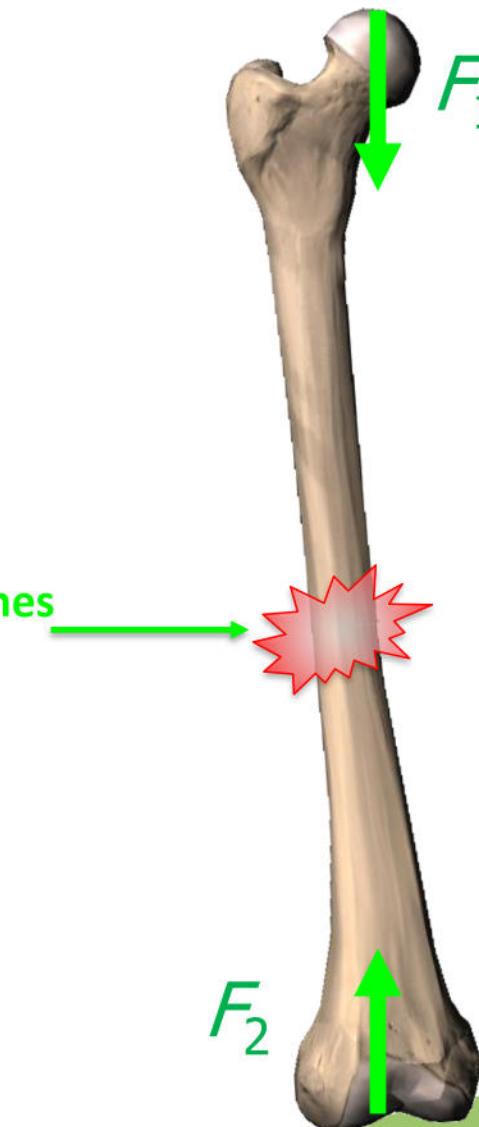
Notion de contrainte

Adapté du cours de Philippe ROUCH

L'équilibre statique doit être vérifié



Il doit y avoir des efforts internes

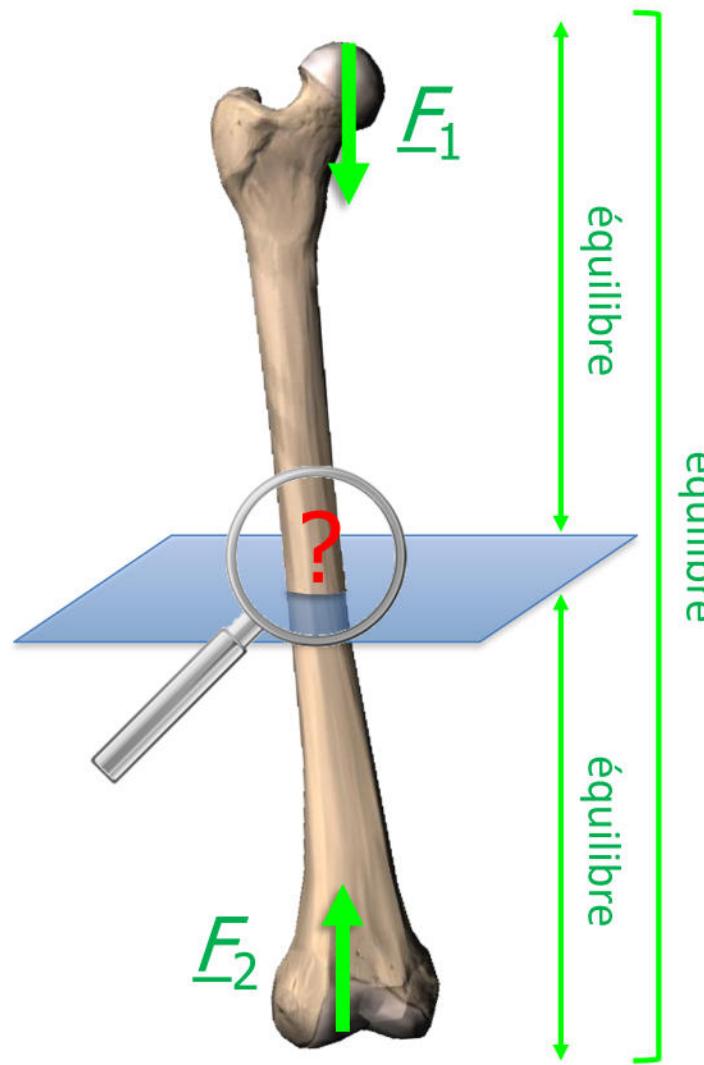




Notion de contrainte

Adapté du cours de Philippe ROUCH

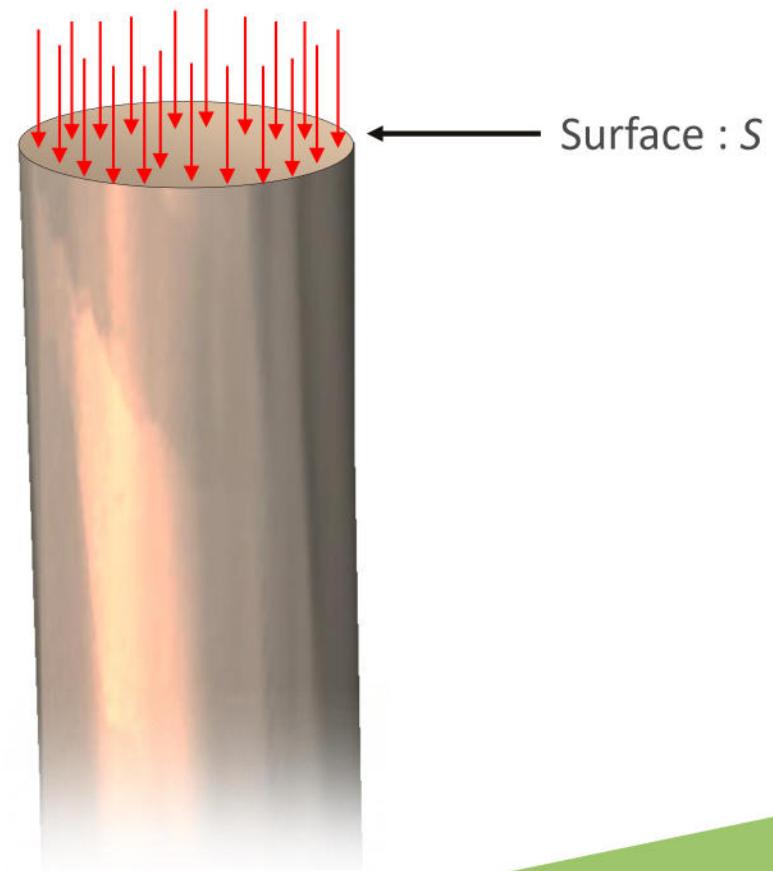
Distribution surfacique des efforts



Équilibre : $F_1 = -F_2$

Vecteur contrainte : \underline{T}

Une infinité : Mécanique des Milieux continus

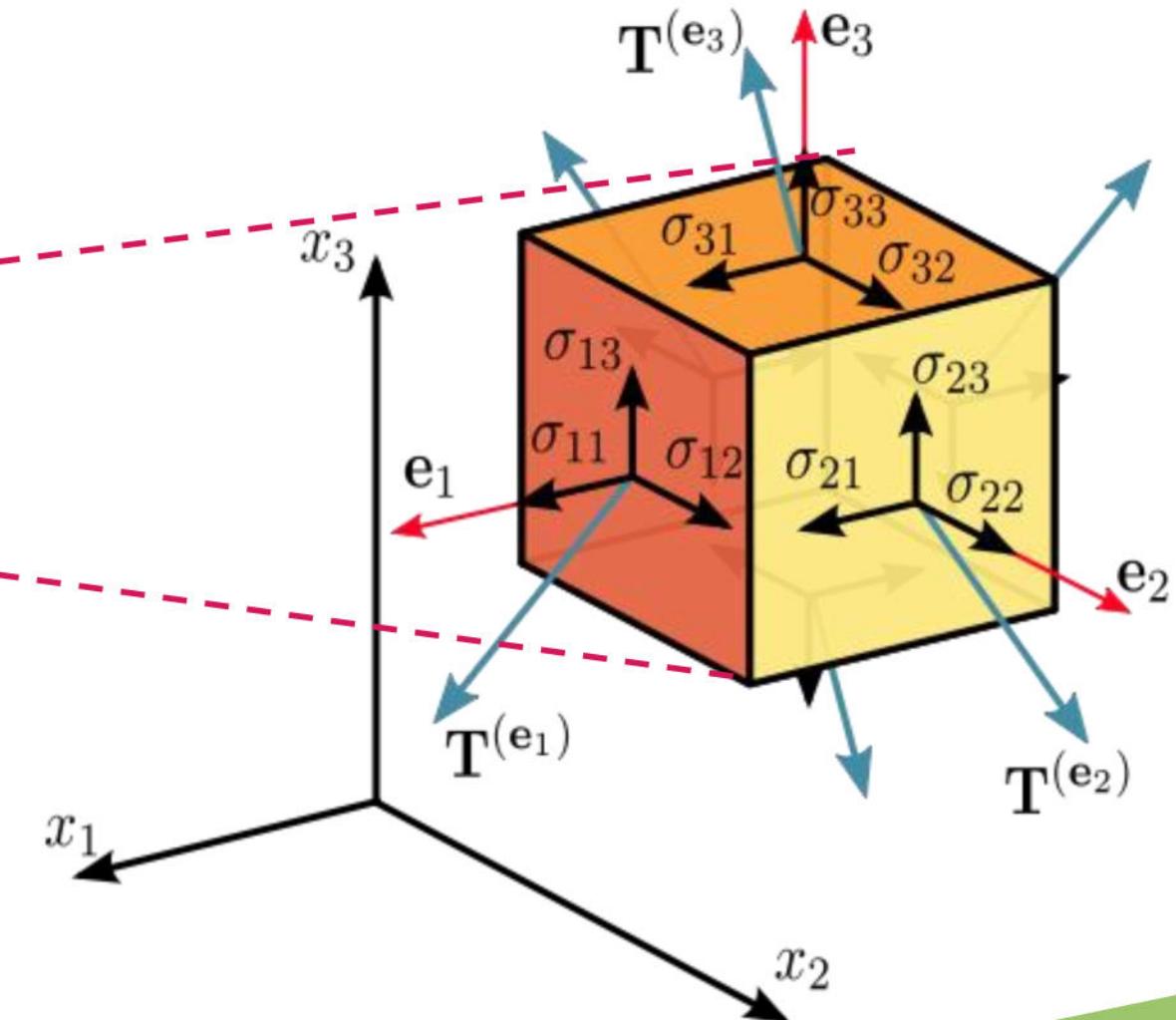
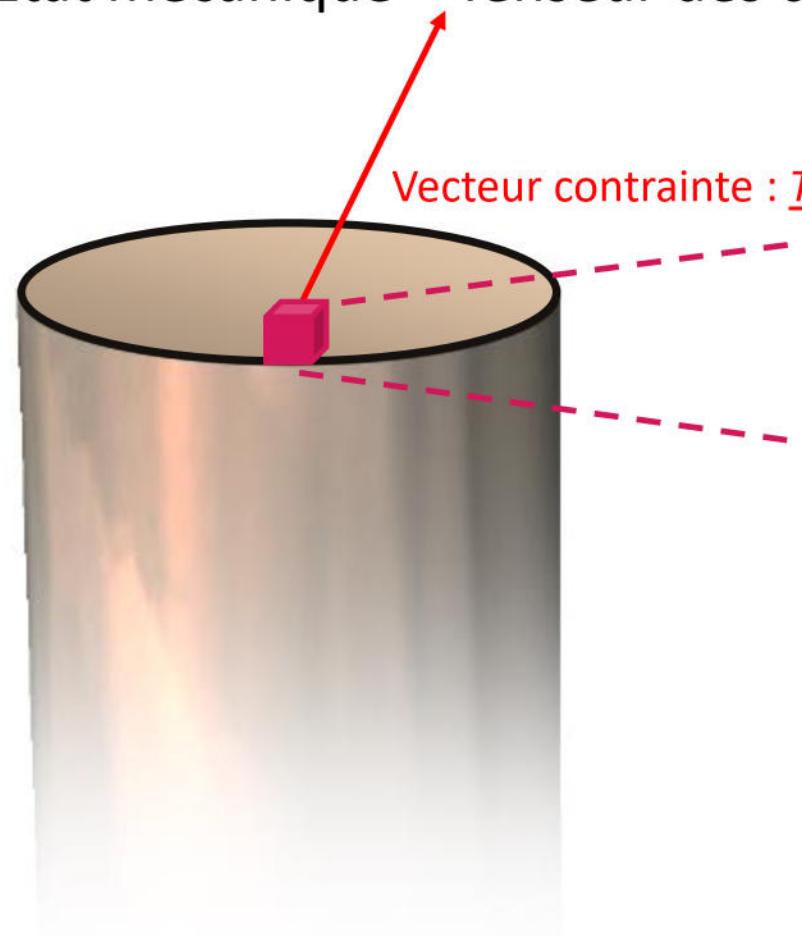




Notion de contrainte

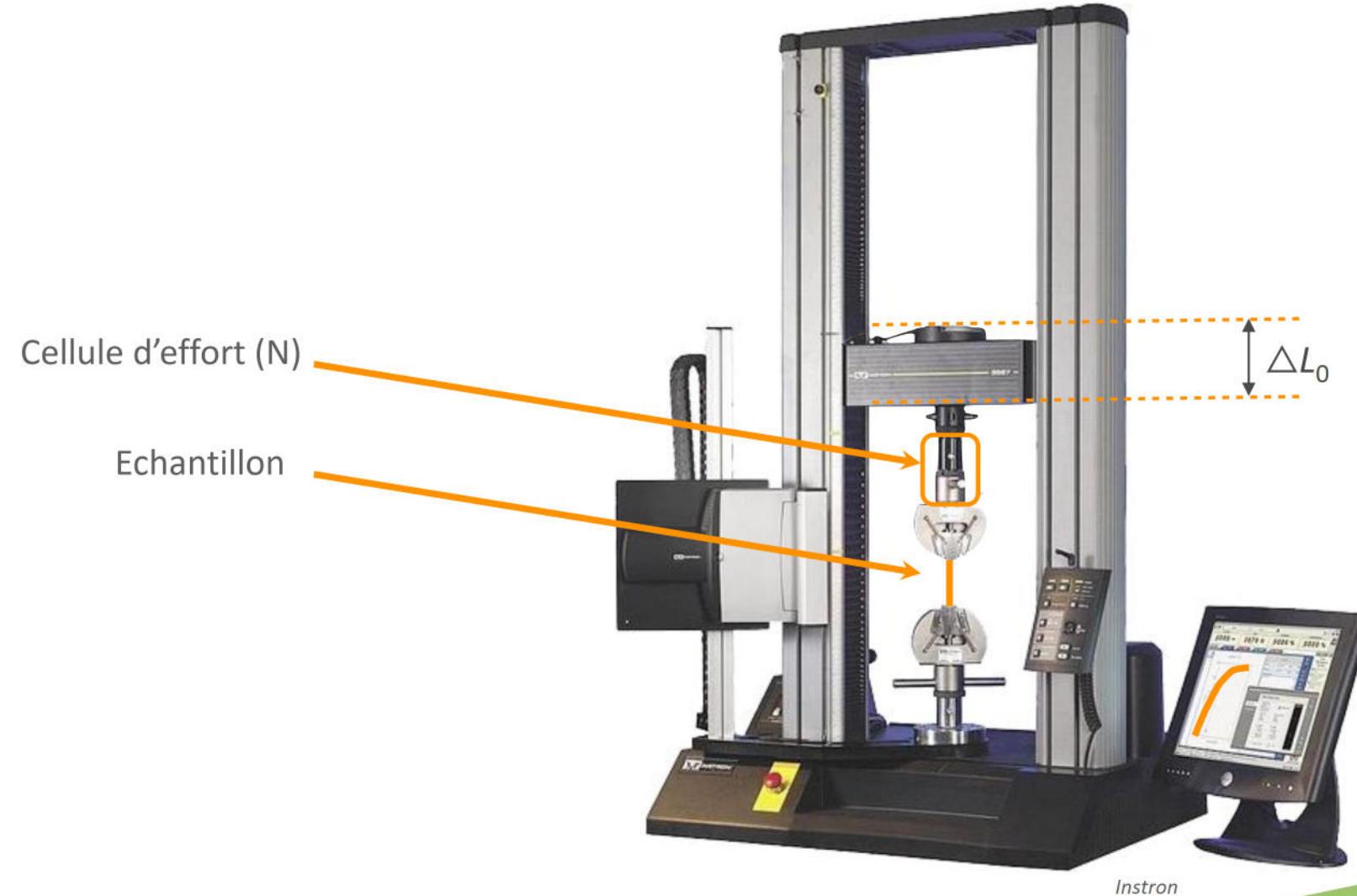
Zoom :

Etat mécanique = Tenseur des contraintes



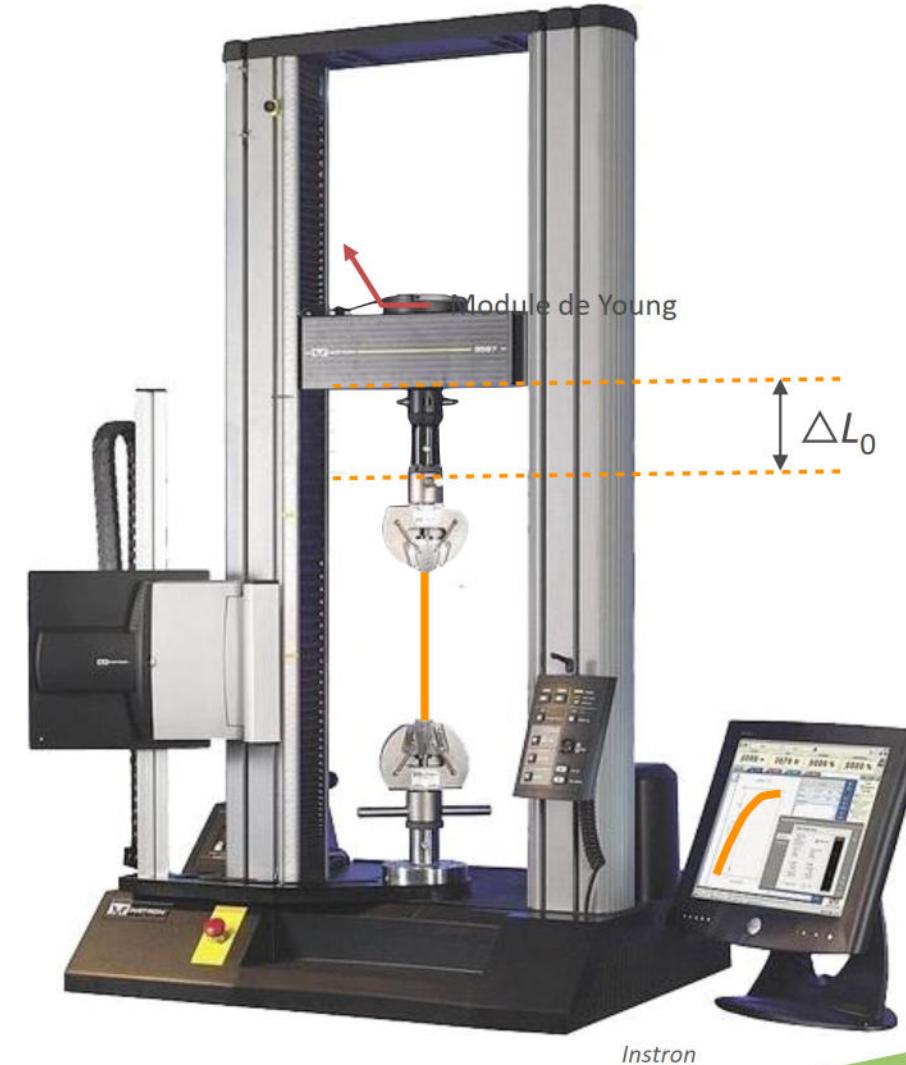


Elasticité





Elasticité



$$\sigma = \frac{F}{S} \quad \varepsilon = \frac{\Delta L_0}{L_0}$$

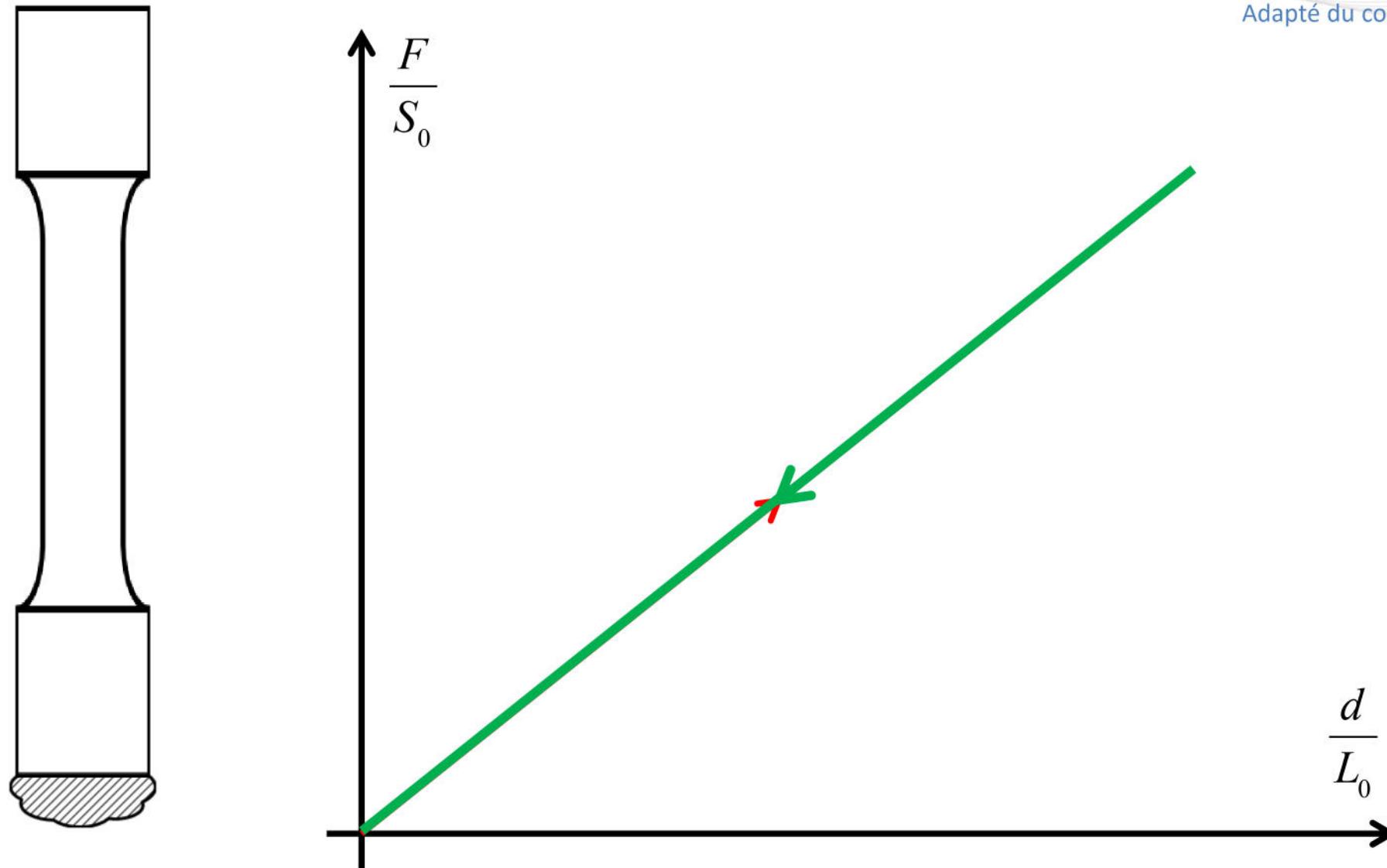
Loi de Hooke :

$$\sigma = E \varepsilon$$



Elasticité linéaire

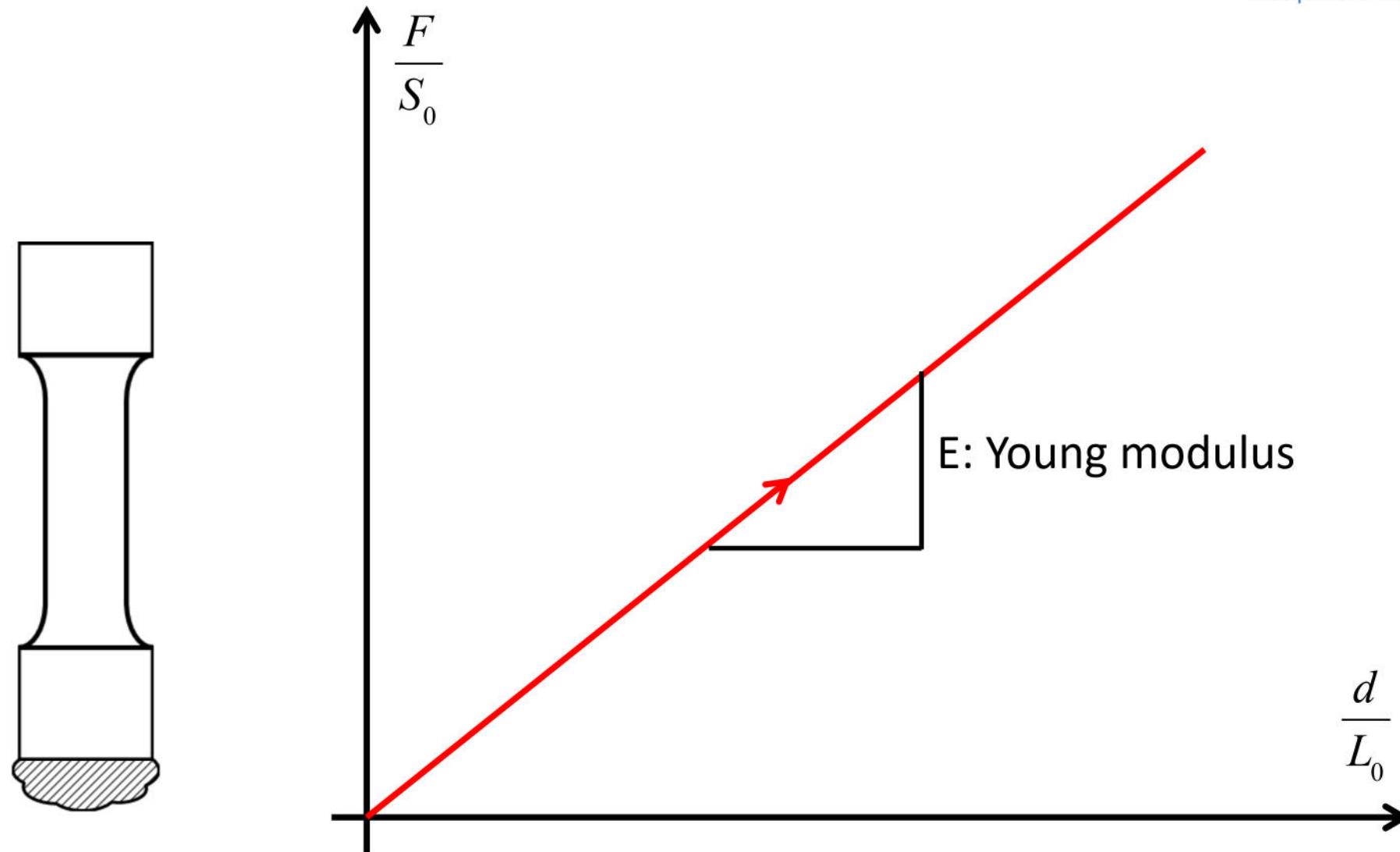
Adapté du cours de Sébastien LAPORTE





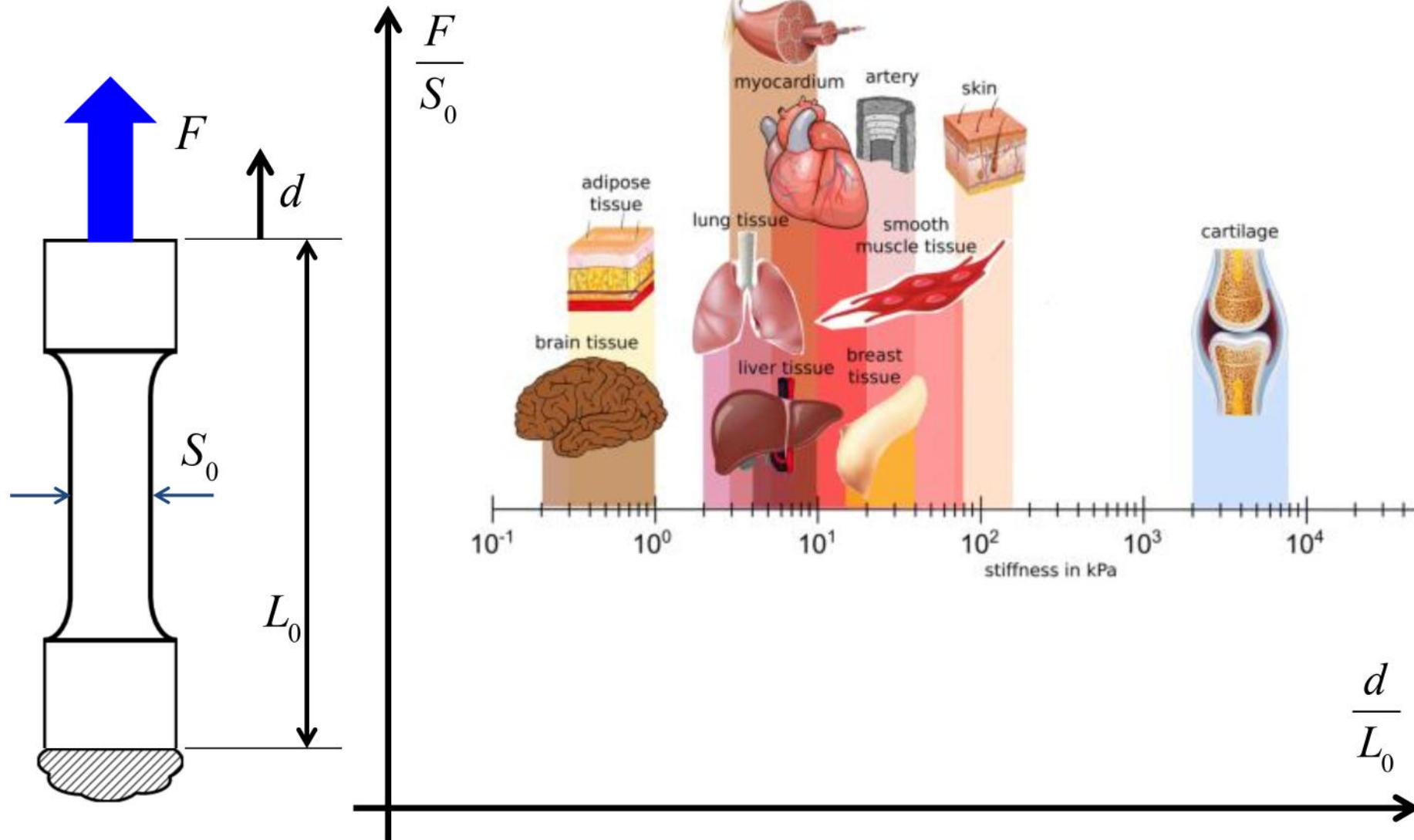
Loi de Hooke

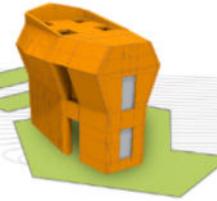
Adapté du cours de Sébastien LAPORTE





Loi de Hooke



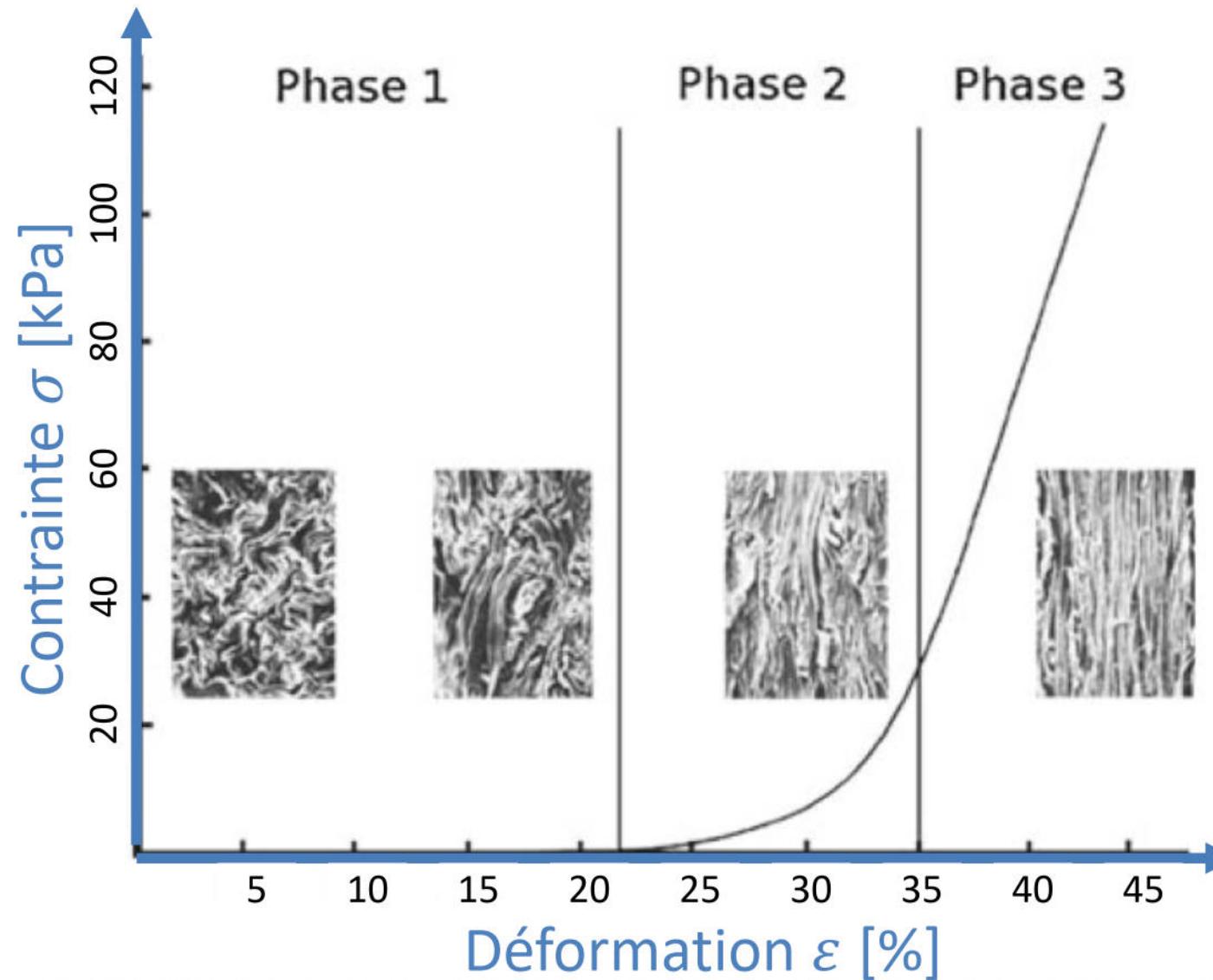


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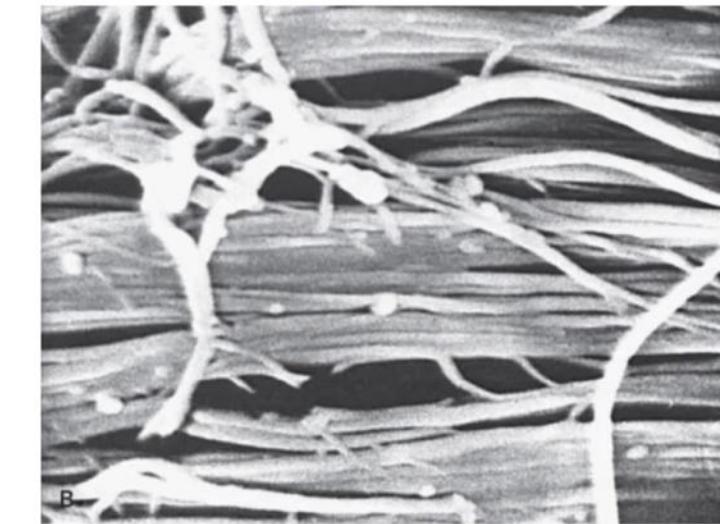
Caractérisation mécanique de la peau



Elasticité non-linéaire



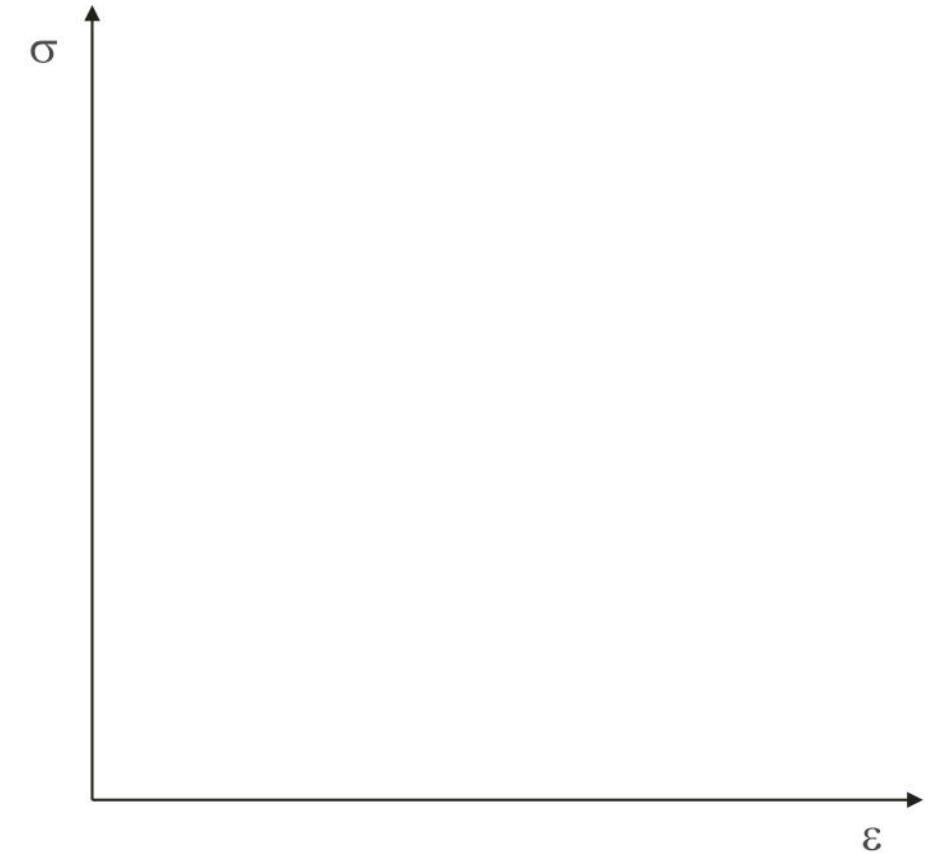
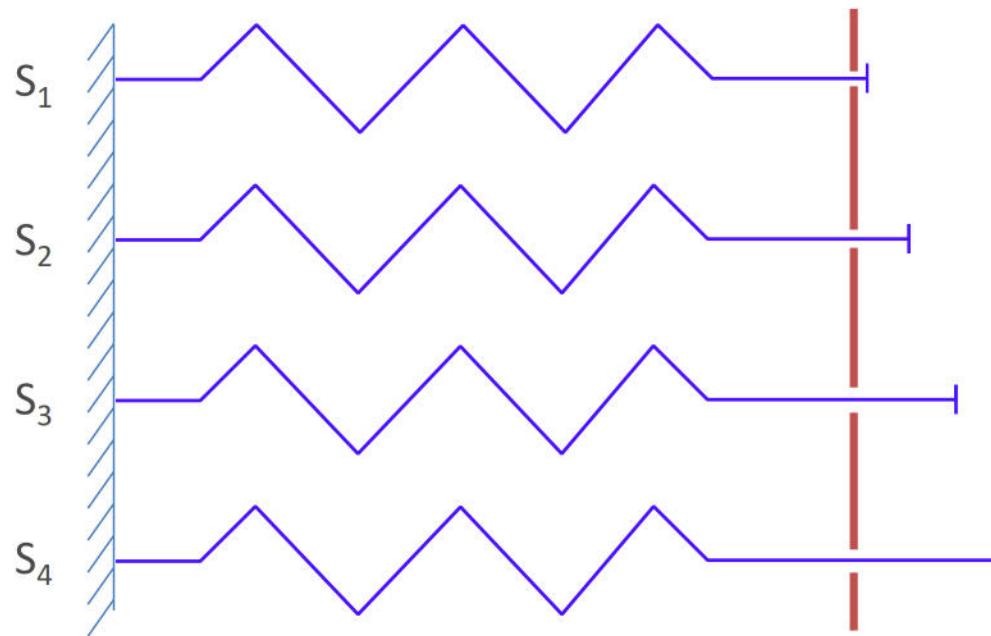
Les ensemble de fibres ont des ondulations



Wolters Kluwer Health 2013

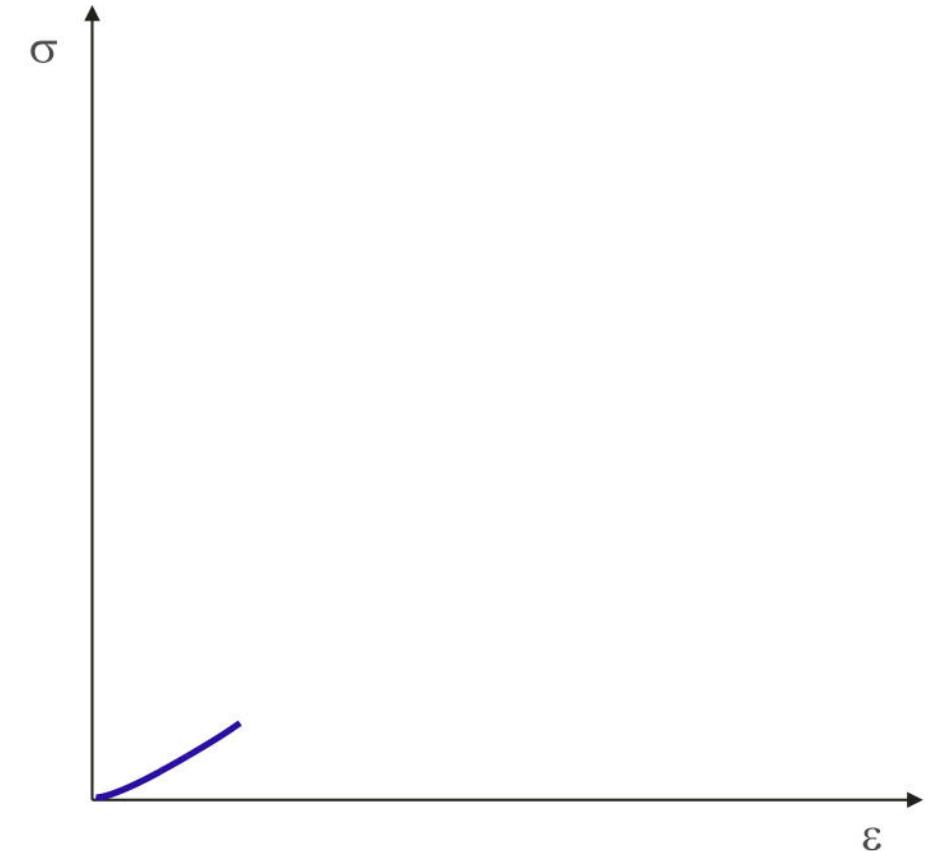
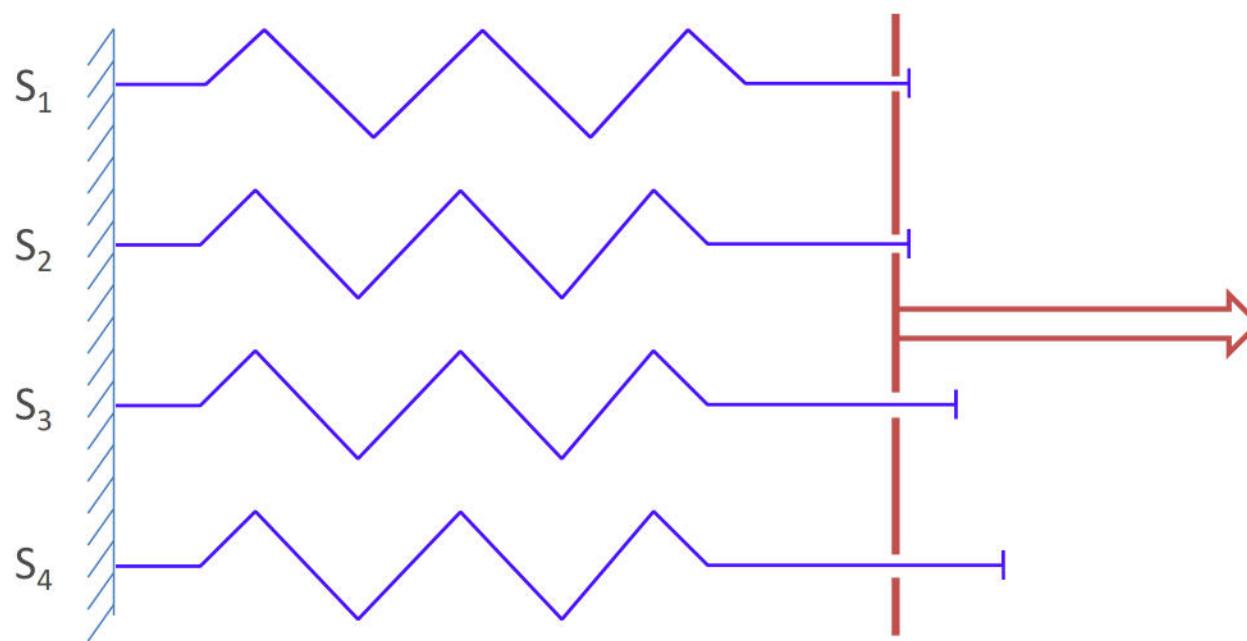


Elasticité non-linéaire



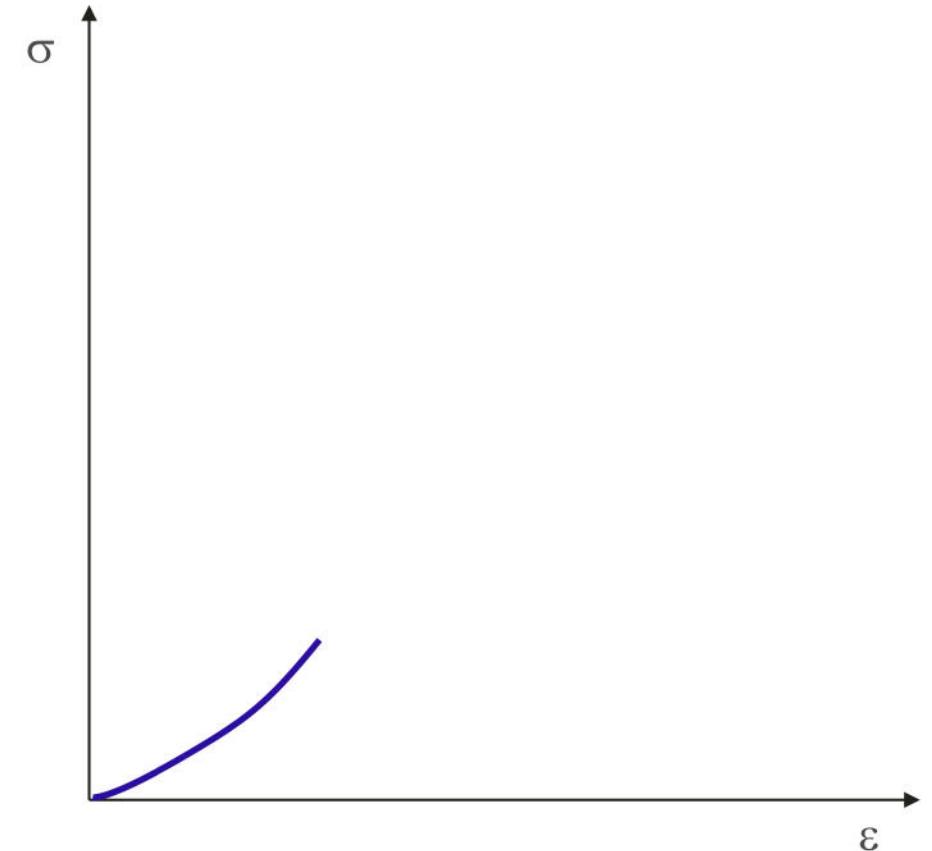
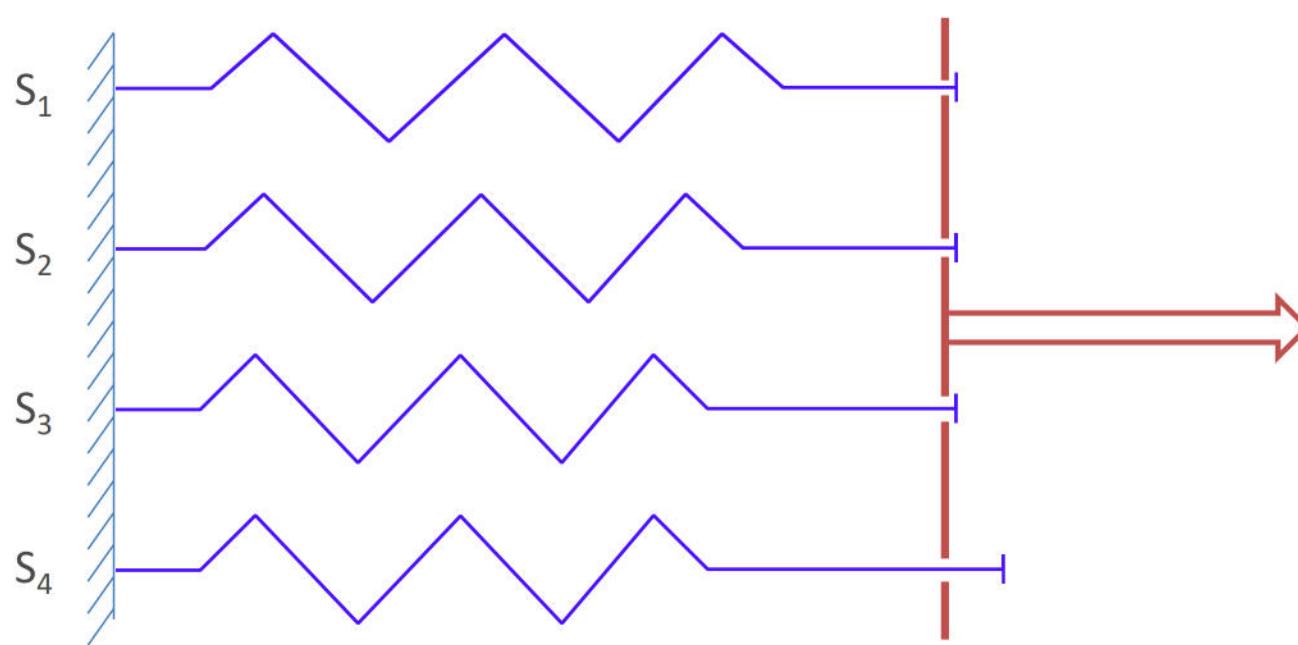


Elasticité non-linéaire



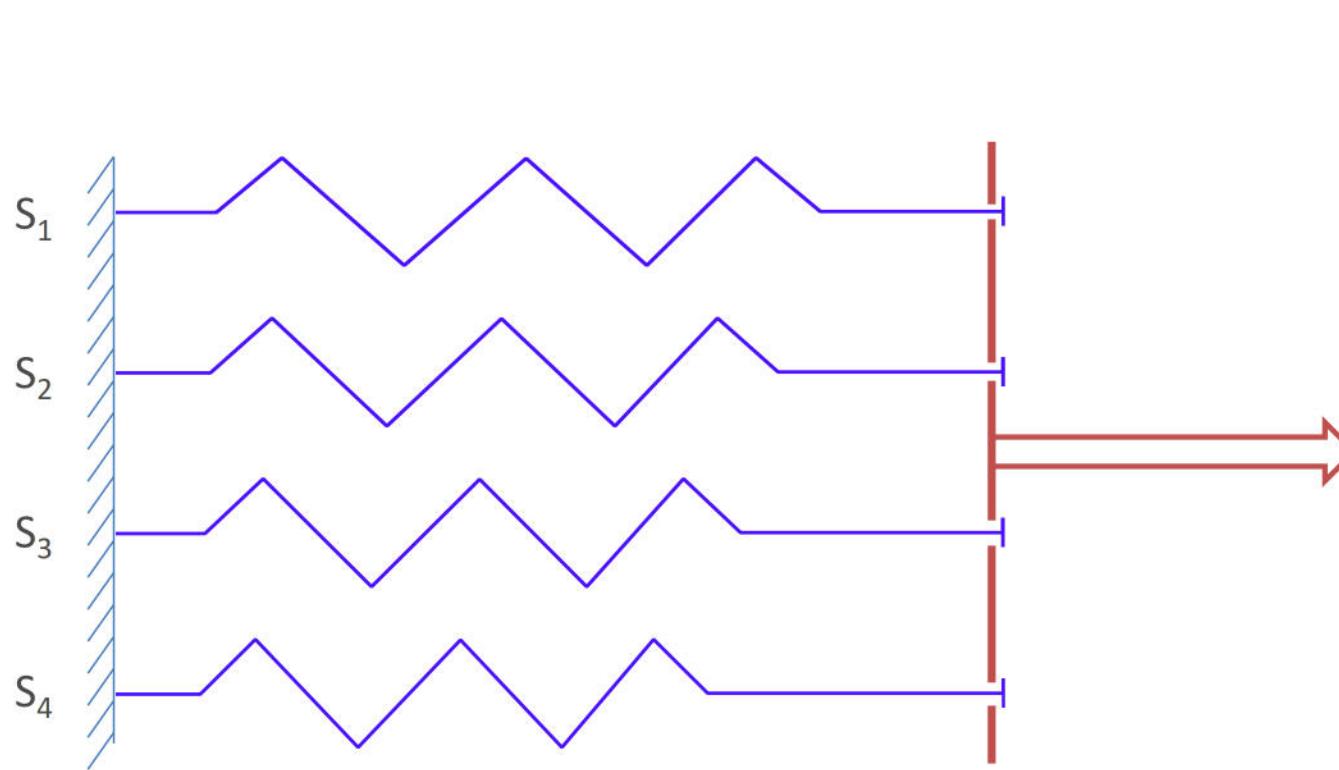


Elasticité non-linéaire



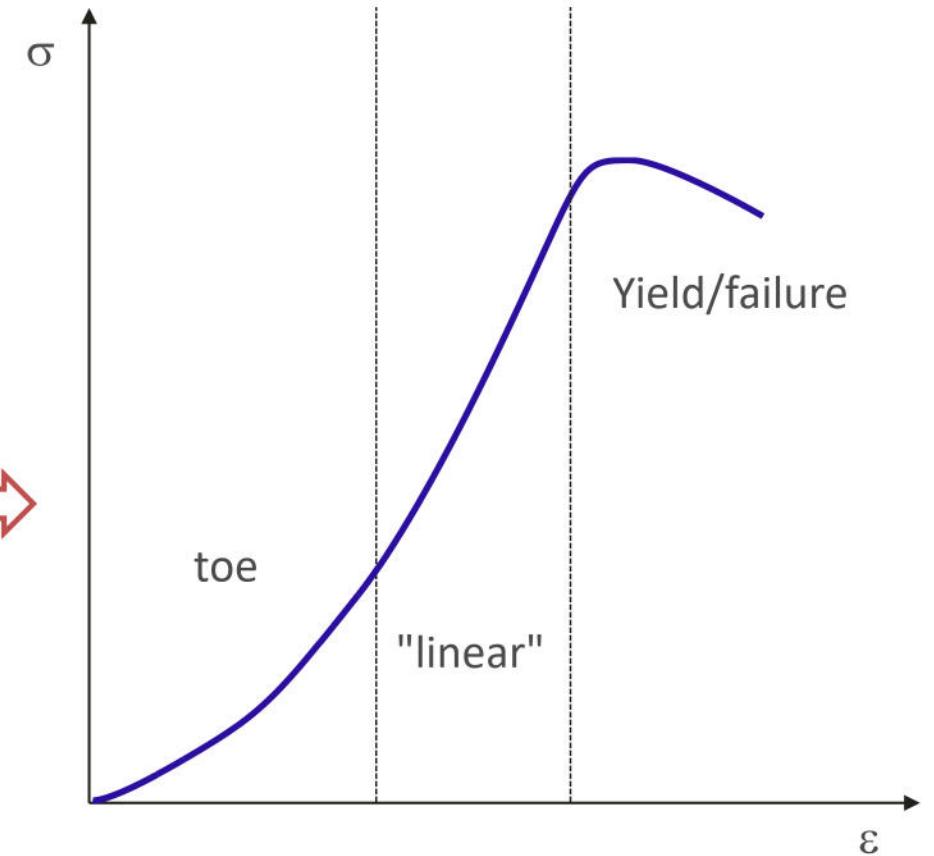
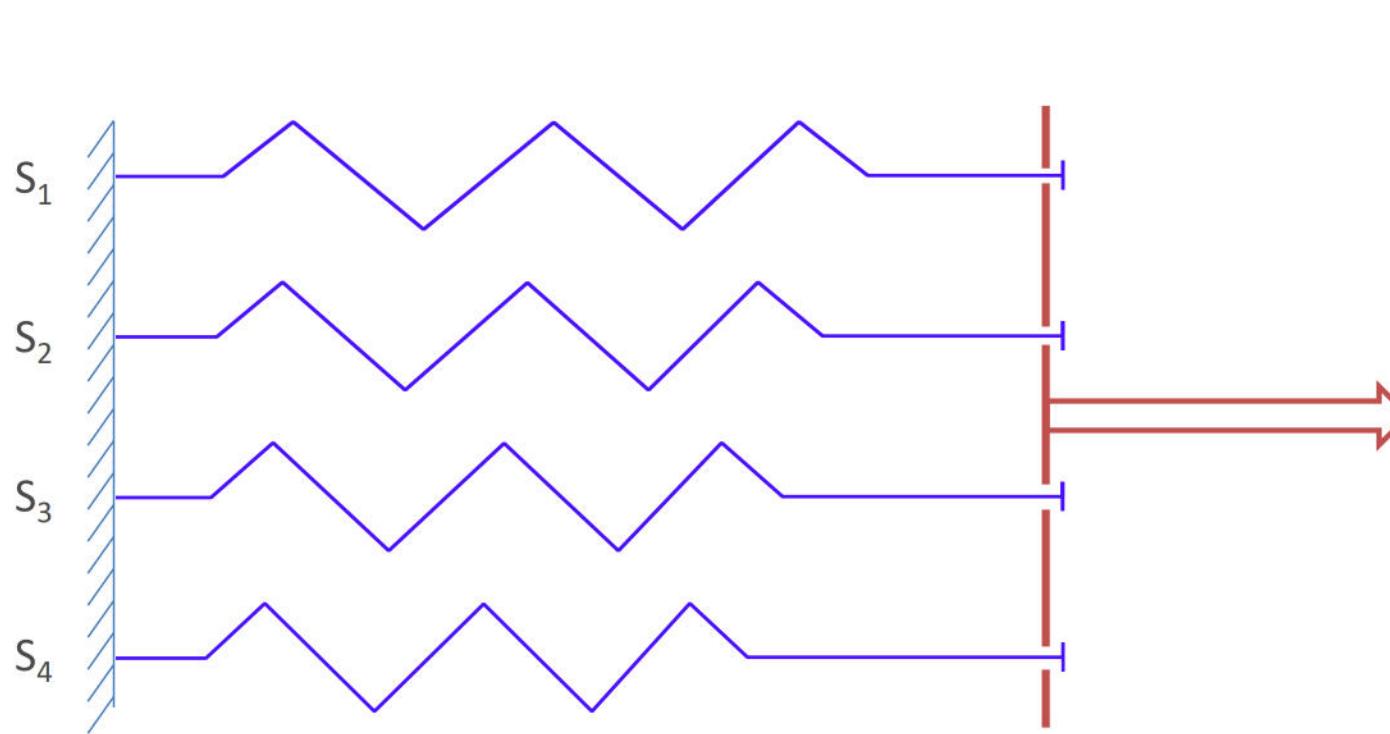


Elasticité non-linéaire



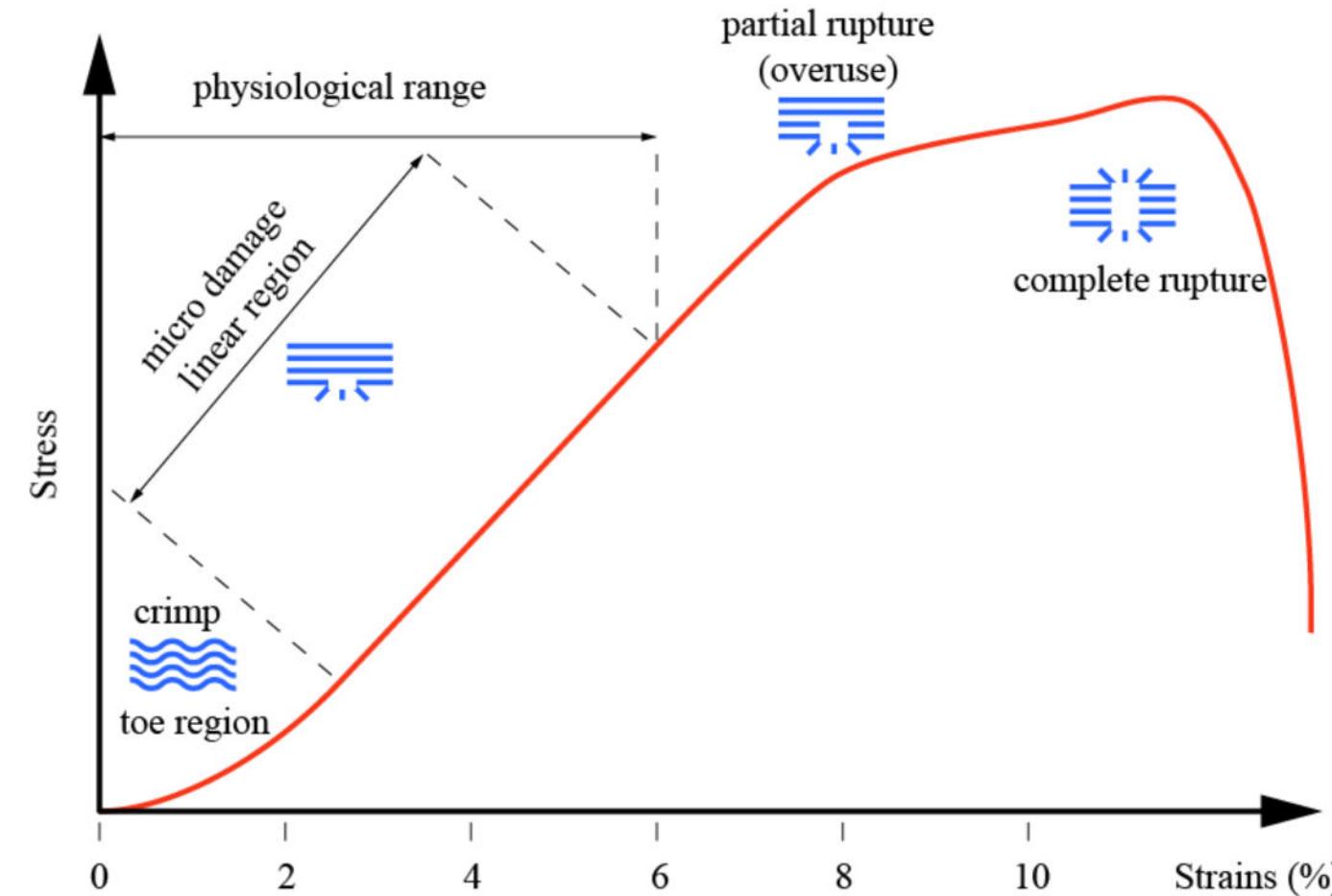


Elasticité non-linéaire



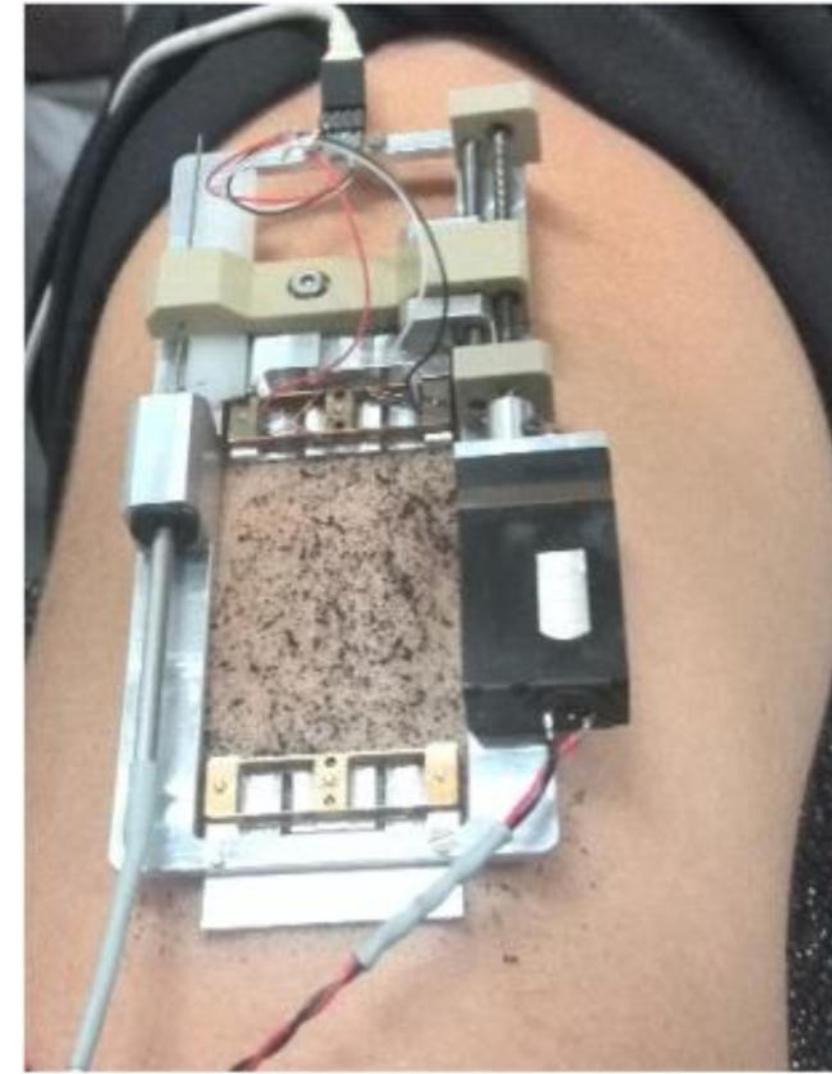


Elasticité non-linéaire – ex vivo

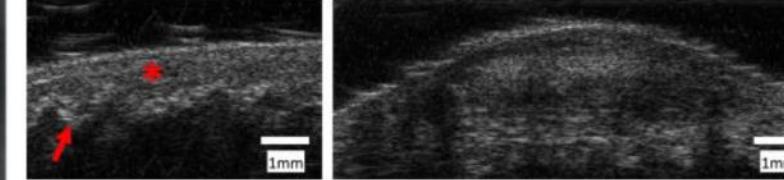




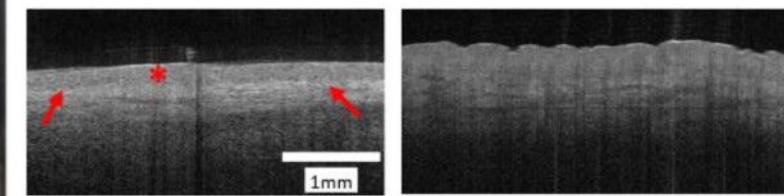
Elasticité non-linéaire – *in vivo*



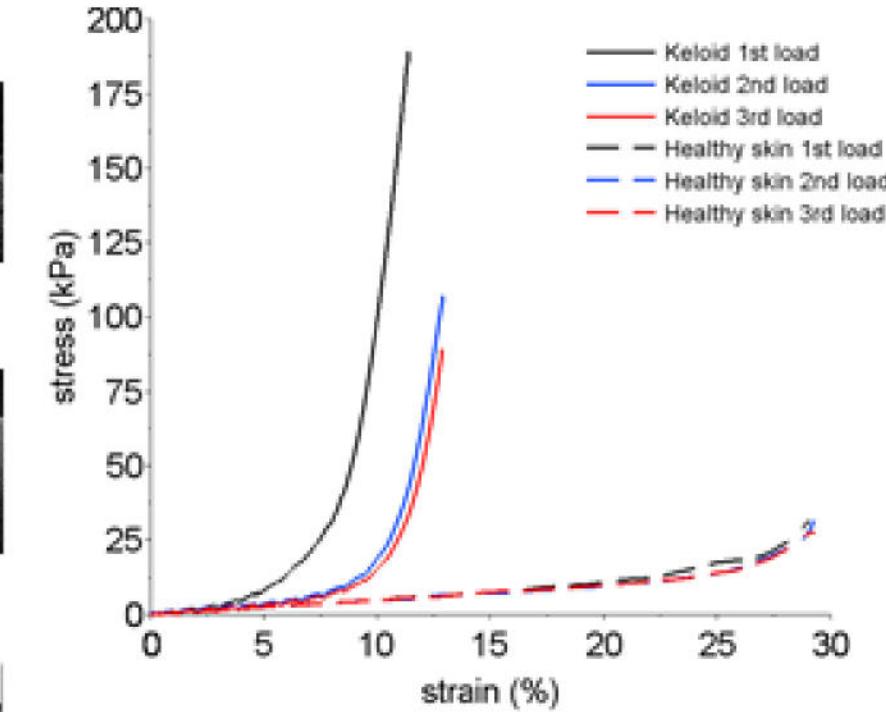
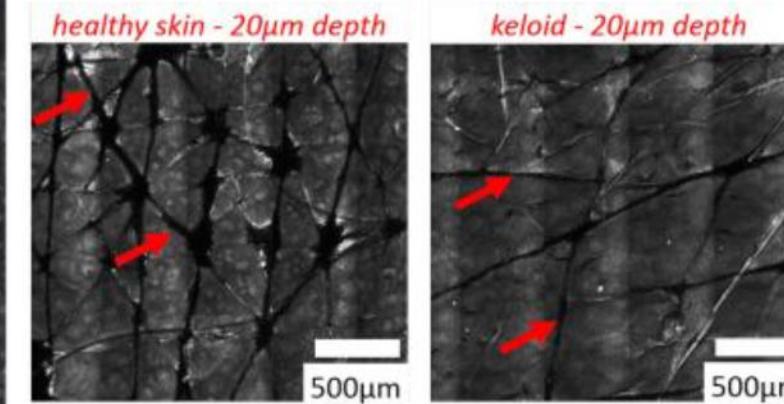
Ultrasound echography



OCT

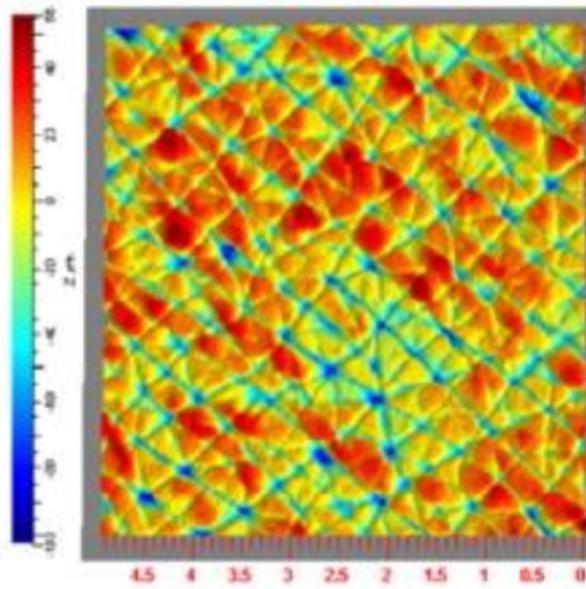


Confocal microscopy

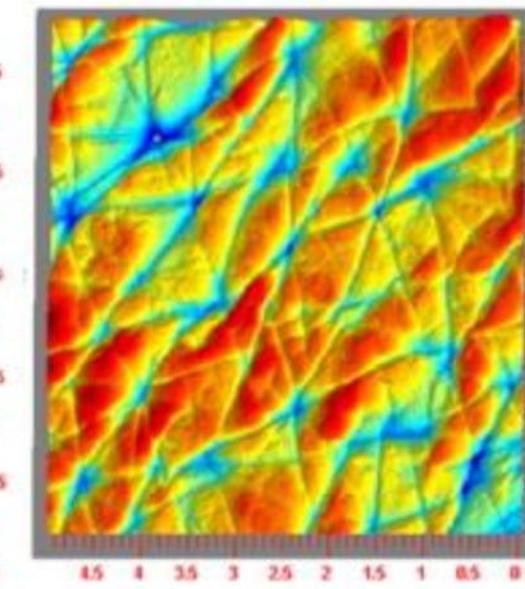




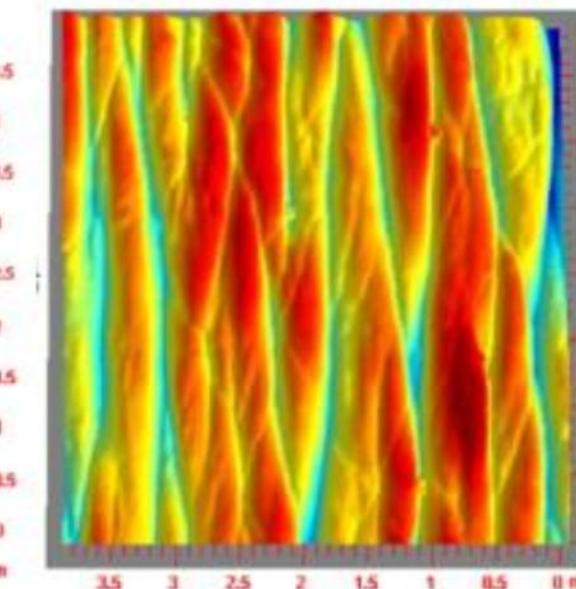
Anisotropie



30-40 Years (62 dBA)



50-60 Years (63.5 dBA)



70-80 Years (65 dBA)

Le comportement ne dépend pas de la direction. On parle alors **d'isotropie**

Le comportement dépend de la direction. On parle alors **d'anisotropie**





Elasticité non-linéaire – in vivo et multicouche

Figure a.

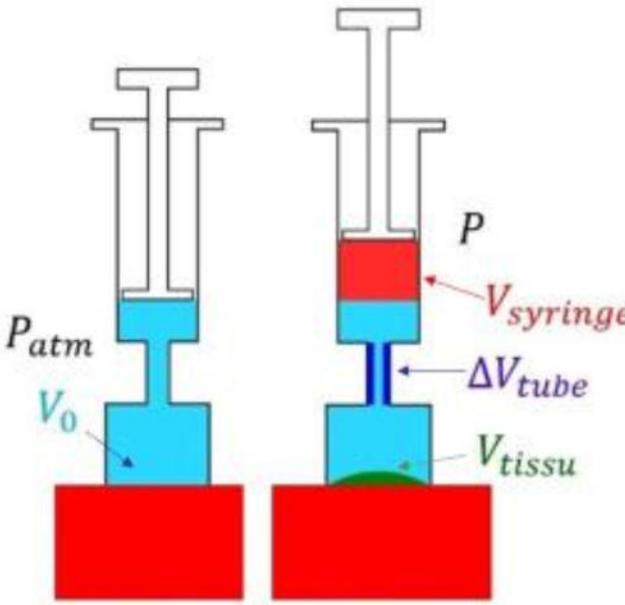
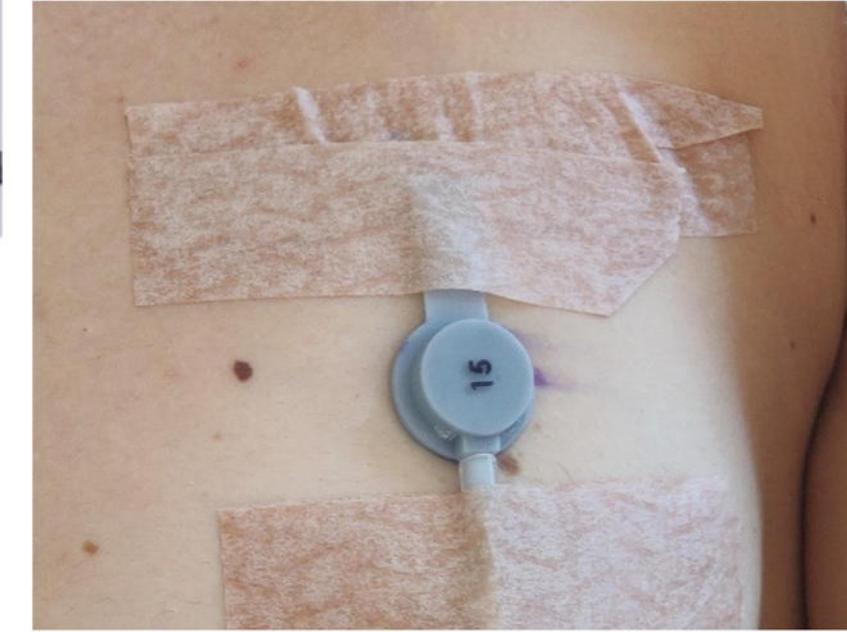


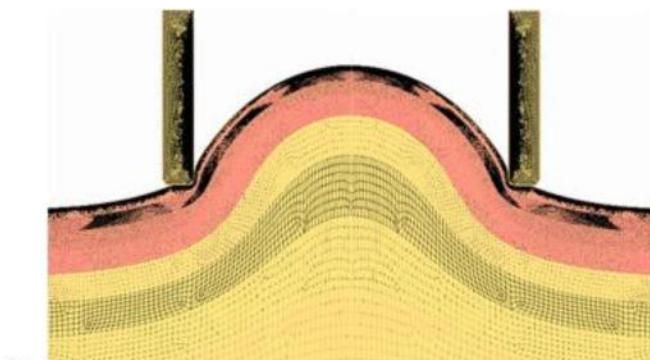
Figure b.



Figure c.



[Briot et al., 2022]





Elasticité linéaire – *in vivo*

Raideur : biomarqueur ?

Comportement des ligaments



Image : Supersonic Imaging

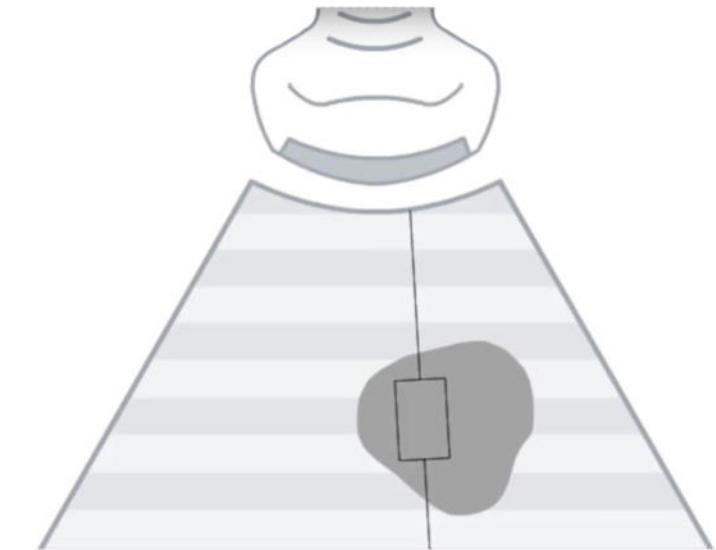


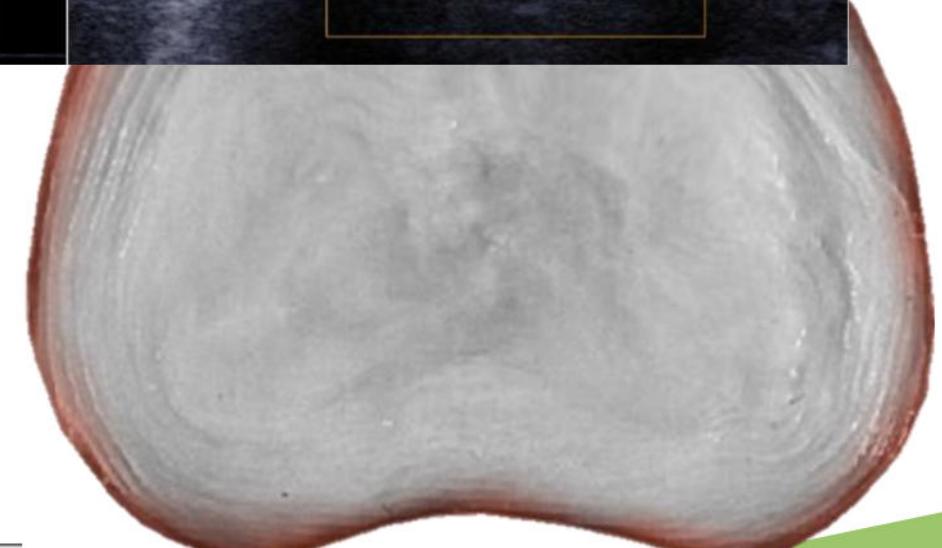
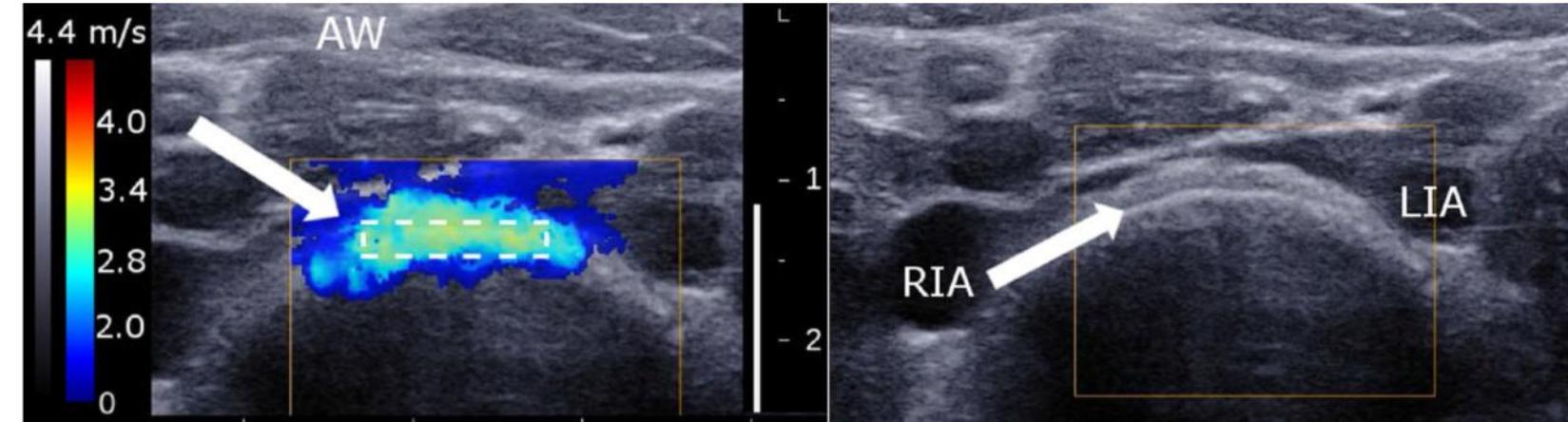
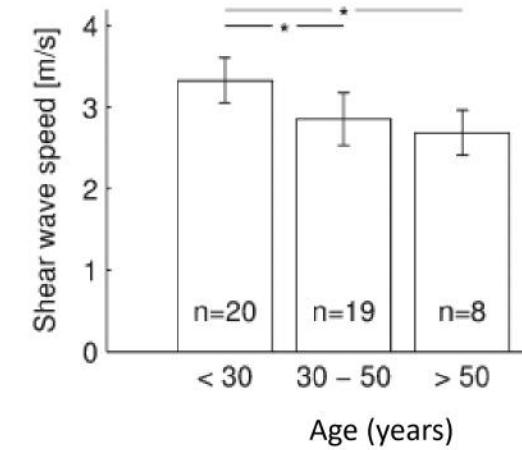
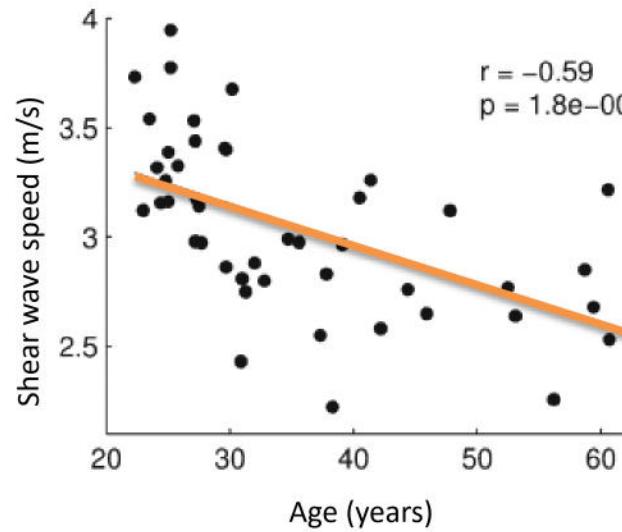
Image : Siemens



Elasticité linéaire – *in vivo*

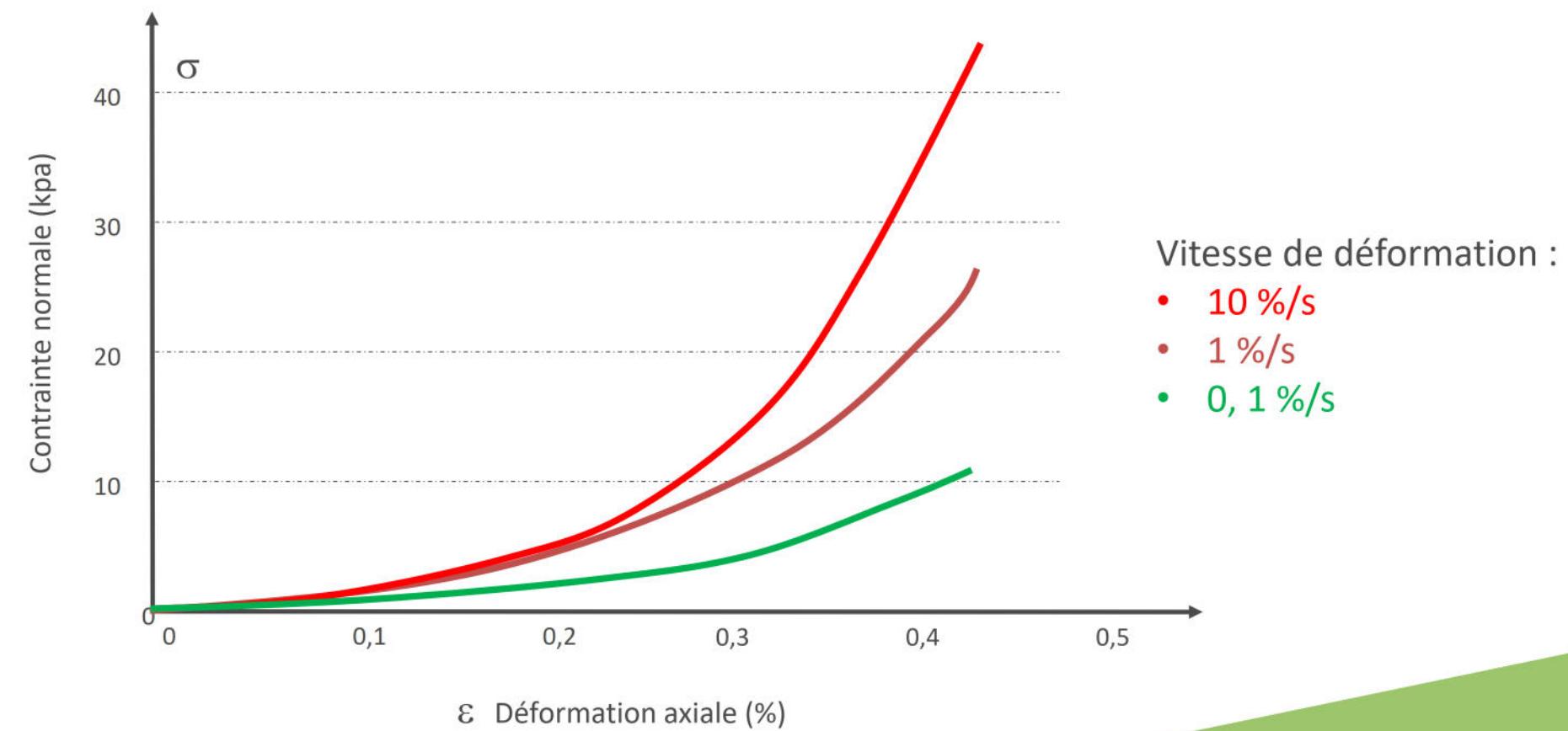
Raideur : biomarqueur ?

SUPERSONIC
imagine



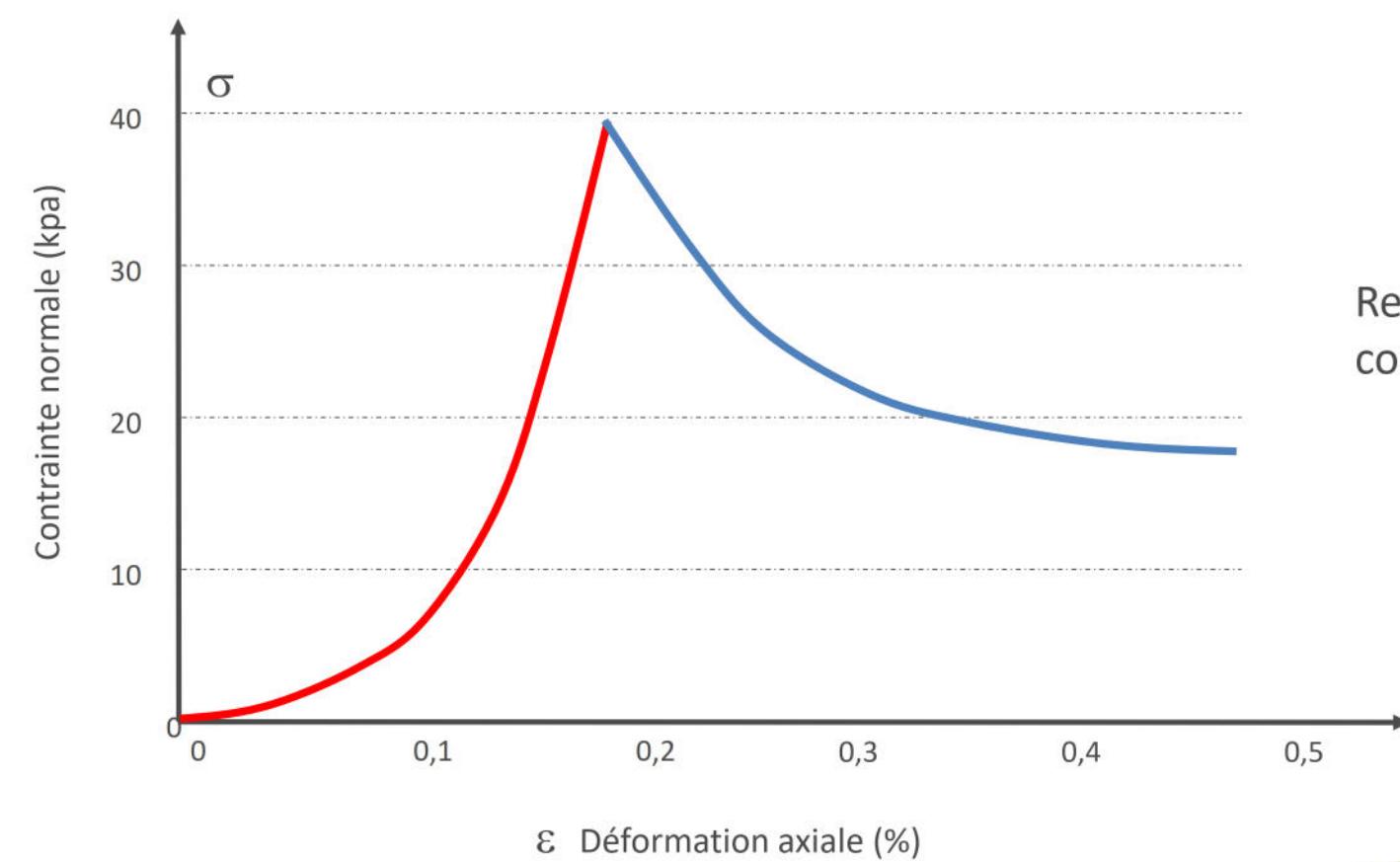


Visco-Elasticité





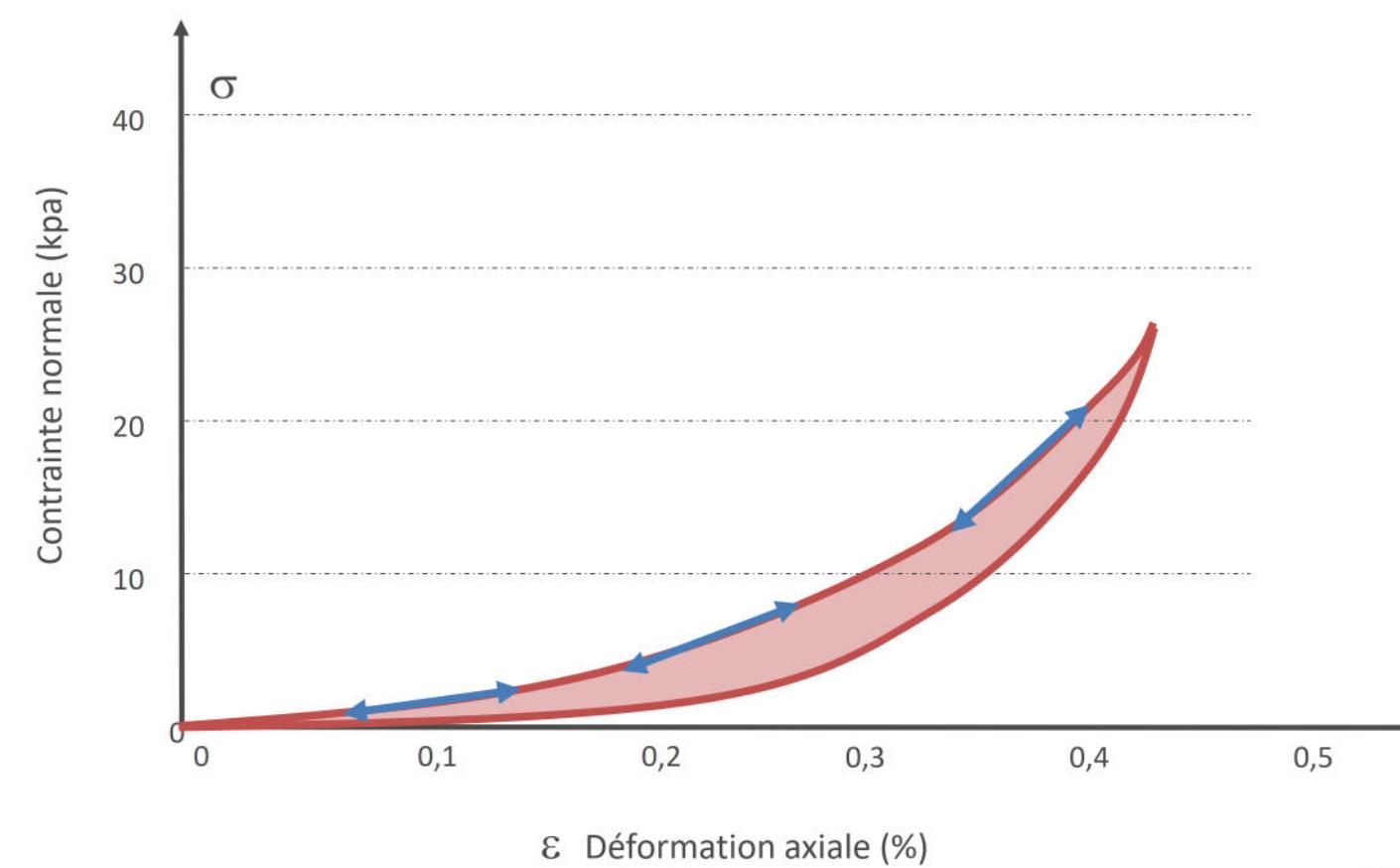
Visco-Elasticité



Relaxation des contraintes

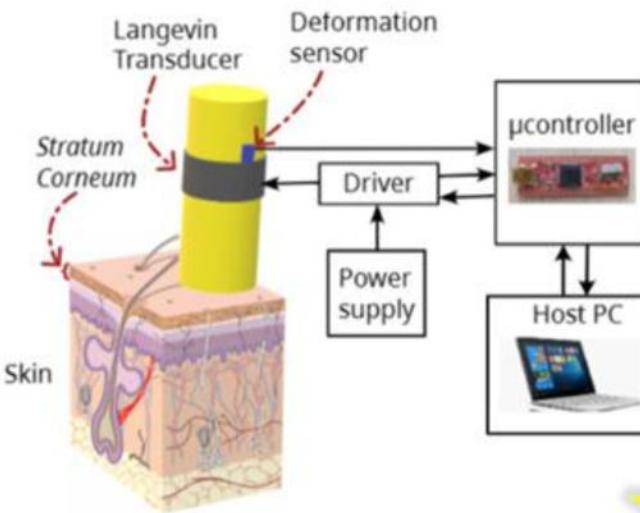


Visco-Elasticité

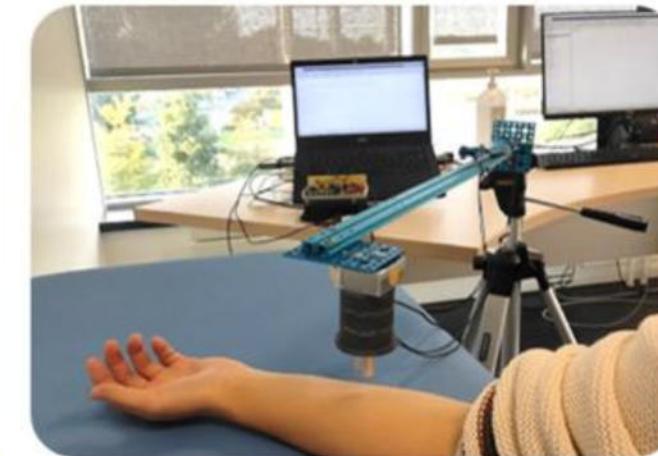




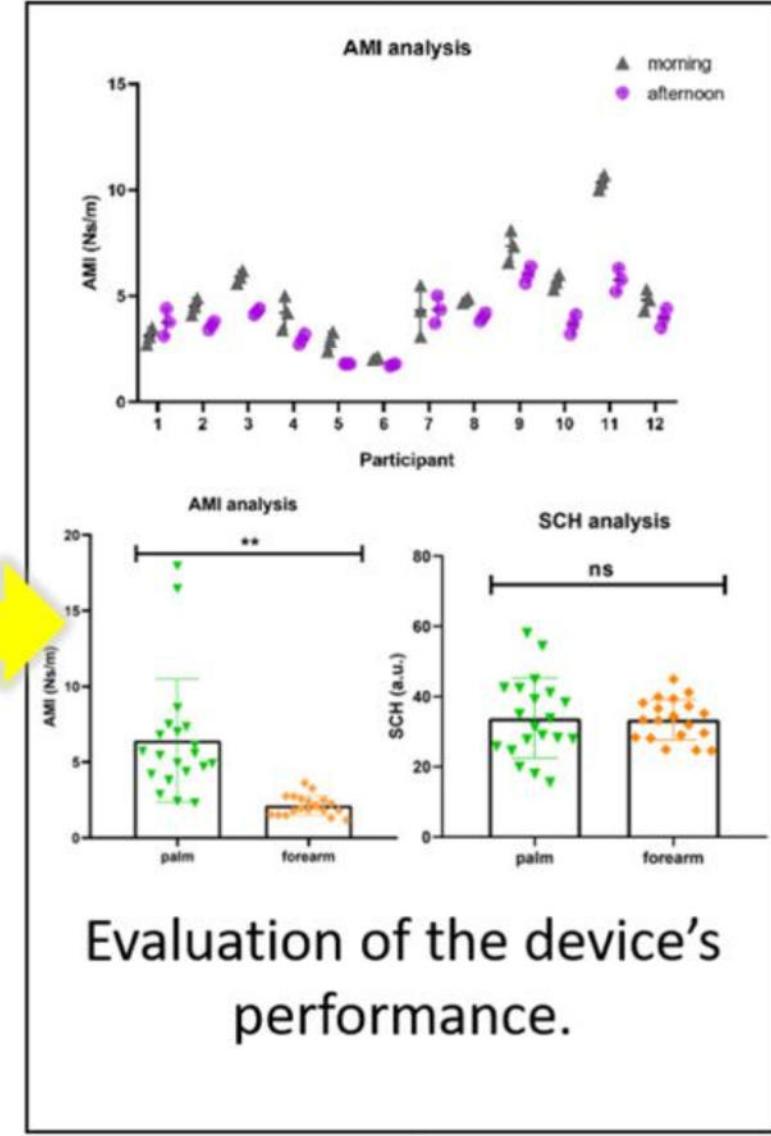
Essais dynamiques



Development of a skin mechanical impedance sensor for skin diagnosis.



Experimental tests on healthy skin.
Study 1: same site and different times of a day
Study 2: different sites with different mechanics.





Comportement mécanique de la peau



Visco élasticité non linéaire anisotrope

- ↑ Raideur dépendante de l'orientation du prélèvement
- ↑ Raideur dépendante du niveau de chargement
- ↑ Revient à l'état initial si déchargé
- ↑ Dépend de la vitesse de sollicitation

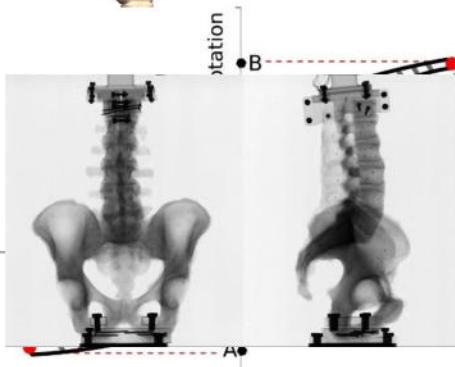
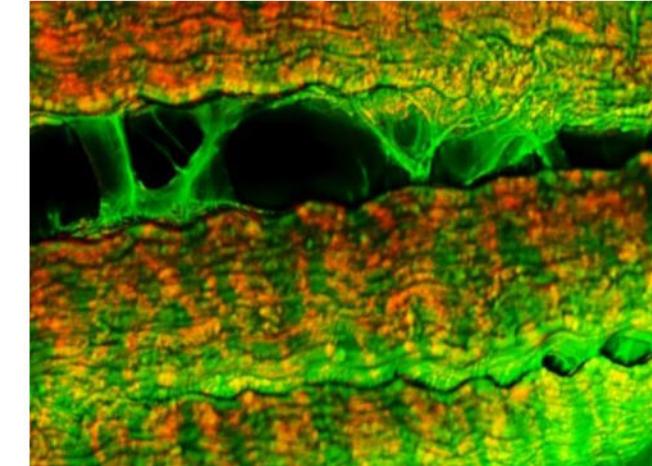
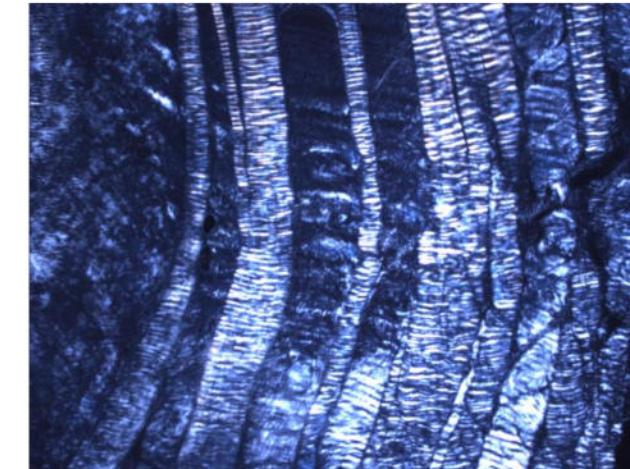
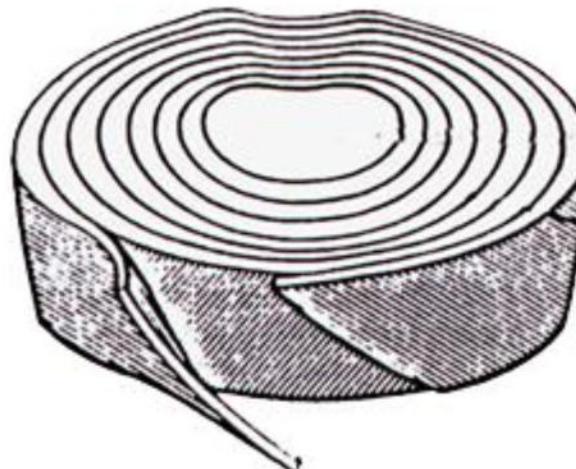
3

Elasticité non-linéaire multi-échelle

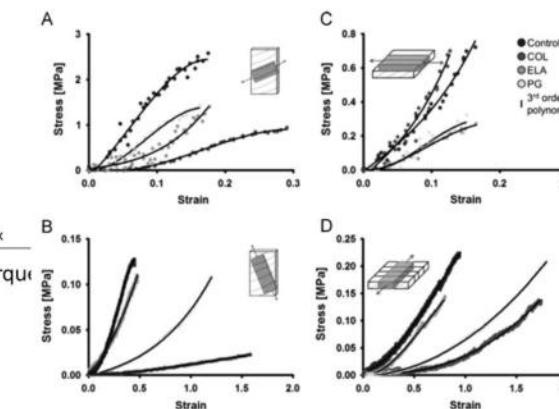


Tissus mous : Organisation multi-échelle

Adapté du cours de Claudio VERGARI



Zirbel et al., 2013



Isaacs et al., 2014

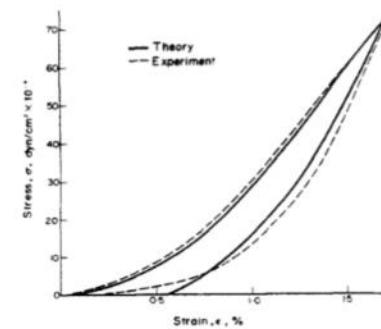
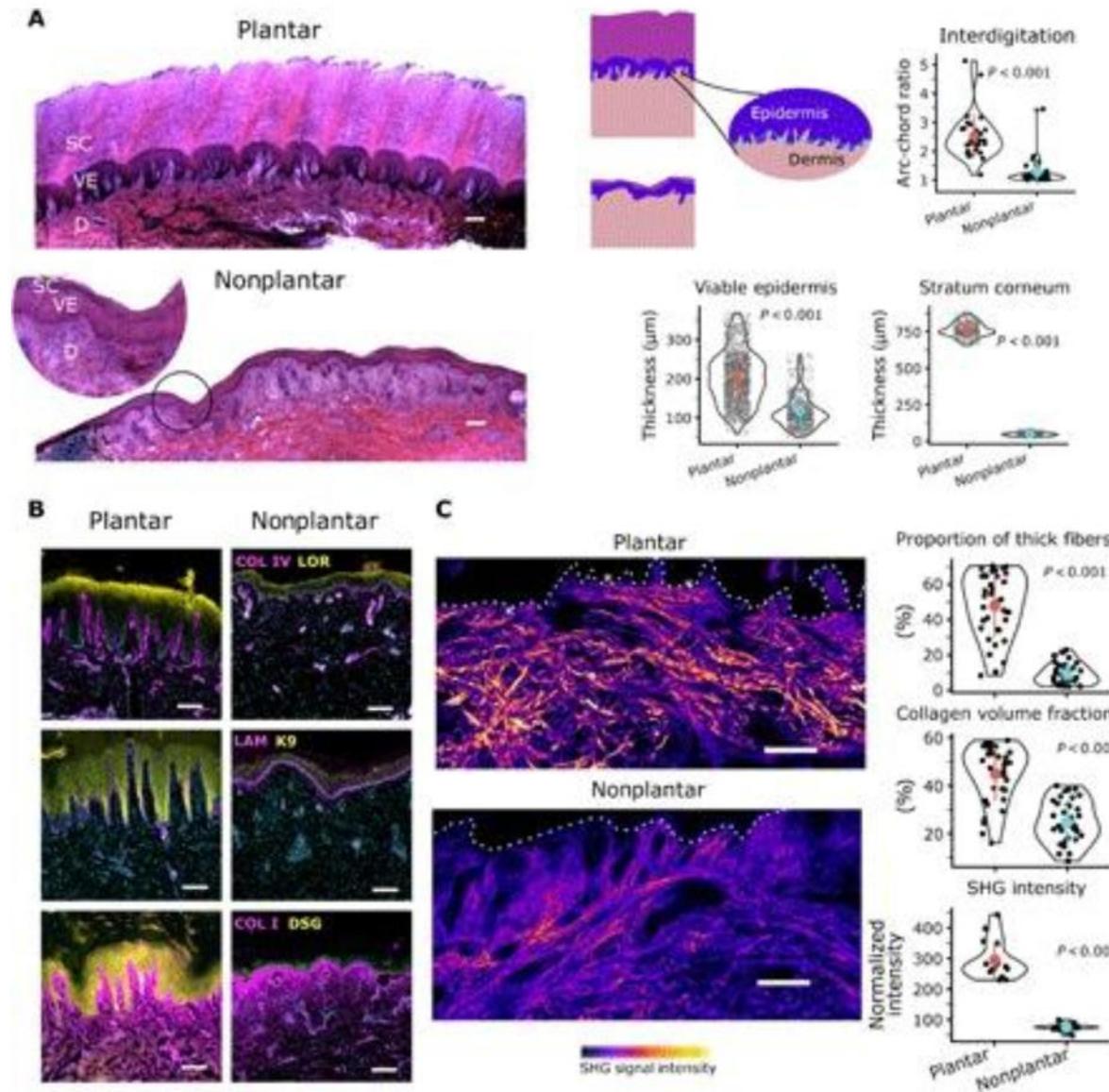


Fig. 10. Hysteresis loop at 3.6%/min strain rate.

Haut and Little, J Biomech 1972



Tolérance de la peau à un chargement



La morphologie et la composition jouent des rôles distincts et complémentaires dans la tolérance de la peau plantaire à la charge mécanique

3

Elasticité non-linéaire multi-physique



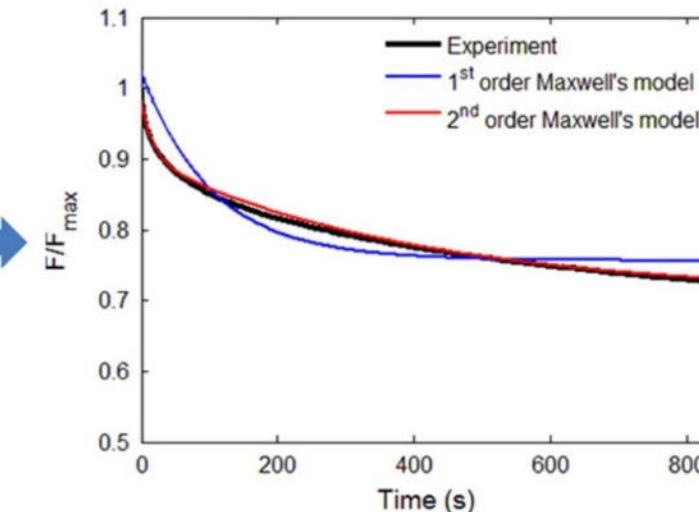
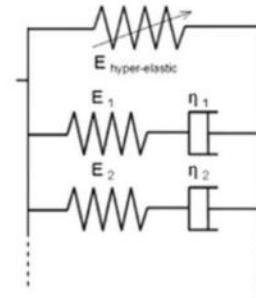
Causes de l'évolution temporelle de la réponse

Approche phénoménologique : formulation viscoélastique

Experiment



Modeling

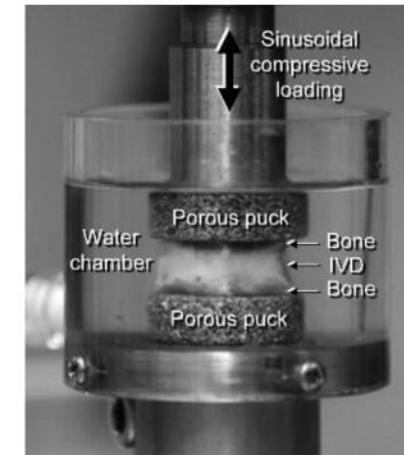


[Gras et al., 2013]

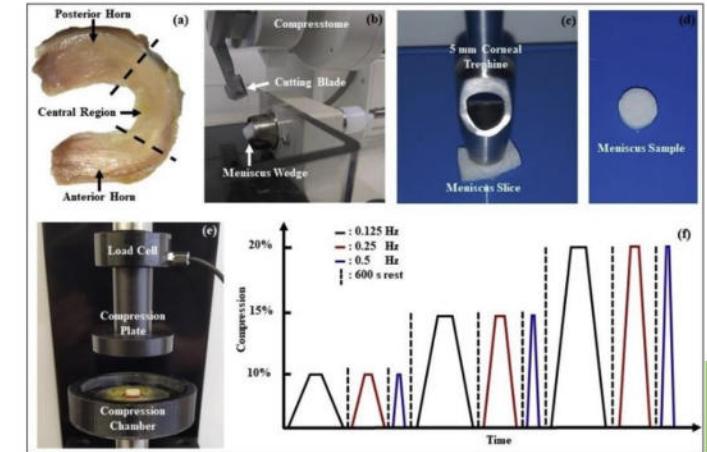
Pressurisation fluide : un mécanisme présent partout dans les tissus mous?



[Inoue et al., 2011]



[Gu et al., 2011]



#51



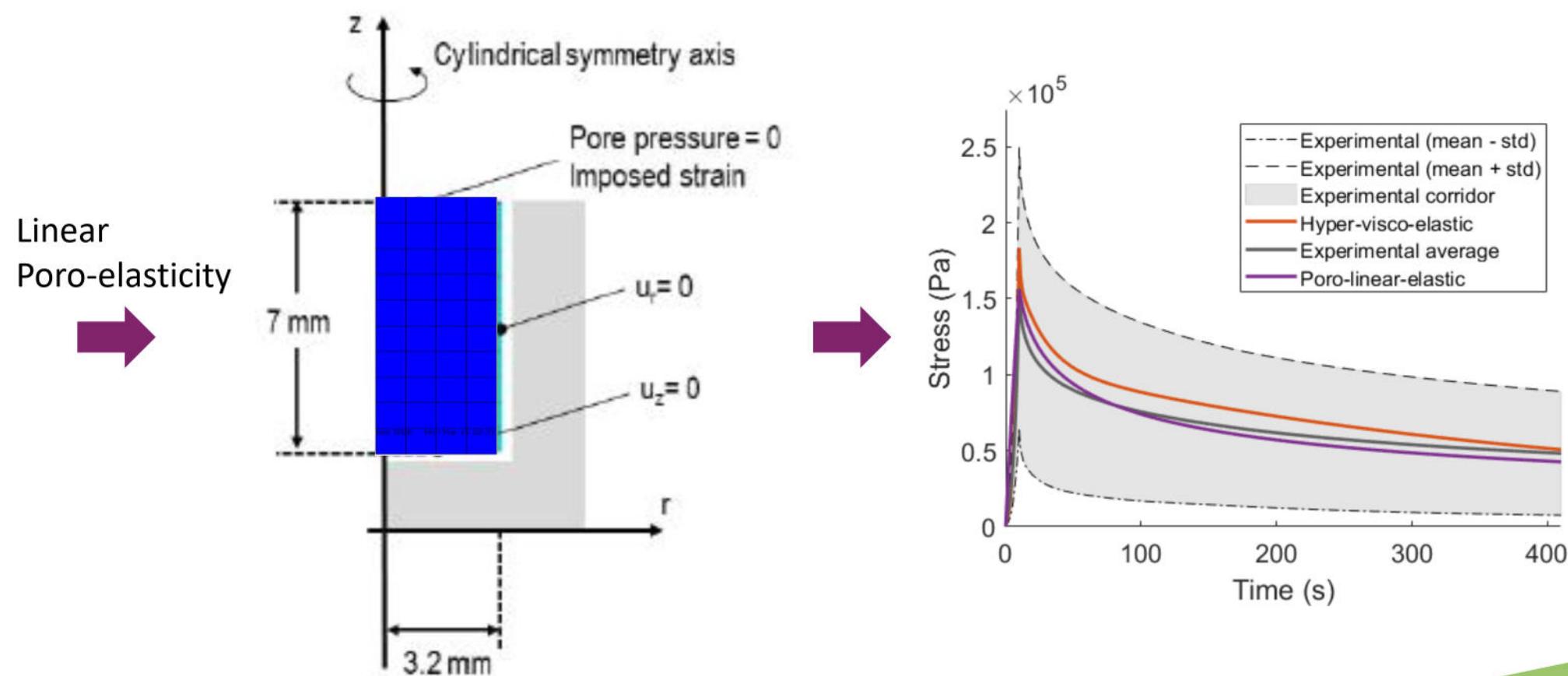
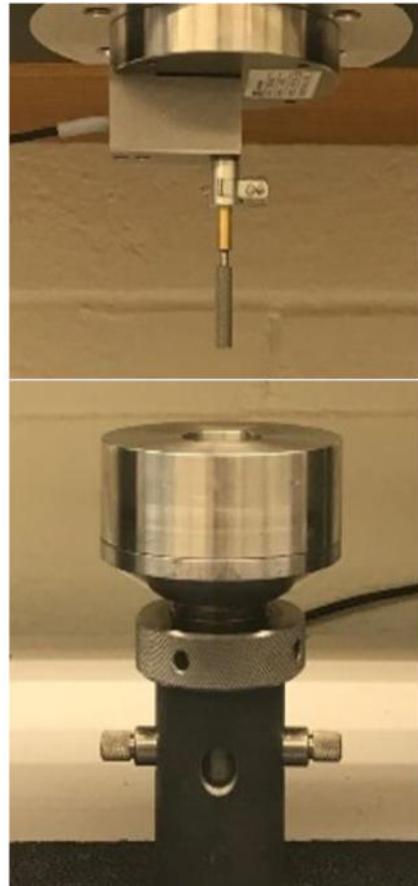
Causes de l'évolution temporelle de la réponse



Bucknell
UNIVERSITY

I2M

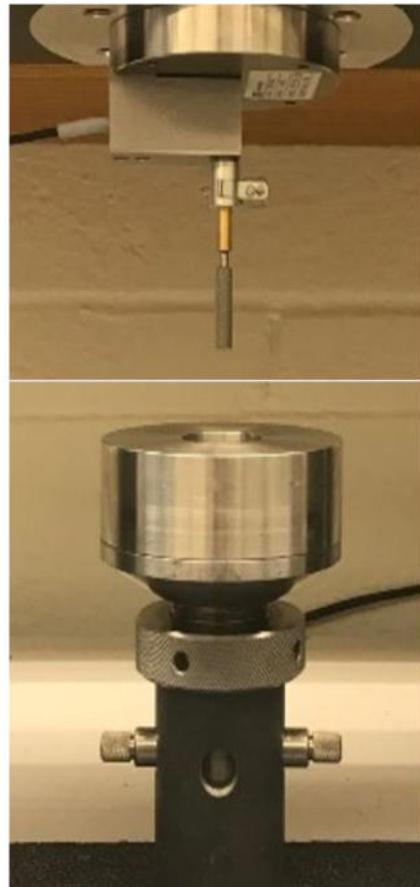
M2: Thomas LAVIGNE (2021)



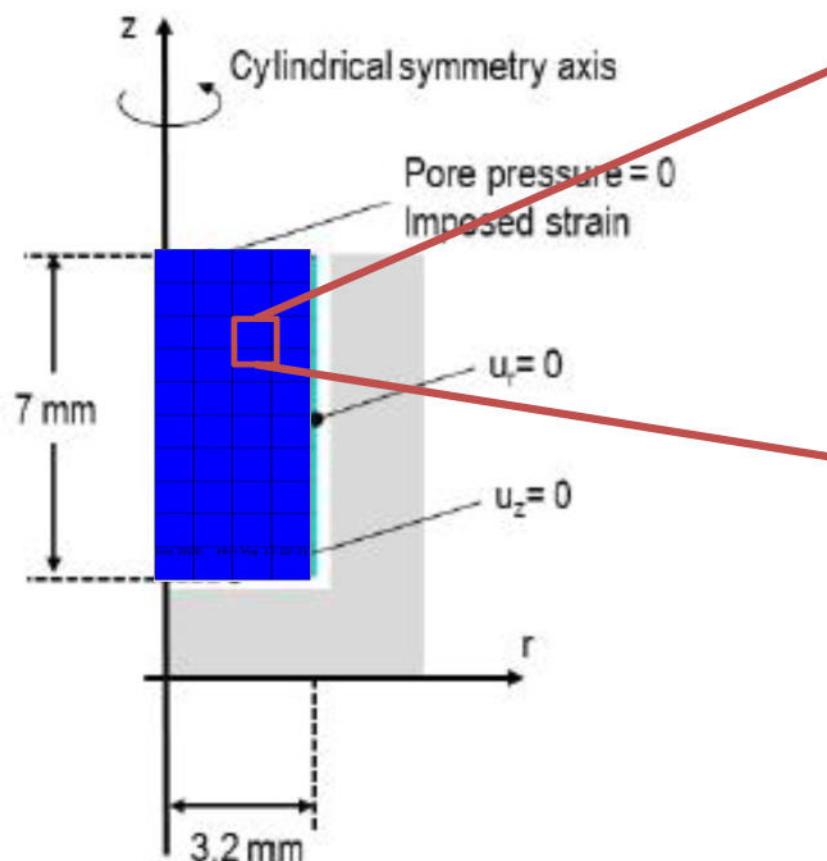


Causes de l'évolution temporelle de la réponse

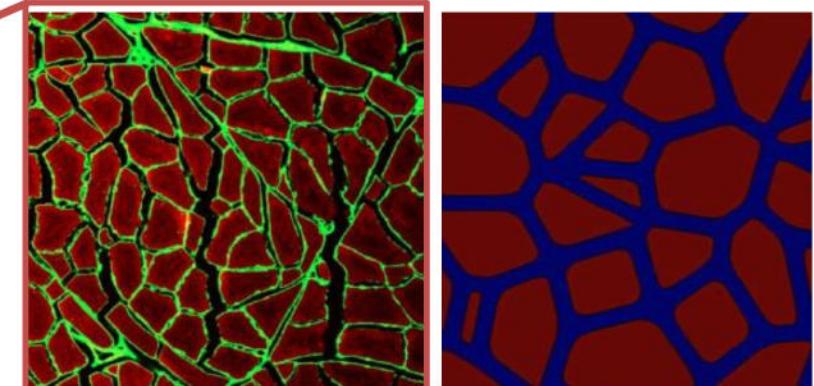
Aller plus loin? Matrice extracellulaire visco-élastique?



Linear
Poro-elasticity

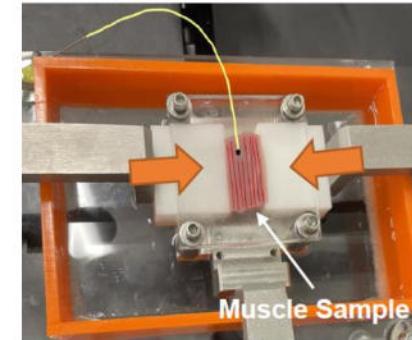


No hypothesis on geometry

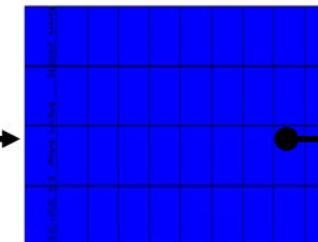




Causes de l'évolution temporelle de la réponse



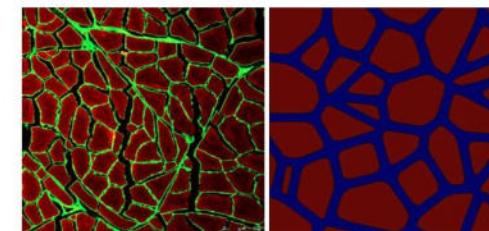
Tissue FE model



Update
 $\sigma_{macro}; S_{macro}$

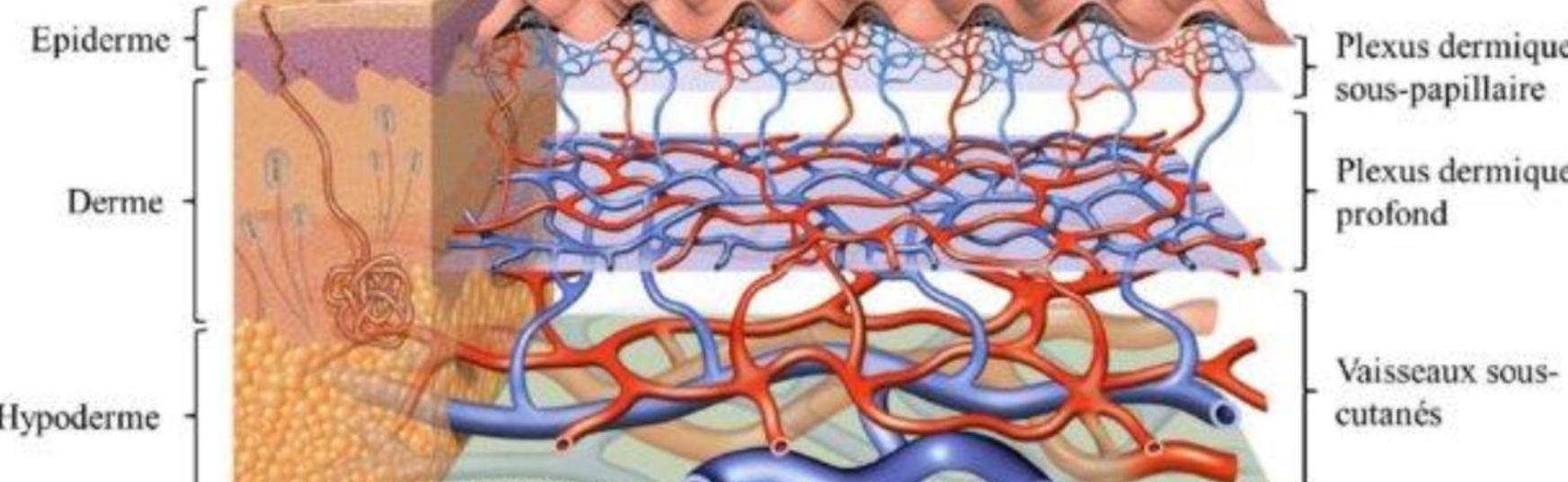
Determine B.C.
Microstructures

Microstructural FE model

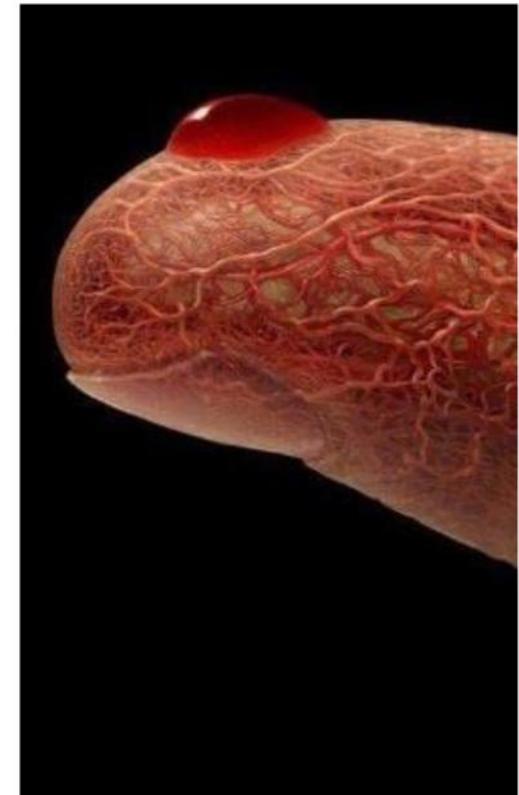




Et quid de la peau?



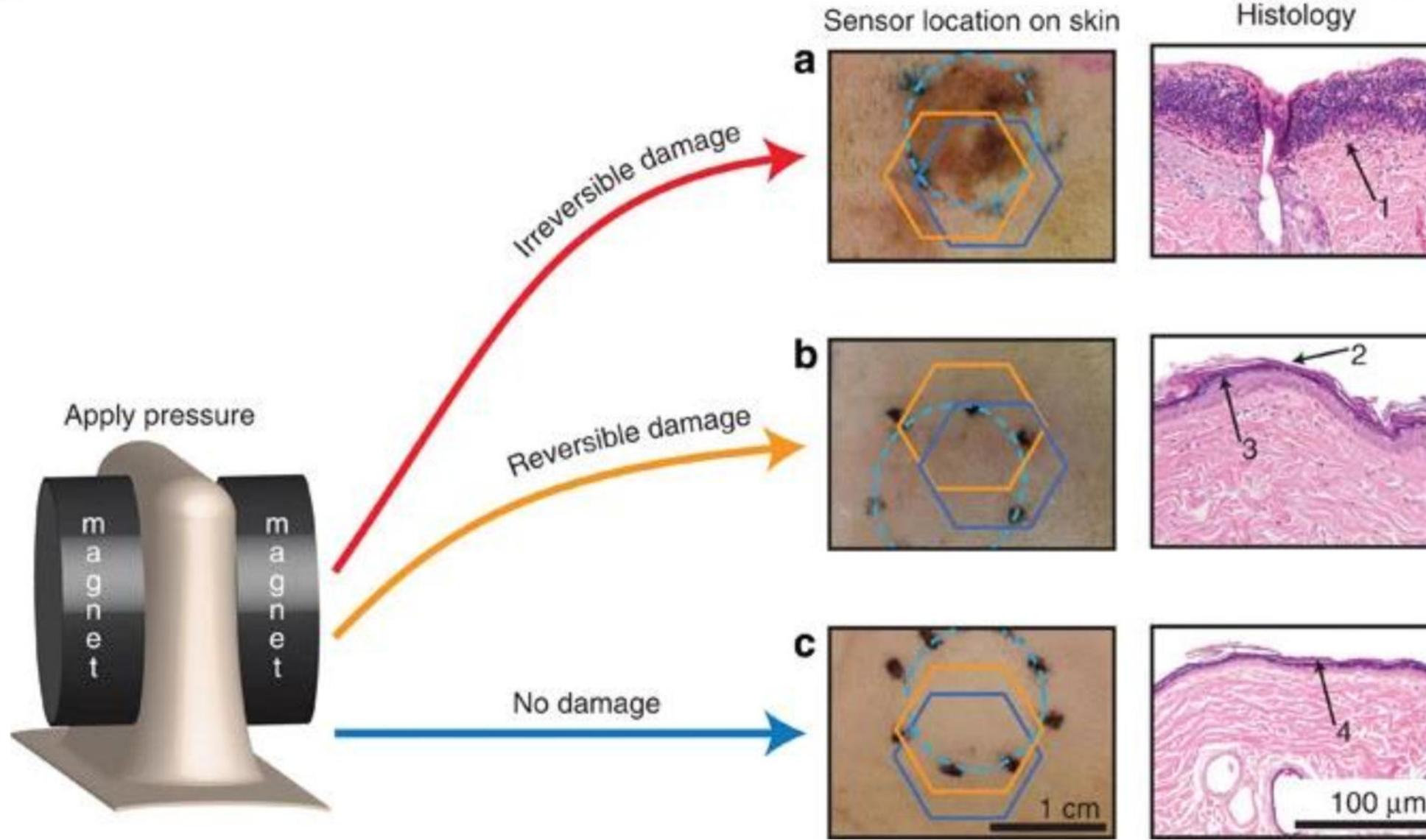
www.carecreations.bASF.com



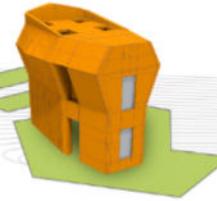
www.thevisualmd.com



Couplage mécano-biochimique



[Swisher et al. 2015]

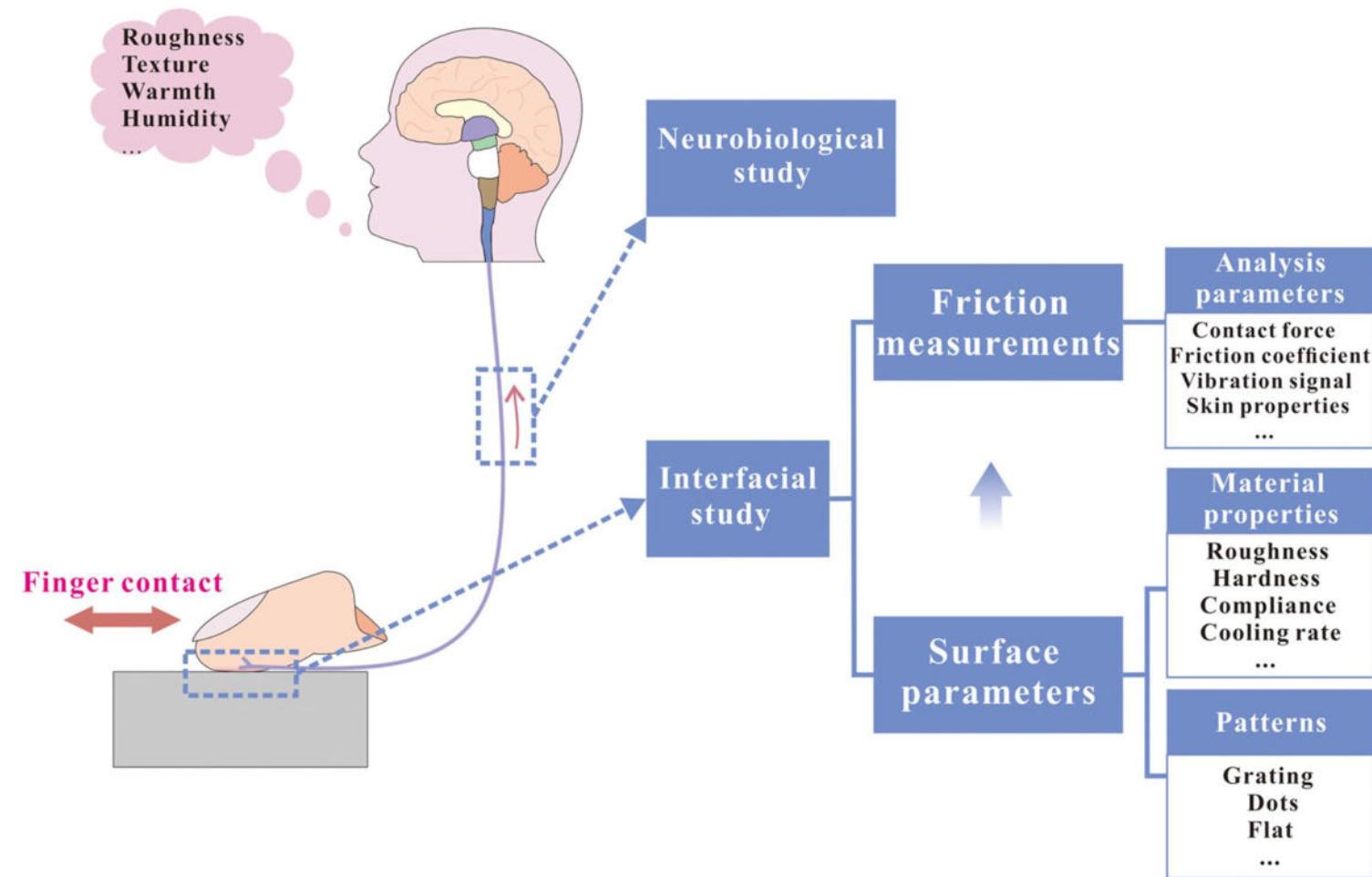
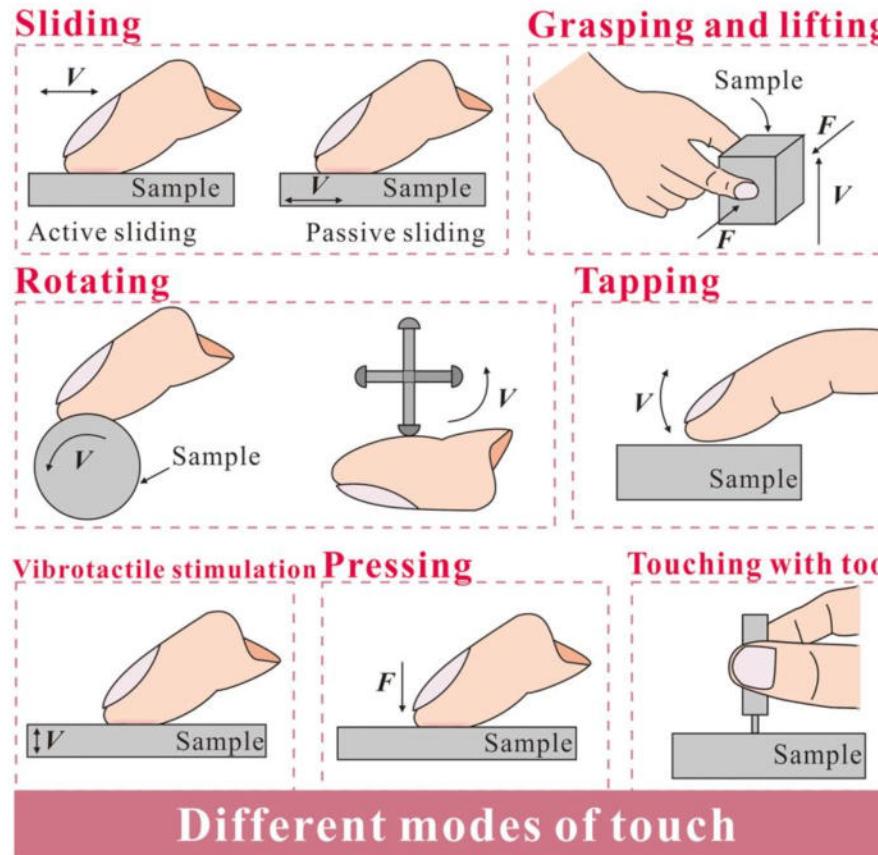


4

Interface mécanique avec la peau



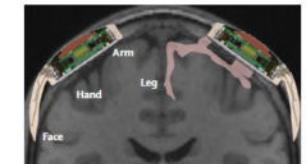
Friction des doigts et de la perception tactile



Interface mécanique DM avec la peau



B WIMAGINE wireless recorder

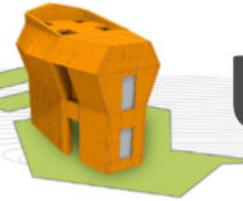


C EMY exoskeleton



<https://www.usine-digitale.fr>

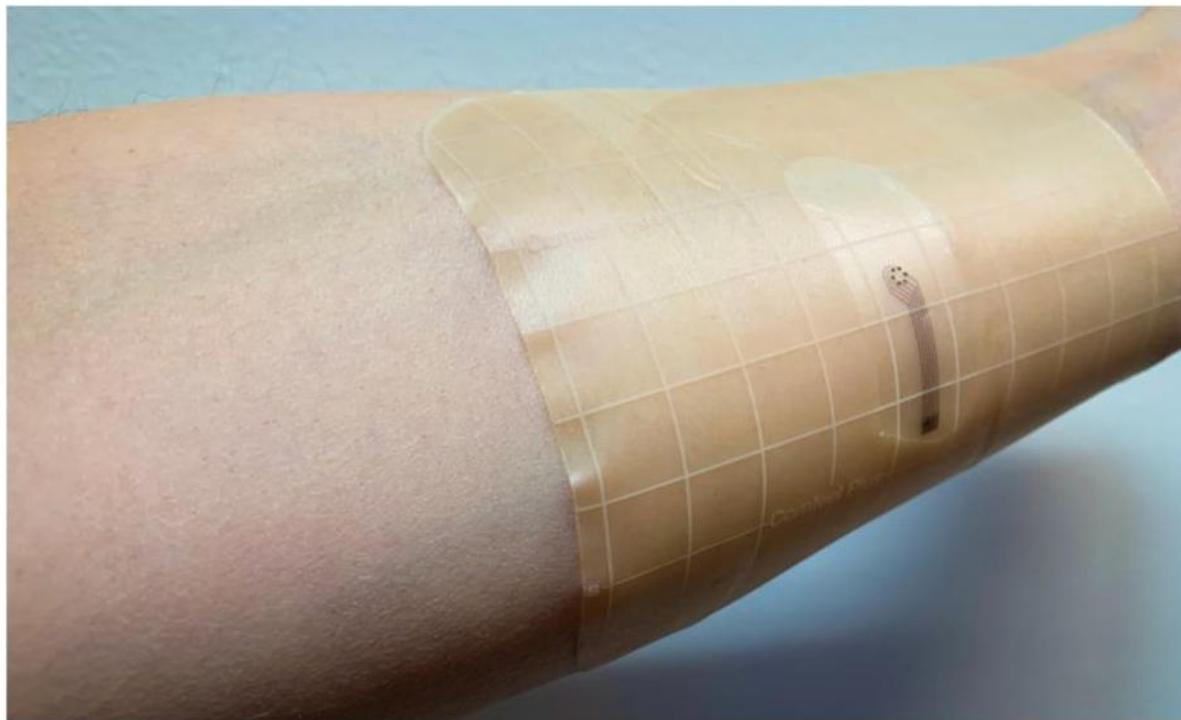




Utilisation de capteurs pour évaluer le risque

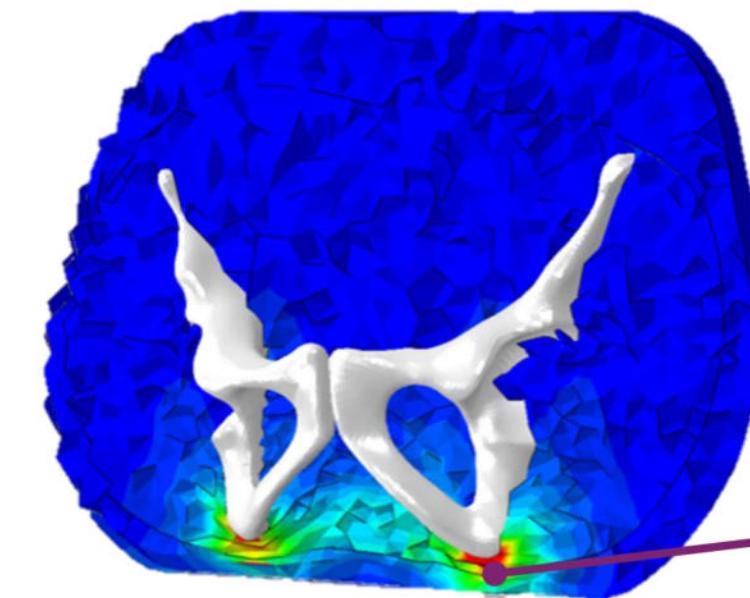
'Smart Bandages' Look to Identify Pressure Ulcers Quicker

Author: Angel Mendez, Communications Manager | NOVEMBER 19, 2019

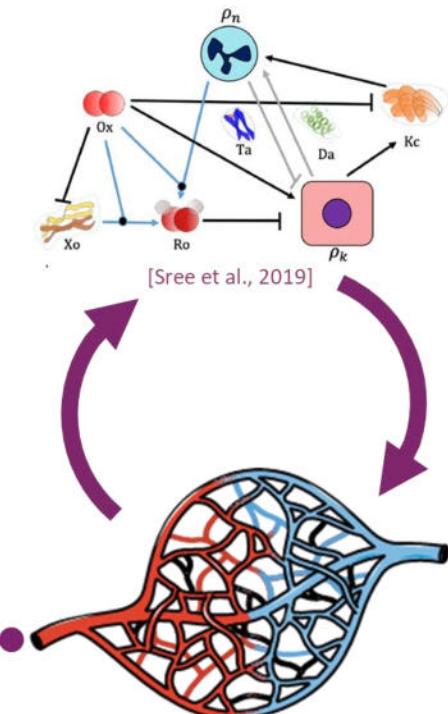


A mock-up of what a sensor array printed on a "smart bandage" may look like.

[source: <https://med.umn.edu>] (University of Minnesota Medical School website)



[Servier Medical Art]





Conclusion



Take Home Message

1. Echelle macroscopique : Visco élastique non linéaire anisotrope

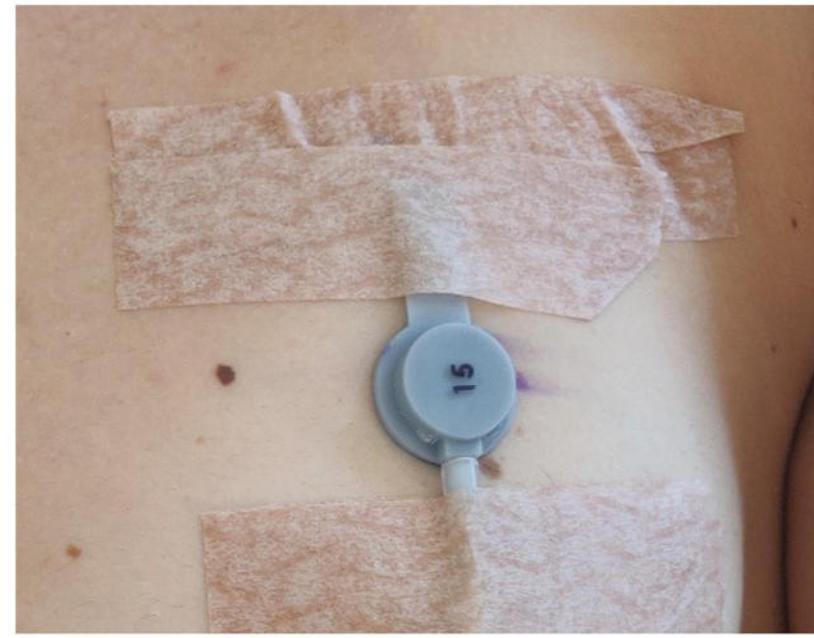


- ↑ Raideur dépendante de l'orientation du prélèvement
- ↑ Raideur dépendante du niveau de chargement
- ↑ Revient à l'état initial si déchargé
- ↑ Dépend de la vitesse de sollicitation



Take Home Message

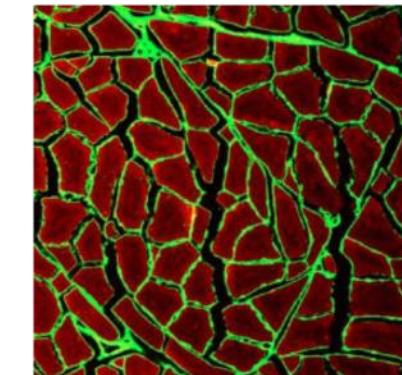
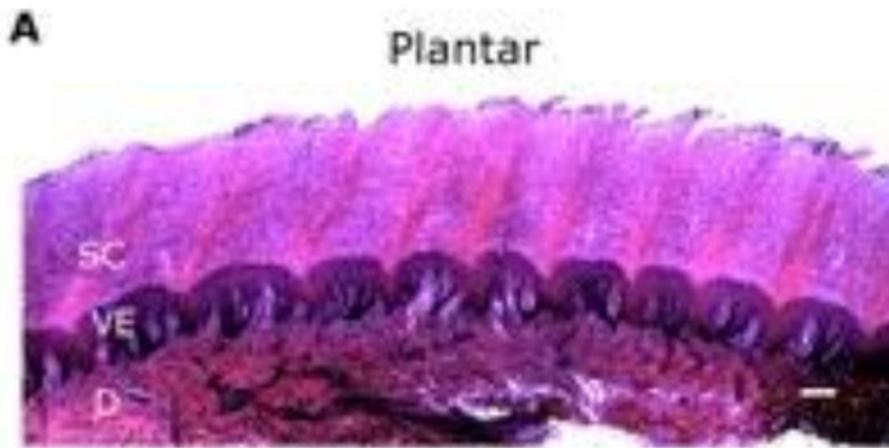
1. Echelle macroscopique : Visco élastique non linéaire anisotrope
2. Caractérisation in vivo versus ex vivo

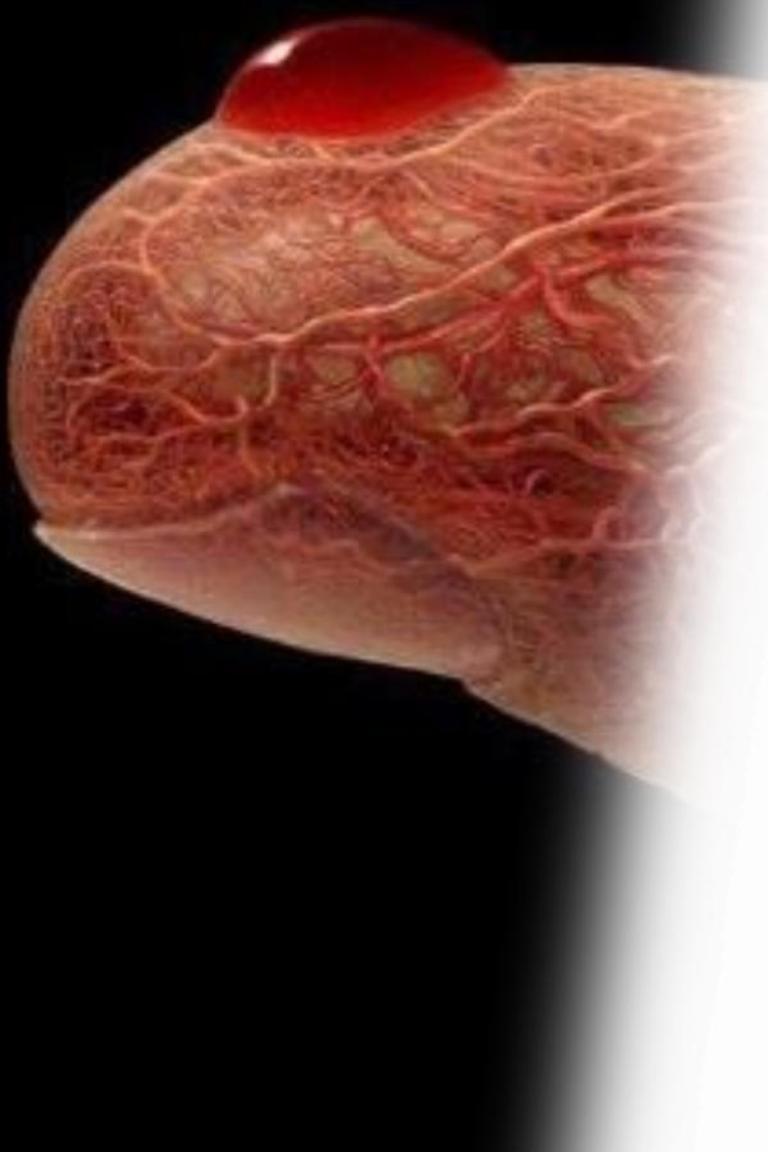




Take Home Message

1. Echelle macroscopique : Visco élastique non linéaire anisotrope
2. Caractérisation *in vivo* versus *ex vivo*
3. Quelles sont les déterminants micro de ce comportement macro ?
4. Quels sont les couplages importants?





Journée thématique du GDR TACT

« Propriétés mécaniques de la peau, du doigt »

24 novembre 2023, ISIR Sorbonne Université

Modélisation mécanique de la peau

Pierre-Yves ROHAN

