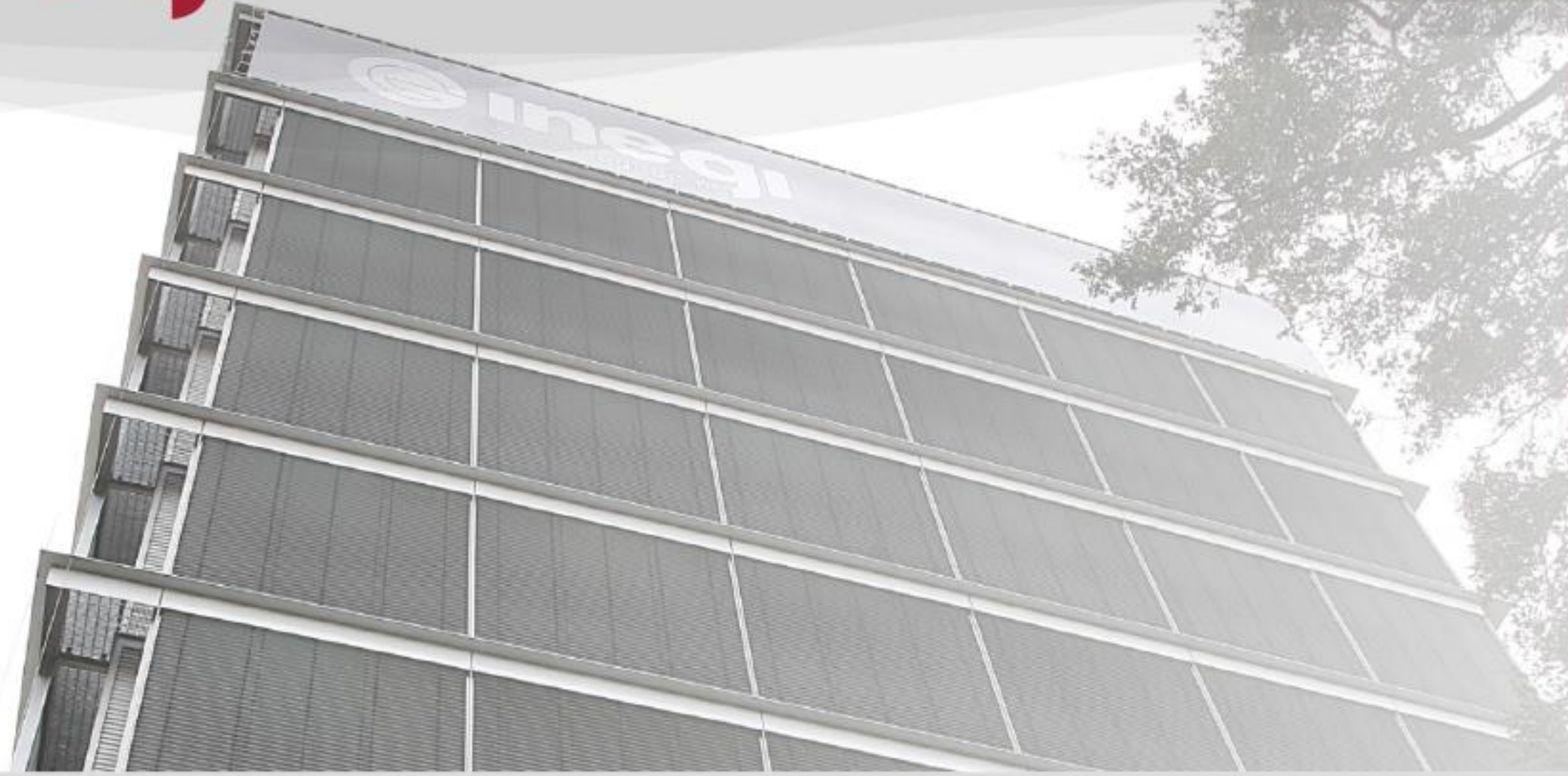
since 1986



Biomechanics: experimental and computational applications

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U.PORTO

Abstract:

Biomechanics or the 'mechanics of living things' is commonly perceived as the study of the mechanics of biological entities, specially of muscles and their movement. These notions are fairly common - even among the "scientifically educated". However, the word Biomechanics has largely transcended its etimology.

This talk will present an overview of some experimental and computational works developed on the **biomechanics LAB at INEGI (mainly experimental)** and **by the research group (mostly computational)**

The broad scope and diversity of the team's work is spread across a multitude of disciplines:

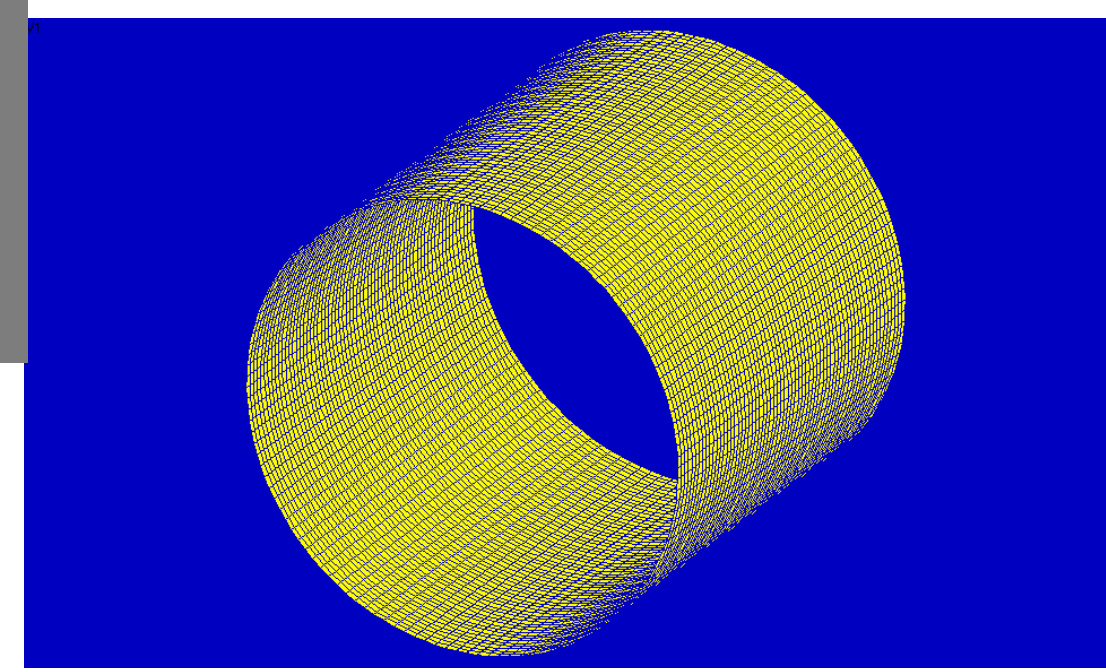
- applied mathematics (optimization, finite element simulations)
- physics (nonlinear elasticity)
- biology (everything bio)
- biomaterials (material science)
- image analysis (for everything ...)
- Robotics (with biomimetic, surgical, assistive or other purposes)

BIOMECHANICAL STUDIES

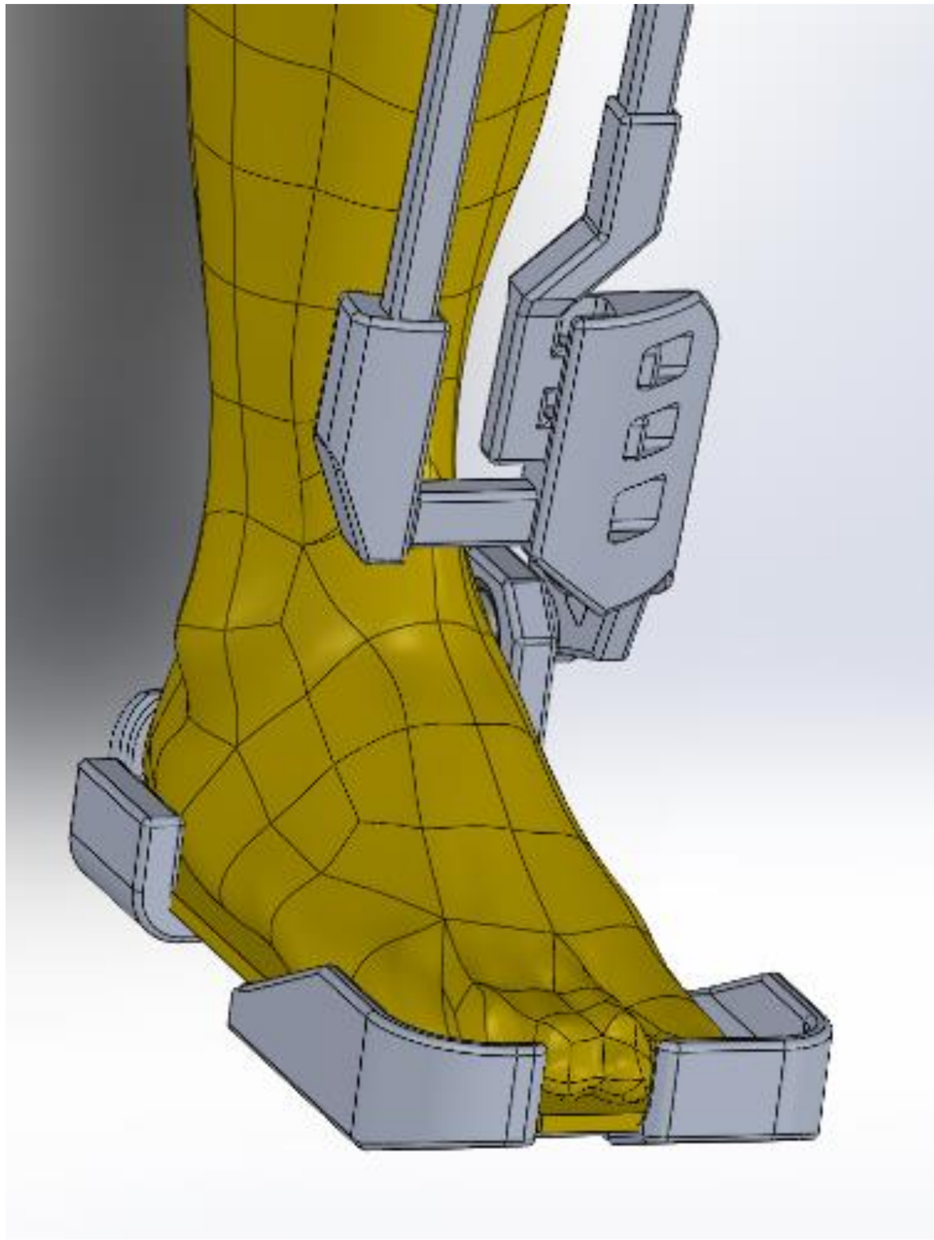
- Scale

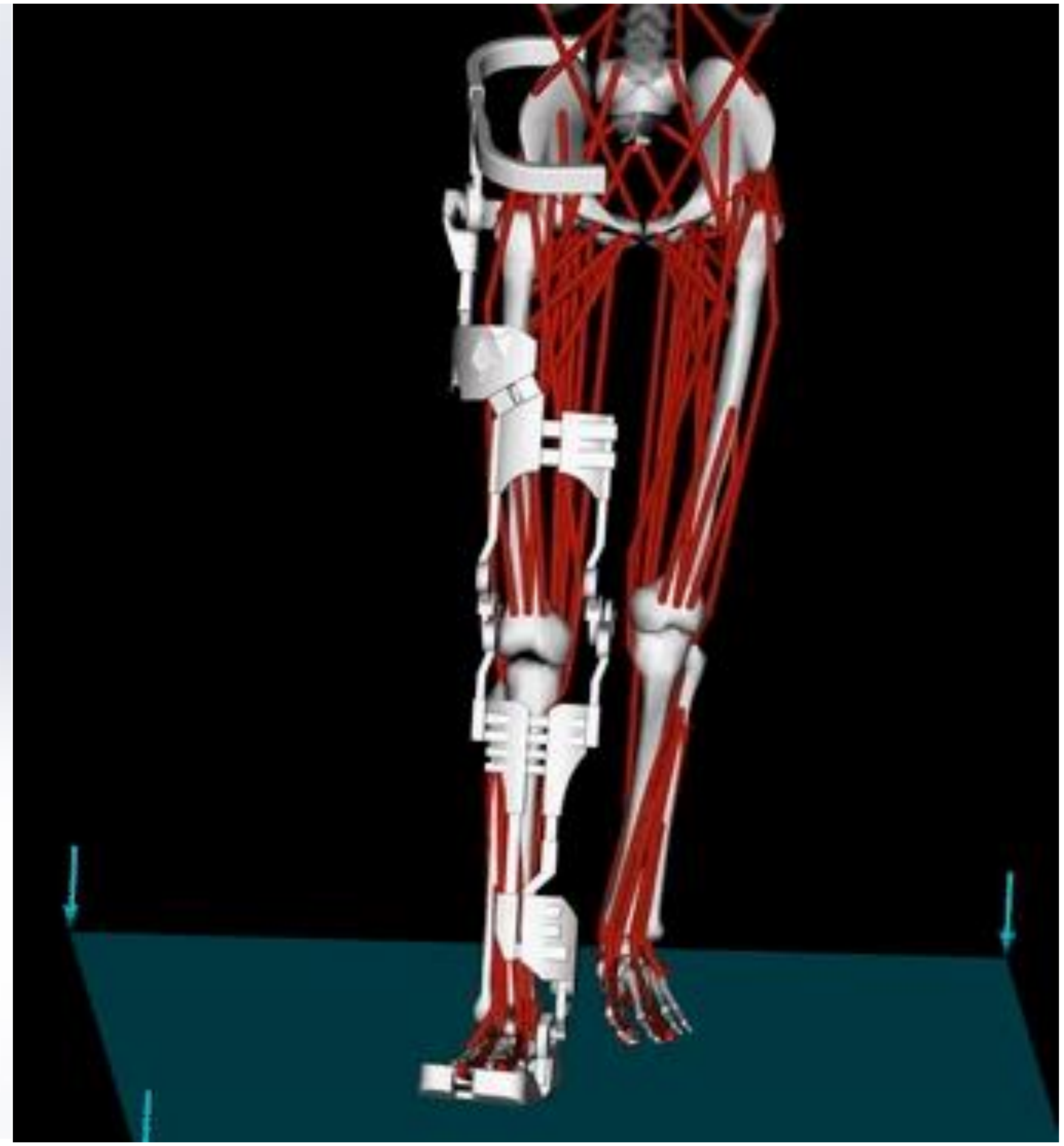
- Detail

- Biomechanics = Movement?



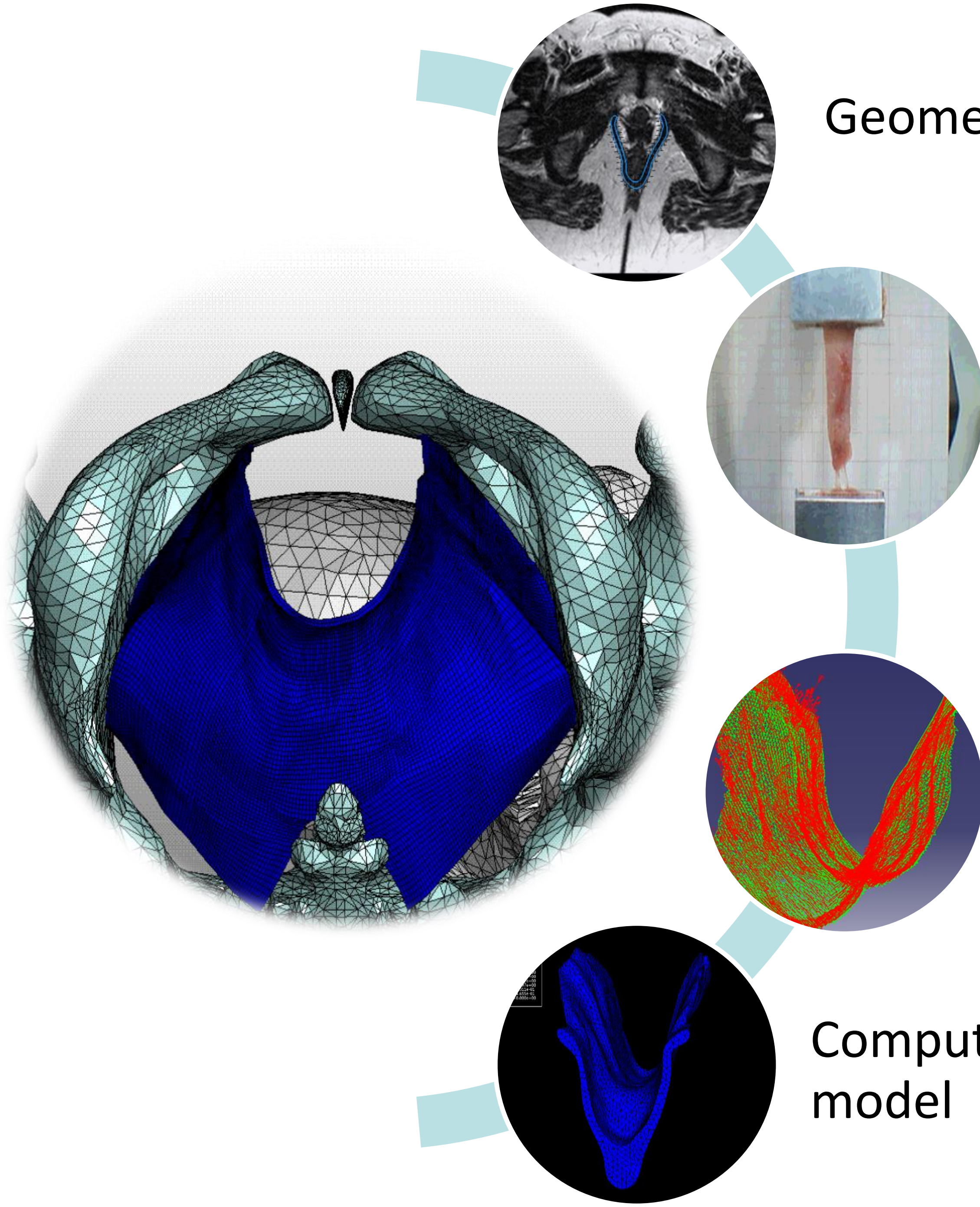
Development of an exoskeleton





(D Pina et al., Advances Mechanical Engg, 2018)

What do we need to do a biomechanical study?



Geometry

Mechanical properties

Boundary conditions and loads

Computational model

Biomechanics of female pelvic cavity: motivation

During exercise, the increase in intra-abdominal pressure (IAP) may result in stress urinary incontinence (SUI) if the pressure inside the abdomino-pelvic cavity is higher than the urethral closure pressure.

(B.T. Haylen et al., Neurourol Urodyn, 2010)

Consequences of a pelvic floor dysfunction

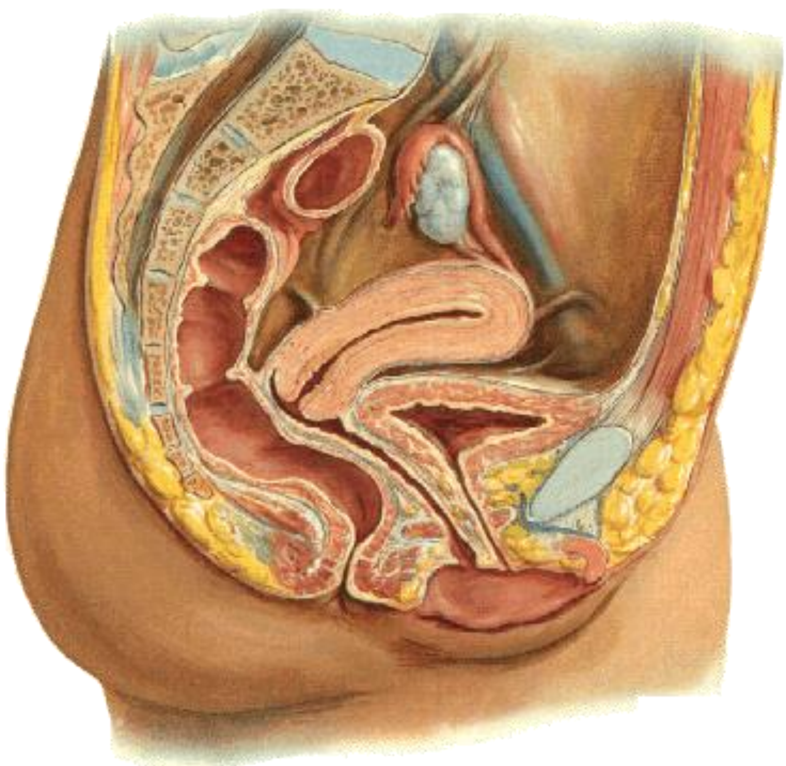
MOTIVATION

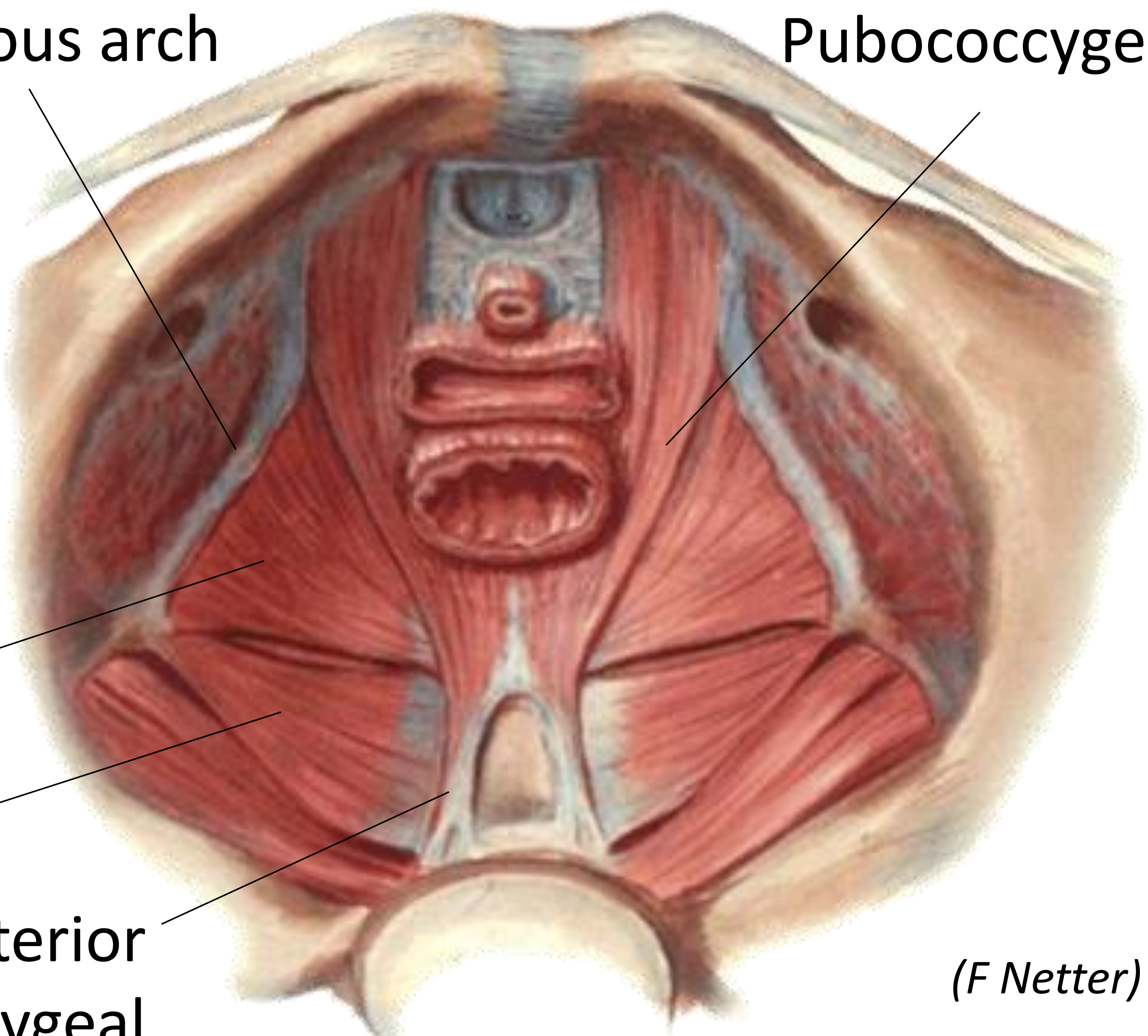
- –Urinary or fecal incontinence
- –Pelvic organ prolapse (POP)
- –Rectal pain
- –Constipation
- –Pelvic pain/trauma
- –Sexual dysfunctions

(F Netter)

→ Reduced Quality of Life

Female pelvic cavity: gross anatomy





(F Netter)

Hyperelastic constitutive model for PF muscles

Modified version of the Humphrey and Yin constitutive model

Strain energy function: $$U = U_I\left(\bar{I}_1^C\right) + U_J\left(J\right) + U_f\left(\bar{\lambda}_f, \alpha\right)$$

- U_I: Strain energy stored in the isotropic matrix, embedding the muscle fibers
- U_J: Strain energy associated with the volume change
- U_f: Strain energy (passive & active) stored in each muscle fiber

(JAC Martins et al., Comp Method Applied Mech Engg, 1998)

Hyperelastic constitutive model for PF muscles

The strain energy stored in the isotropic matrix, embedding the muscle fibers:

$$U_I = c\left[e^{b\left(\bar{I}_1^C - 3\right)} - 1\right]$$

$\bar{I}_1^C$ 1st I. of the right Cauchy-Green strain tensor with the vol. change eliminated

$$\bar{I}_1^C = \mathrm{tr}\,\bar{\mathbf{C}} = \mathrm{tr}\left(\bar{\mathbf{F}}^T\bar{\mathbf{F}}\right) = J^{-2/3}\,\mathrm{tr}\,\mathbf{C}$$

$\bar{\mathbf{F}}$ Deformation gradient with the volume change eliminated $\bar{\mathbf{F}} = J^{-1/3}\mathbf{F}$

The strain energy associated with the volume change: $U_J = \frac{1}{D}\left(J - 1\right)^2$

(JAC Martins et al., Comp Method Applied Mech Engg, 1998)

Hyperelastic constitutive model for PF muscles

The strain energy stored in each muscle fiber, can be divided into a passive elastic part and an active part due to the contraction:

$$U_f\left(\bar{\lambda}_f,\alpha\right)=U_{pas}\left(\bar{\lambda}_f\right)+U_{act}\left(\bar{\lambda}_f,\alpha\right)$$

The passive elastic part is given by: $U_{pas} = A\left\{\exp\left[a\left(\bar{\lambda}_f - 3\right)^2\right]-1\right\}$

$\bar{\lambda}_f$ Fiber stretch ratio in the direction N of the undeformed fiber:

$$\bar{\lambda}_f = \sqrt{\mathbf{N}^T - \mathbf{CN}}$$

The active part is given by:

$$U_{act} = \alpha\, T_0^M \int_1^{\bar{\lambda}_f} 1-4\left(\bar{\lambda}-1\right)^2 \, d\bar{\lambda} \quad \text{when} \quad 0.5<\bar{\lambda}_f<1.5$$

α → Activation level, ranging from 0 to 1

(JAC Martins et al., Comp Method Applied Mech Engg, 1998)

Visco-hyperelastic constitutive model for PF muscles

Strain Energy Function:

$$\Psi = \Psi_{\mathrm{vol}} + \Psi_{\mathrm{mat}} + \Psi_{\mathrm{fib}} + \boldsymbol{\Psi}_{\mathbf{vsc}}$$

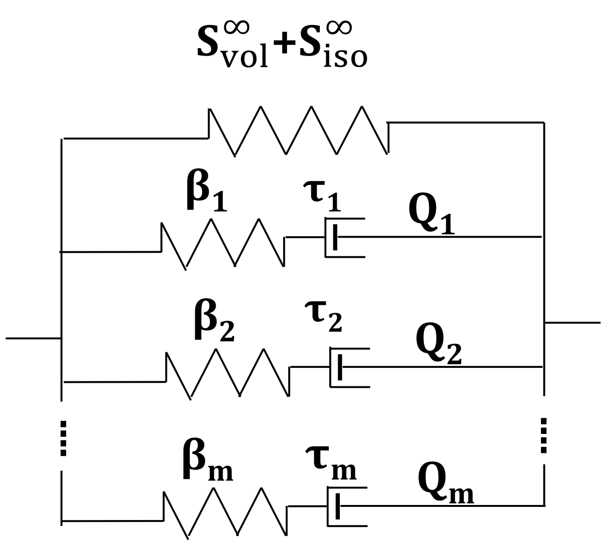
Generalized

Maxwell Model

$$\mathbf{S} = 2\left[\left(\frac{\partial \Psi}{\partial I_1} + I_1 \frac{\partial \Psi}{\partial I_2}\right)\mathbf{I} - \frac{\partial \Psi}{\partial I_2}\mathbf{C} + I_3 \frac{\partial \Psi}{\partial I_3}\mathbf{C}^{-1}\right]$$

$$= \mathbf{S}_{\mathrm{vol}} + \mathbf{S}_{\mathrm{mat}} + \mathbf{S}_{\mathrm{fib}} + \mathbf{Q}$$

Total Stress **S**



Elastic stress

1st Maxwell element

2nd Maxwell element

⋮

m[th] Maxwell element

$$C = 2\frac{\partial \mathbf{S}(\mathbf{C})}{\partial \mathbf{C}} = C_{\mathrm{vol}} + C_{\mathrm{mat}} + C_{\mathrm{fib}} + C_{\mathrm{vsc}}$$

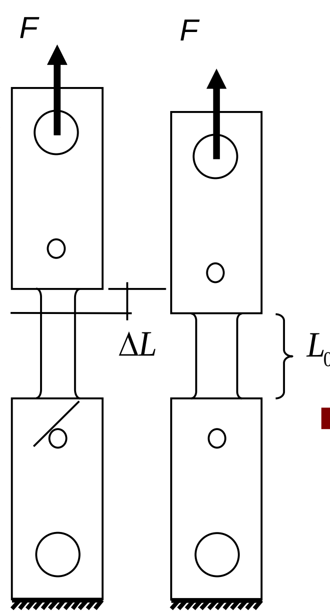
(M Vila Pouca et al., Int J Numer Meth Biomed Engg, 2018)

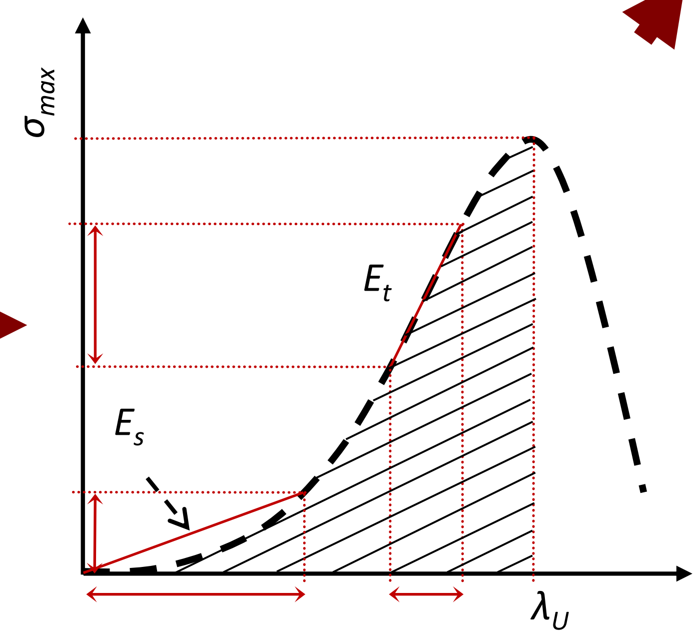
Typical approach

For (bio)mechanical and/or (bio)materials engineering

Sample collection

Mechanical Testing





Mechanical Behavior

Immediate
Data driven conclusions

Theoretical modeling

$$\sigma^{\psi}(c_1, c_3, \ldots, c_7) = \sigma(\lambda)$$

$$\chi^2 = \sum_{i=1}^{n}\left(\sigma - \sigma^{\psi}\right)_i^2$$

$$\{c_1, c_3, \ldots, c_7\}$$

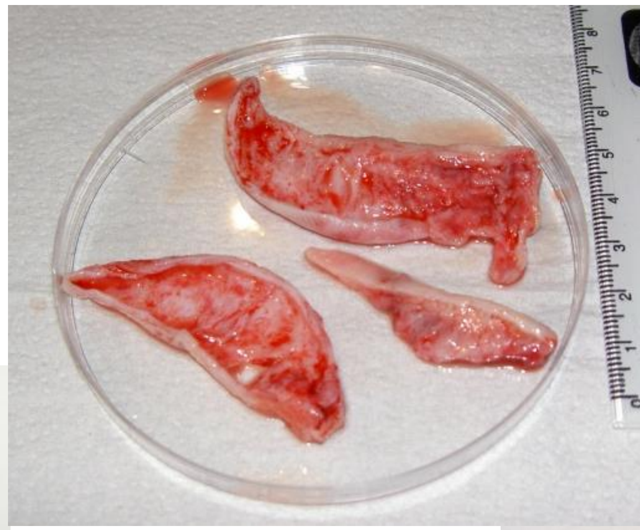
- Applications
  - Simulations
  - Evidence for medical hypothesis

  (…)

(P Martins, 2006 → selected as one of the best papers in honor of Strain's 50th Anniversary, 2016)

Mechanical characterization: Uniaxial tension test

(*M. Ethics C. HSJ*)



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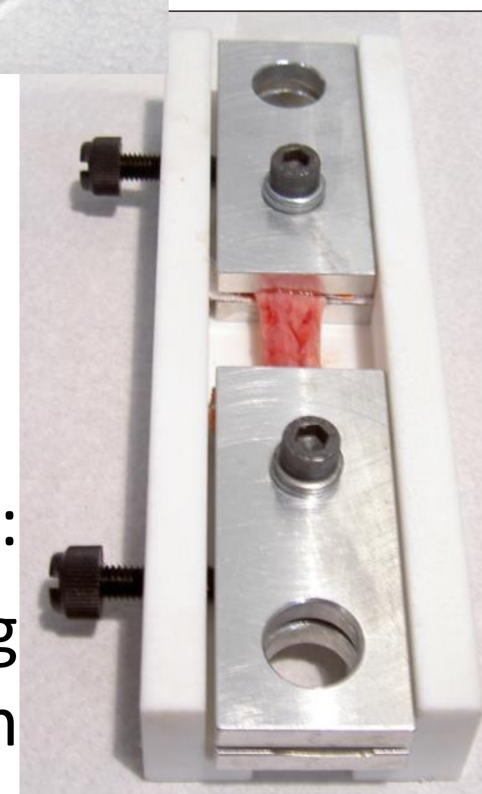
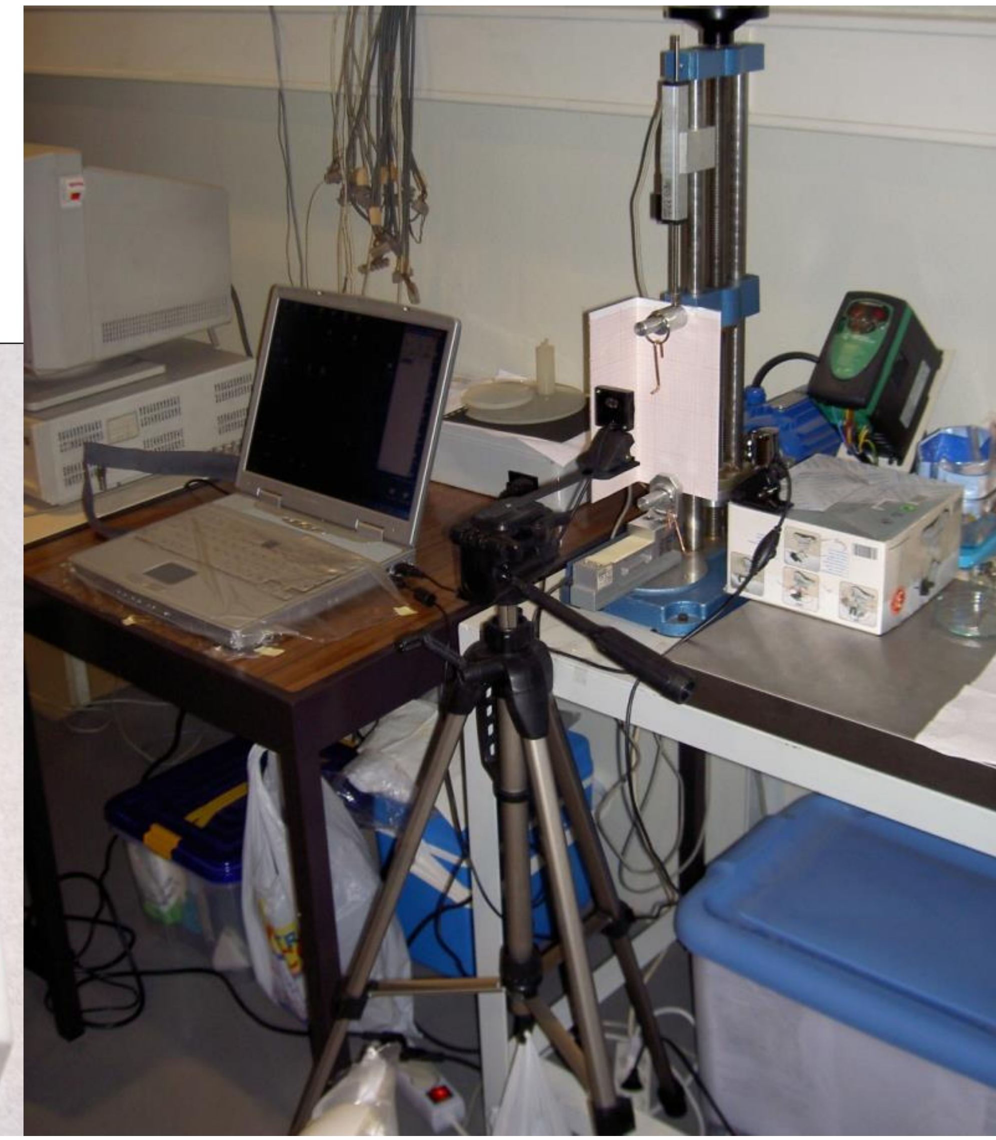
FEUP

Fixation:
special gripping system





(P Martins et al., CompIMAGE, Coimbra, 2006)

Human cadaveric tissue **cd**
Human surgical explant **se**

Abdominal Fascia

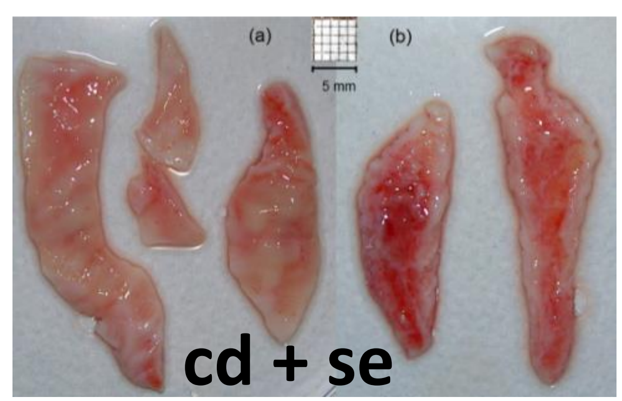
Uterosacral ligament

Round Ligament

Scale 10 mm

Bladder cuff

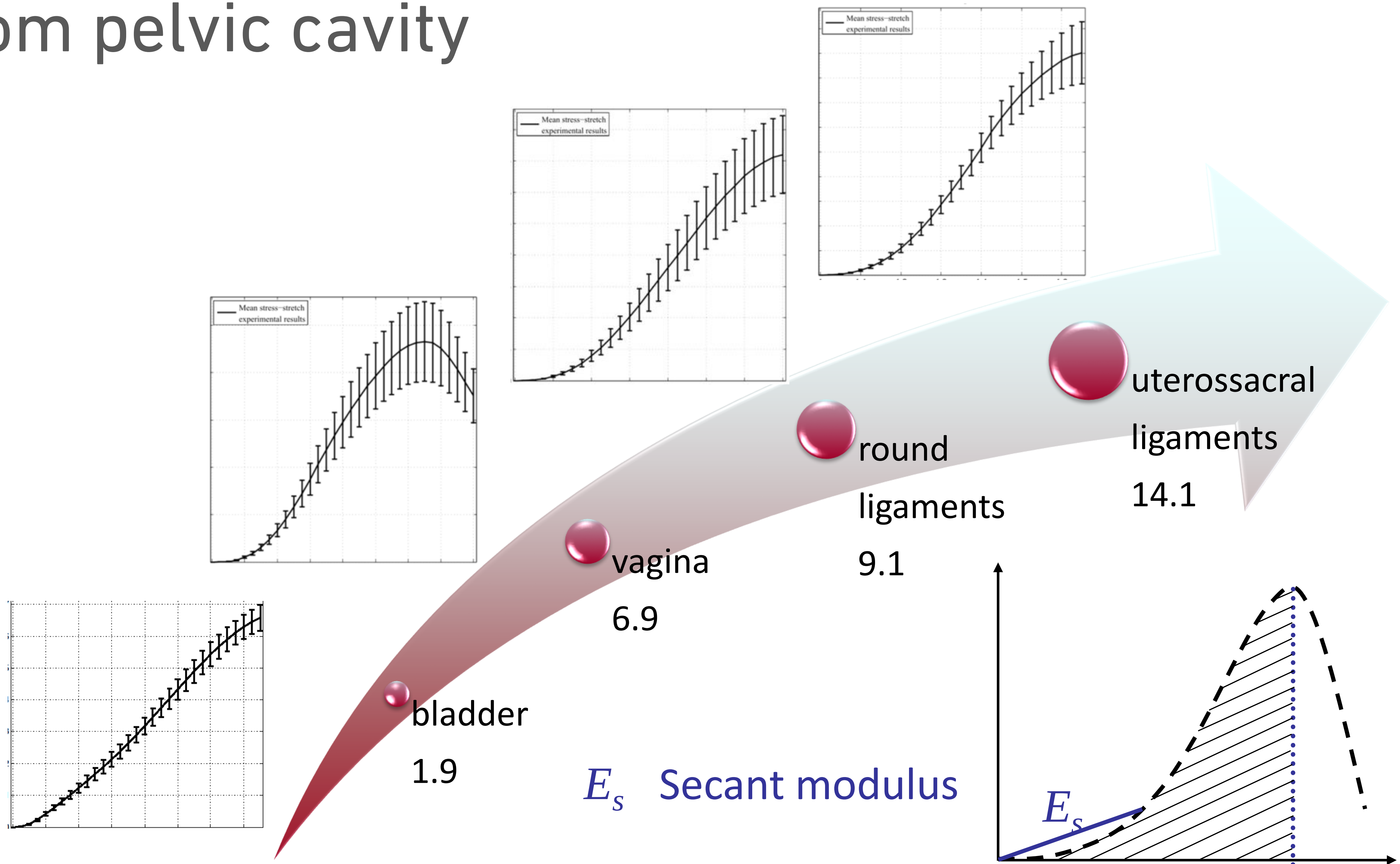
Vagina (anterior + posterior)



levator ani muscle

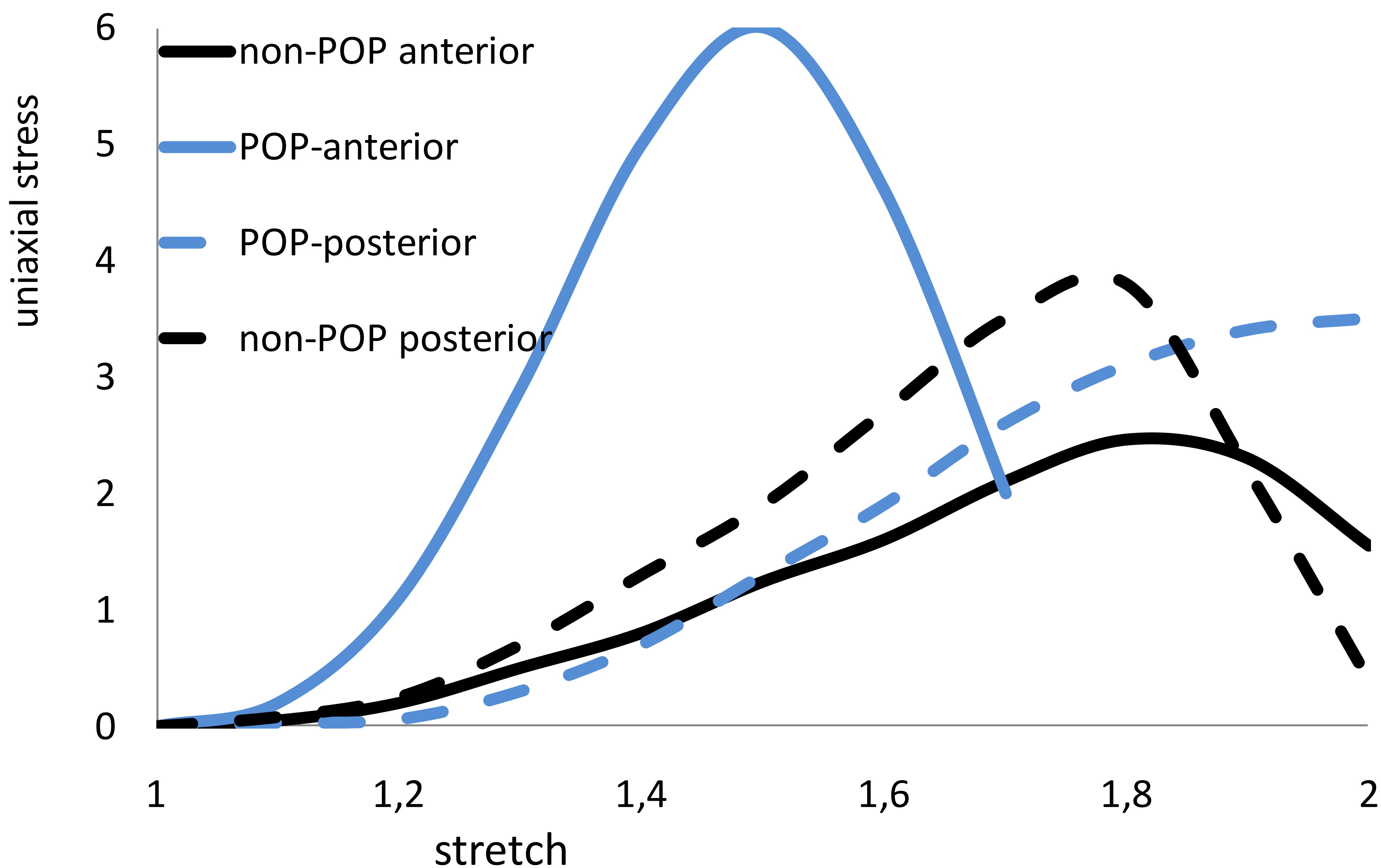
Unpublished
insufficient sample

Uniaxial tension test: different tissues from pelvic cavity



(P Martins et al., VIII Congresso Nacional da APNUG, 2013 → Communication Best Paper Award)

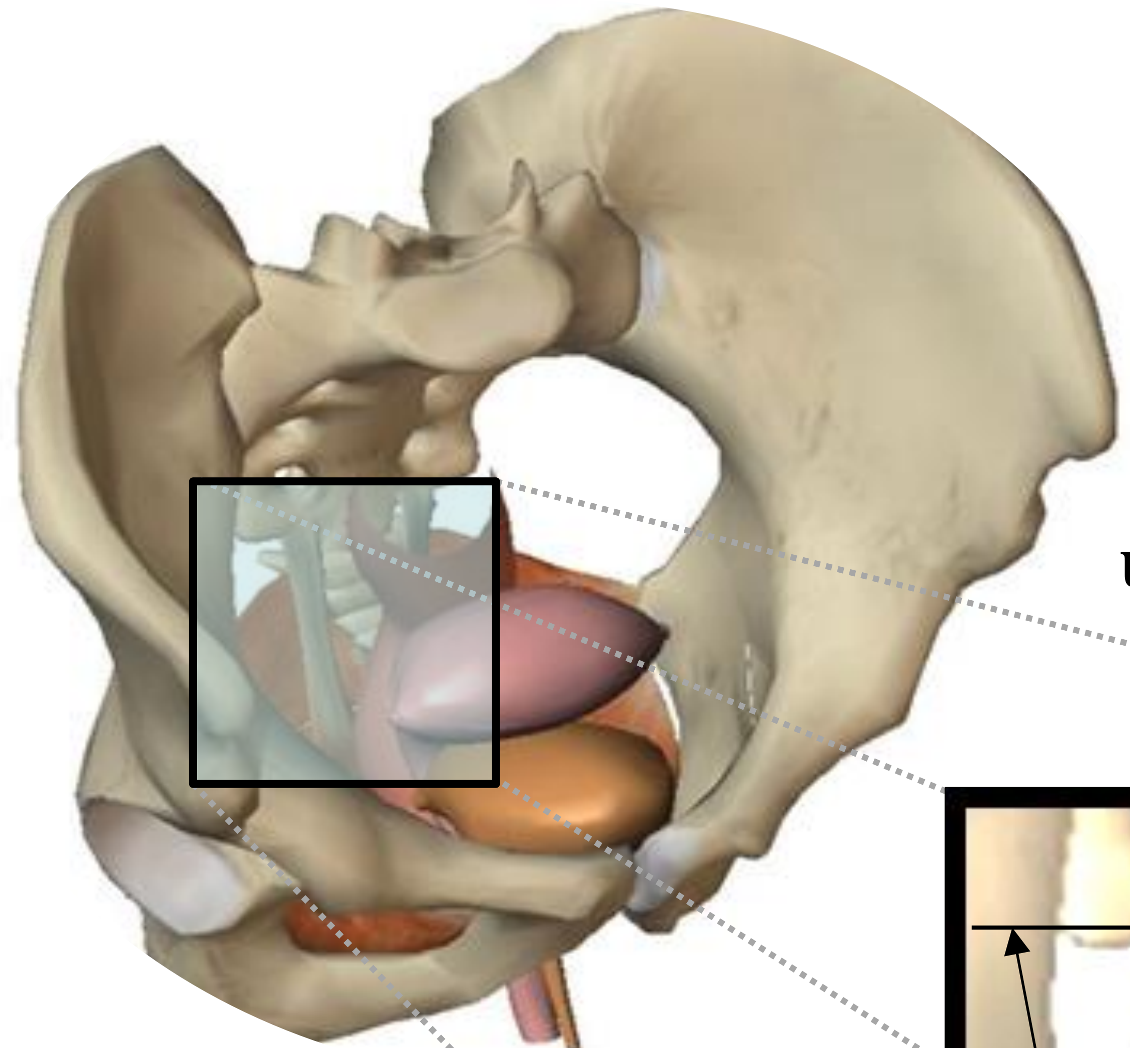
Uniaxial tension test: POP and non-POP vaginal tissue

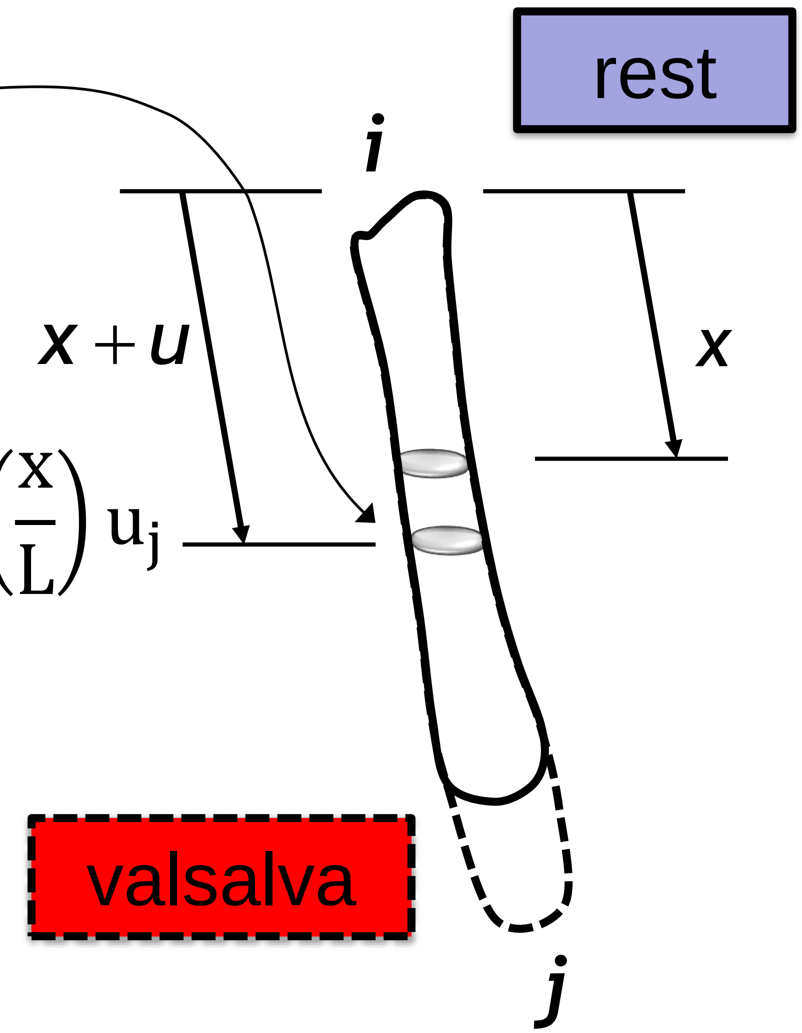


(P Martins et al., Gynecologic and Obstetric Investigation, 2013)

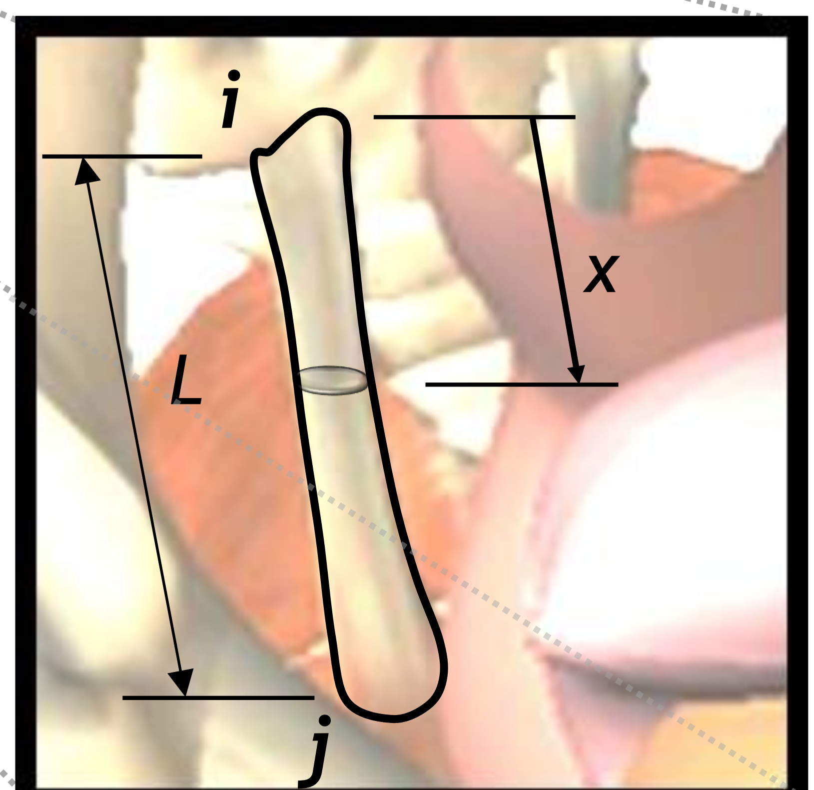
Computational modeling: basic FEM concept

Deformation=?
Stress=?
Stifness=?





$$u = \left(-\frac{x}{L} + 1\right) u_i + \left(\frac{x}{L}\right) u_j$$



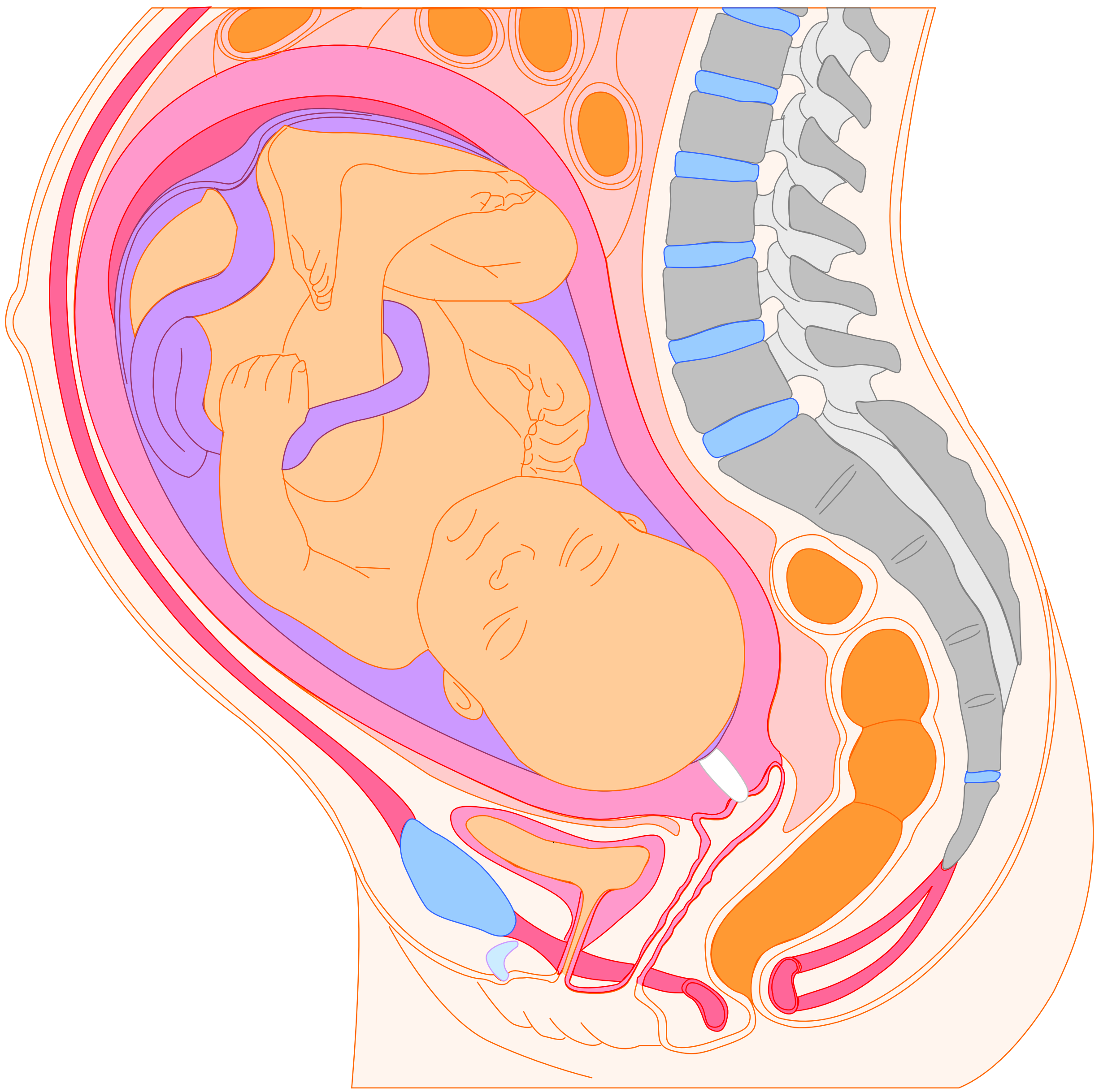
$$\text{Stiffness} = \frac{EA}{L}$$

$$\text{Deformation} = \frac{1}{L}(u_j - u_i)$$

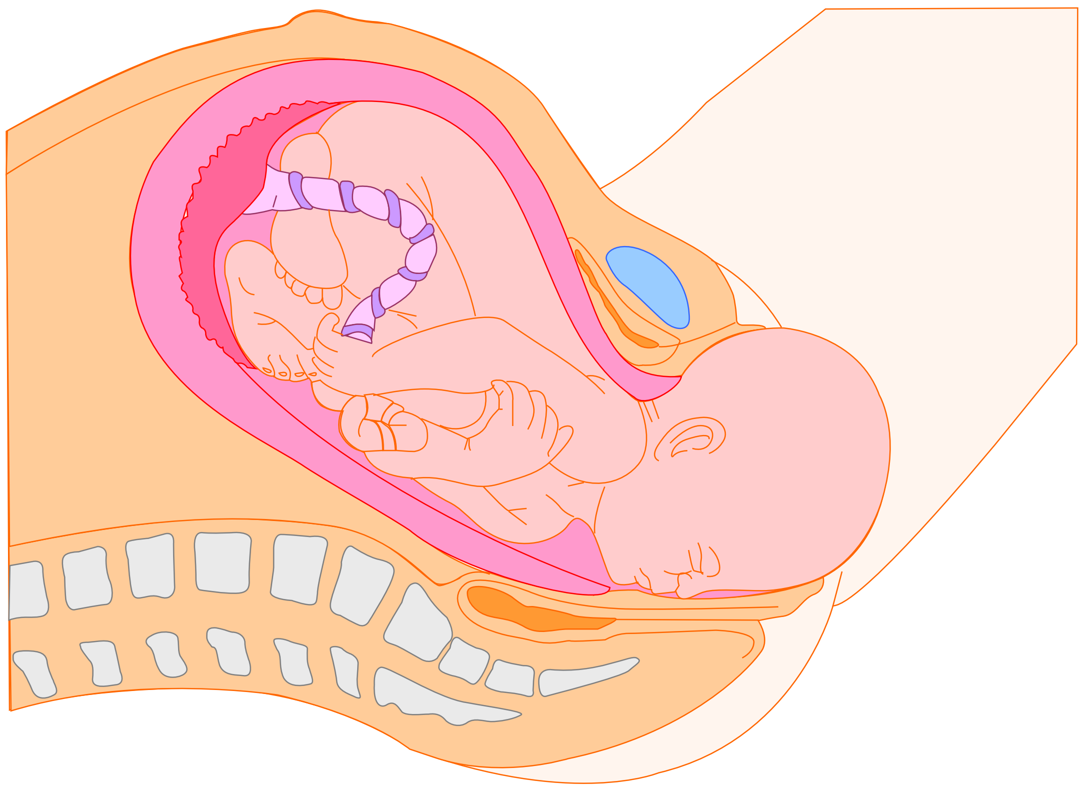
Stress = E x Deformation

(R Natal, IUGA 2013)

Risk factors associated with pelvic floor disorders

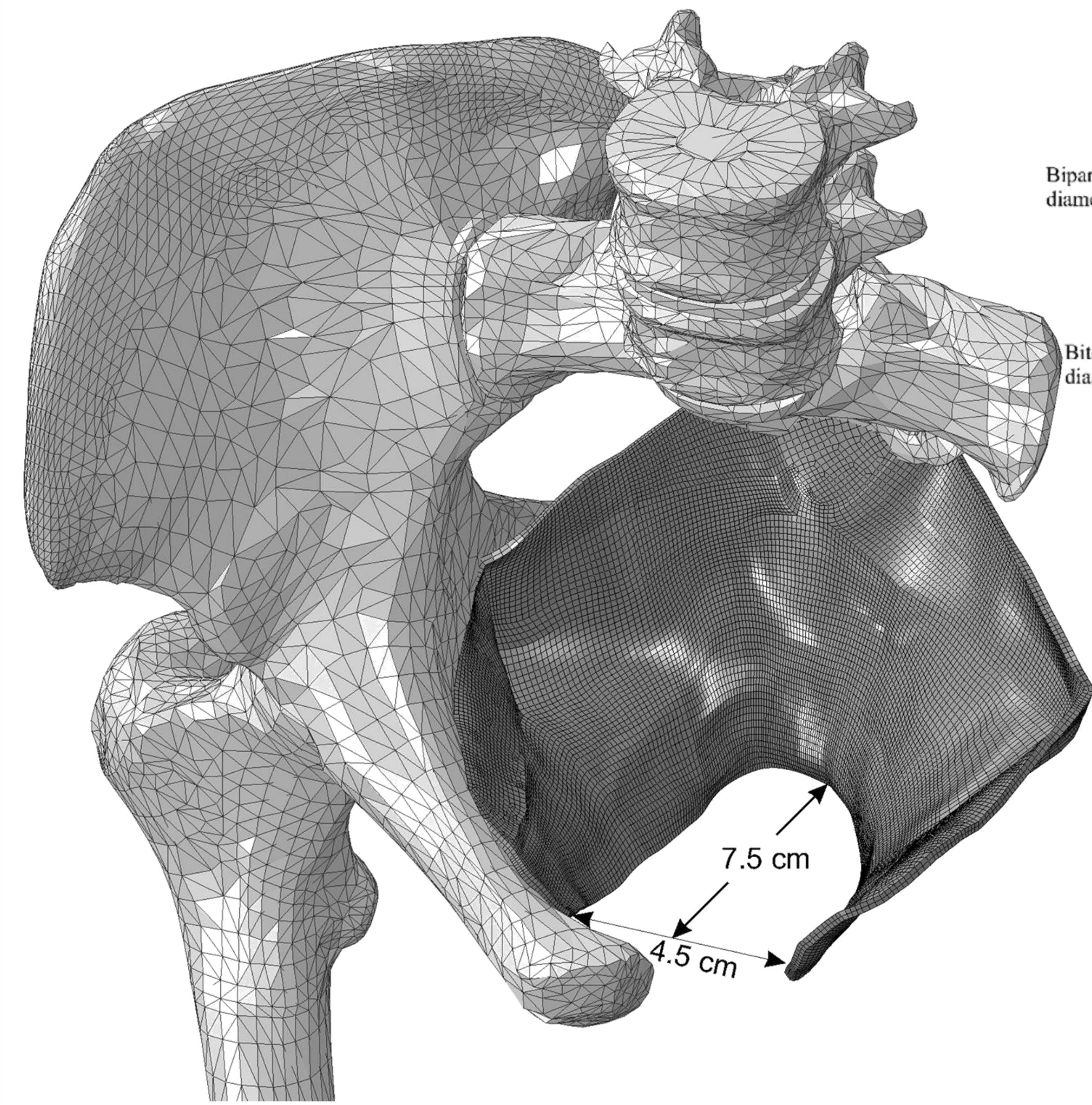


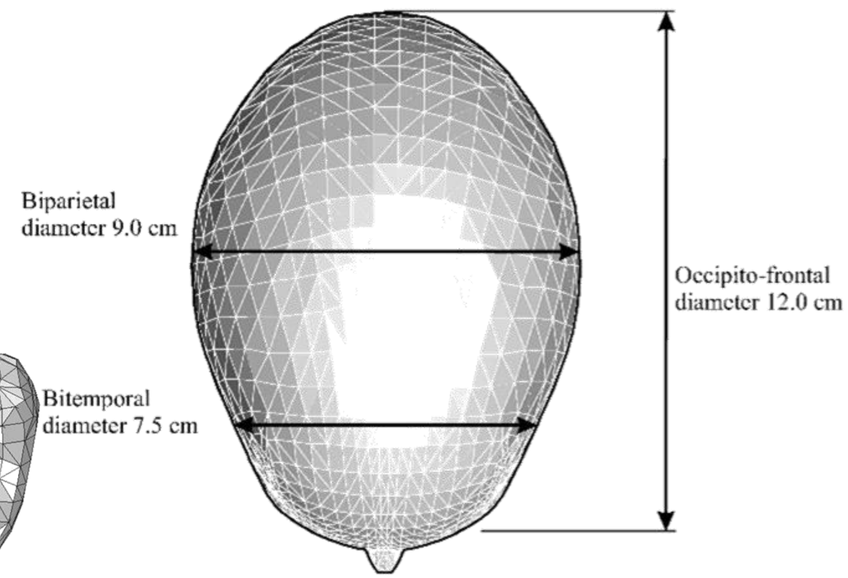
Pregnancy

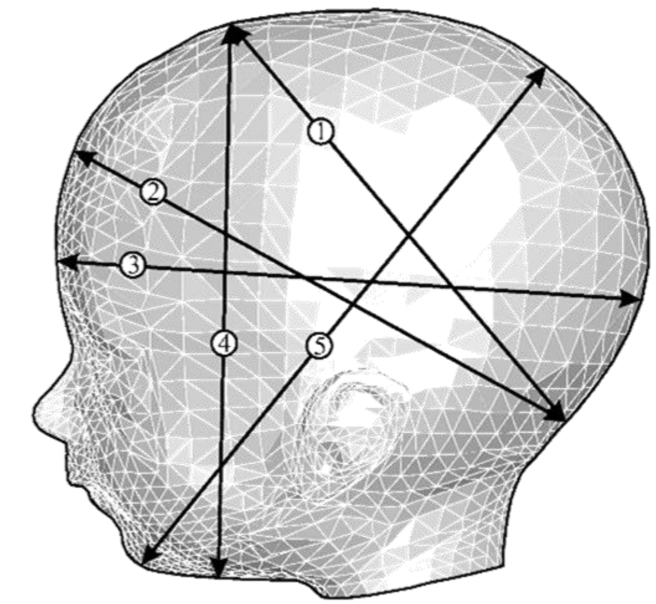


Childbirth

Simulation of vaginal delivery: Geometrical constraints



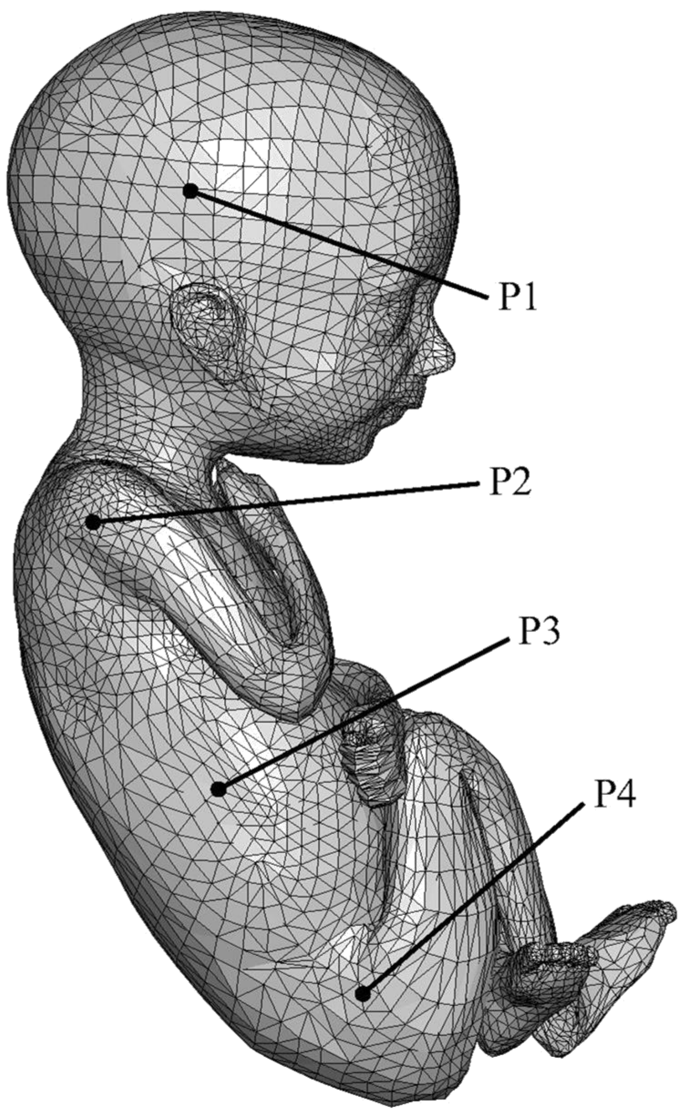


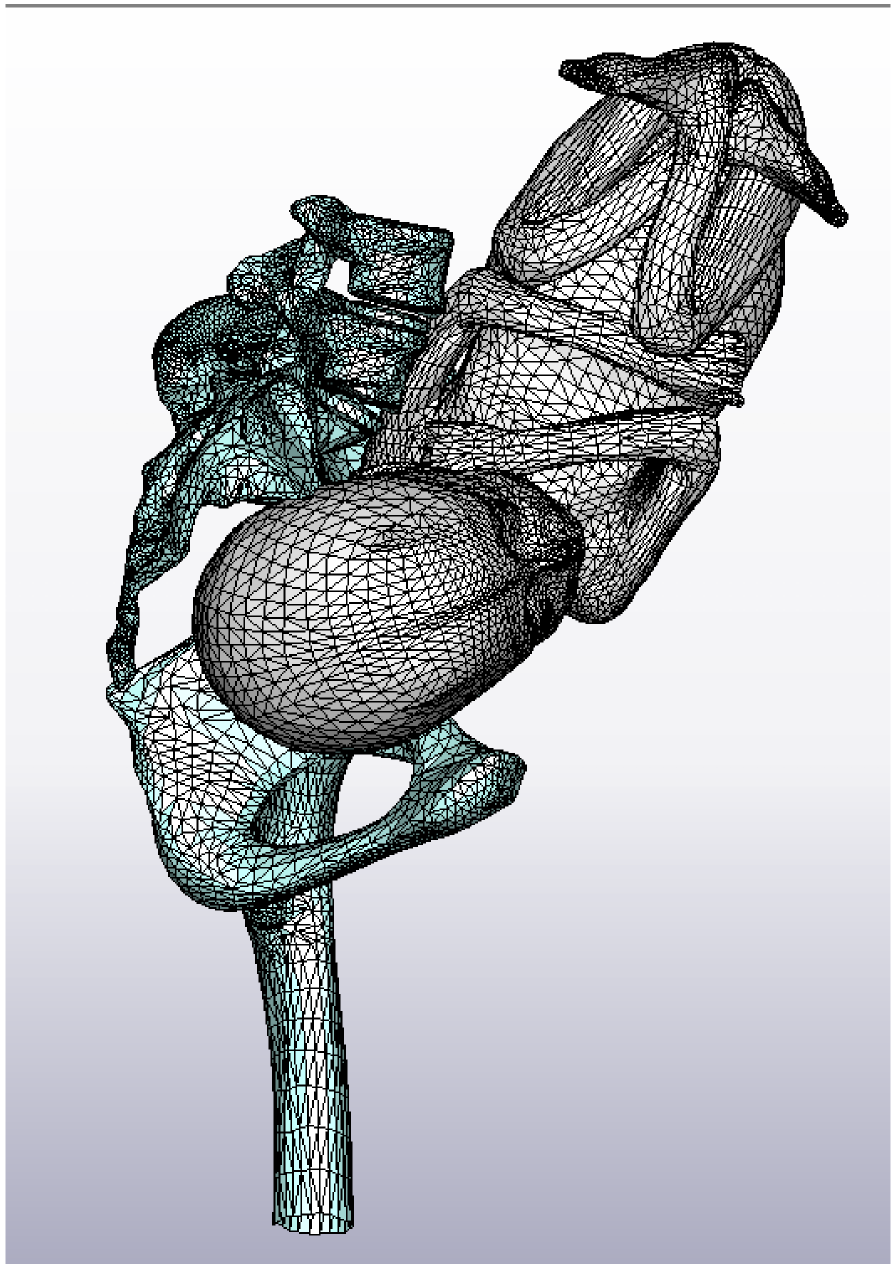


Diameter	Length
1 Suboccipito-bregmatic	9.5
2 Suboccipito-frontal	10.5
3 Occipito-frontal	11.5
4 Mento-vertical	13.0
5 Submento-bregmatic	9.5

(M Parente et al., Int Urogynecology J, 2008)

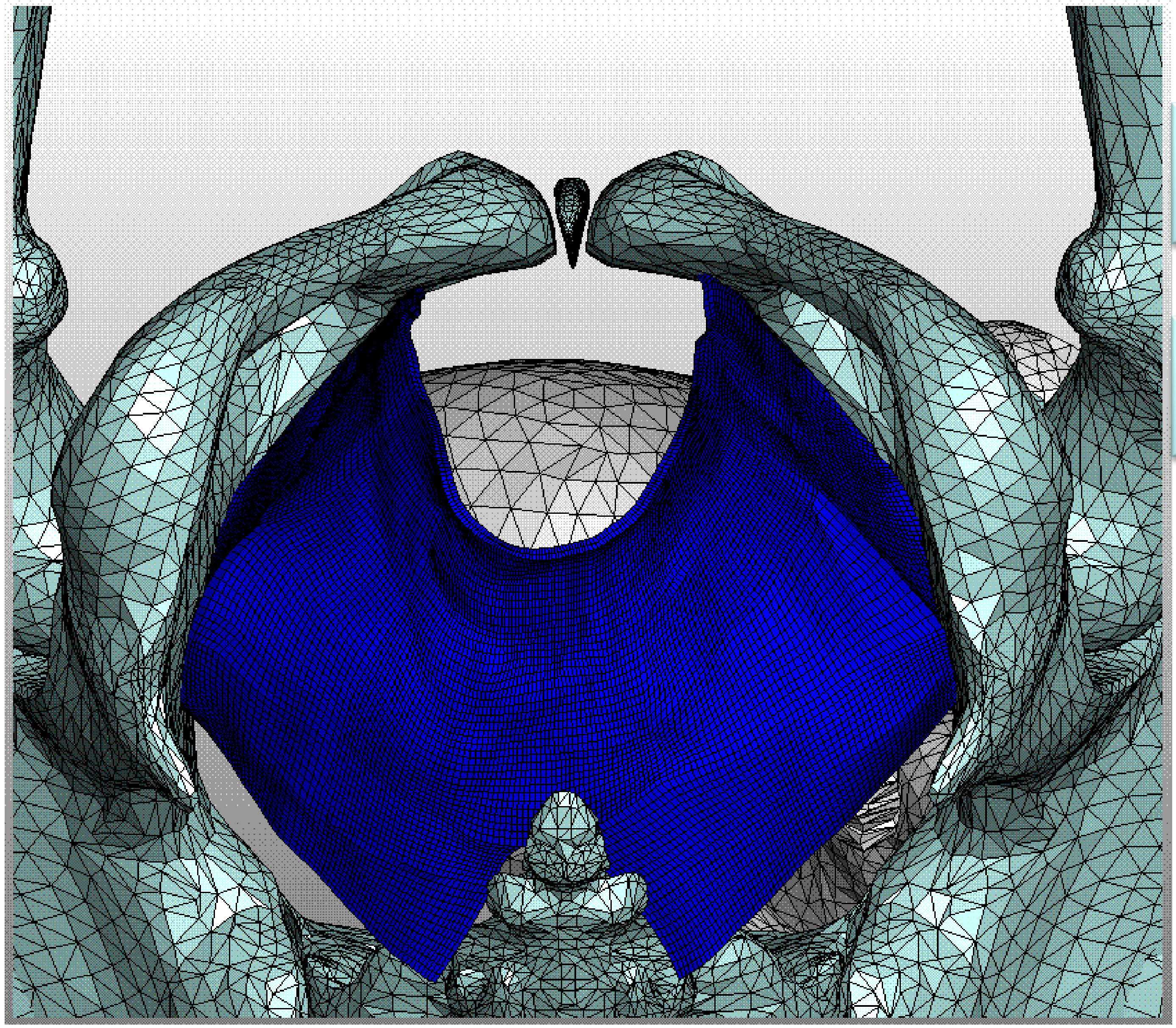
Simulation of vaginal delivery: descent movements





(M Parente et al., SINUG, 2012 → Communication Best Paper Award)

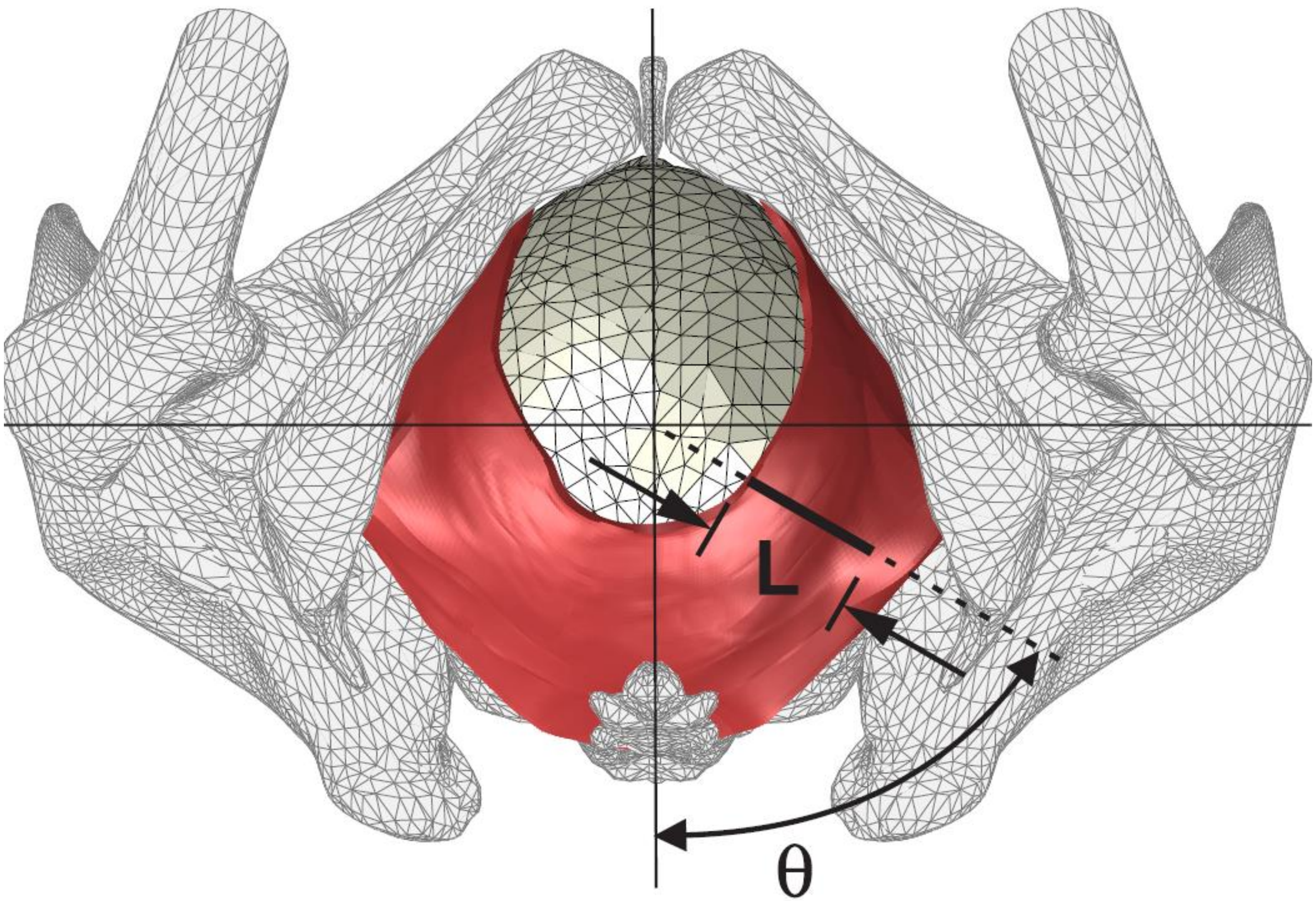
Simulation of vaginal delivery: deformation field of the PF



(M Parente, 2009 → IBM Award – Honorable Mention)

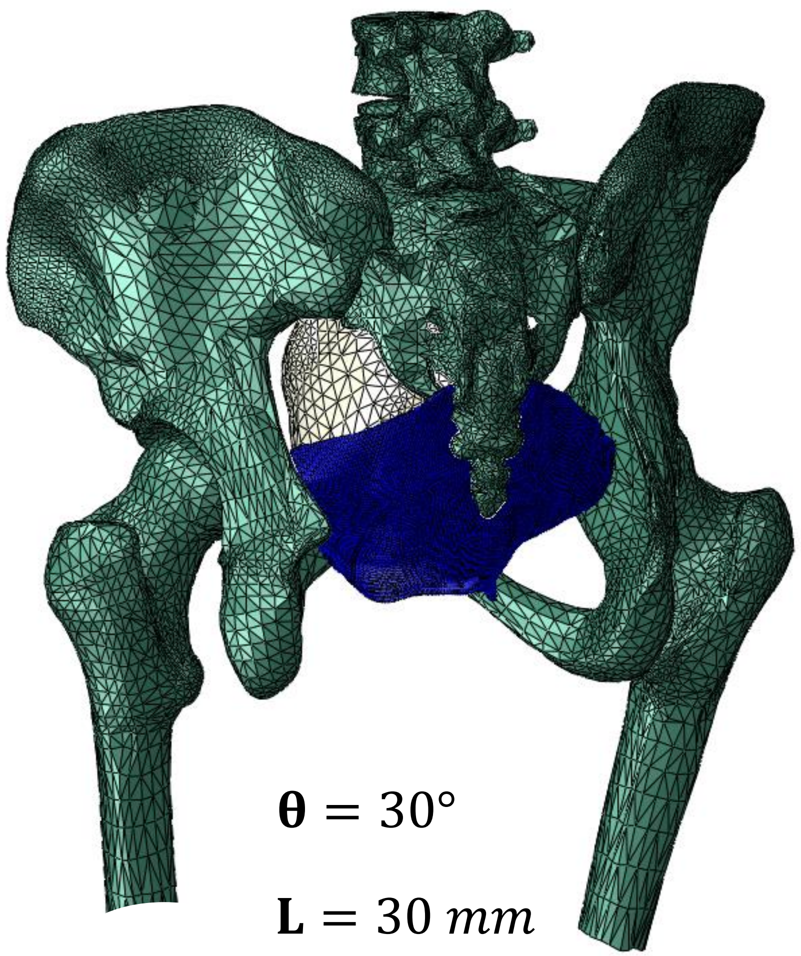
(M Parente, 2012 → SIMULIA Best Animation Award, academic sector)

Simulation of vaginal delivery: effects of episiotomy



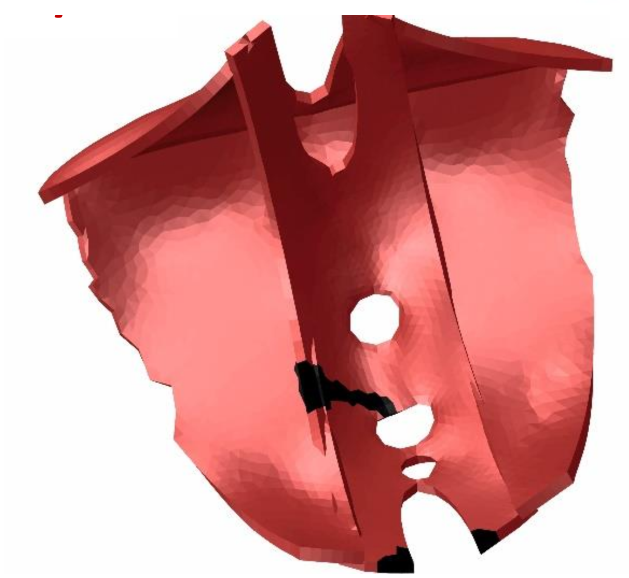
(D Oliveira, 2016 → IBM Award – Honorable Mention)

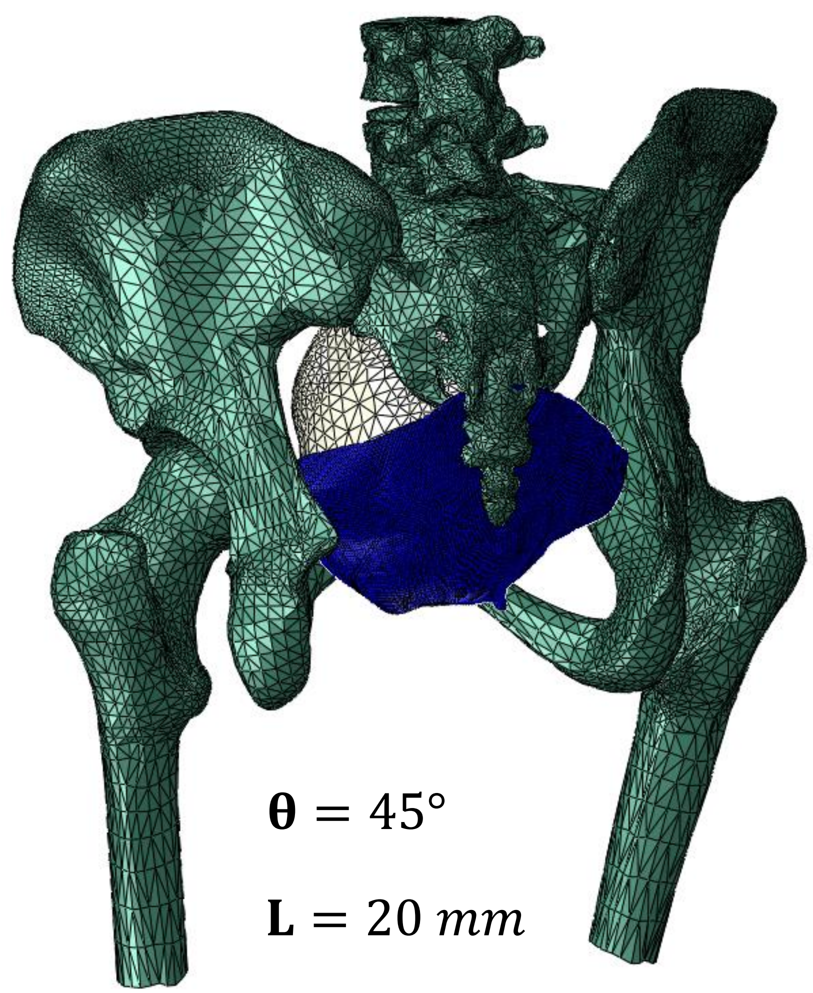
Simulation of vaginal delivery: effects of episiotomy



$\boldsymbol{\theta} = 30°$

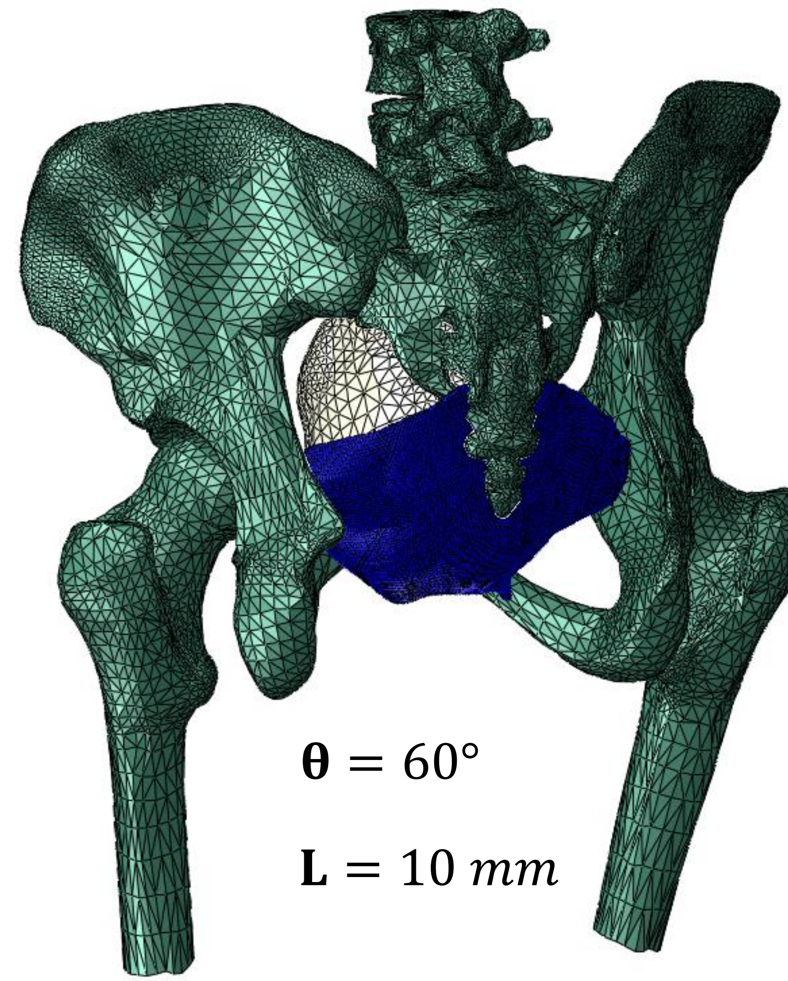
$\mathbf{L} = 30\ mm$





$\boldsymbol{\theta} = 45°$

$\mathbf{L} = 20\ mm$

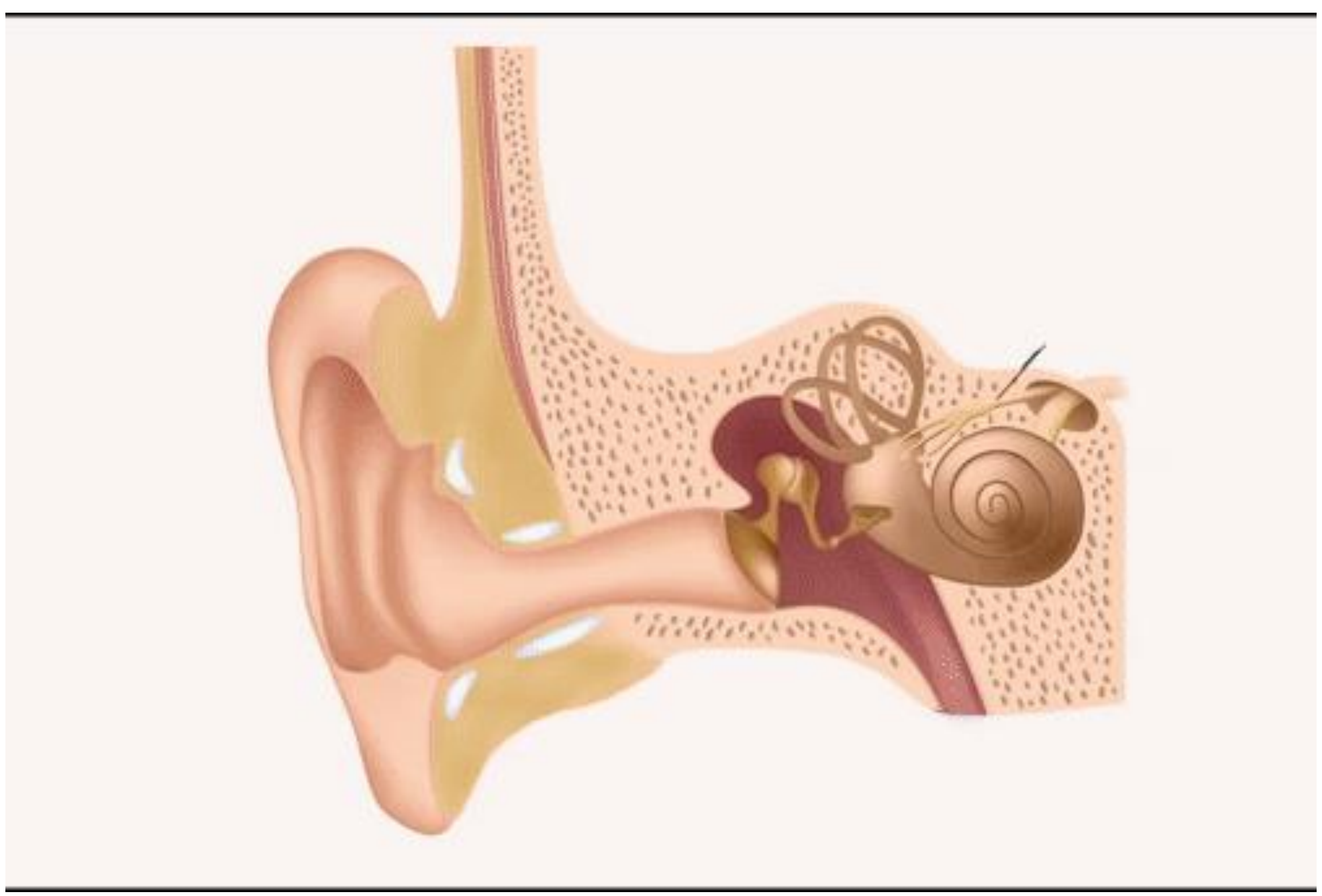


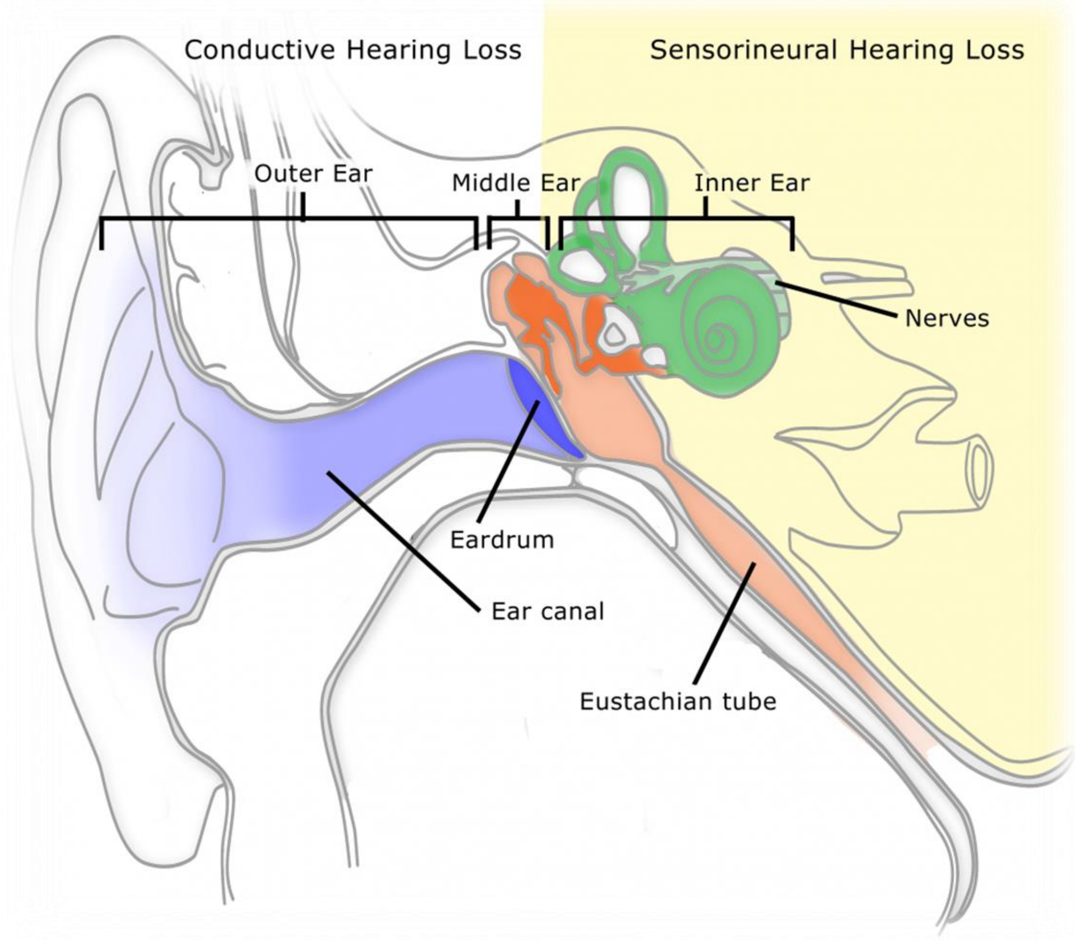
$\boldsymbol{\theta} = 60°$

$\mathbf{L} = 10\ mm$

(D Oliveira et al., Comp M Biomech Biomed Eng, 2017)

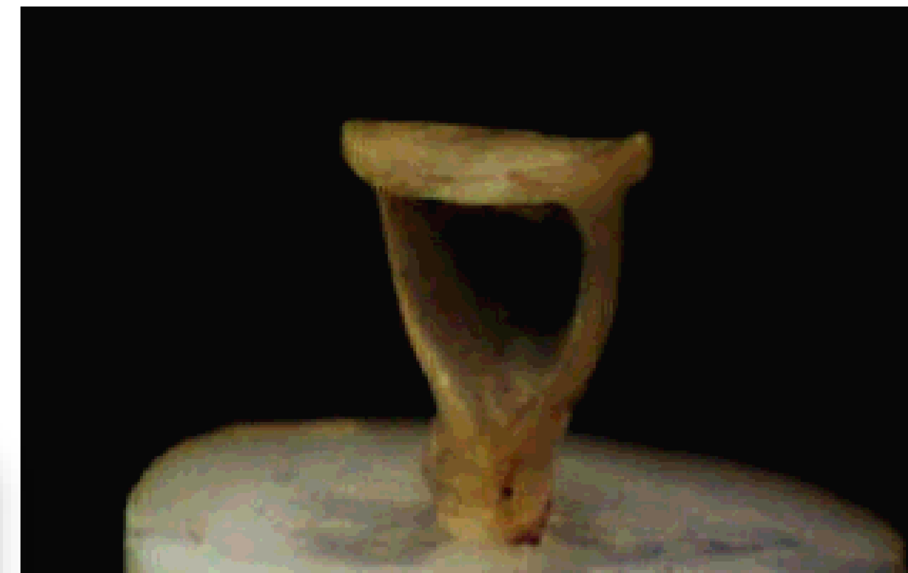
Biomechanical study of the human ear



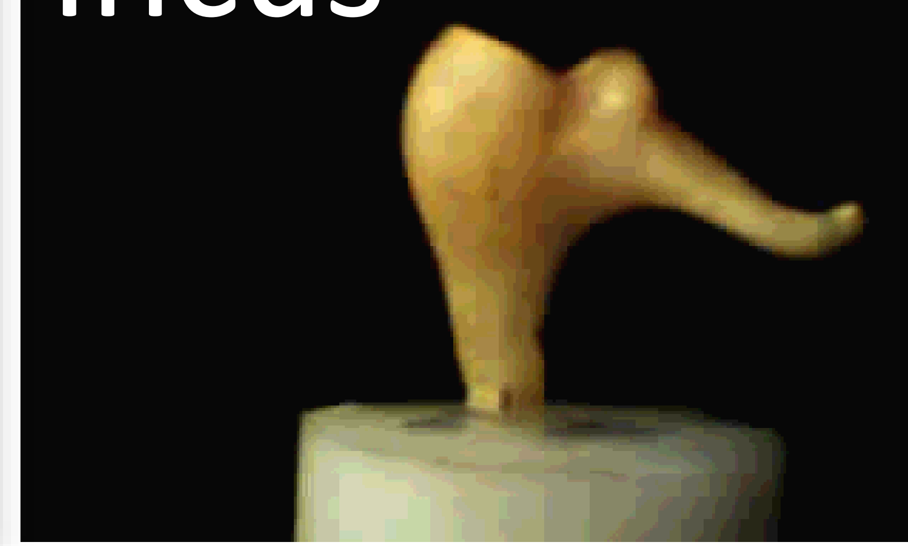


Biomechanical study of the human ear

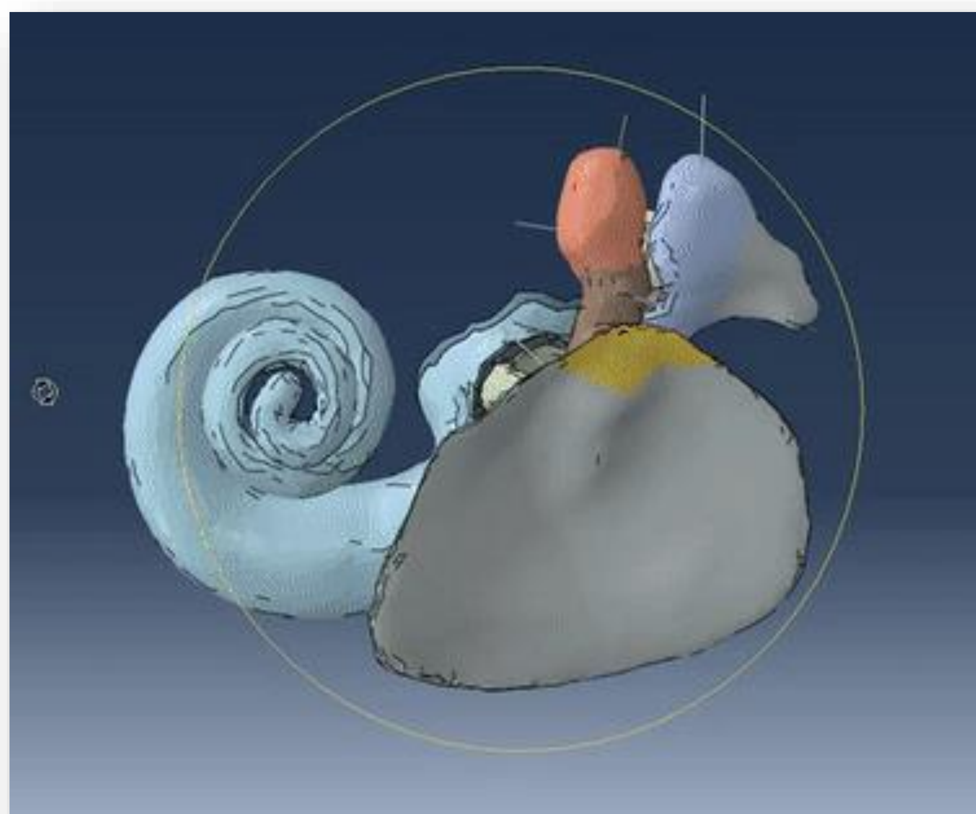
Stapes



Incus

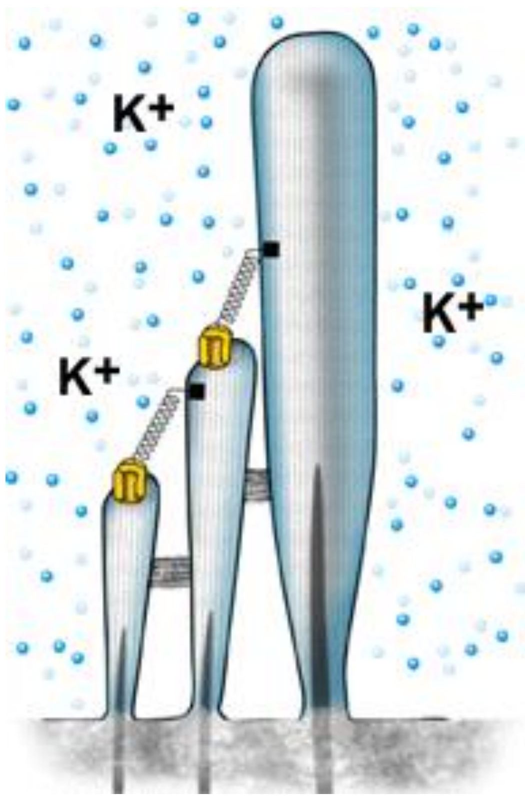


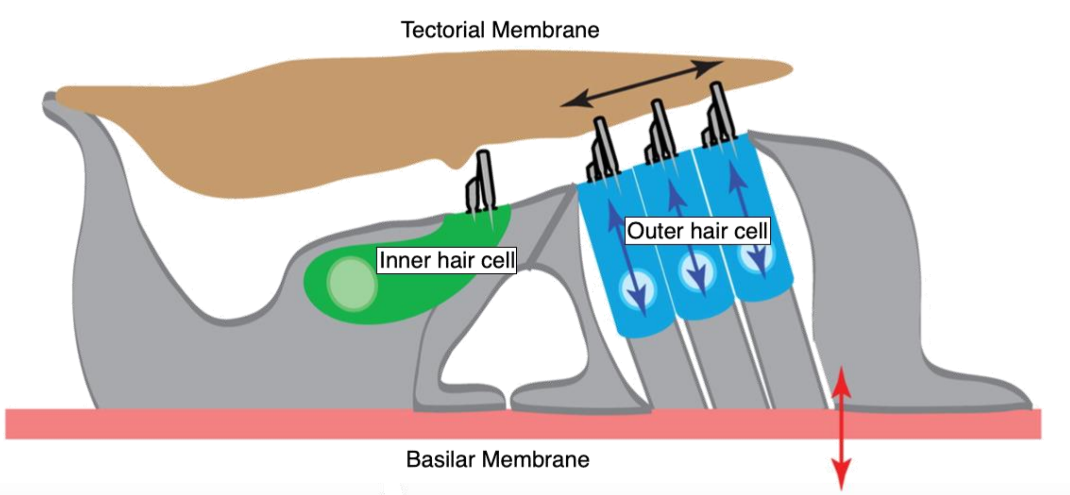
Malleus

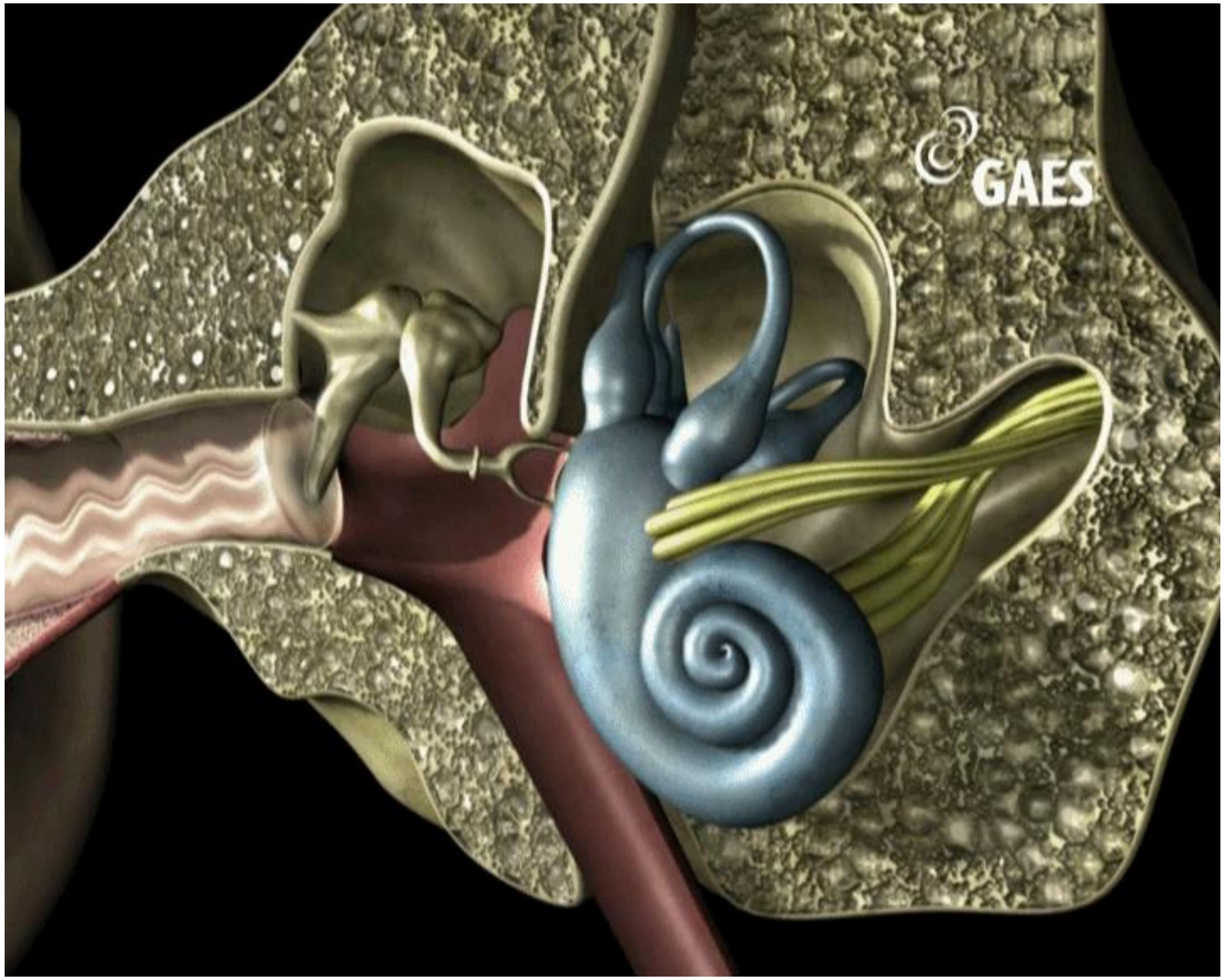


*(**F Gentil et al,** IMechE Part H: J Eng Medicine, 2011)*

Inner ear

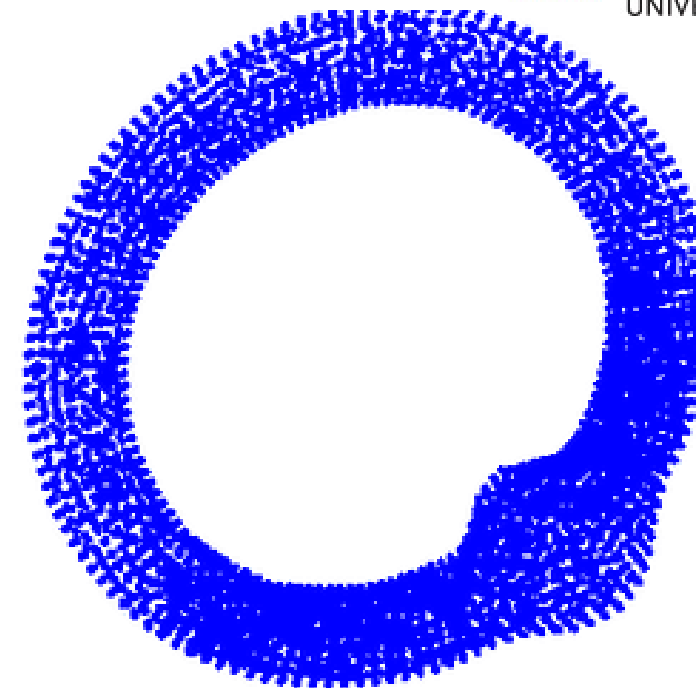

K+
K+
K+

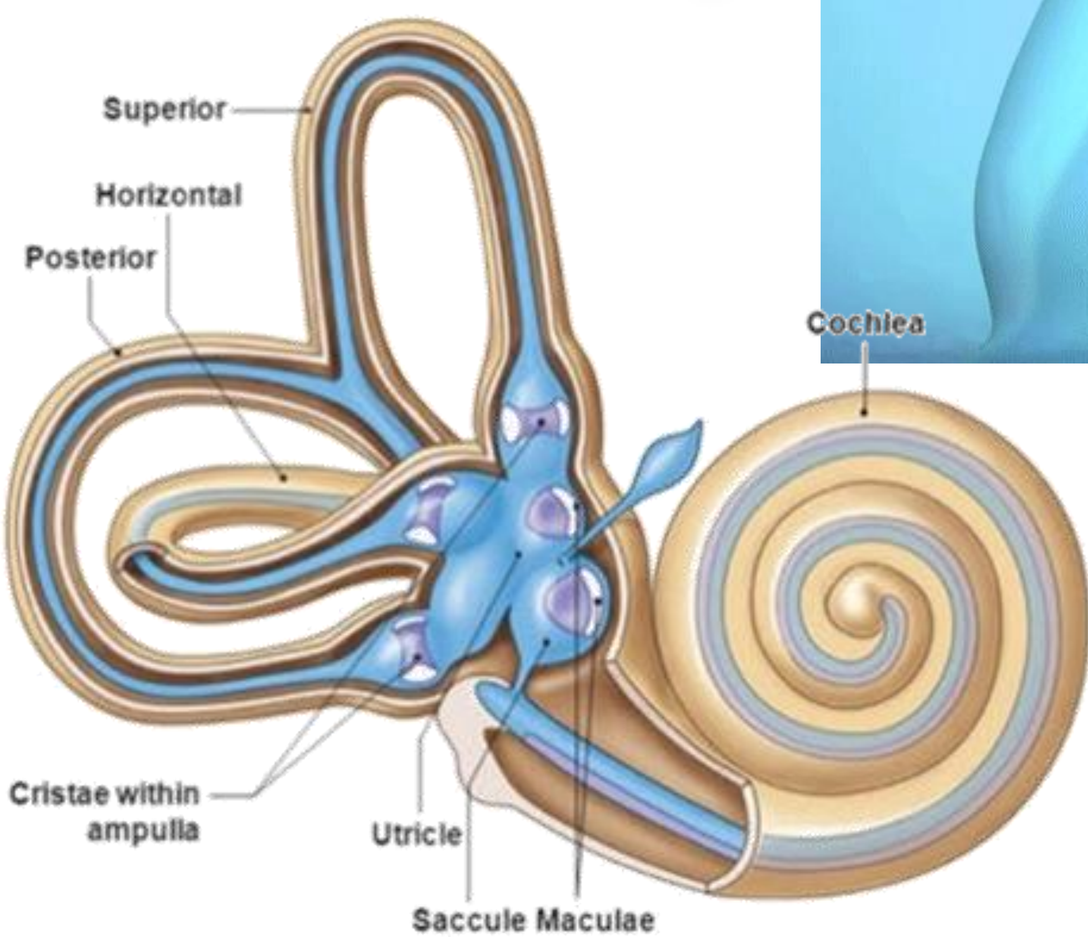

Tectorial Membrane
Inner hair cell
Outer hair cell
Basilar Membrane

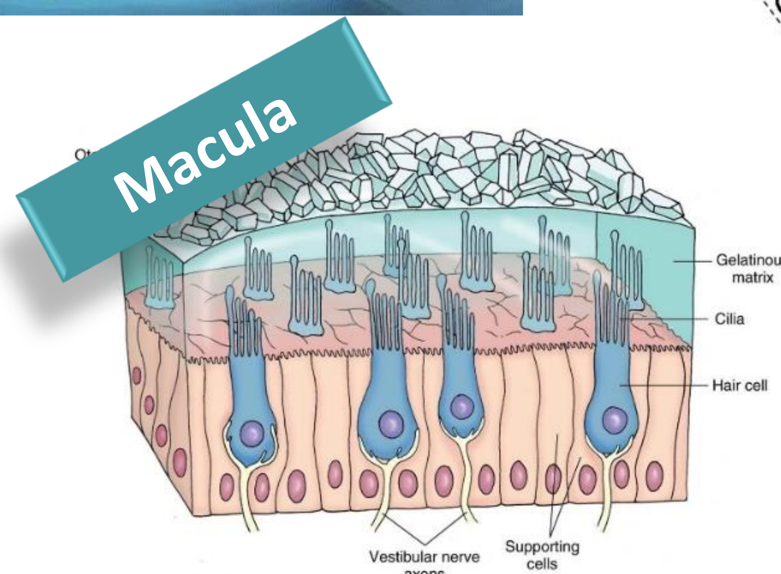

GAES

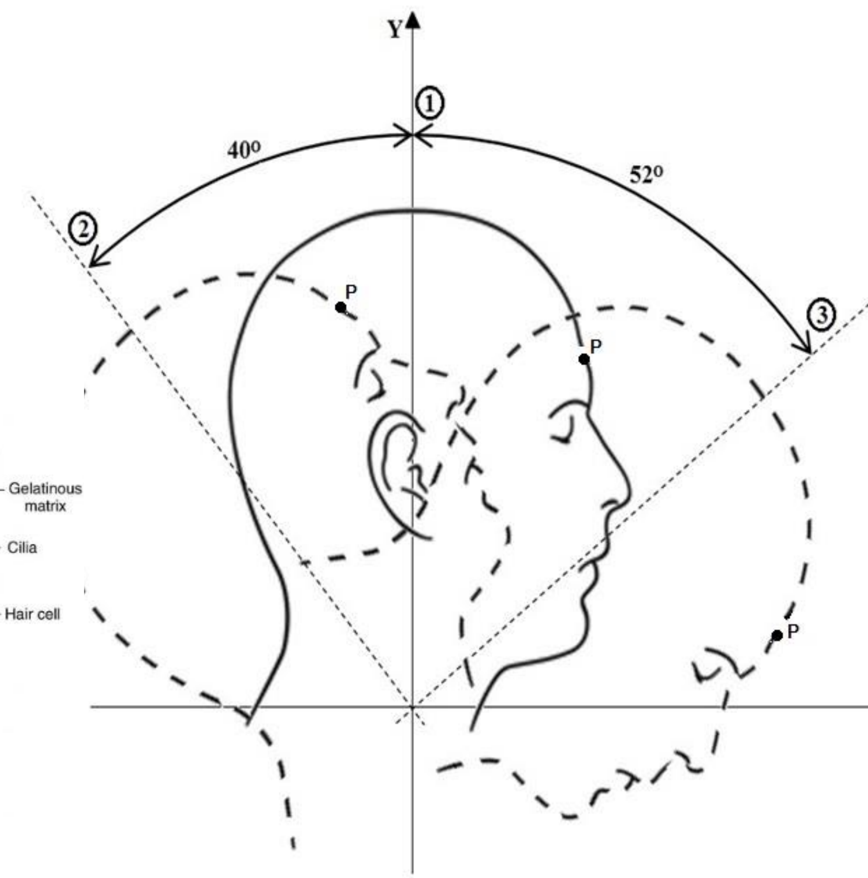
Vestibular system

Cupula shape take an important role in the vestibular rehabilitation efficiency.





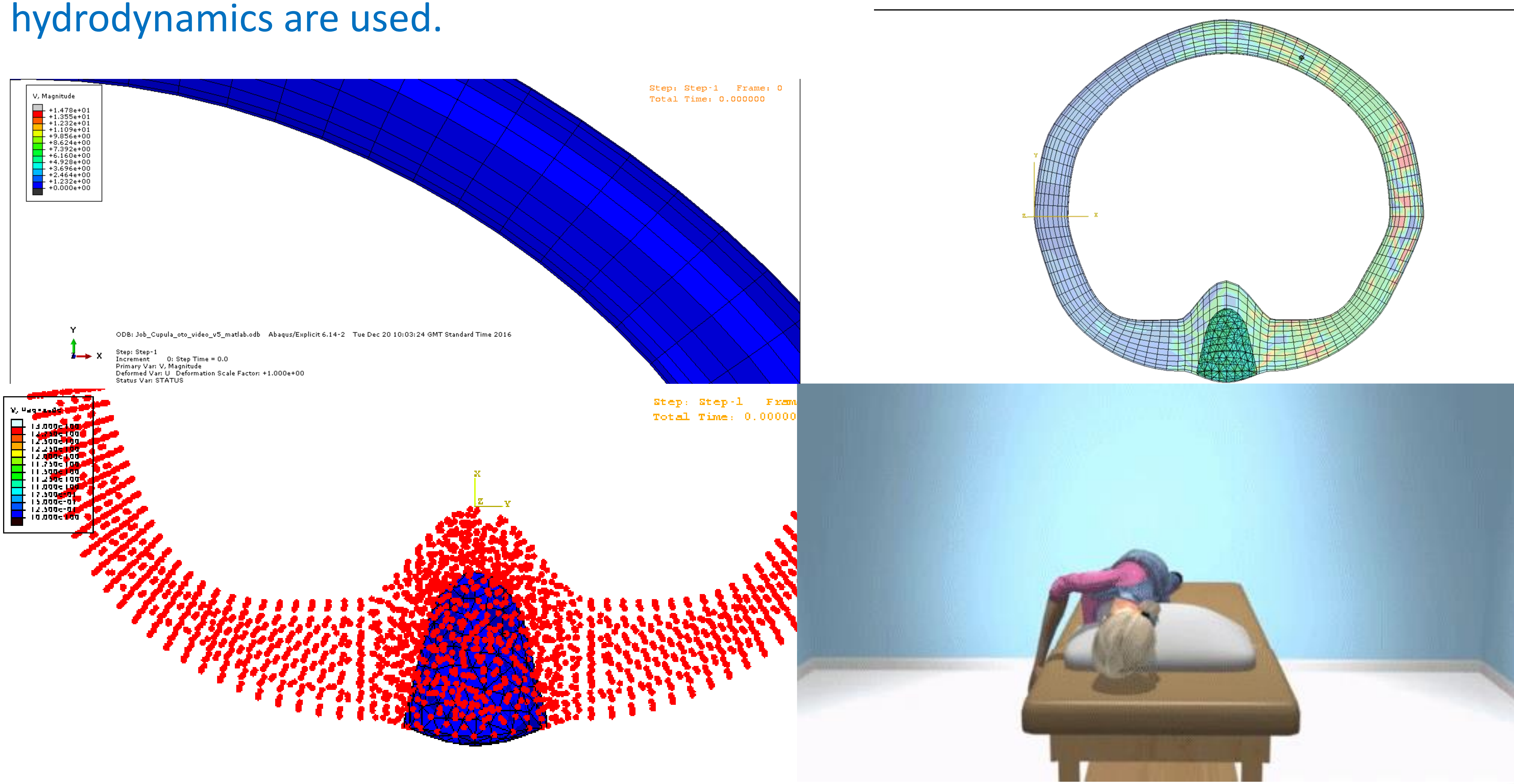




(C Santos et al., Comp M Biomech Biomed Eng, 2018)

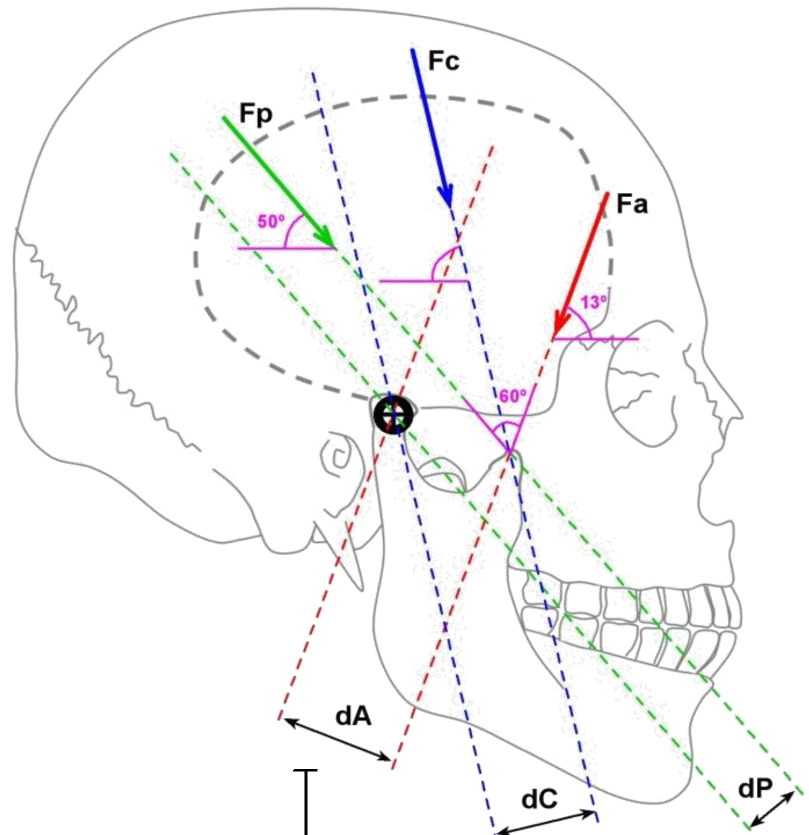
Vestibular system

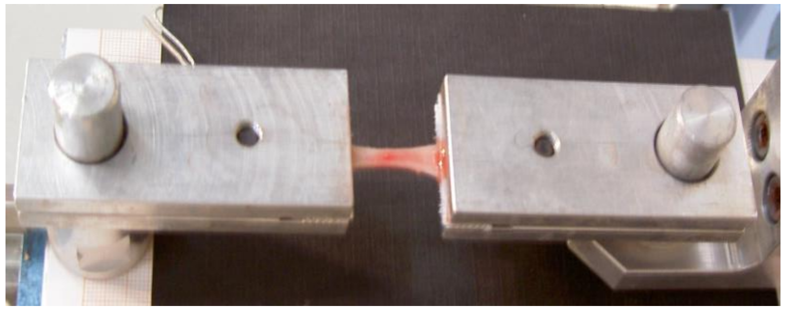
Complex fluid / structure interaction: adequate FEM and smoothed-particle hydrodynamics are used.



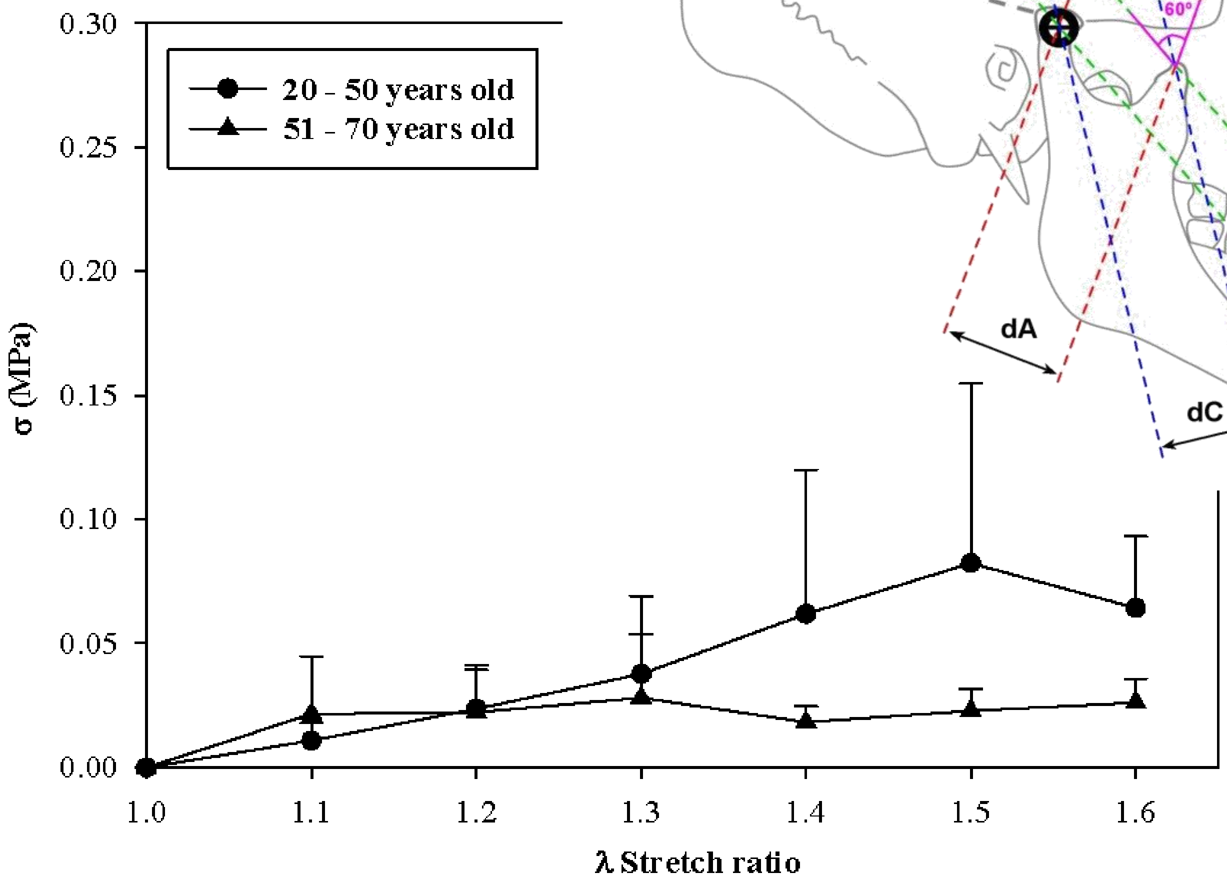
(C Santos et al., Acta Bioengg & Biomech, 2016)

Masticatory system: mechanical props
temporal muscles

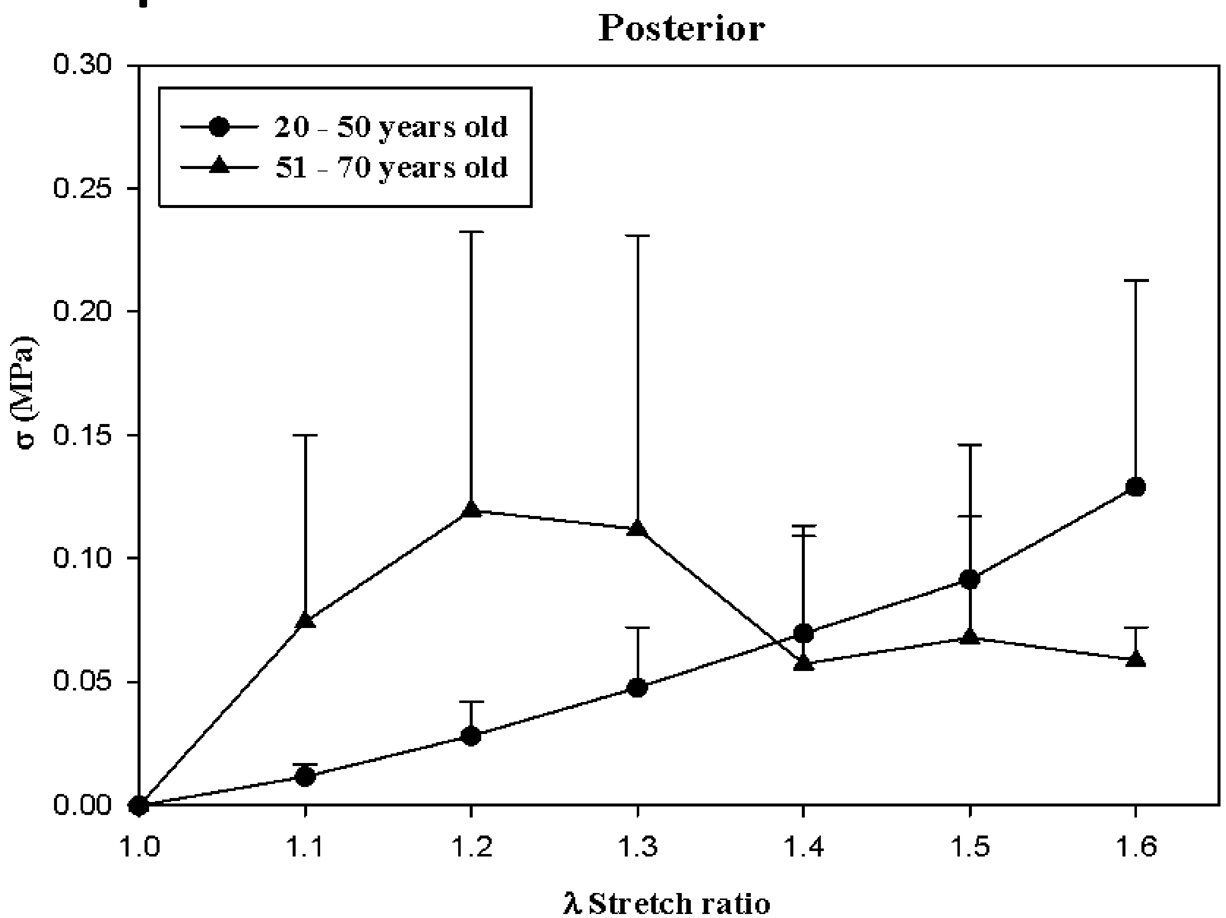




anterior

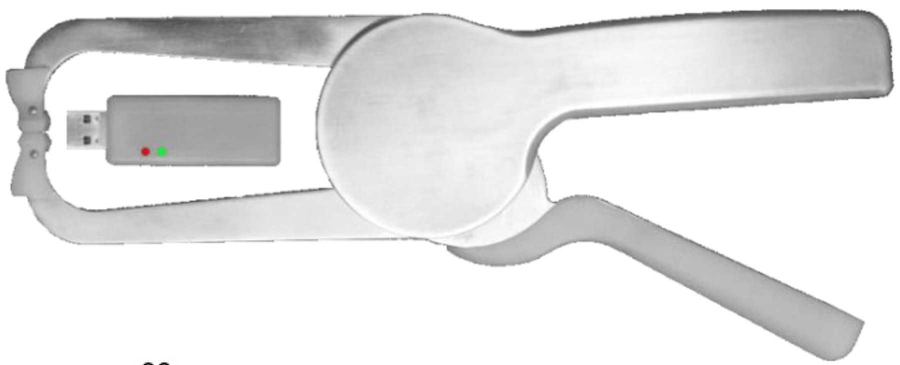


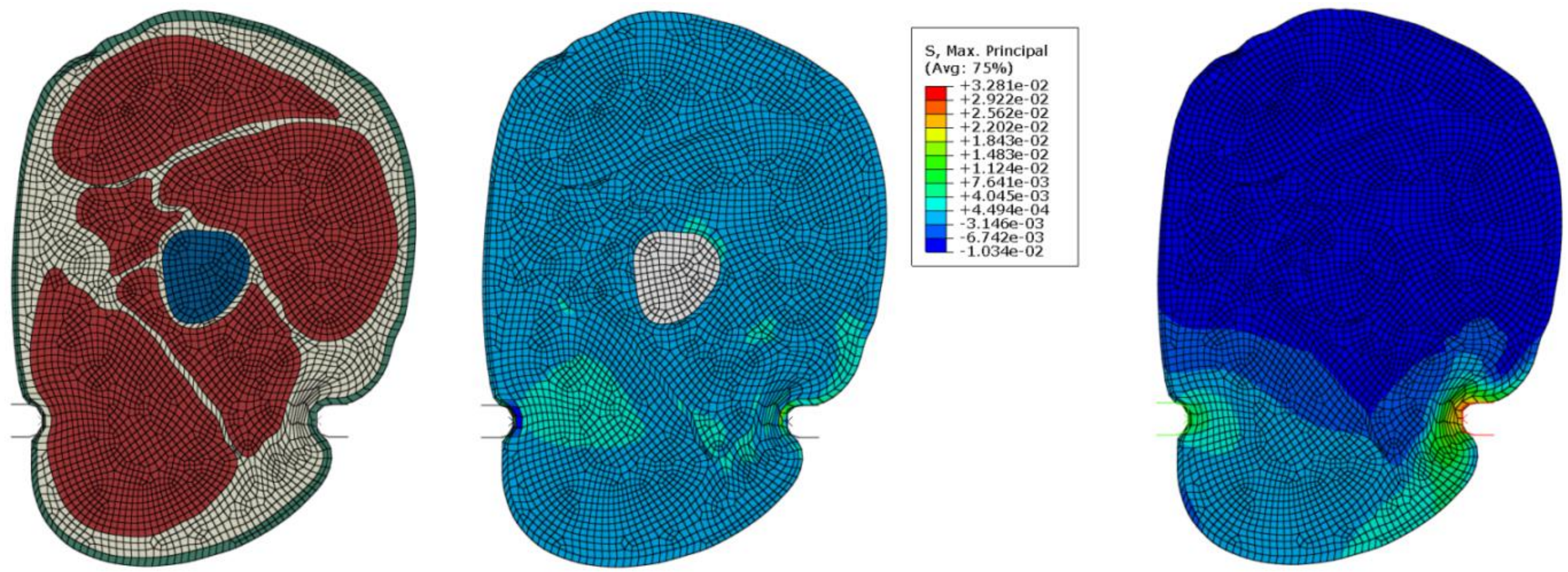
posterior

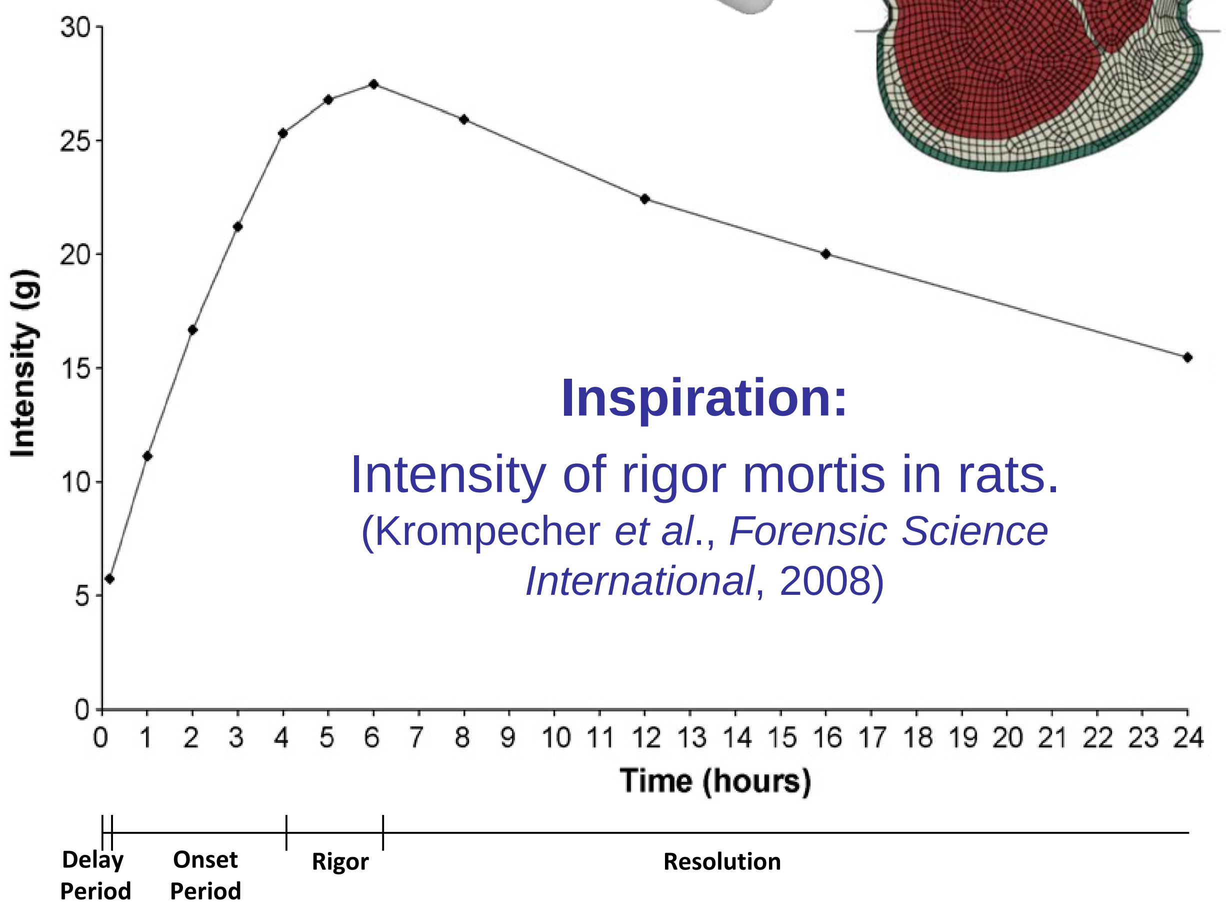


***(V Trindade et al.,** J Biomech, 2013)*

Estimation of cadaveric rigidity - Necromechanics







Inspiration:

Intensity of rigor mortis in rats.

(Krompecher *et al.*, *Forensic Science International*, 2008)

Measuring point: biceps brachii

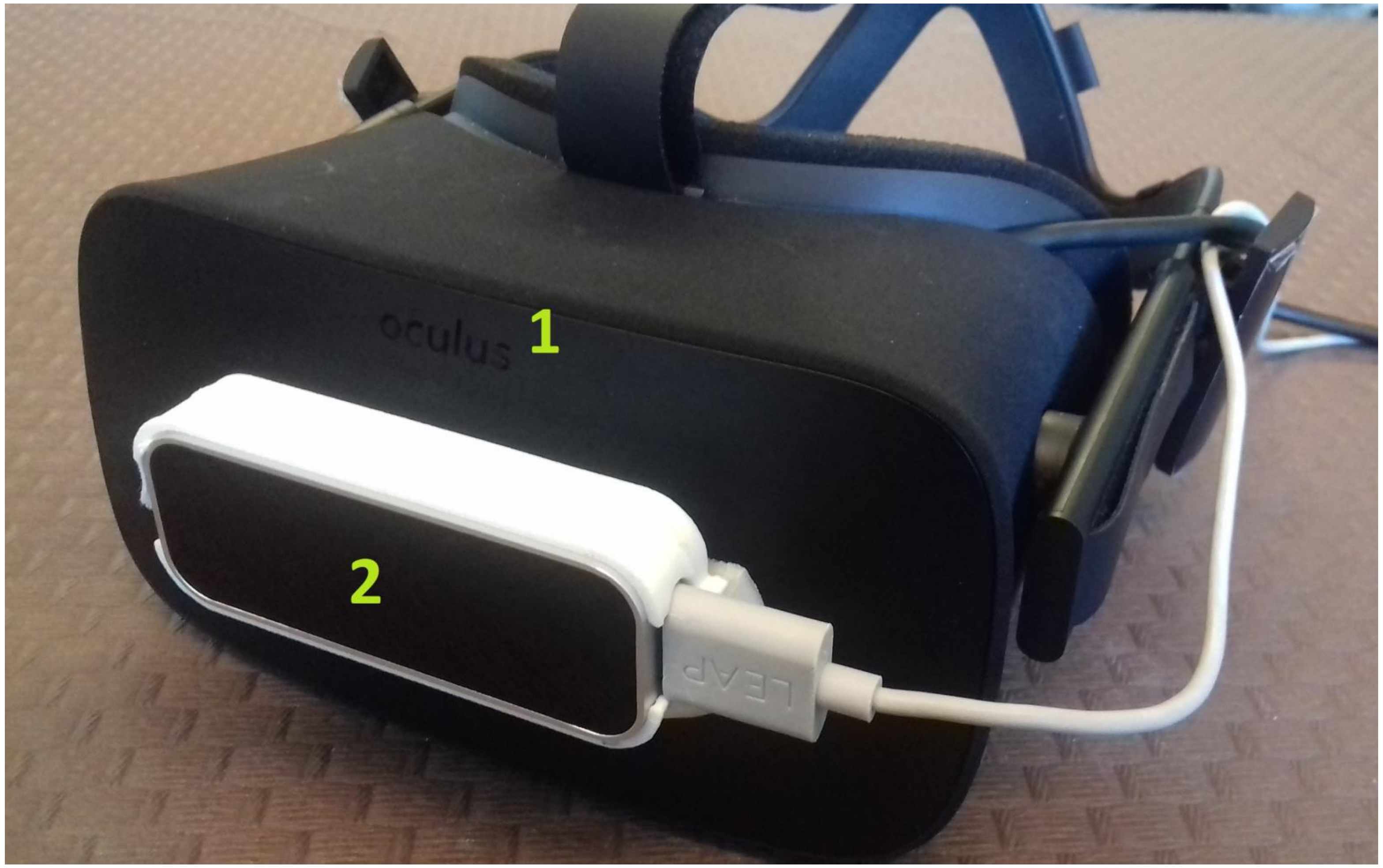
(P Martins et al., Proc IMechE Part H: J Eng Medicine, 2015)

Virtual Reality (VR) applied to Biomechanics

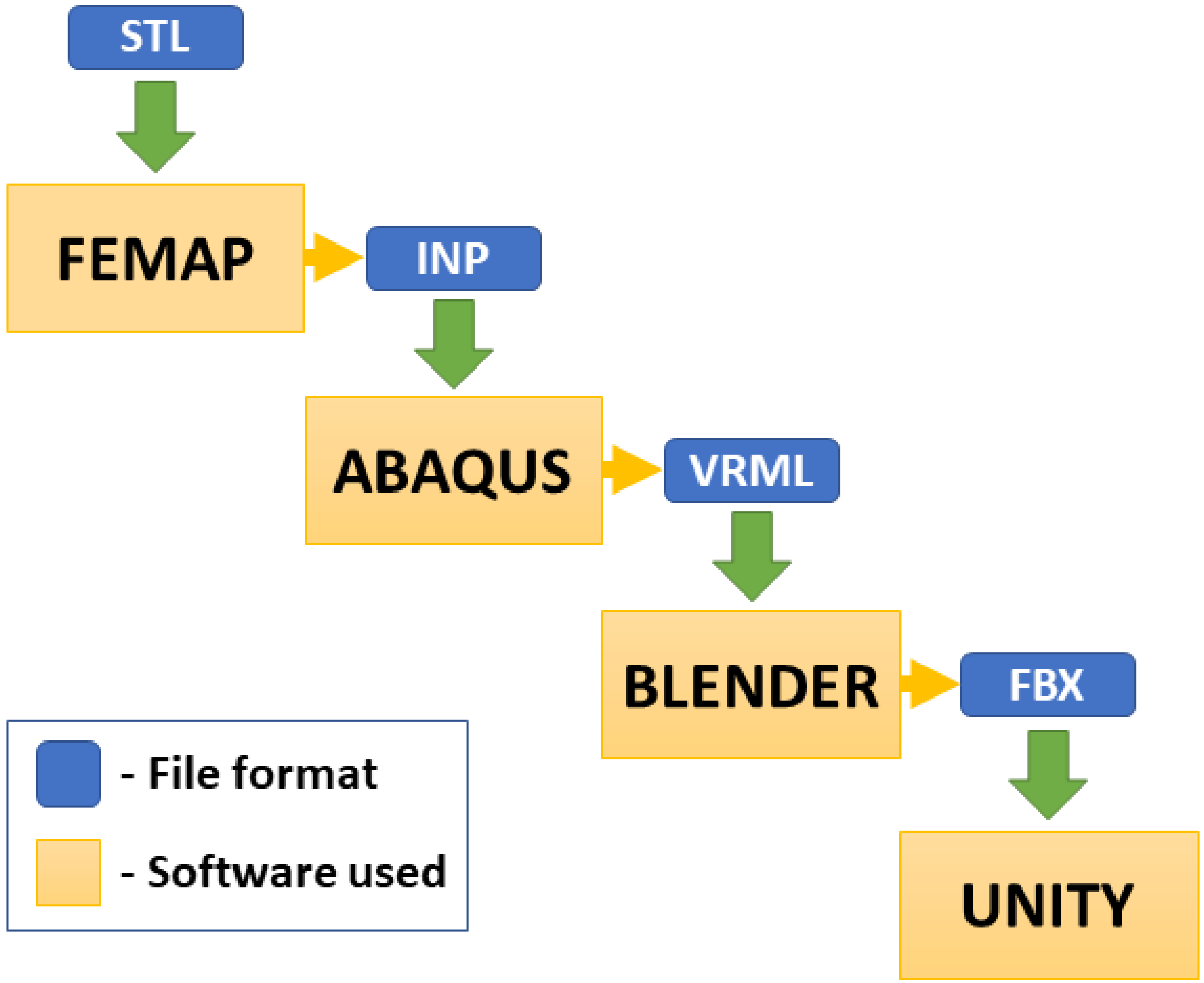
Setup used

1 – *Oculus Rift*

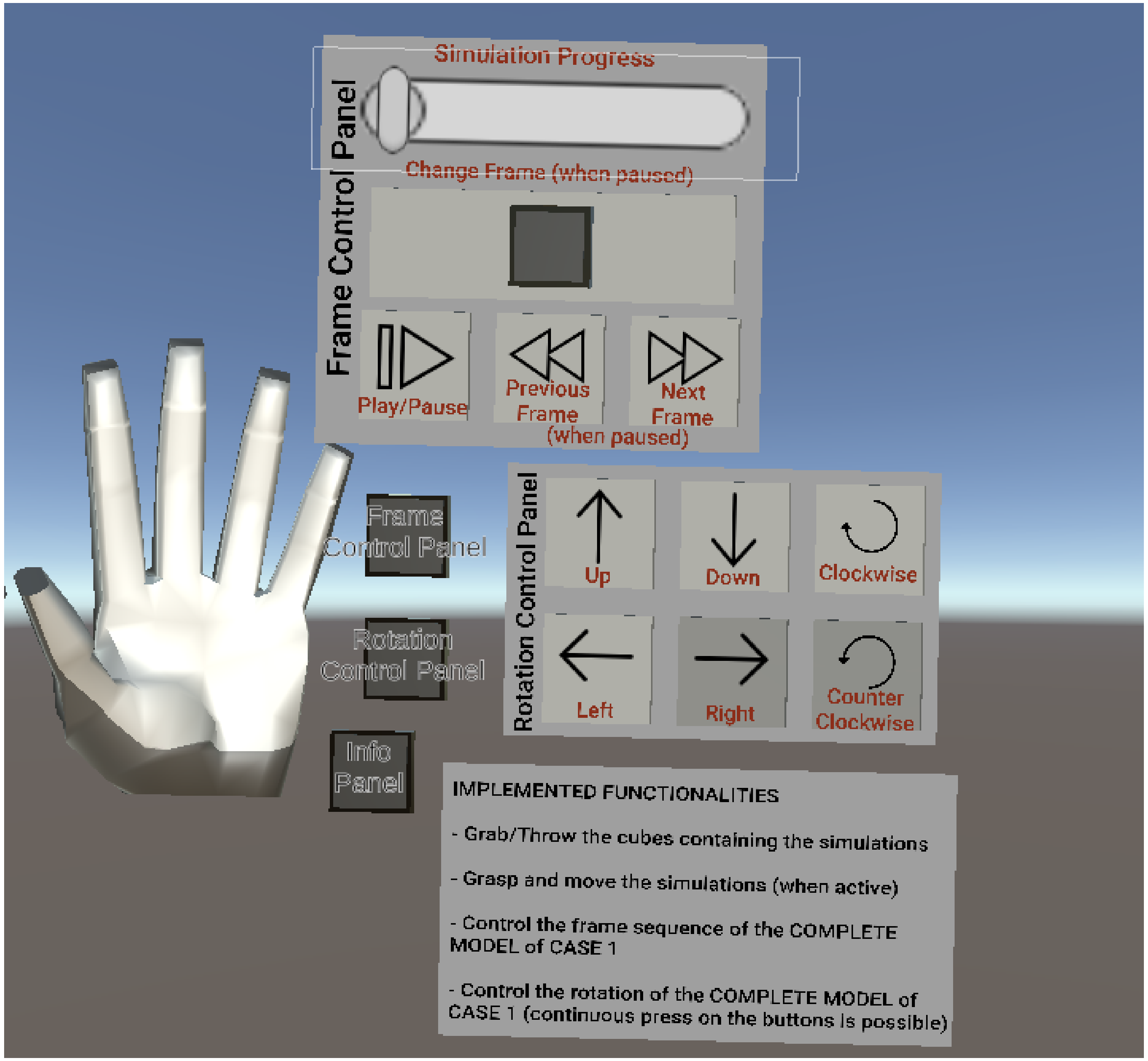
2 – *Leap Motion*



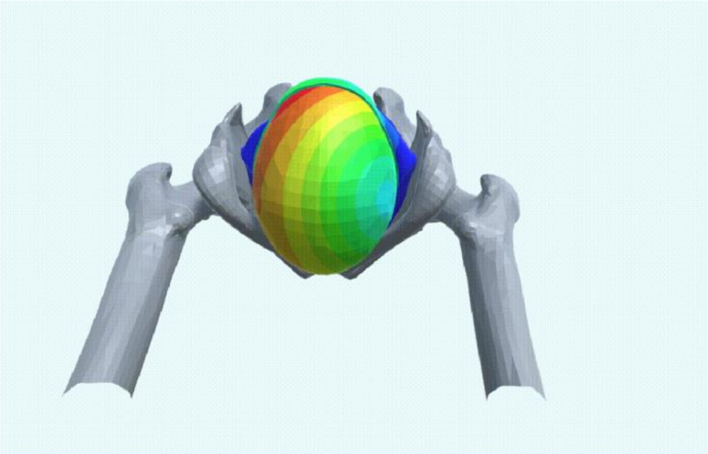
Methods


STL
FEMAP
INP
ABAQUS
VRML
BLENDER
FBX
UNITY
- File format
- Software used

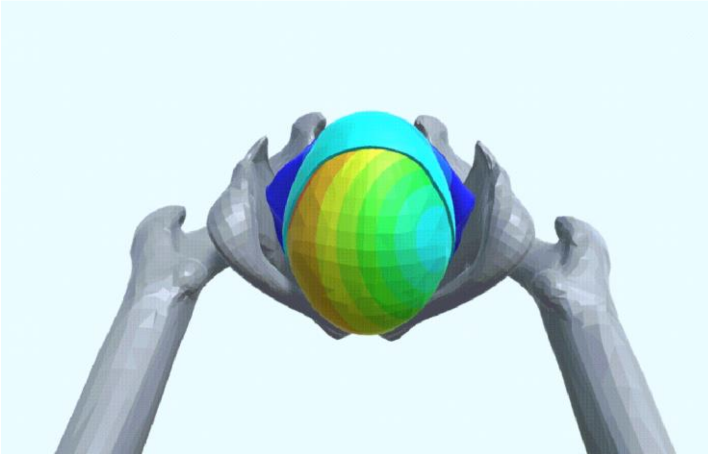
Implemented Menu



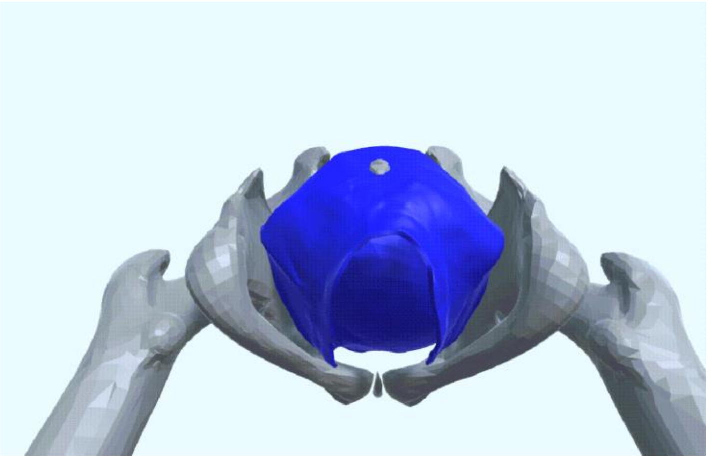
Some examples: implemented functions



Activation of the menu

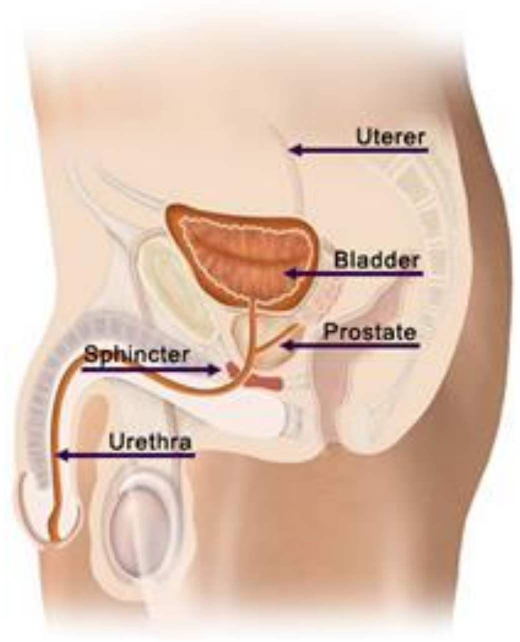


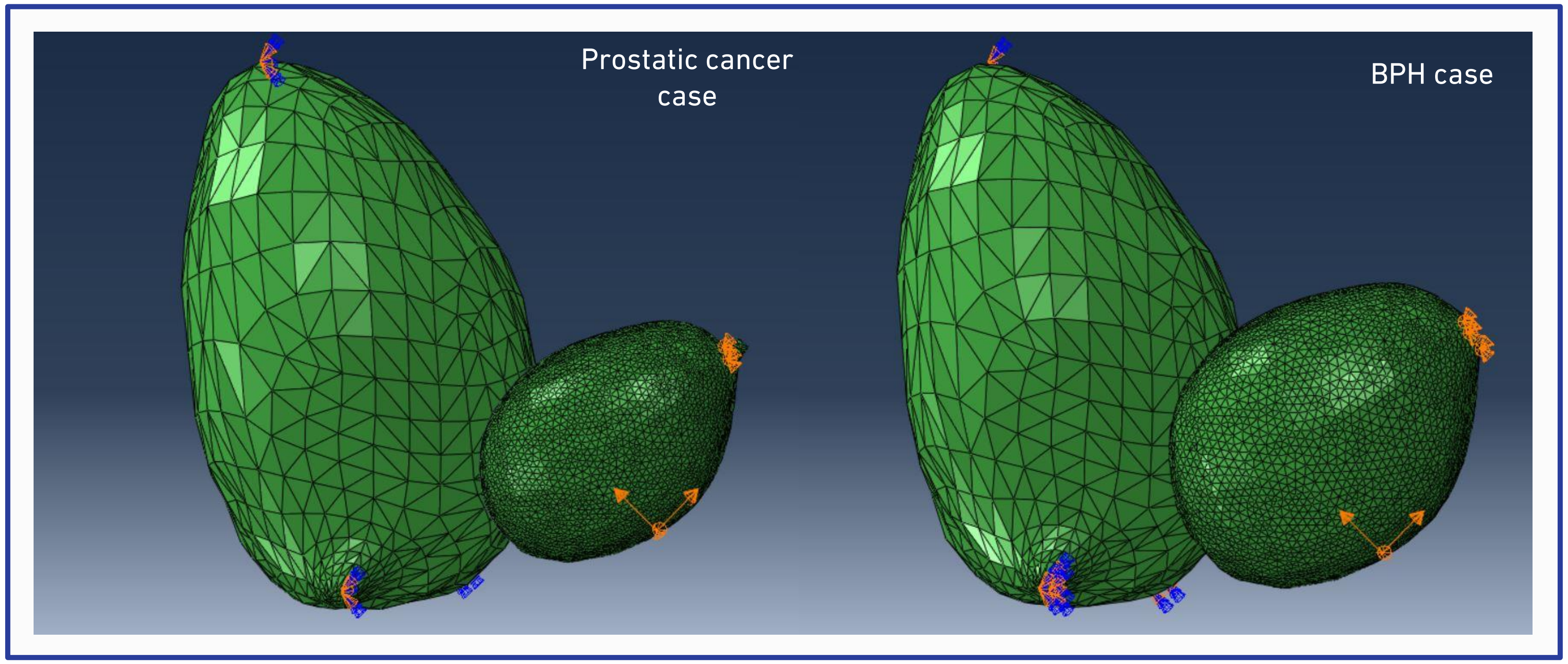
Model rotation

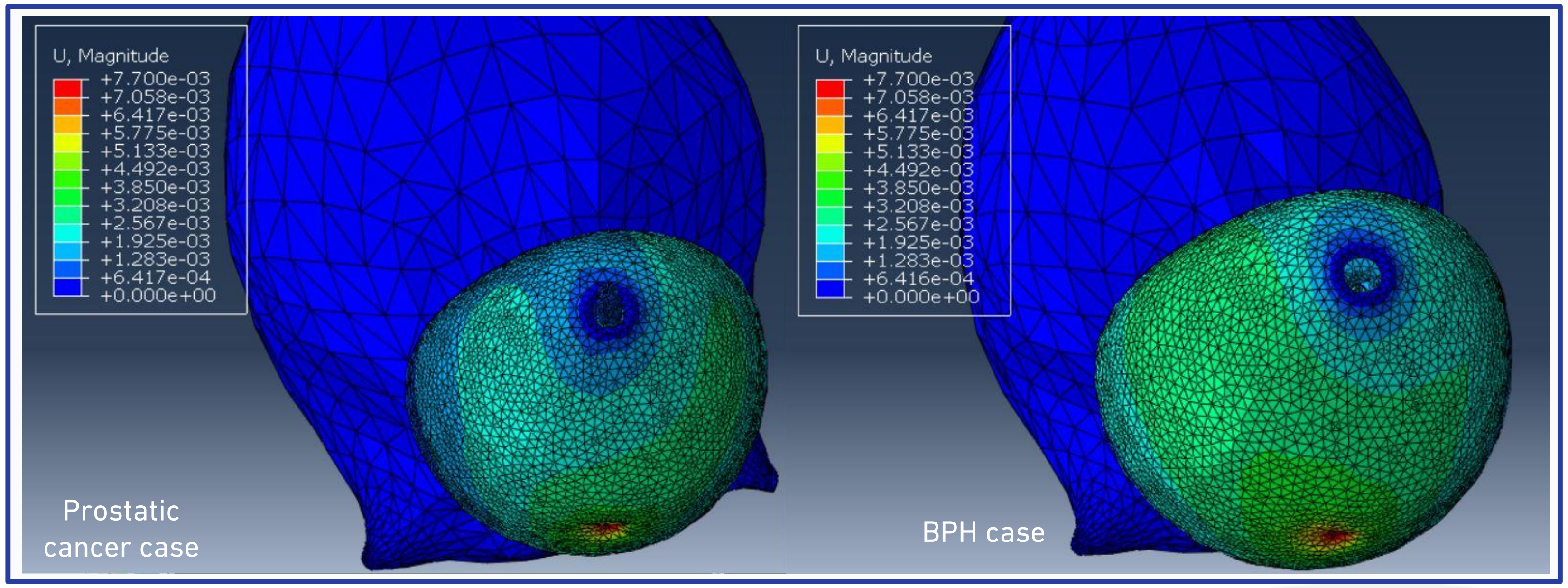


Model translation

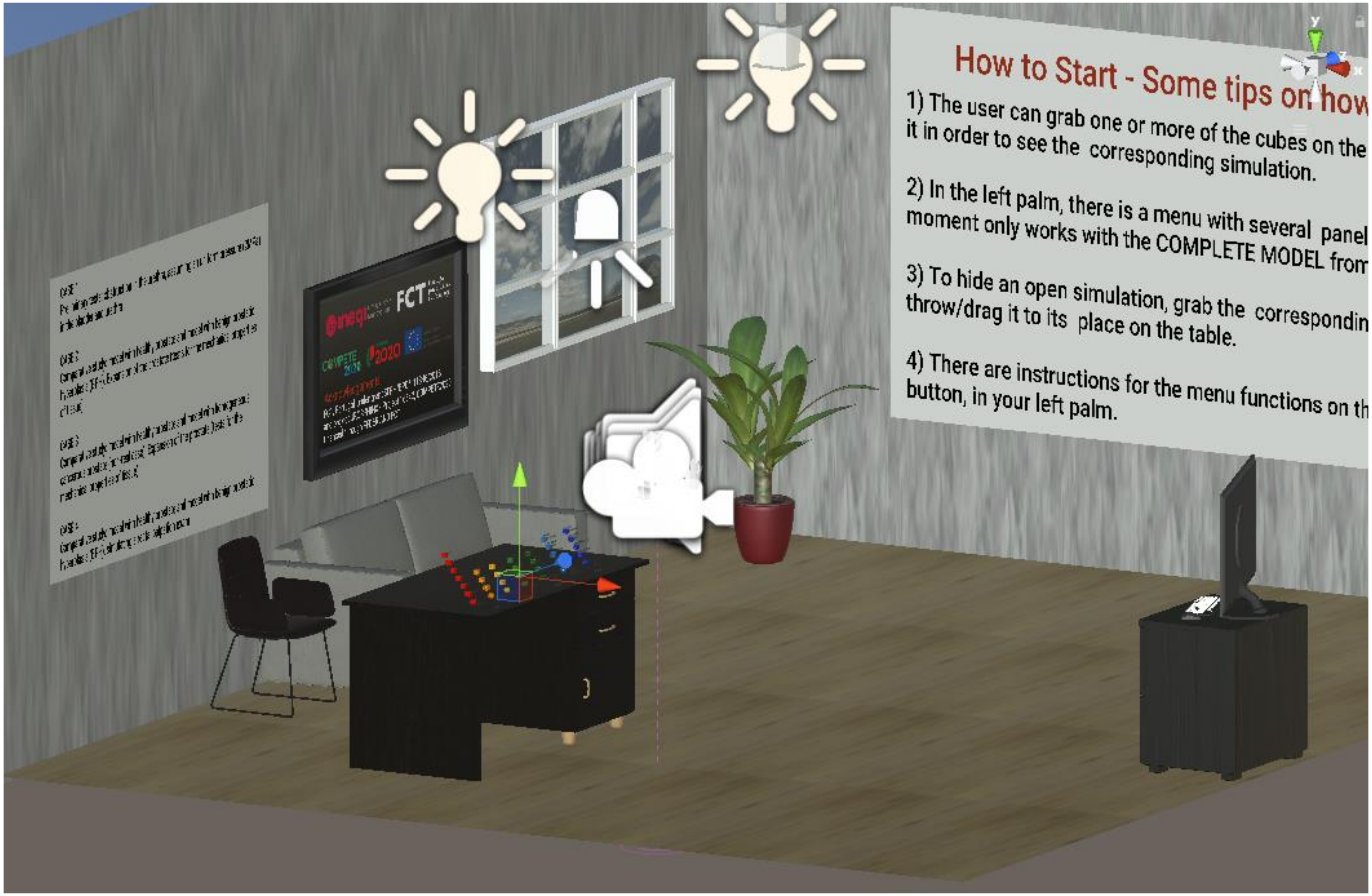
UROSPHINX – FCT Project – VR application







Constructed Environment

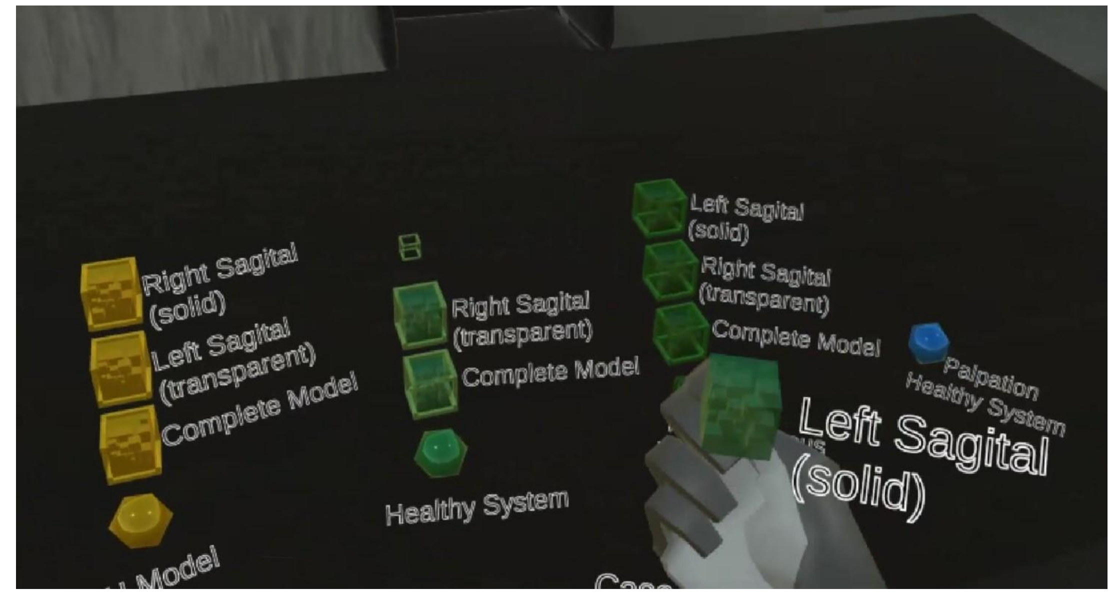


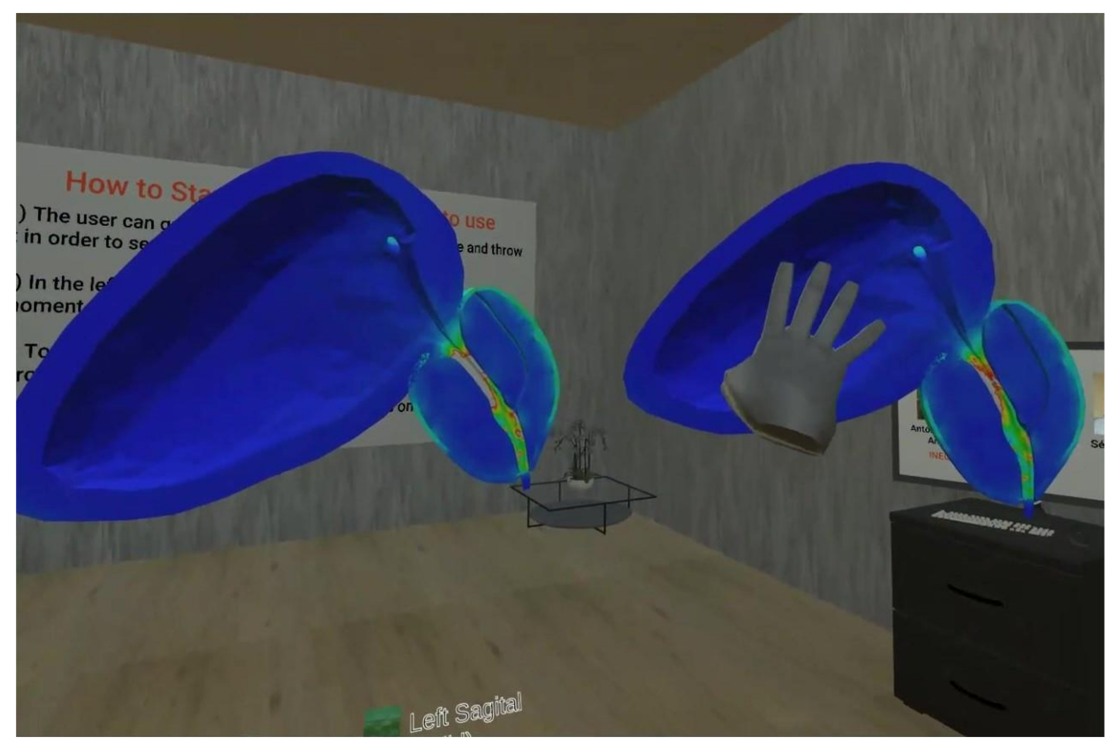
Results - I

- Application with:
  - multiple models
  - different pathologies
  - Interactive manipulation

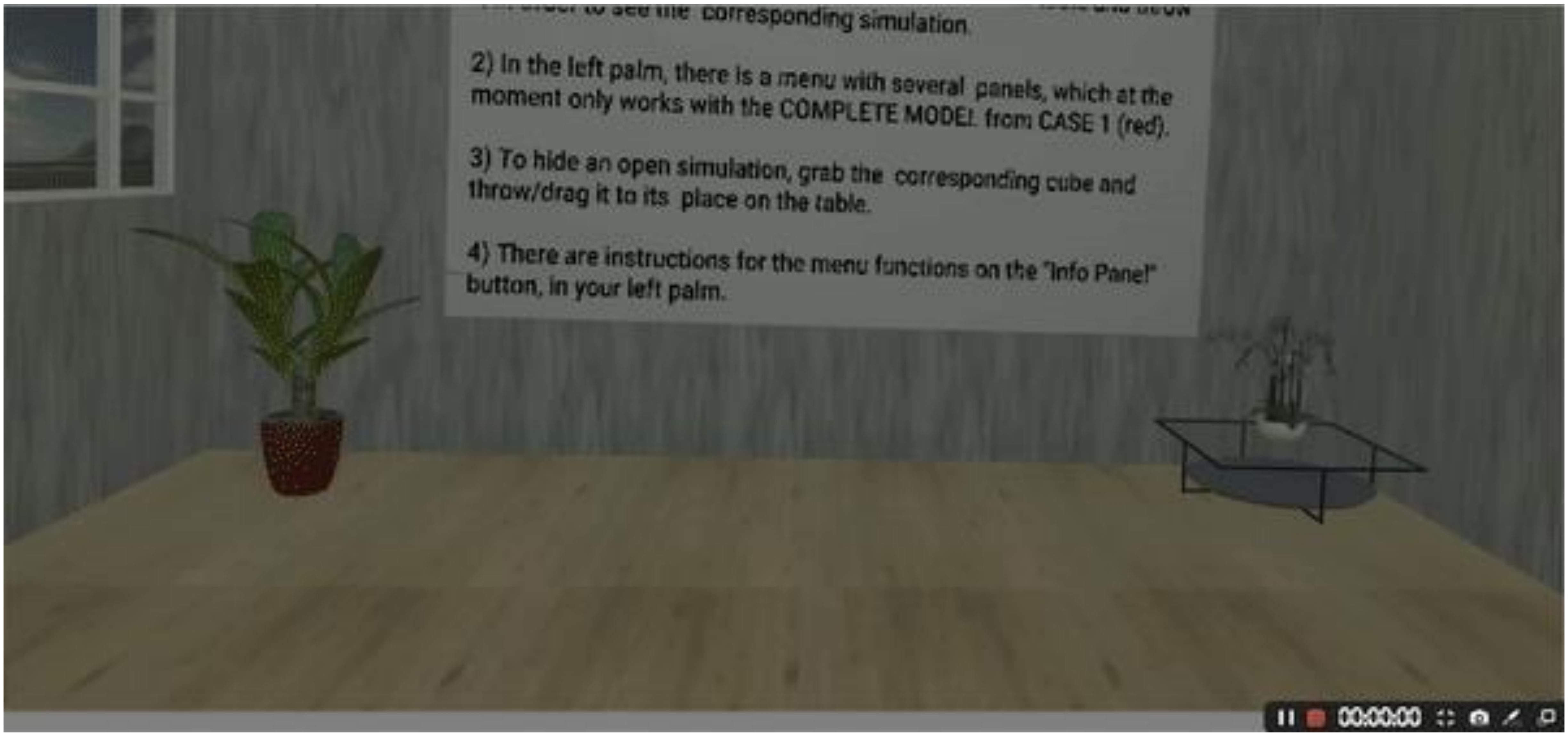
- 'on the fly' clinical case comparison

- Intuitive case storage and access.





Results - II


2) In the left palm, there is a menu with several panels, which at the moment only works with the COMPLETE MODEL from CASE 1 (red).
3) To hide an open simulation, grab the corresponding cube and throw/drag it to its place on the table.
4) There are instructions for the menu functions on the "Info Panel" button, in your left palm.
00:00:00

Acknowledgements

Funding from FCT, Portugal, under grant SFRH/BPD/111846/2015 and projects **UROSPHINX**/Project16842(COMPETE2020), and **MImBI** - PTDC/EME-APL/29875/2017 financed through FEDER and FCT, are gratefully acknowledged.

Thank you!