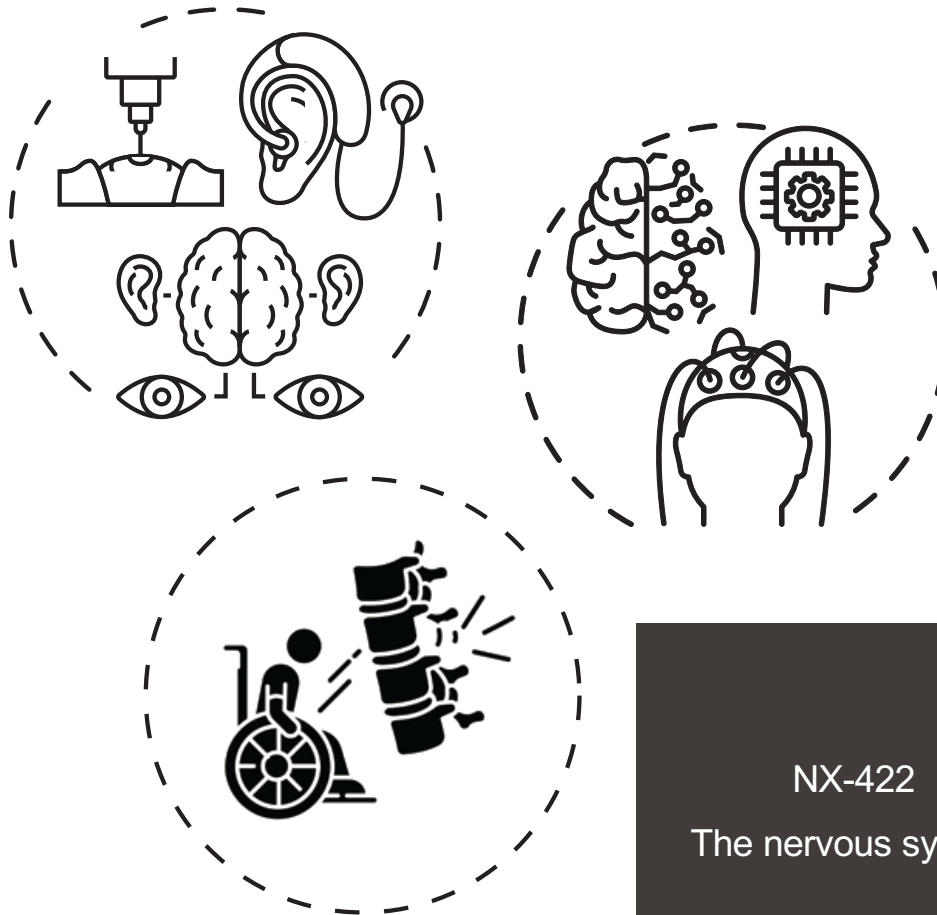




Neural Interfaces

NX-422
The nervous system

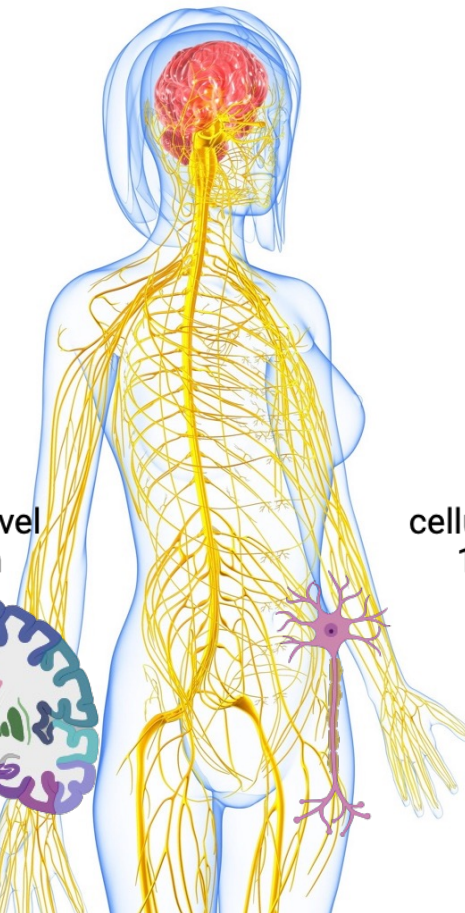
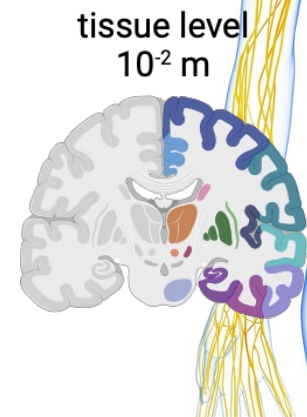
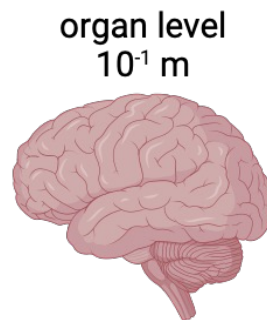
Stéphanie P. Lacour
Neuro-X Institute

- The nervous system
- Neural signals
- Neural electrodes
- Electrochemistry

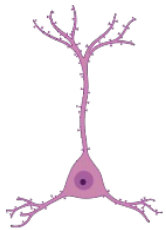
The nervous system

- Topology and mechanical properties

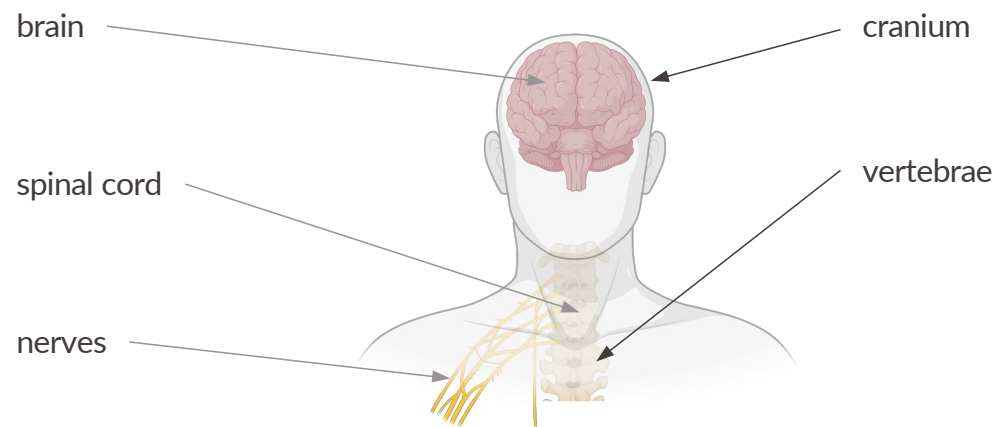
- Soft
- Dynamic
- 3D
- Multi-scale

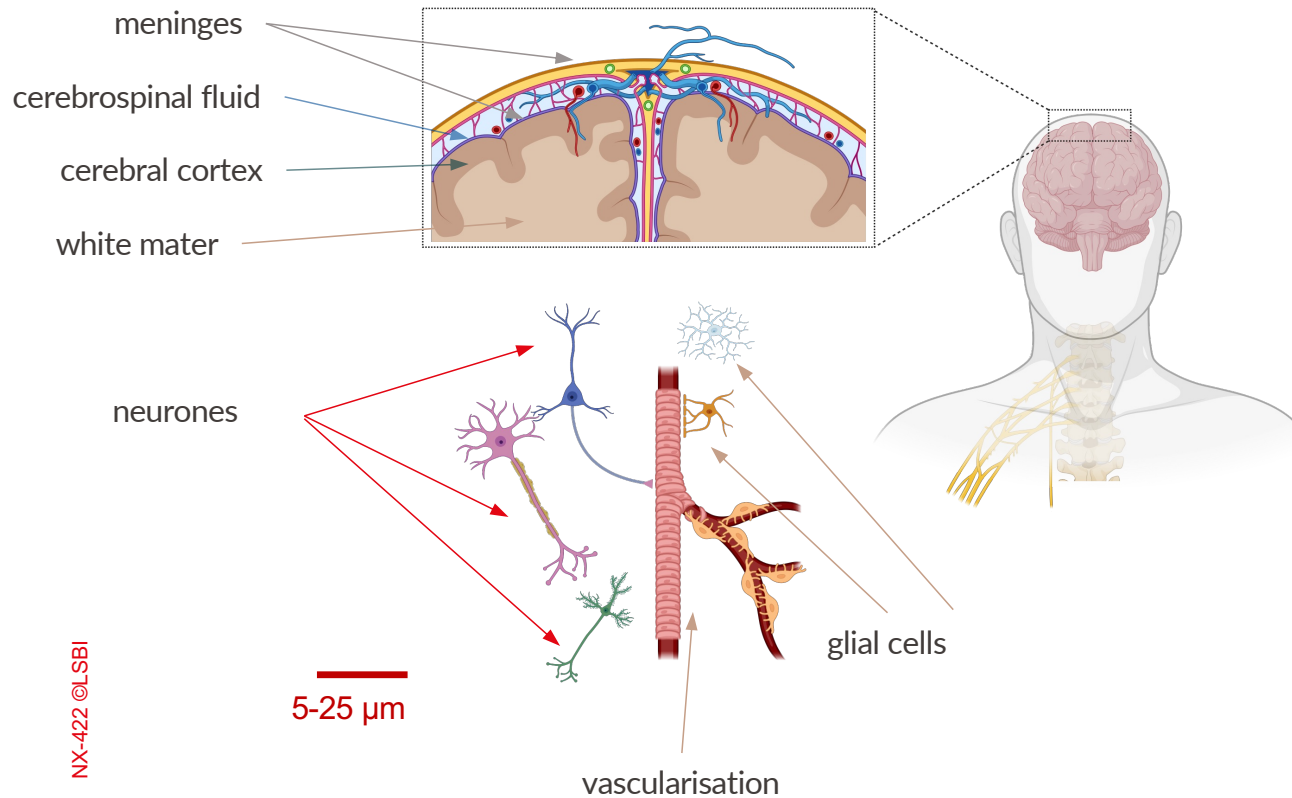


cellular level
 10^{-3} m



The nervous system





- the cranium
bone – solid & dense matrix
- the brain
soft and viscoelastic mater – **hydrated biopolymer**
- the meninges
3 protective layers in collagen:
dura mater, arachnoid, pia mater
- very **vascularized** structure
O₂ and nutrients transport
- a **moving structure**: micro-motions with every heartbeat and breath

Sizes across species

Human brain:

1.4kg (adult)
2'500cm² cortical surface

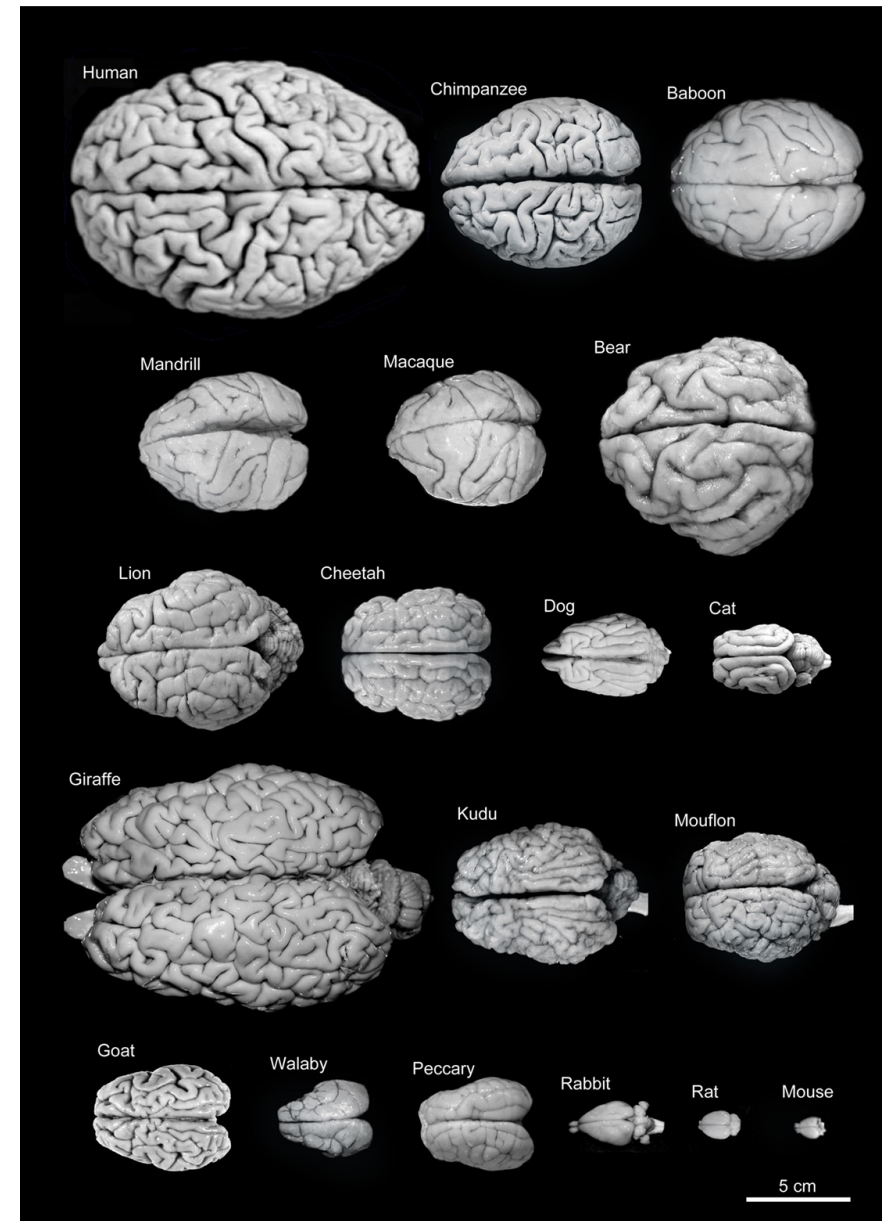
Rhesus monkey brain:

90g (adult)
110cm² cortical surface

Rat brain:

1.8g (adult)
6cm² cortical surface

http://www.frontiersin.org/files/Articles/11068/fnana-05-00029-HTML/image_m/fnana-05-00029-g007.jpg



Key concept in mechanics

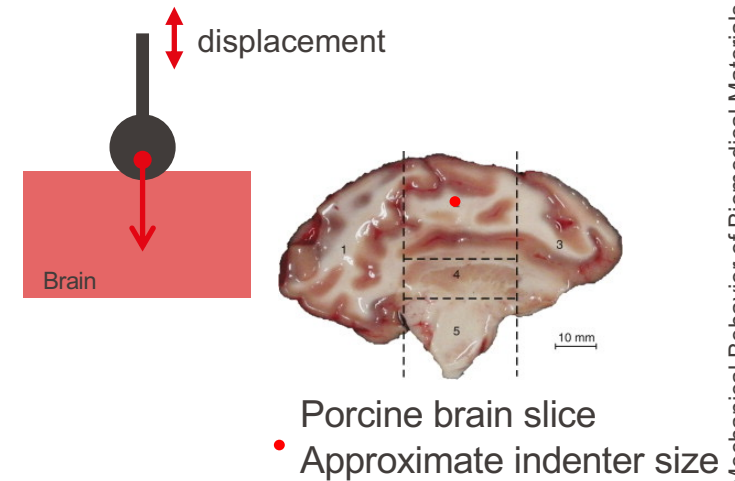
(a) tension (one-dimensional)



Measuring brain mechanical properties

Indentation

- Force-displacement curves
 - Shear modulus (using Hertzian contact theory)
 - For an incompressible material



$$G = \frac{3 F}{16 \delta \sqrt{R \delta}}$$

Shear modulus

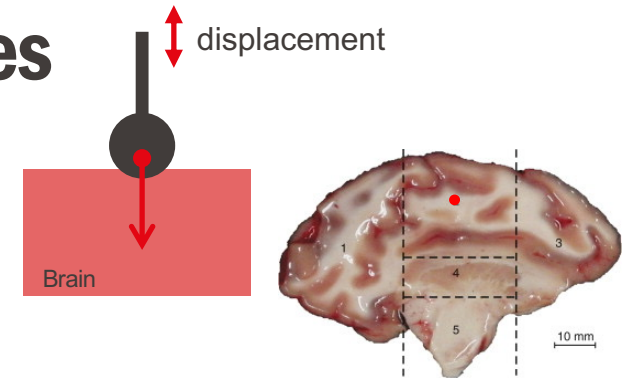
Applied force

Sphere radius

Indented depth

Measuring brain mechanical properties

Indentation



- Vary the indentation speed, depth and time
- Compute modulus G (Pa)

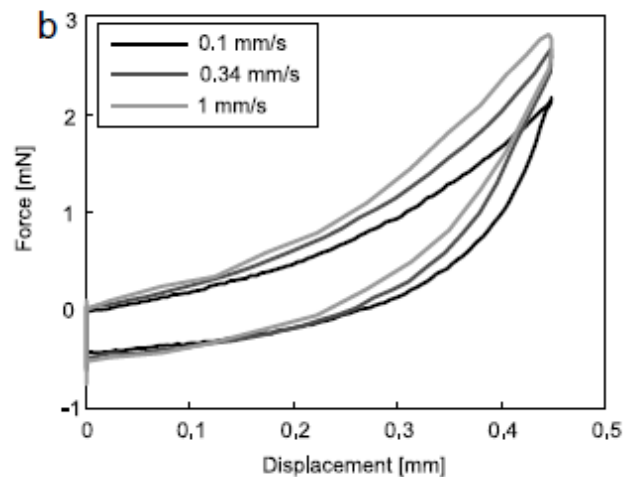


Table 3 – Average shear moduli of various regions (0.1 mm/s).

	G (Pa)	
	White	Gray
Posterior	949 ± 311	669 ± 137
Superior	1209 ± 600	816 ± 213
Anterior	925 ± 354	738 ± 3.2
Thalamus	943 ± 109	
Midbrain	955 ± 137	

Shear (G) and Elastic (E) moduli

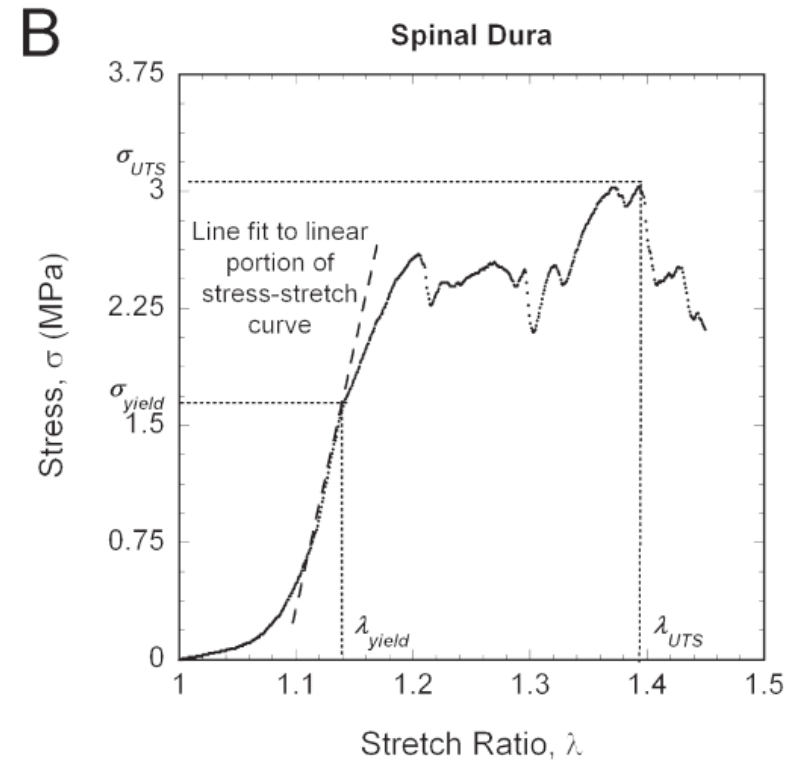
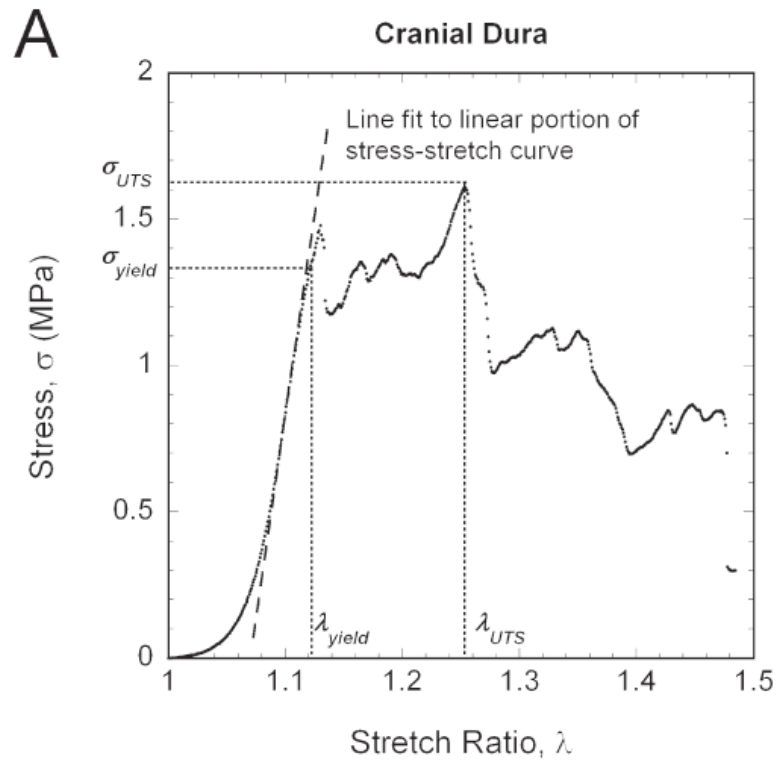
$$E = 2G(1 + \nu)$$

Elastic modulus

Shear modulus

Poisson coef.

Dura mater

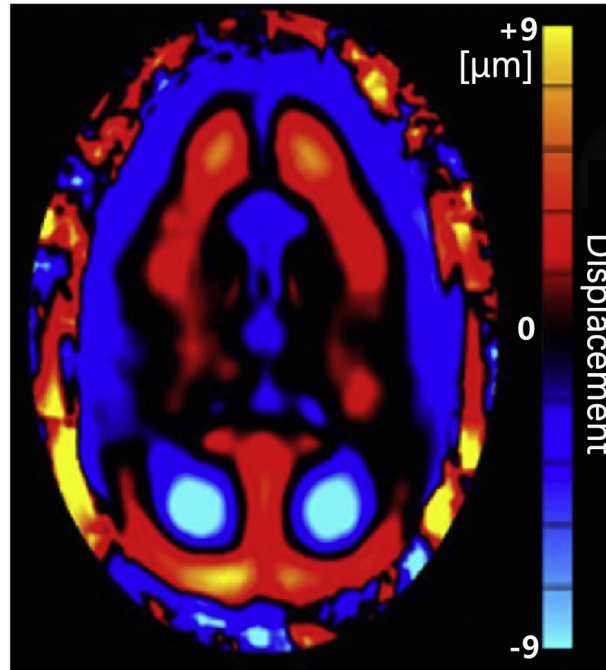


- nonlinear stress-strain behavior typical of collagenous **soft tissue**

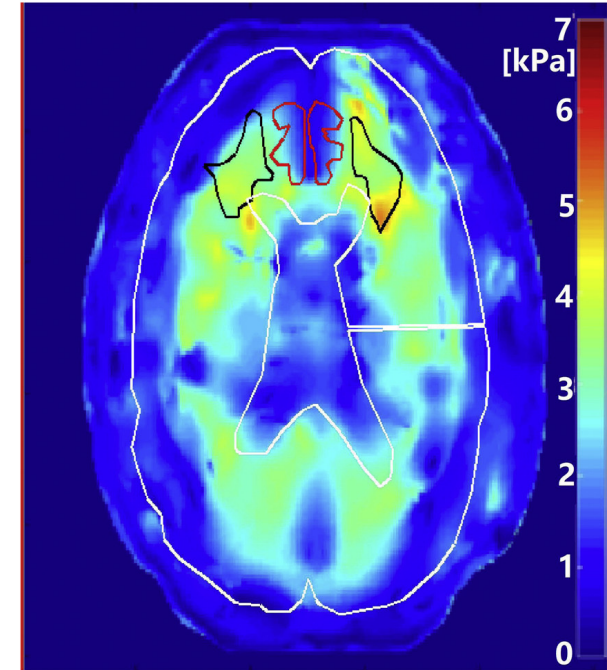
MRI anatomical references

**A**

elastogram

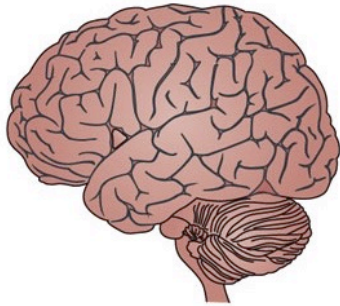
**B**

elasticity map

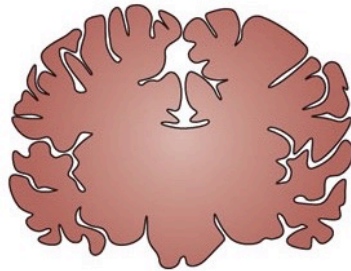
**C**

Brain folding

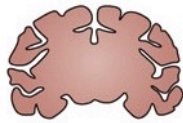
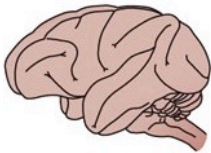
Lateral view
Human



Coronal view



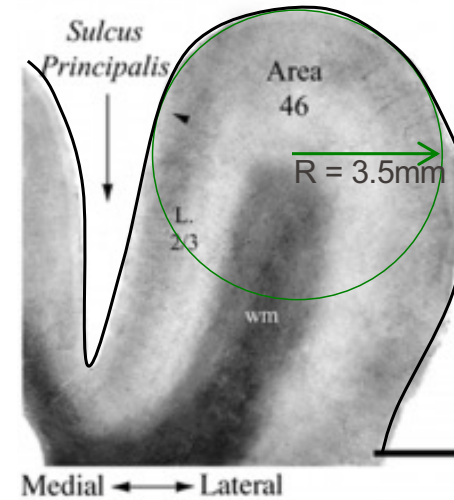
Macaque



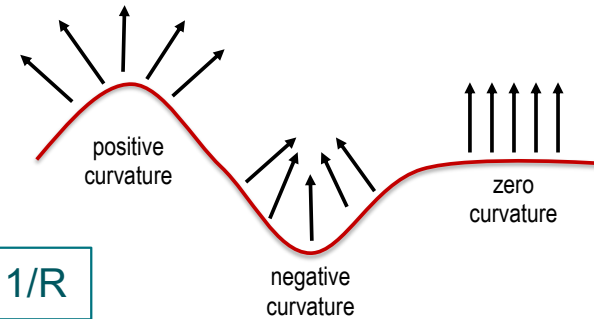
Rat



2 cm



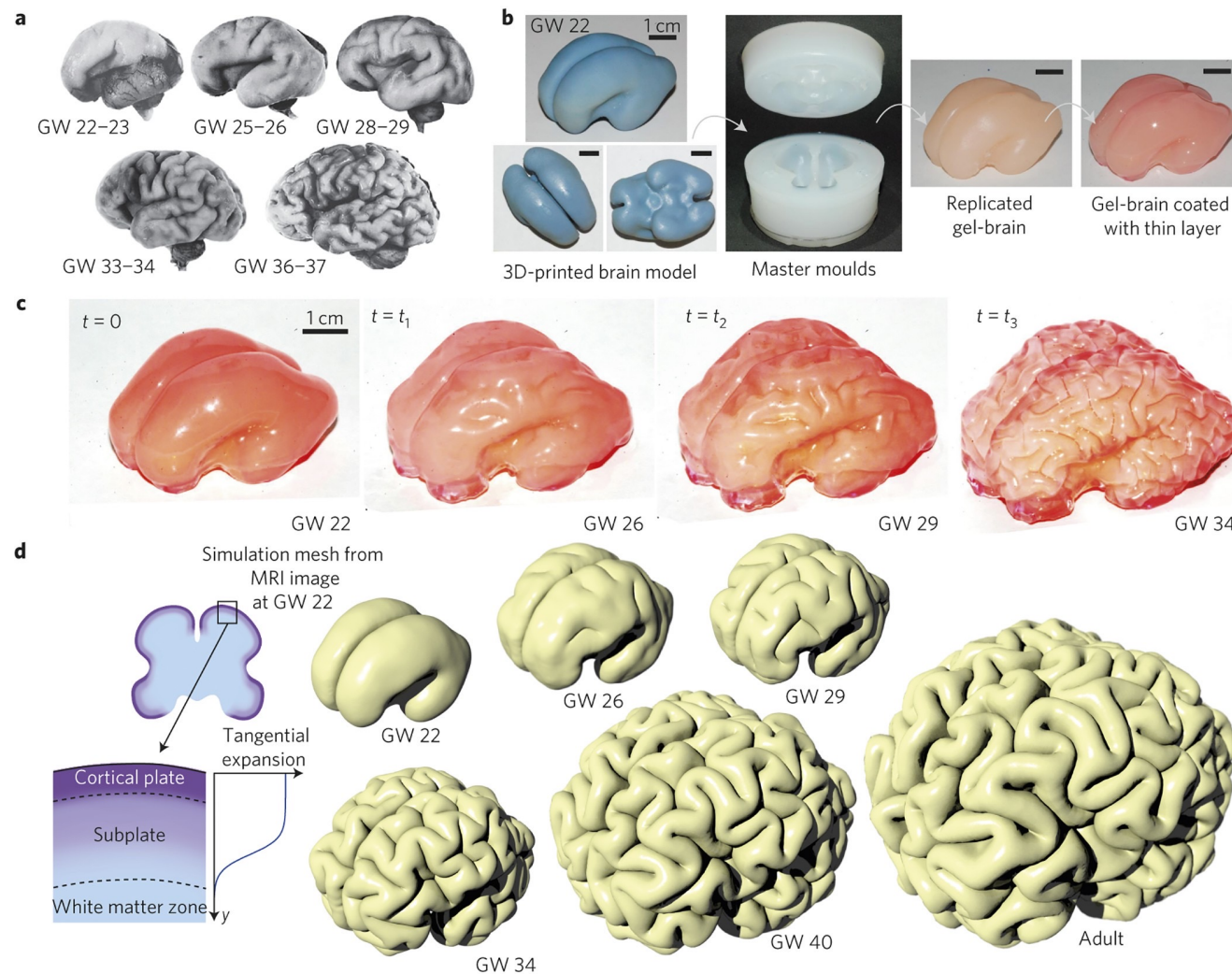
<http://www.bumc.bu.edu/anatneuro/research/cellular-neurobiology/>



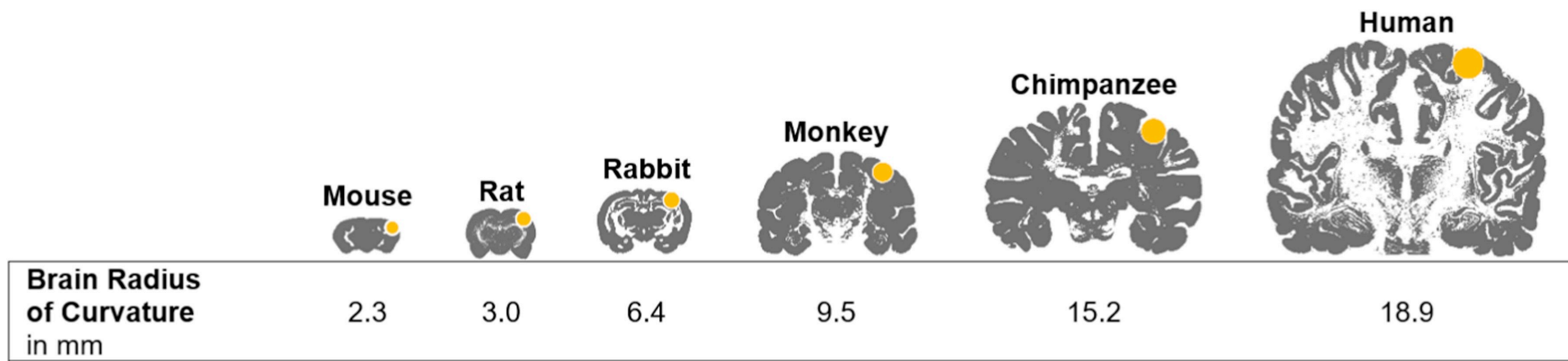
$$\kappa = 1/R$$

R: radius of curvature

Brain folding during development

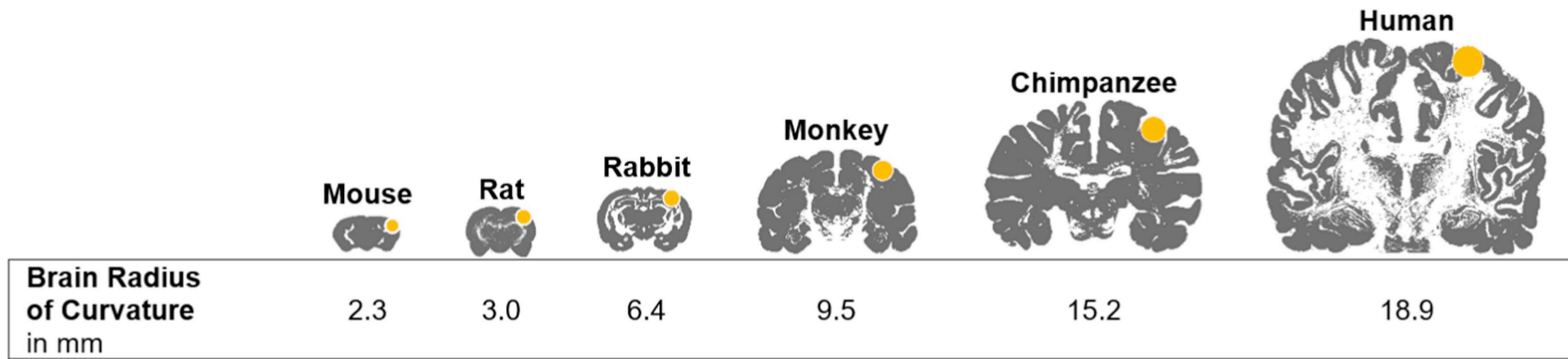


Cortex curvature across species



Which design parameters are important to ensure the implant conforms the surface of the brain?

Cortex curvature across species



Elastic modulus and thickness control the compliance of the device.

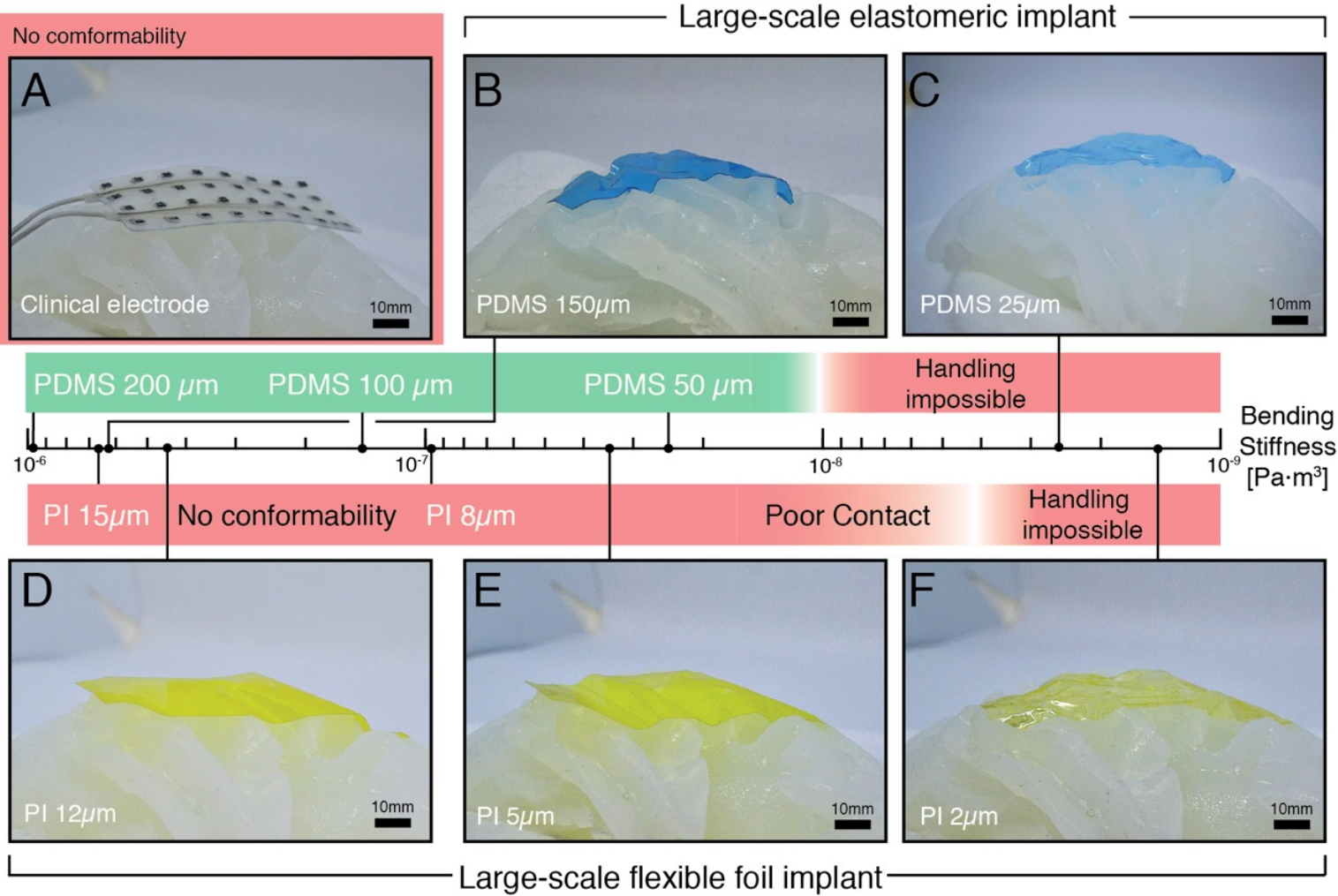
Bending stiffness

$$D = \frac{Eh^3}{12(1-\nu^2)}$$

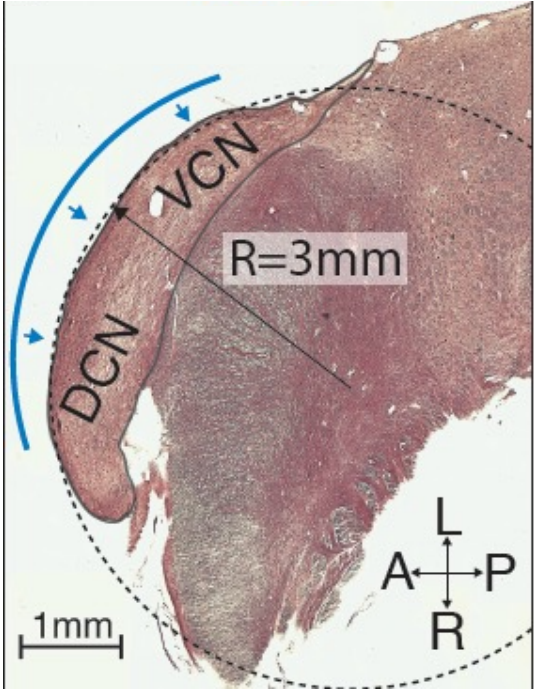
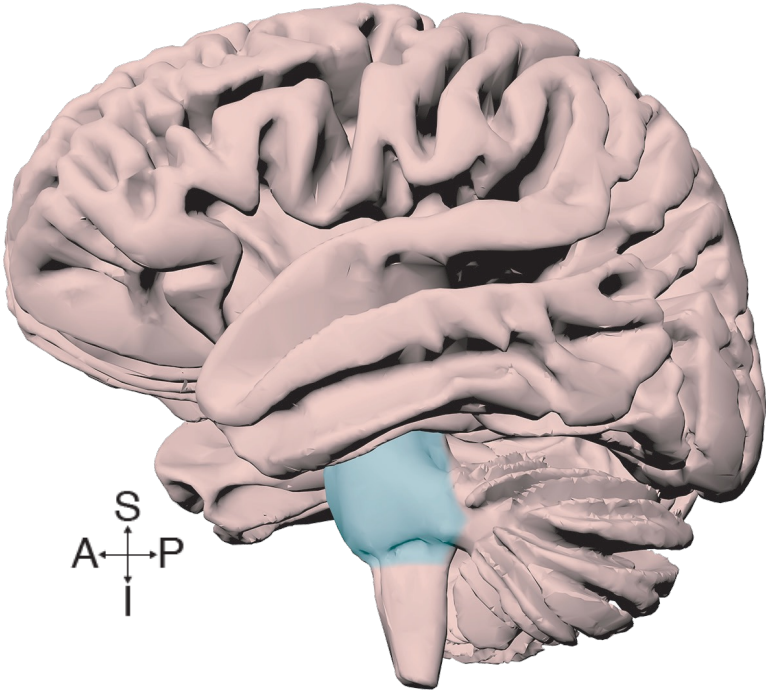
elastic modulus

thickness

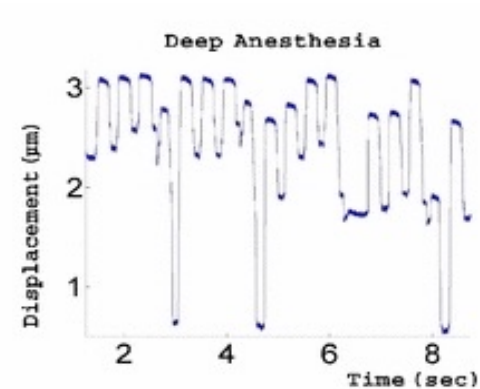
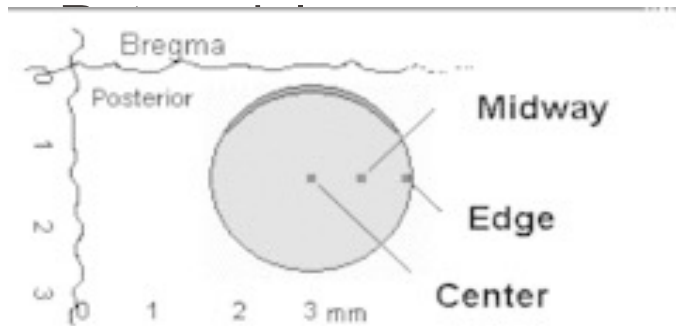
Conformability



The brainstem

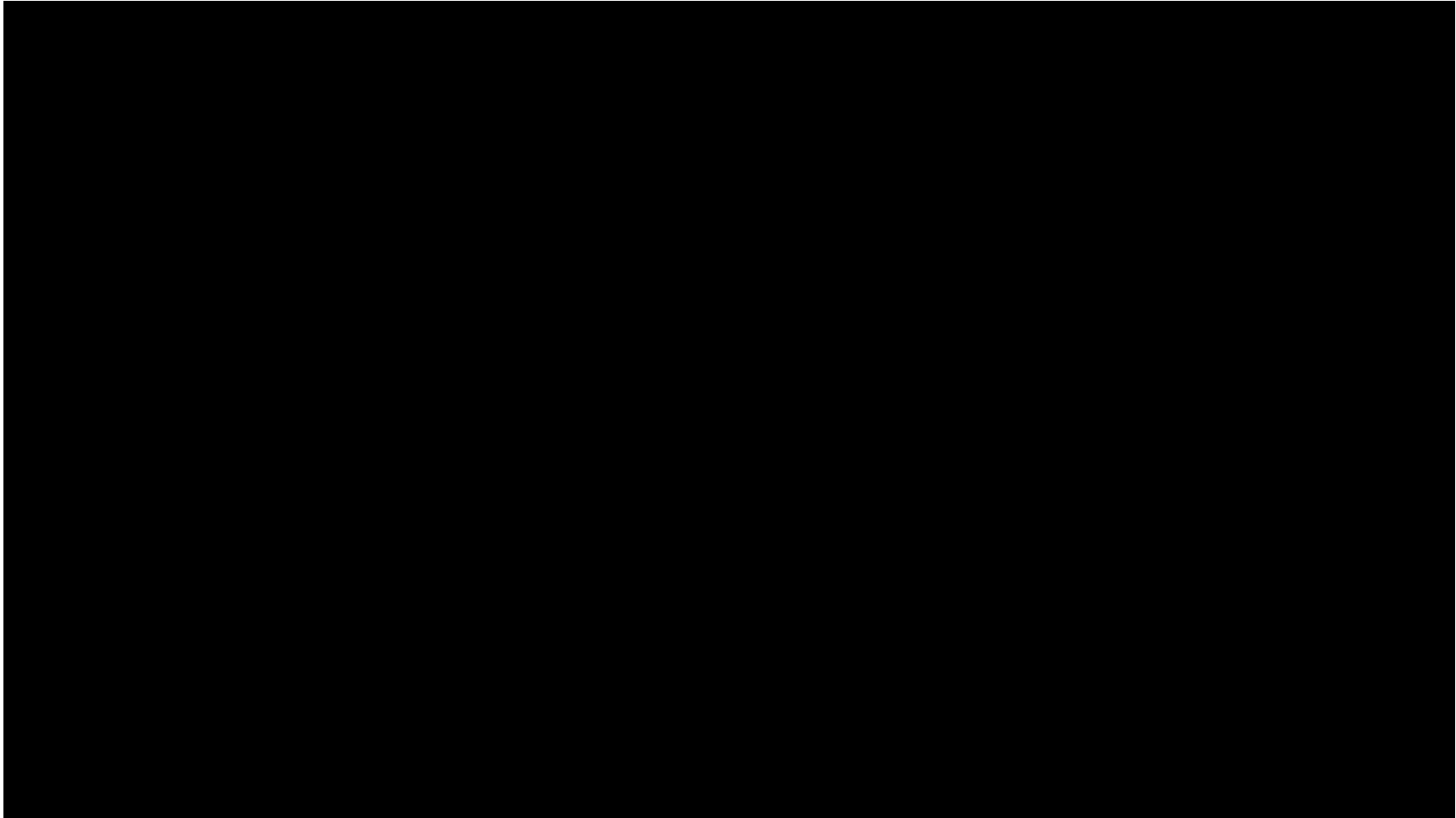


Brain micromotion



Cortical surface displacement

- Micromotion due to respiration: $\approx 30 \mu\text{m}$ in magnitude
- Micromotion due to vascular pulsatility: $\approx 3 \mu\text{m}$ in magnitude

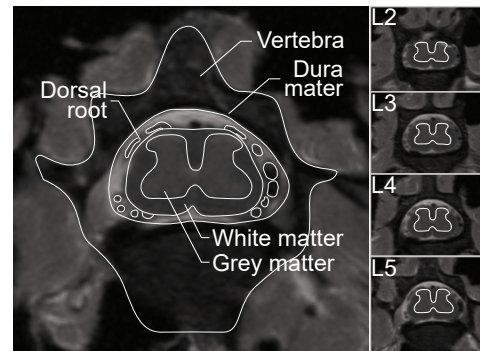


Take-home messages

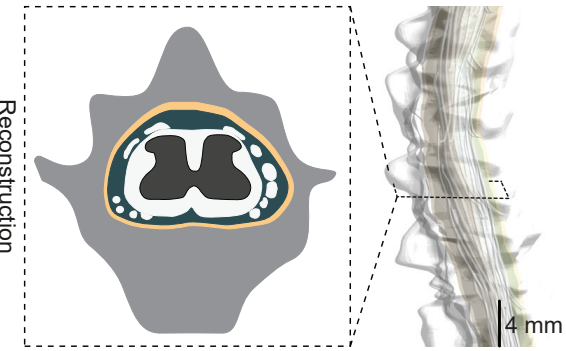
- The brain is a **viscoelastic**, soft organ ($E \sim 1 - 3$ kPa)
- The dura mater is stiffer than the brain ($E \sim 1$ MPa)
- The brain surface pulsates with blood flow and respiratory rhythm

The spinal cord

A High resolution MRI of rat spinal cord



B 3D reconstruction of rat spinal cord



Shape and dimensions vary

- across the length of the spinal cord
- across species

MRI scans

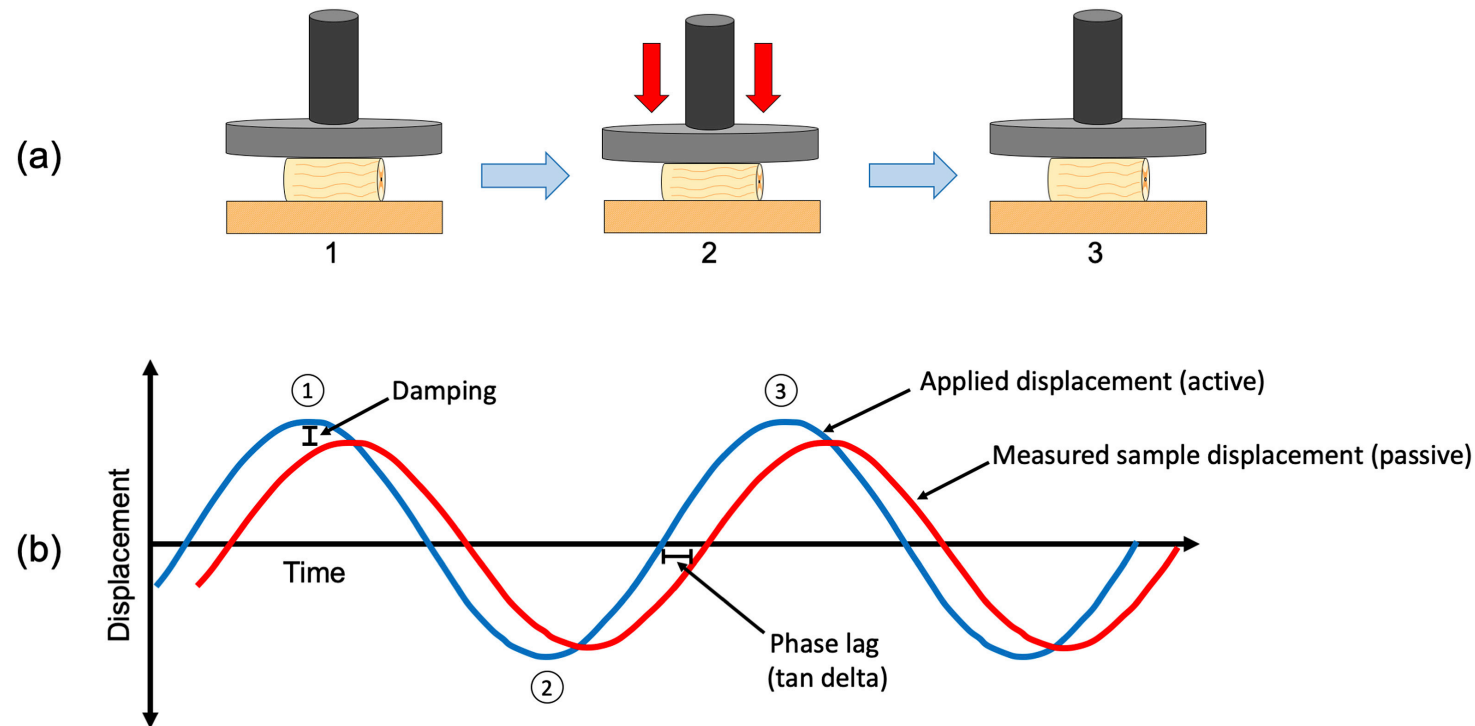
and 3D reconstructions

Courtesy of A. Rowald, G. Courtine
EPFL

■ Bone ■ Epidural fat ■ Cerebrospinal fluid □ White matter ■ Grey matter

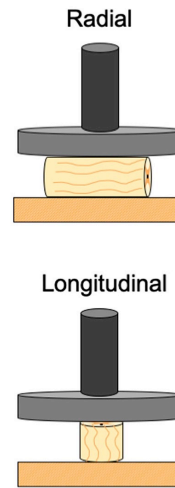
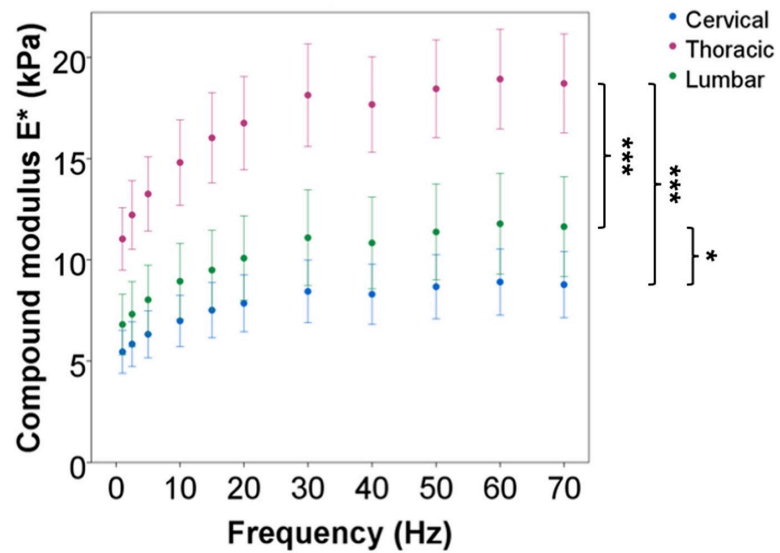
Measuring mechanical properties

Dynamic Mechanical Analysis DMA

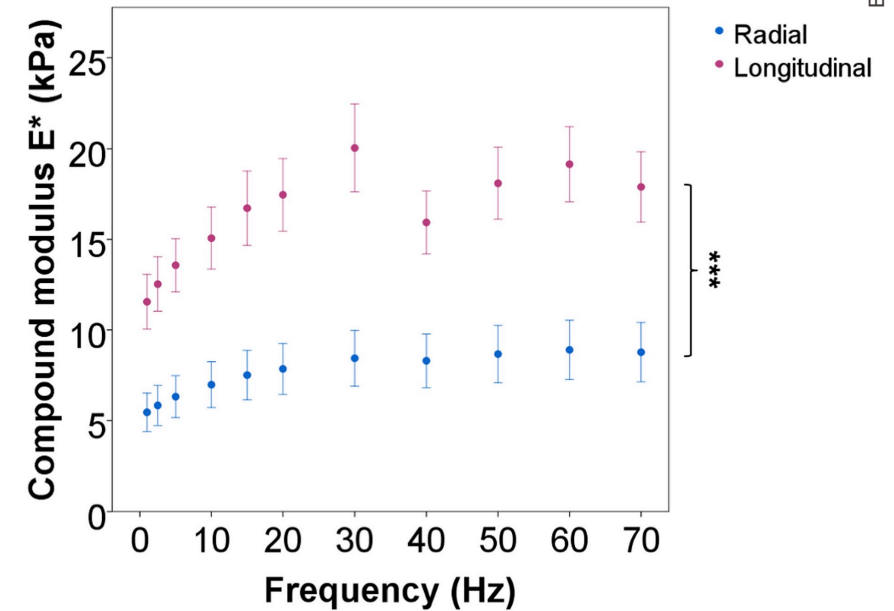


DMA on explanted spinal cord (rat model)

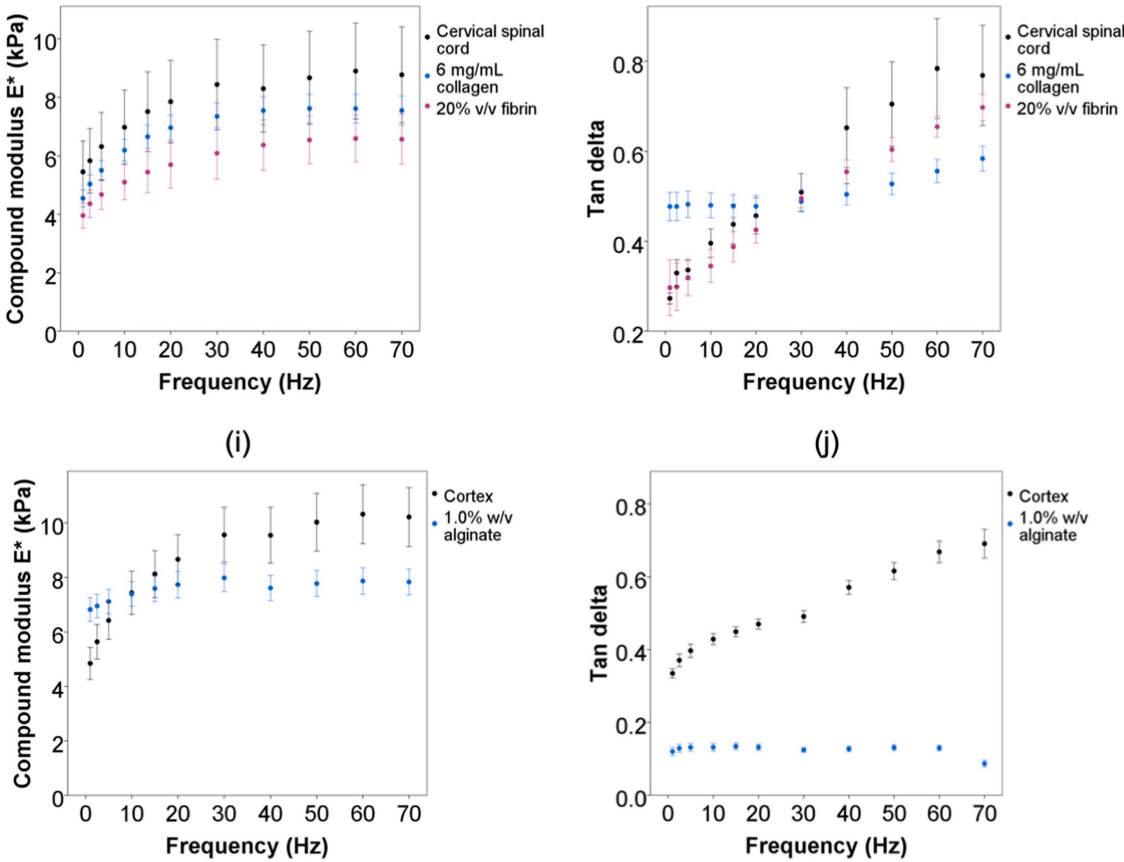
Dependency on anatomy



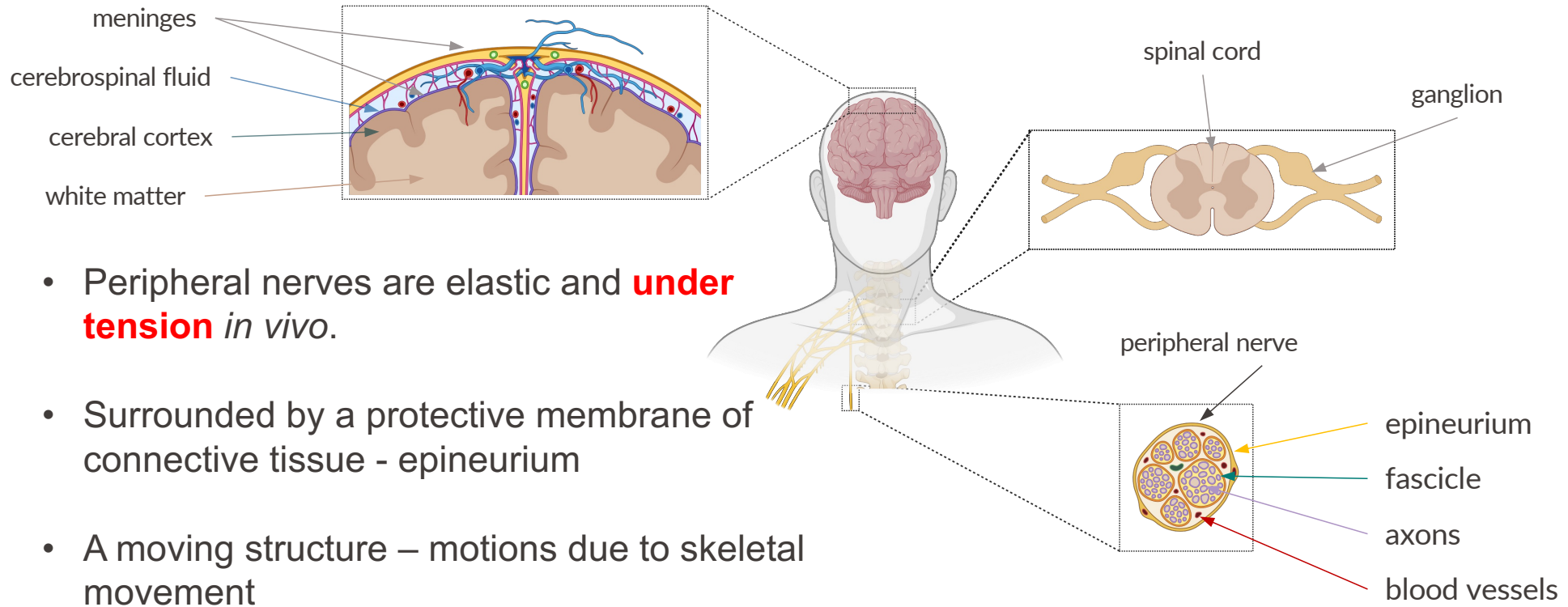
Mechanical anisotropy



DMA on explanted spinal cord, brain and hydrogels (rat model)

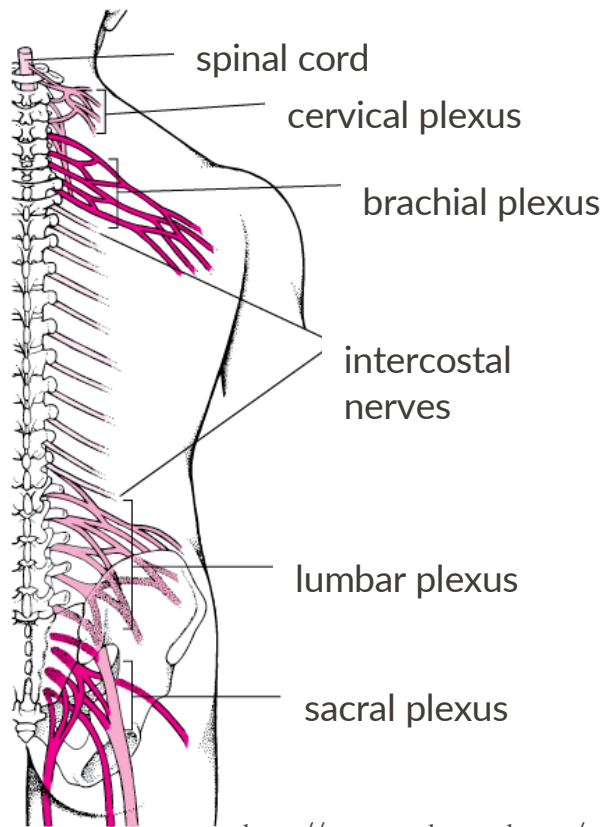


Peripheral nerves



- Peripheral nerves are elastic and **under tension** *in vivo*.
- Surrounded by a protective membrane of connective tissue - epineurium
- A moving structure – motions due to skeletal movement
- Blood vessels supplying the nerve are bundled together with nerve fascicles within the
 - epineurium.

The peripheral nervous system (PNS)



<https://www.msmanuals.com/>

Fascicles

- sensory nerves
- motor nerves
- mixed nerves

Ganglions

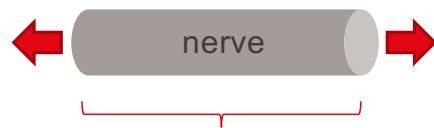
Plexus

- cervical
- brachial
- lumbar - sacral

Autonomic system

- sympathetic
- parasympathic

Mechanical properties of a nerve (tensile)



stress = Force / Surface Area
strain = elongation / initial length

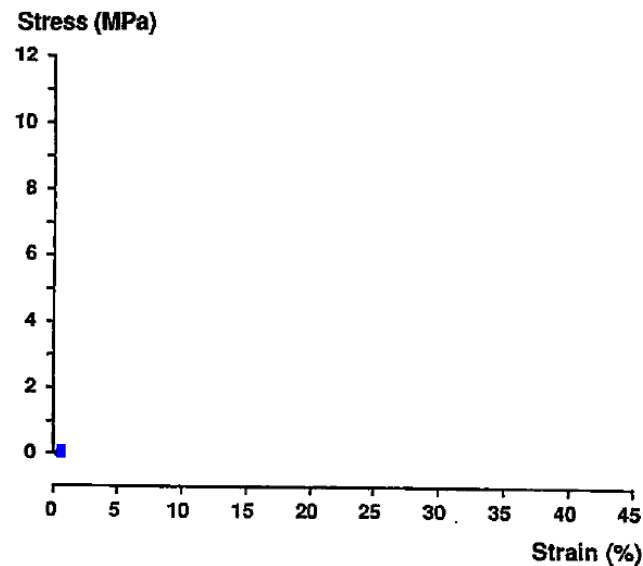
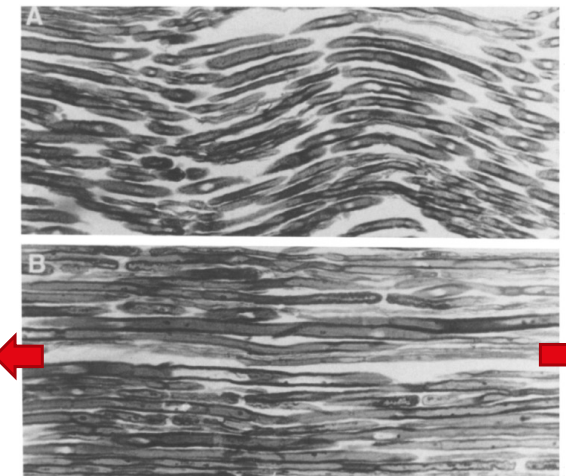


Figure 2. Stress-strain curve for rabbit tibial nerve, which is found to be nonlinear. In situ, the nerve is under large strains, but minimal stresses.

Acta Orthop Scand 1992; 63 (3): 267–272

Bands of Fontana in peripheral nerve



Longitudinal section of nerve showing long waves giving rise to the bands of Fontana.

A. Nerve held **under no tension**

B. Nerve **stretched** to the point where the bands have completely disappeared

Pourmand, R., et al. (1994). *Neuroscience* 61(2): 373-380.

Take-home messages

- The neural tissues are **soft and viscoelastic** with regional differences