Living matter:

from biomechanical modeling to shape analysis

Scientific projet *Biomaterials*

V. Sansalone, V. Varano

Kick-off meeting of the IRP Coss&Vita
October 17, 2019, École des Ponts – ParisTech, Champs sur Marne

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Scientific project BIO

- Biomaterials: materials from and for the biological systems (*living* materials)

- Objective: to improve our understanding of the biomechanical behavior and physiological functions of biomaterials

- Responsibles: V. Sansalone (MSME, UPEC)
  V. Varano (LaMS, UR3)

Scientific project BIO

- Summary of activities
  - 8 scientific exchanges

    ~2 per year (in & out) = 15 weeks
  - 1 PhD student jointly supervised @ MSME & LaMS
  - 2 international meetings

    Bone biomechanics: multiscale and multiphysical aspects
    Rome, 2017 (jointly organized with IMOA federation)

    MS *Biomechanics of Growth & Remodeling* @ SB2017 (Reims)
  - 5 joint papers

Scientific project BIO

- Upcoming events
  - BIO-ELADYN Workshop

    Créteil, November 2020
  - Thematic session @ SB2020 (to be confirmed)

    Metz, October 26-28, 2020

Scientific project BIO

- Main scientific challenge (past & future):

  Understanding and modeling the functional adaptation of biomaterials

  – Living systems can adapt to their mechanical and biochemical environment

  – Functional adaptation … multiple scales!

Functional adaptation

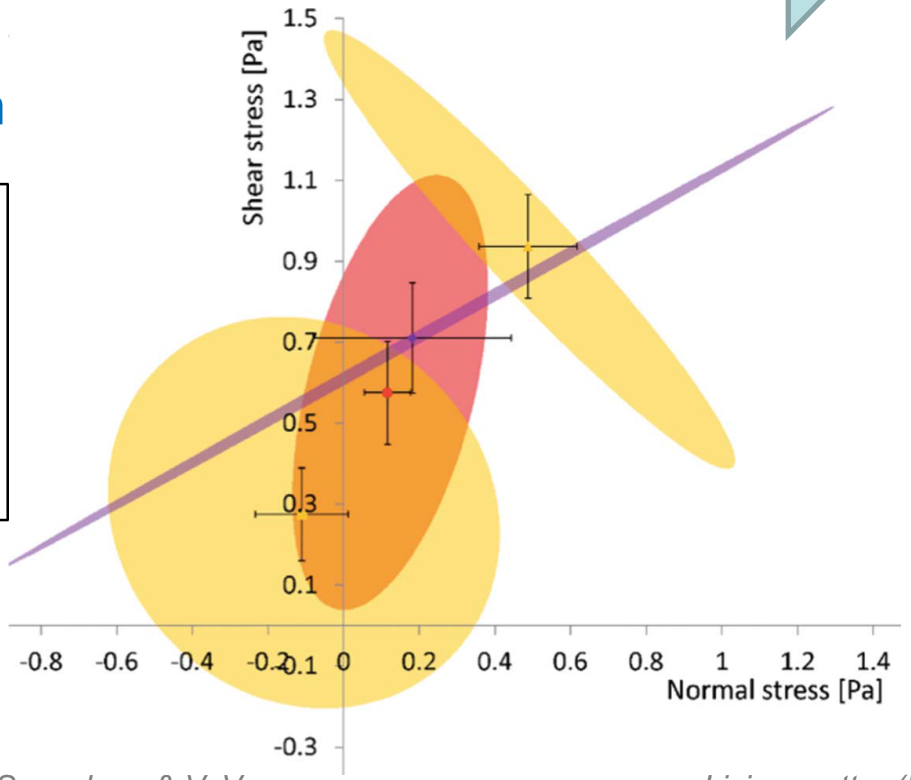
- Multiple length and time scales

Cell

Commitment, differentiation

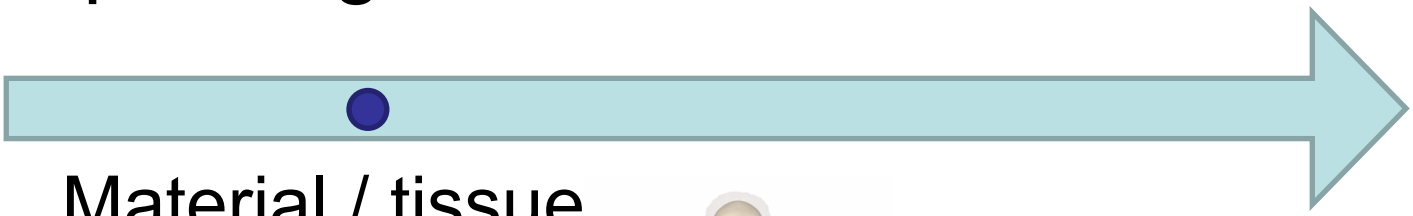
MSC lineage commitment

- Chondrogenesis
- Chondrogenesis and haematopoesis
- Chondrogenesis, haematopoesis and osteogenesis



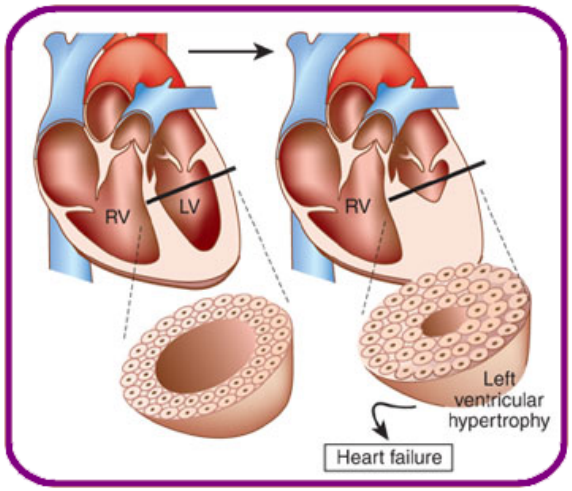
Functional adaptation

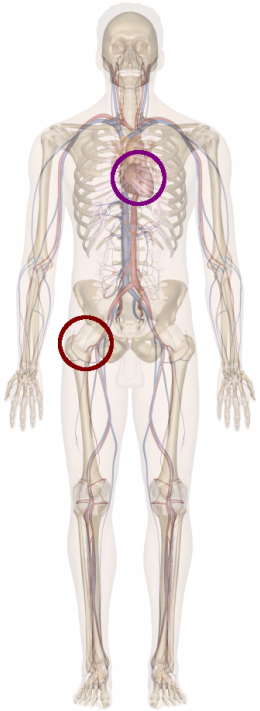
- Multiple length and time scales



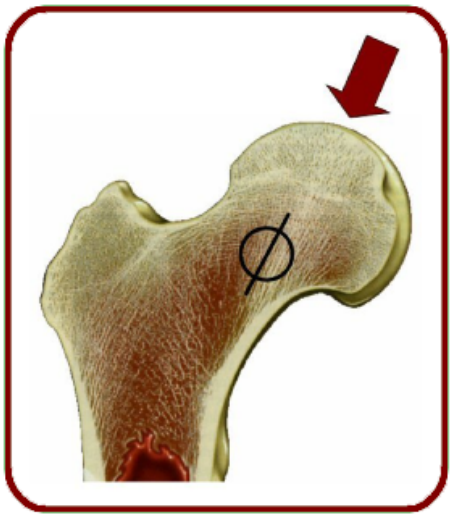
Material / tissue

Growth



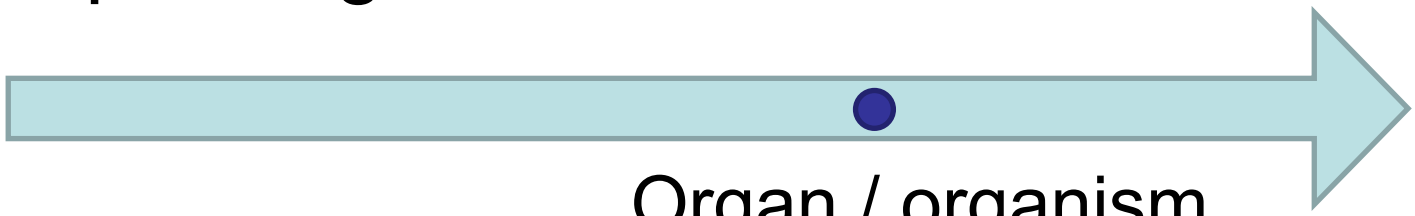


Remodeling



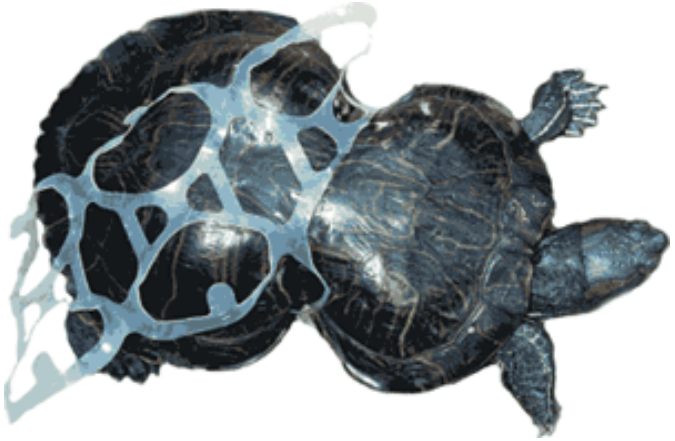
Functional adaptation

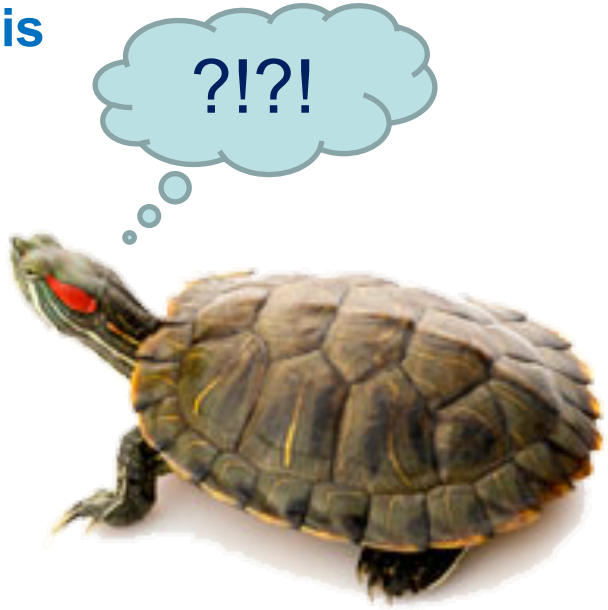
- Multiple length and time scales



Organ / organism

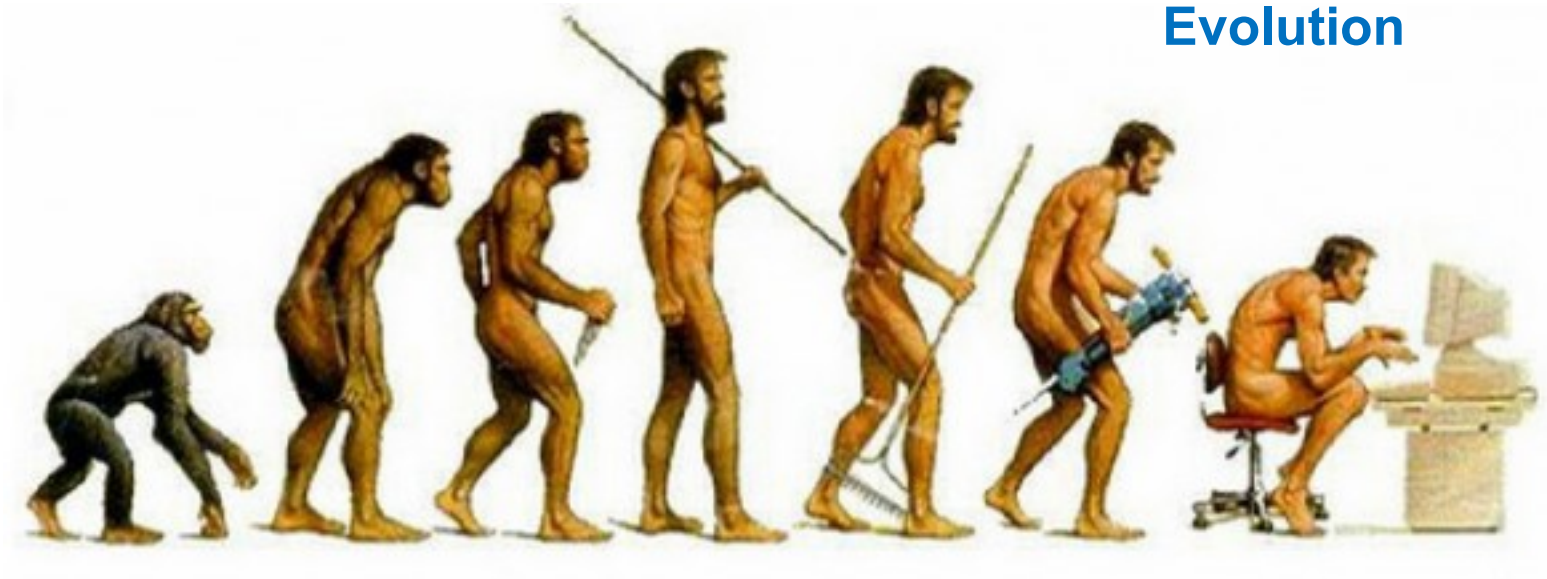
Morphogenesis



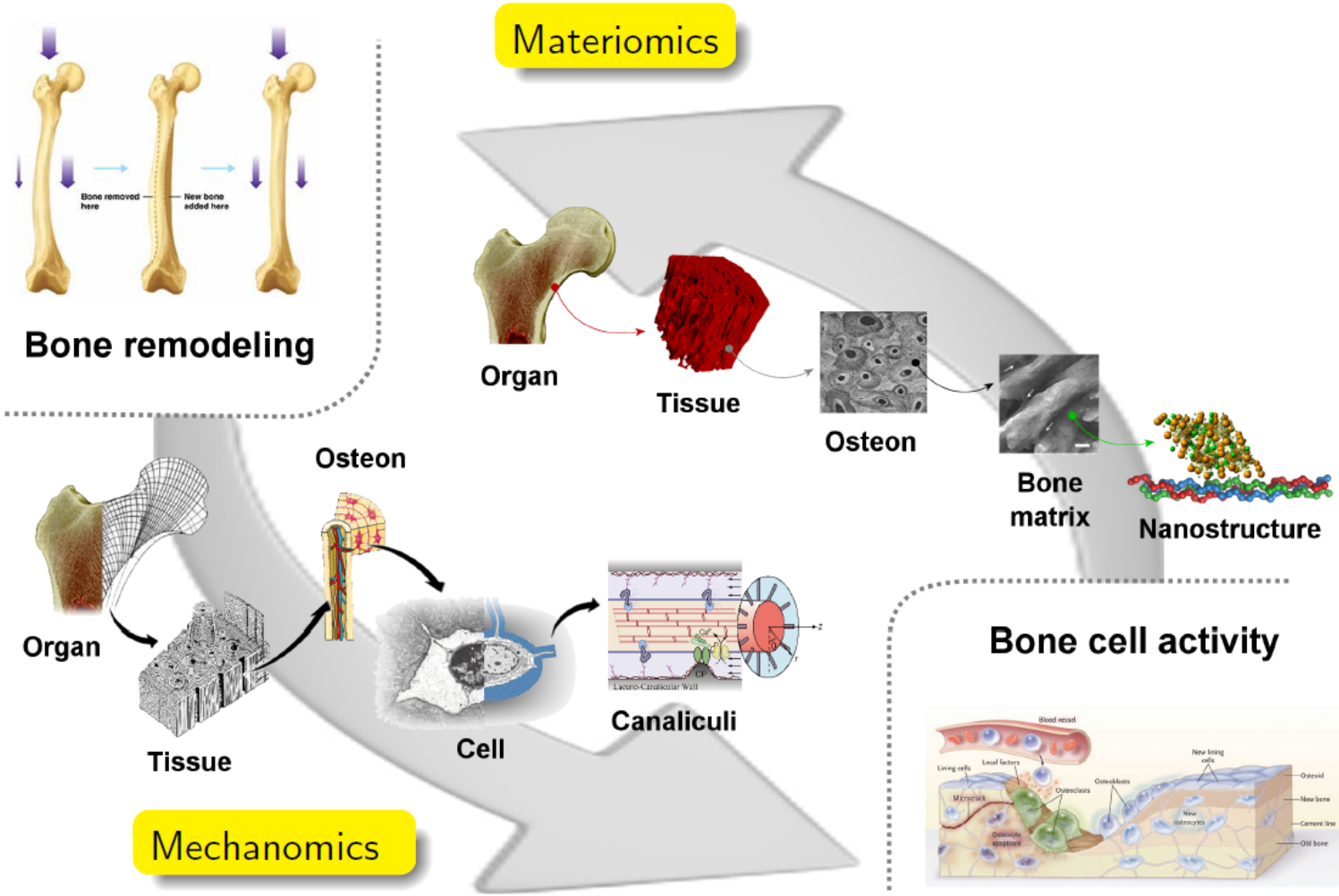


Functional adaptation

- Multiple length and time scales

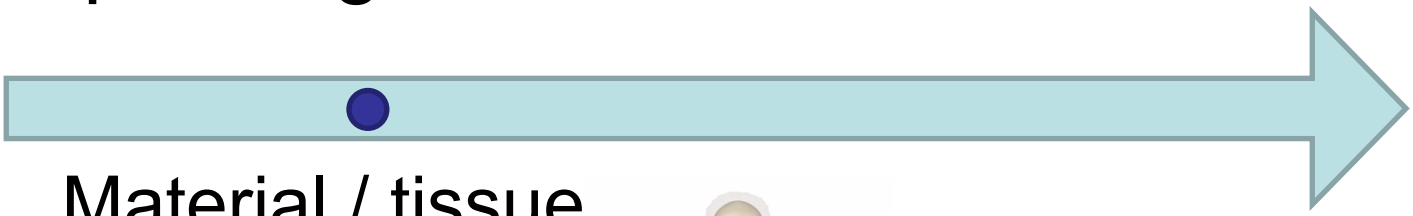


Functional adaptation



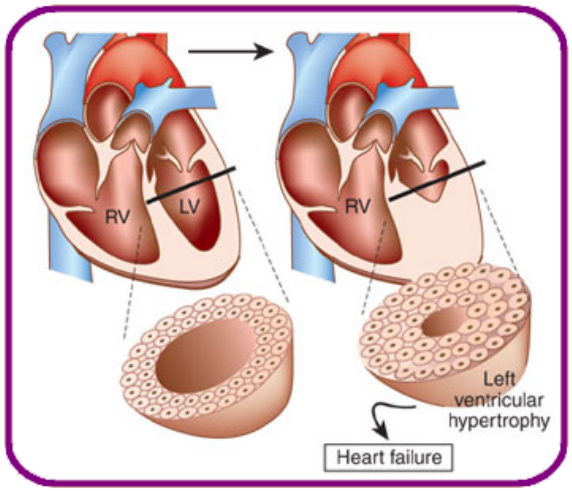
Functional adaptation

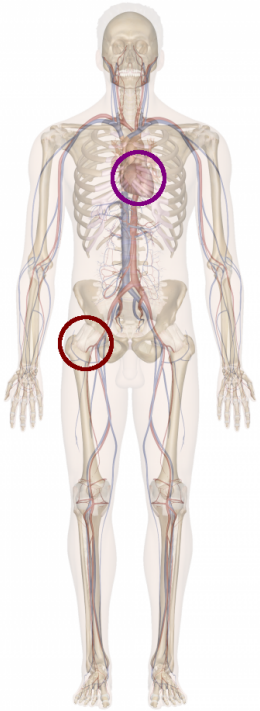
- Multiple length and time scales



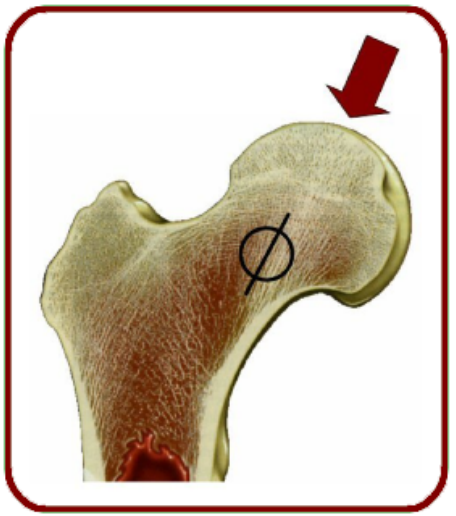
Material / tissue

Growth



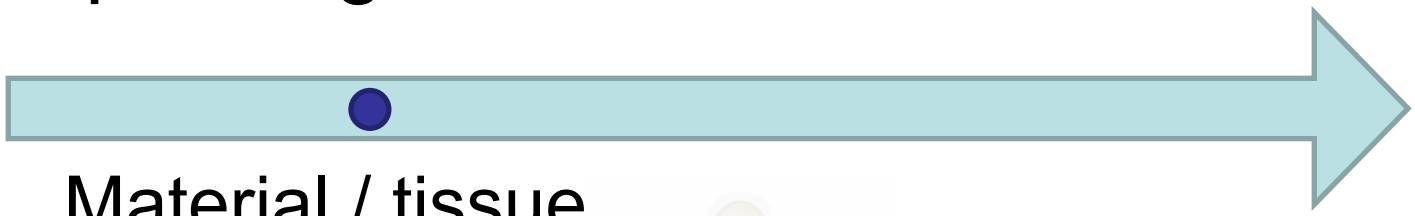


Remodeling



Functional adaptation

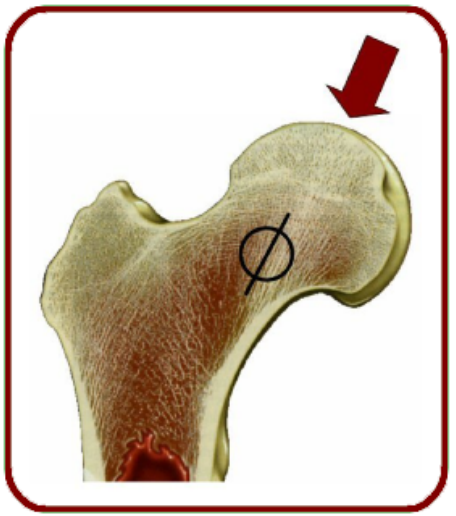
- Multiple length and time scales



Material / tissue

Growth

Remodeling



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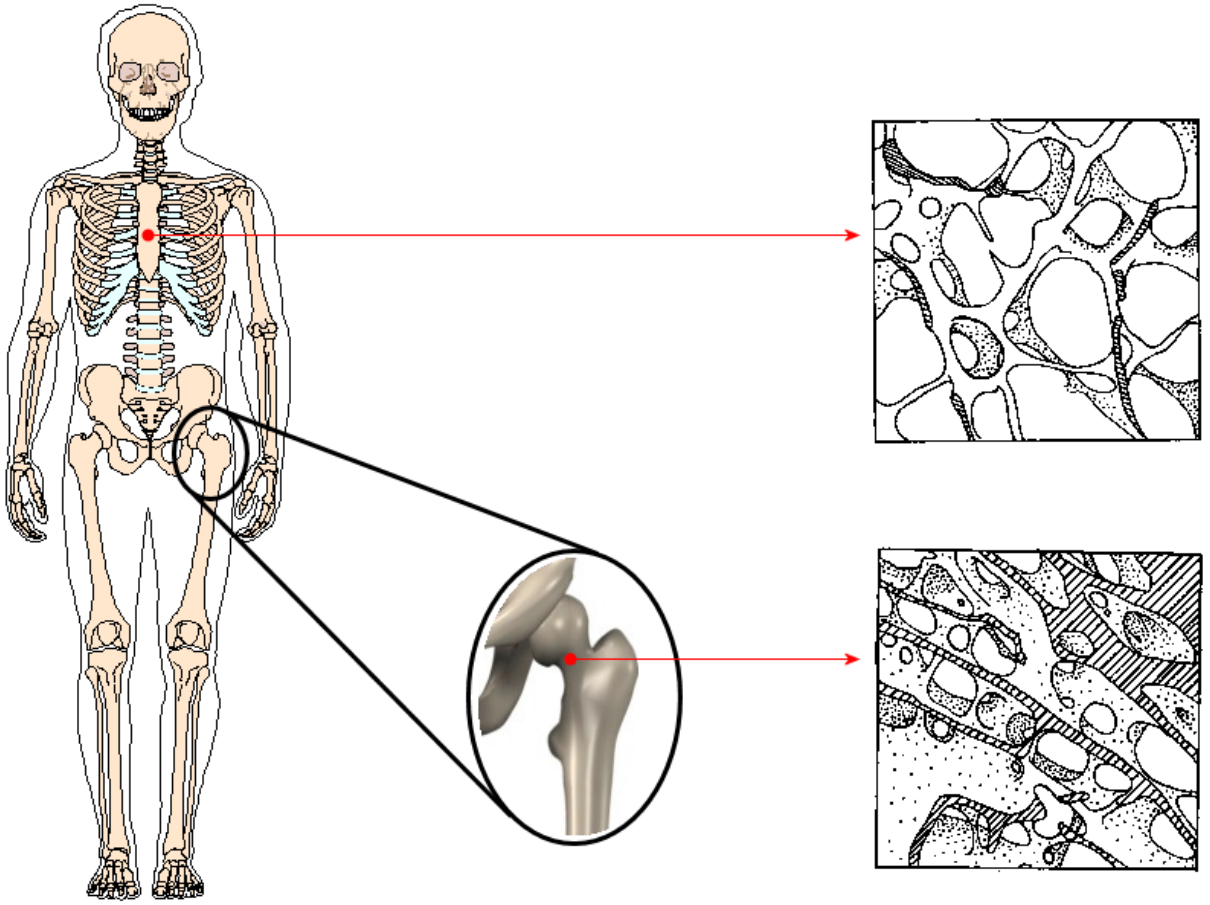
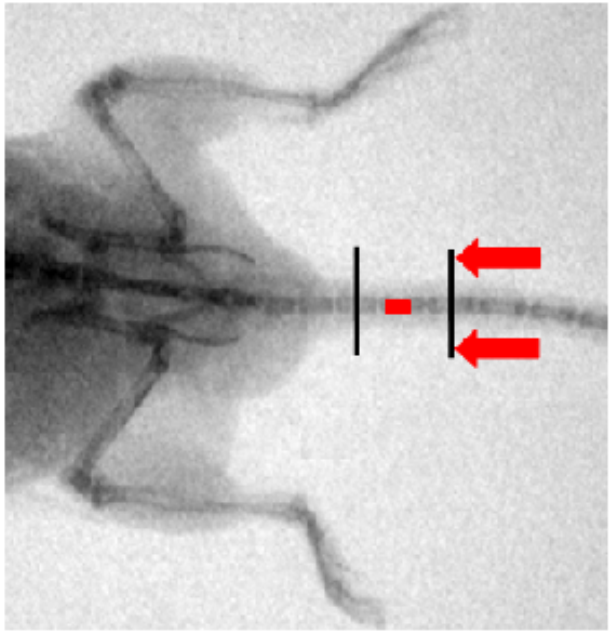
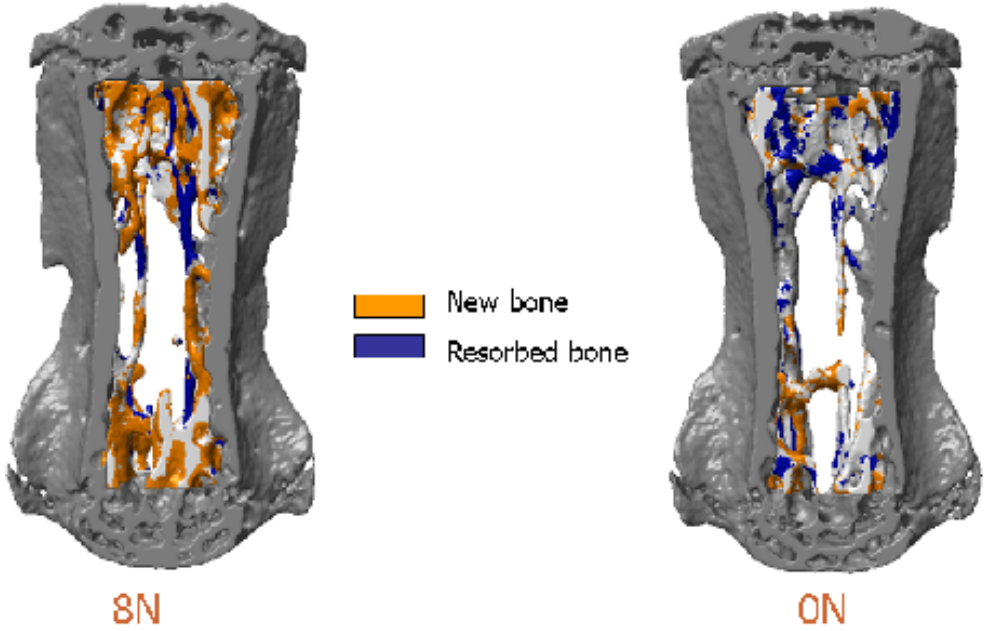


[Currey]

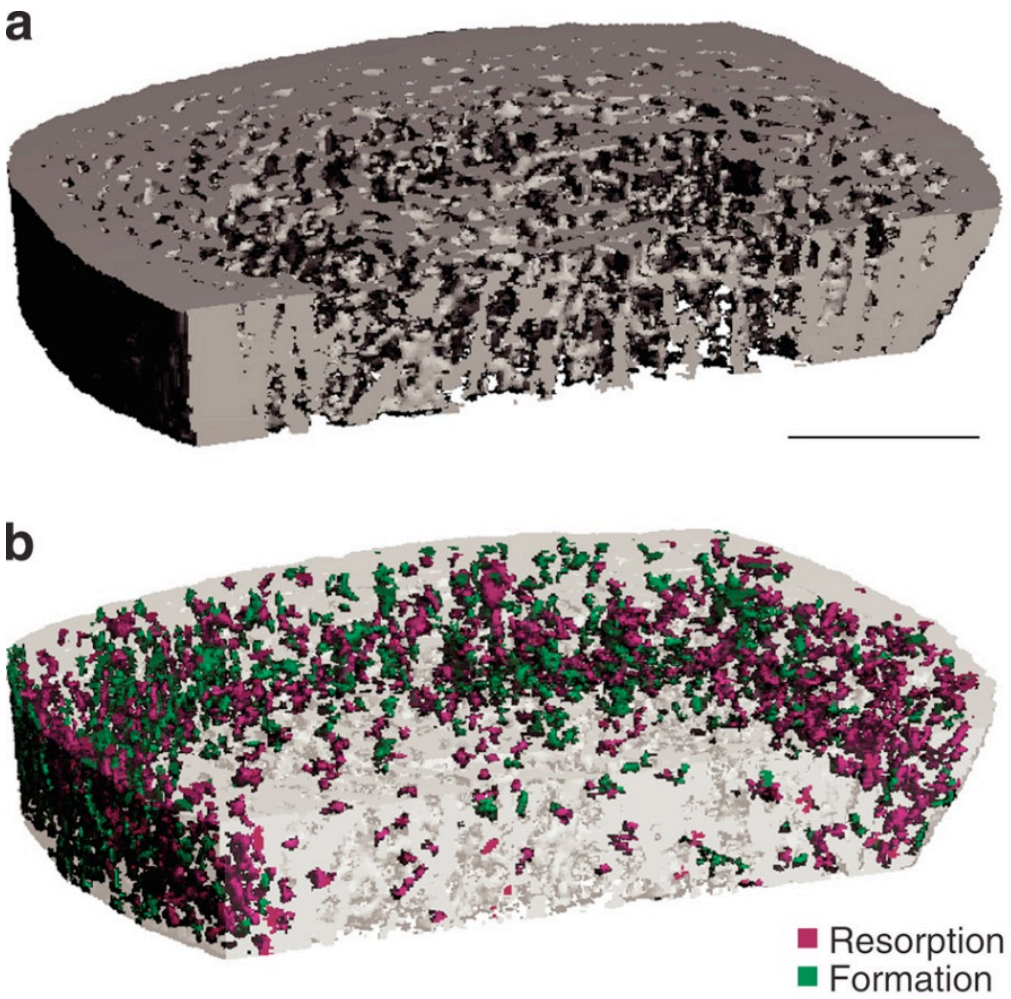
Remodeling





[Müller, ETH]

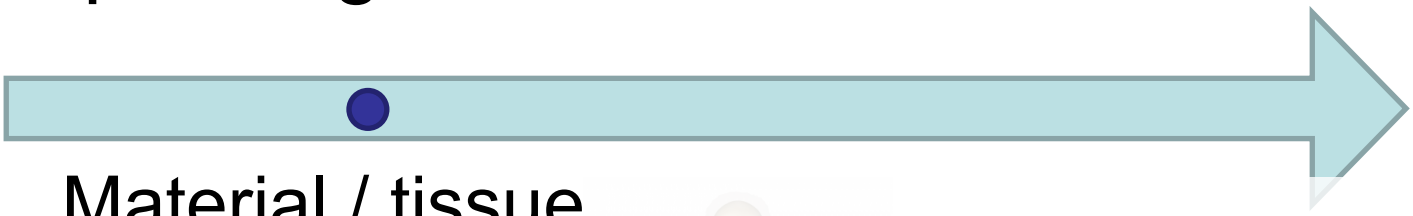
Remodeling



[Müller, ETH]

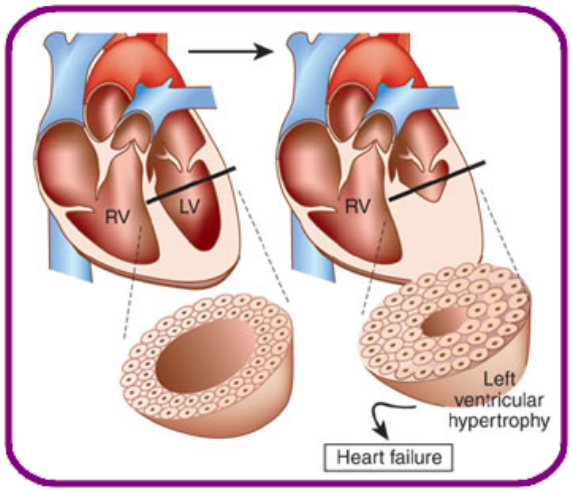
Functional adaptation

- Multiple length and time scales



Material / tissue

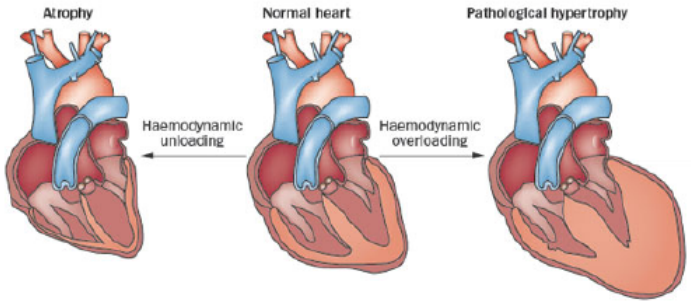
Growth



Remodeling

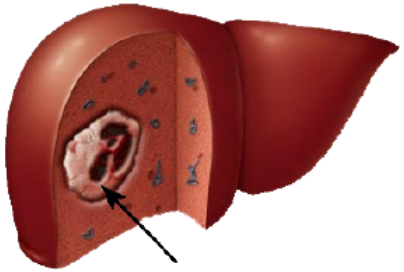
Growth

Heart

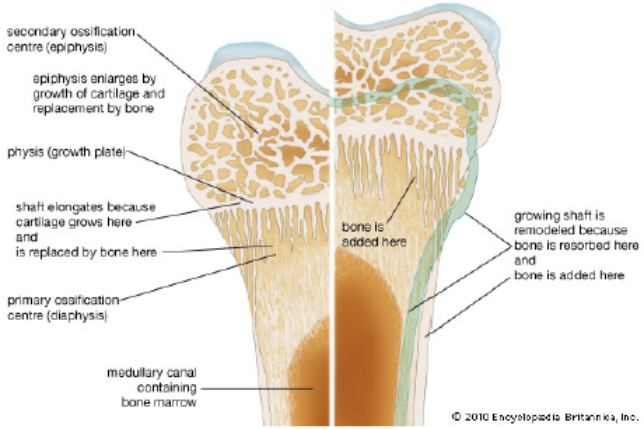


Aneurysm

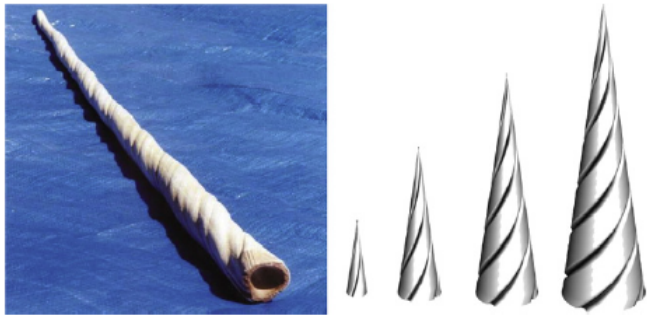
Tumor



Bone

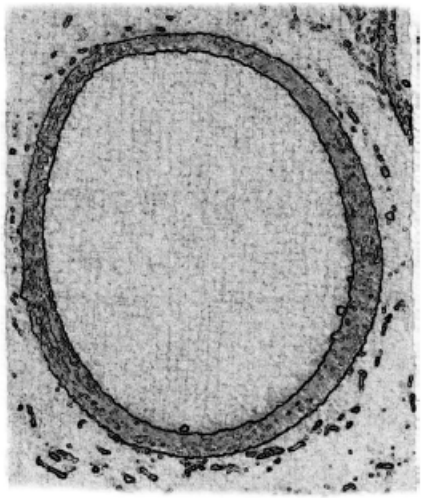


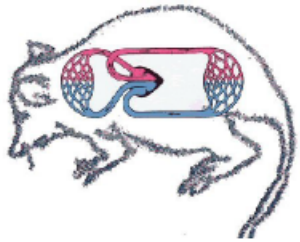
Shell



Growth

ex vivo

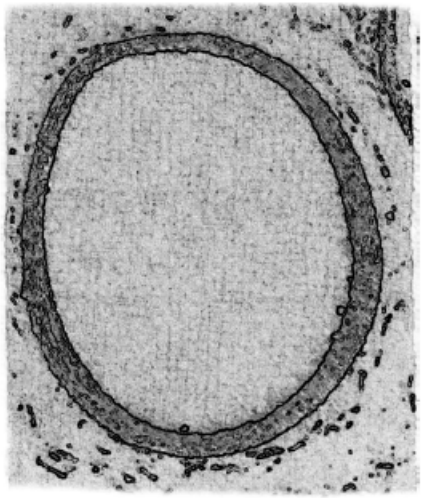


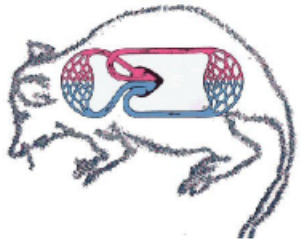


[Fung, 1993]

Growth

ex vivo





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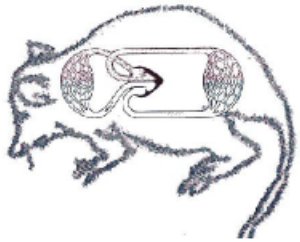
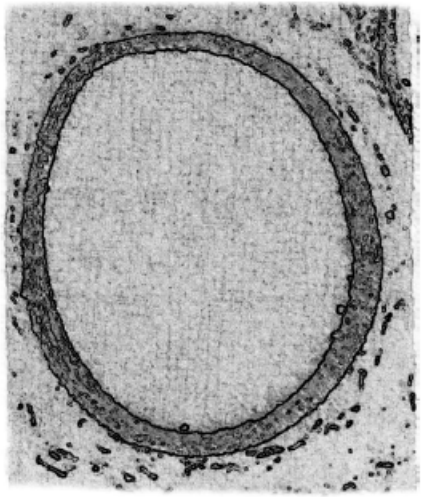
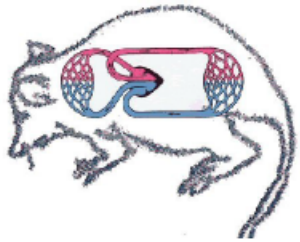


[Fung, 1993]

Growth

ex vivo





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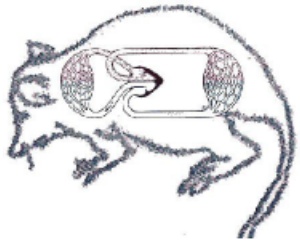
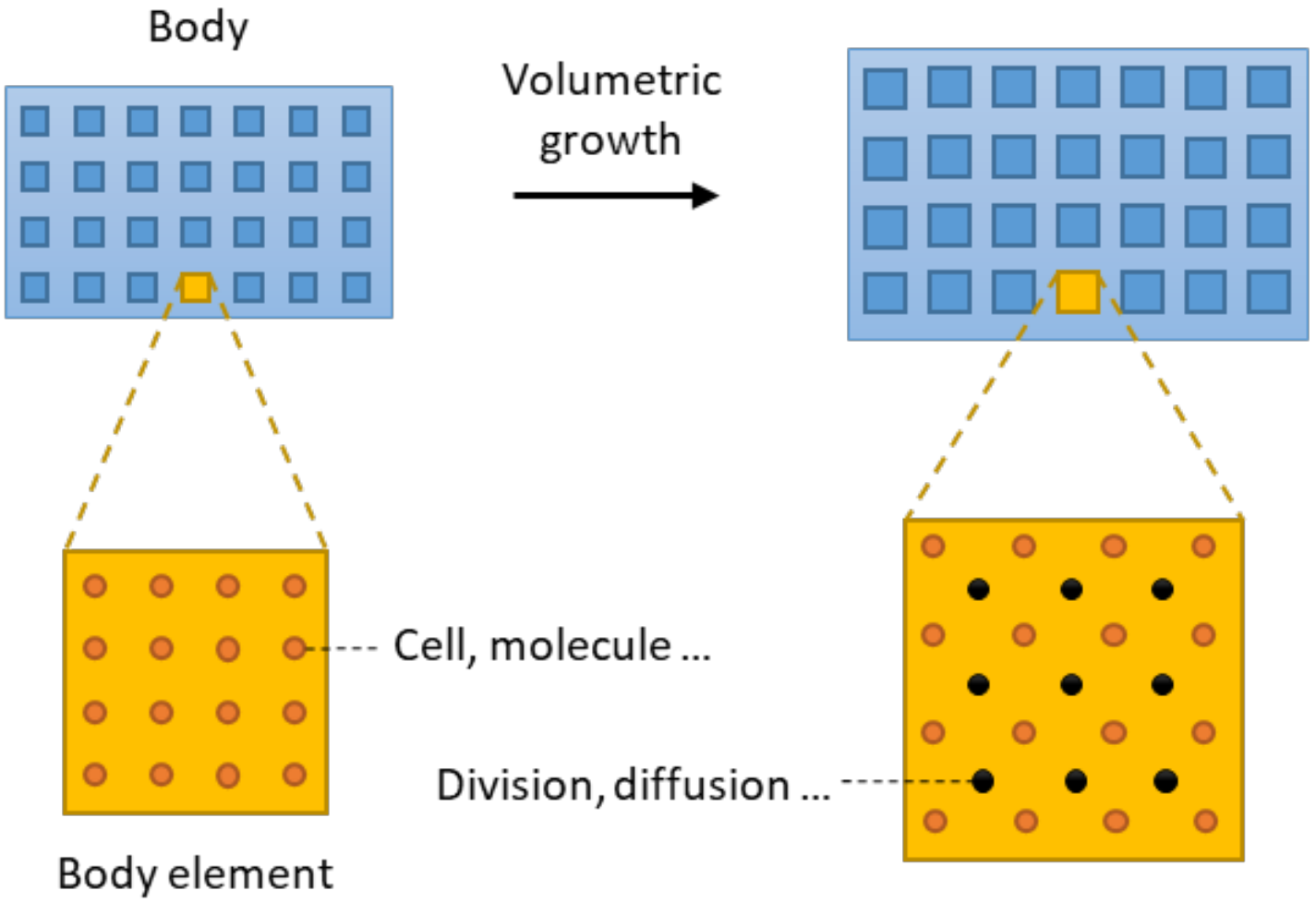


stress-free (?)

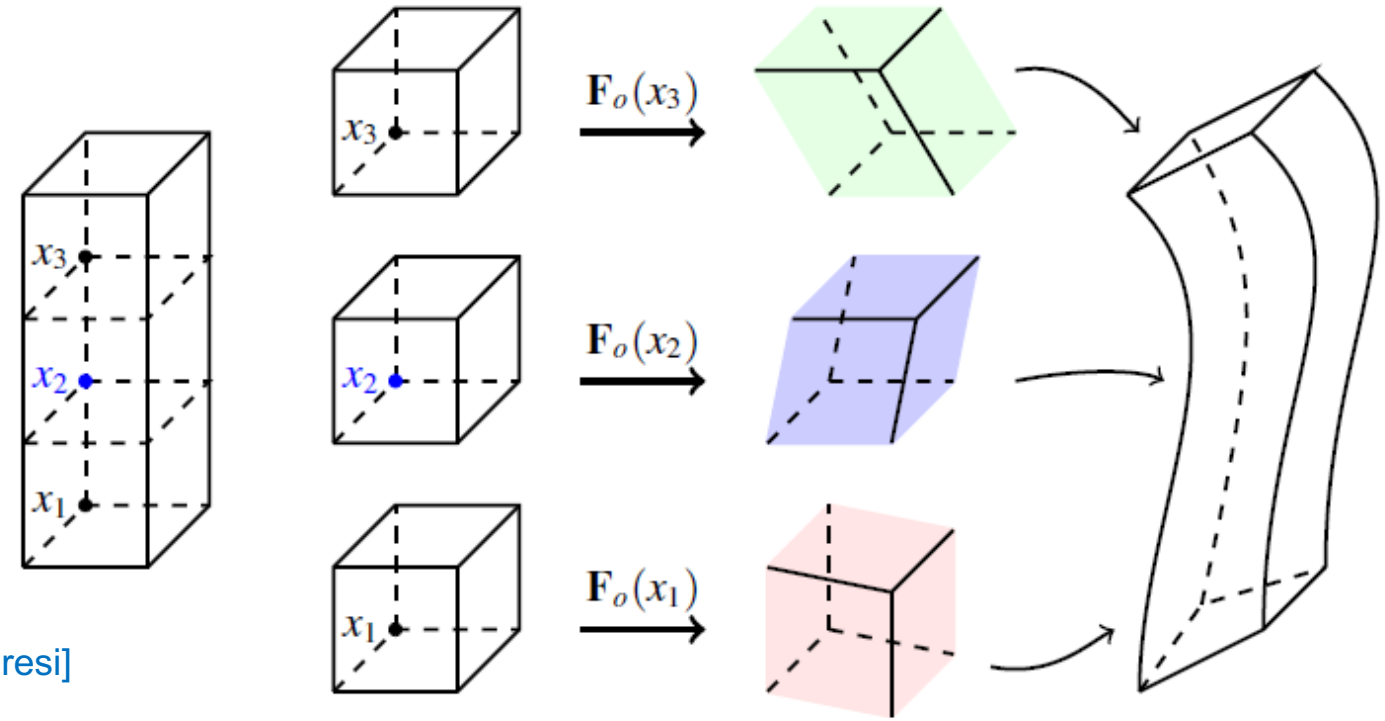
[Fung, 1993]

Growth


Body
Volumetric growth
Cell, molecule ...
Division, diffusion ...
Body element

Growth

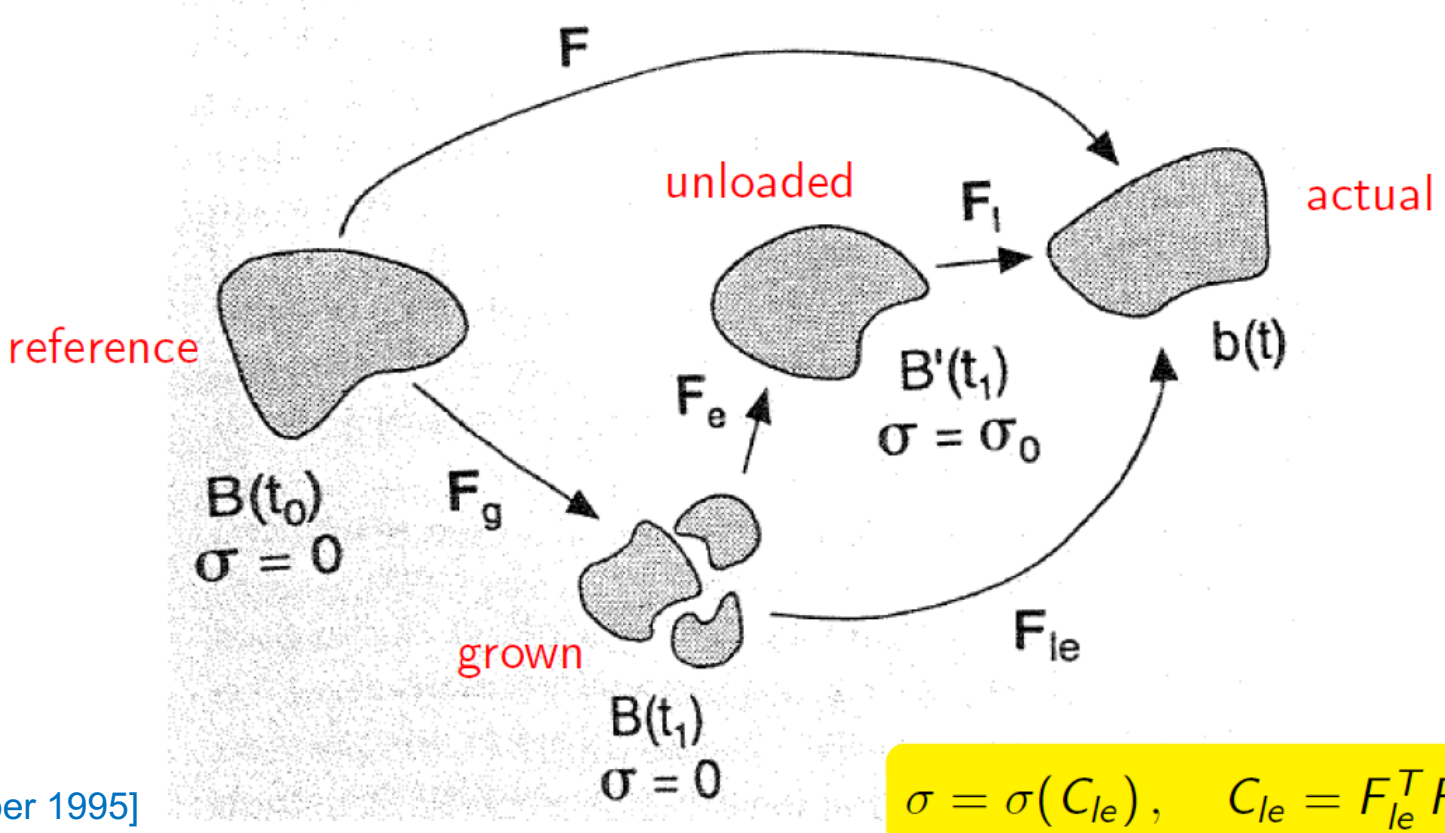
- Growth deformation: incompatible, stress-free
- Unloaded deformation: compatible, residual stress



[Teresi]

Growth

- Biomechanical modeling: *kinematics*



[Taber 1995]

$$\sigma = \sigma(C_{le}), \quad C_{le} = F_{le}^T F_{le}$$

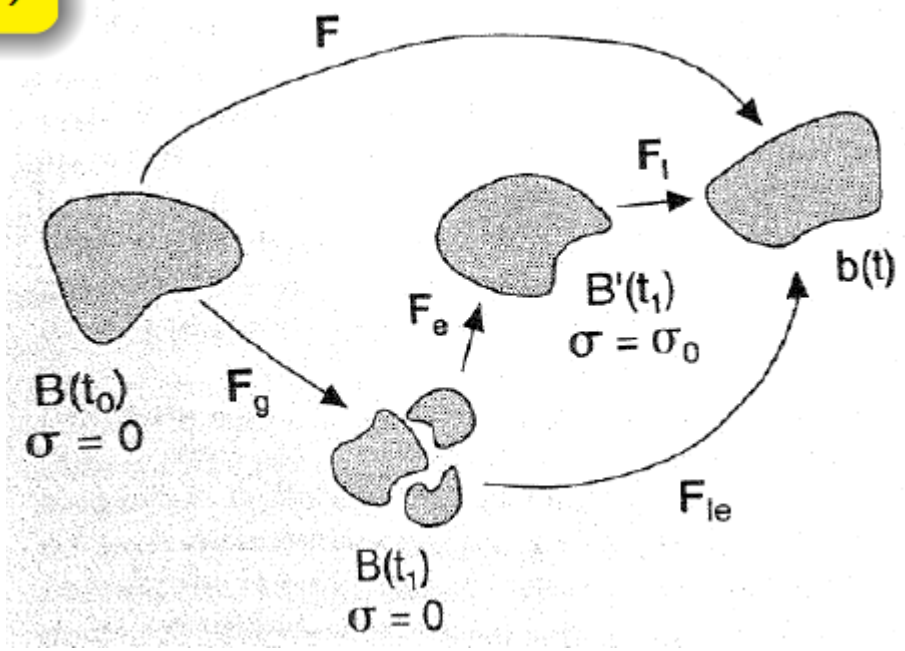
Growth

- Biomechanical modeling: *growth law*

$$\dot{F}_g = \dot{F}_g(\sigma - \sigma^{\odot})$$

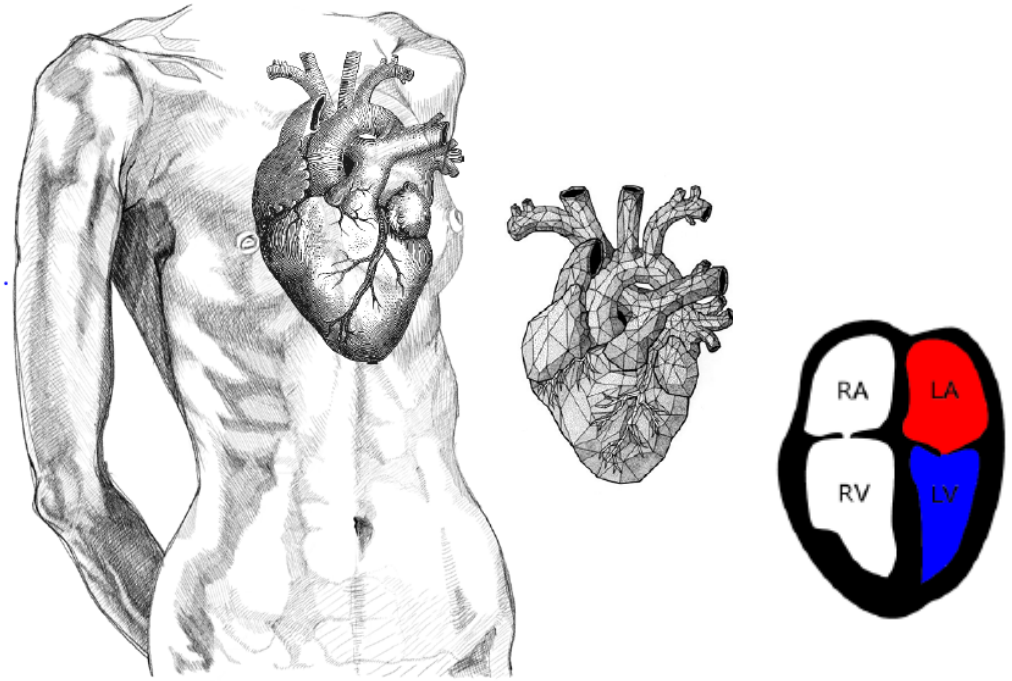
- Growth stimulus: σ
  - Stress / strain
  - Stress / strain rate
  - Energy density

- Equilibrium state: $\sigma^{\odot}$



IRP Coss&Vita active project

Biomechanical modeling of the left human heart for early diagnosis of heart pathologies



IRP Coss&Vita active project

Biomechanical modeling of the left human heart for early diagnosis of heart pathologies

- PhD work of J.I. Colorado-Cervantes (2016-…)
  Directors: V. Sansalone (MSME, UPEC)
  L. Teresi (LaMS, UR3)

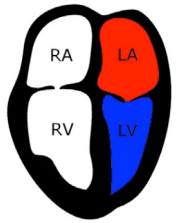
MSME Laboratoire Modélisation et Simulation Multi Echelle

UPEC

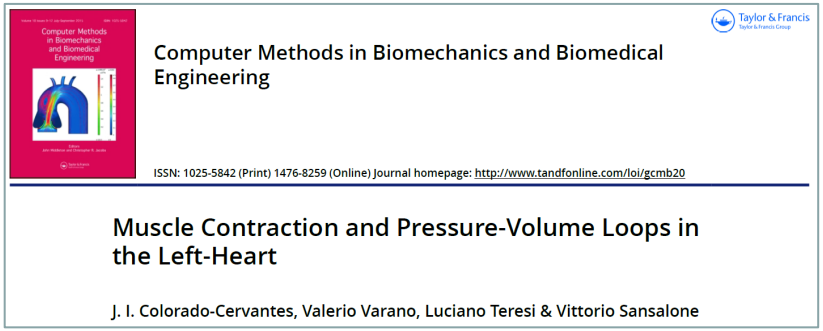
LaMS Modelling & Simulation Lab

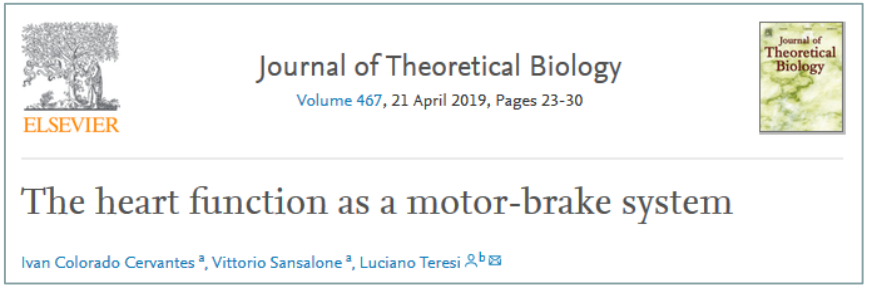
ROMA TRE UNIVERSITÀ DEGLI STUDI

Publications



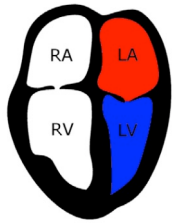
- Papers: 2 (CMBBE 2017, JTB 2019)
  + 1 submitted (PNAS)



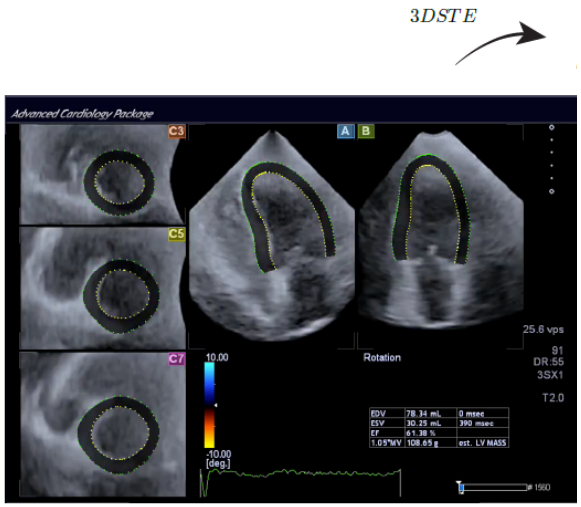


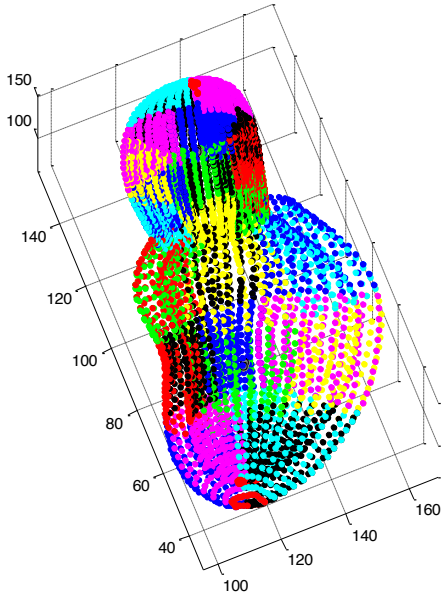
- Conference proceedings: 4

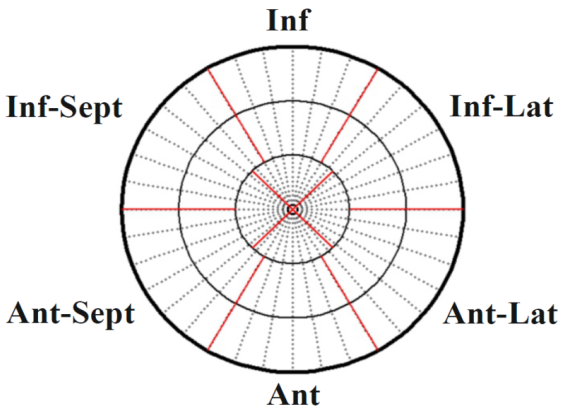
Materials and methods



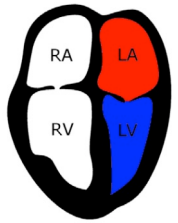
- ~ 200 patients: 80 healthy + 120 diseased
- 3DSTE



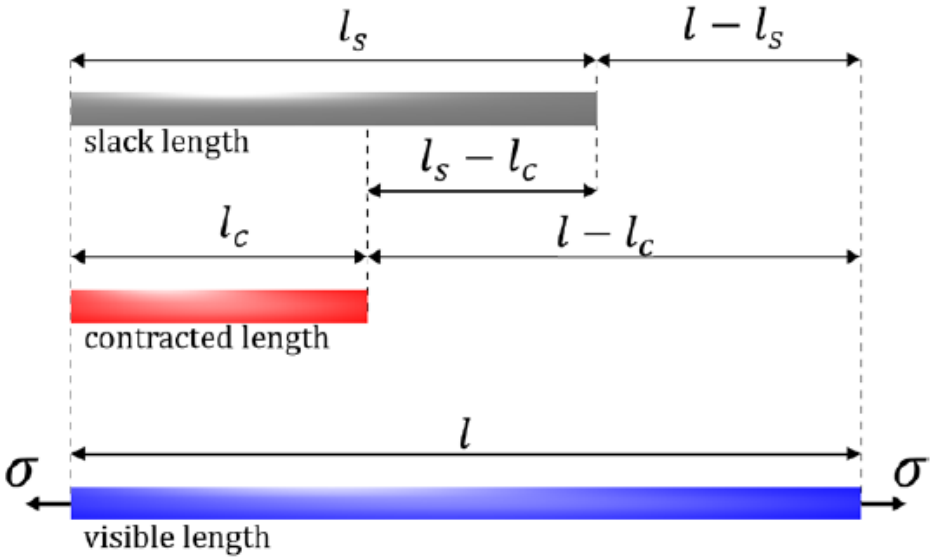


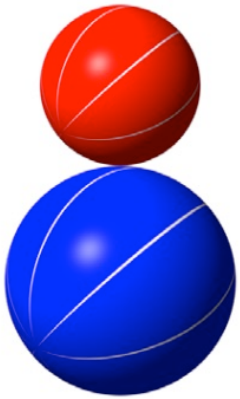


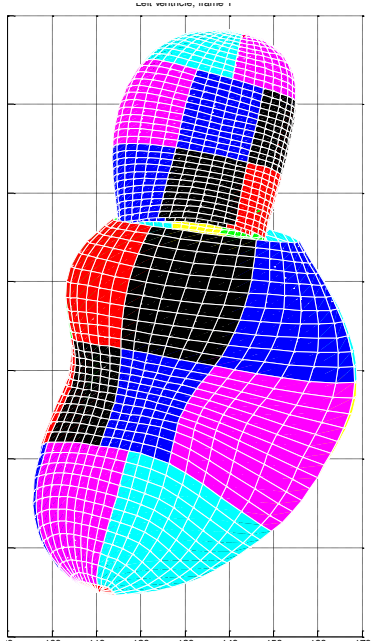
Materials and methods



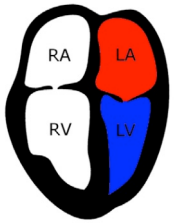
- Contraction of heart fibers: Active stretch
- Biomechanical modeling: 0D & 3D (FEM)



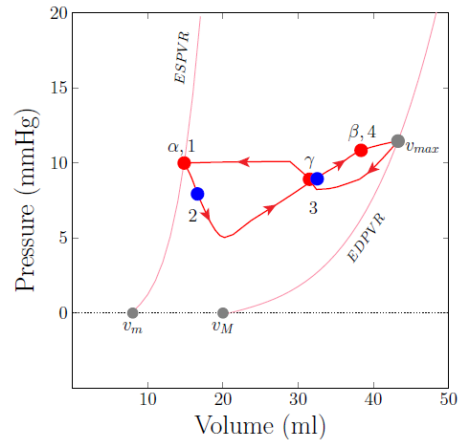


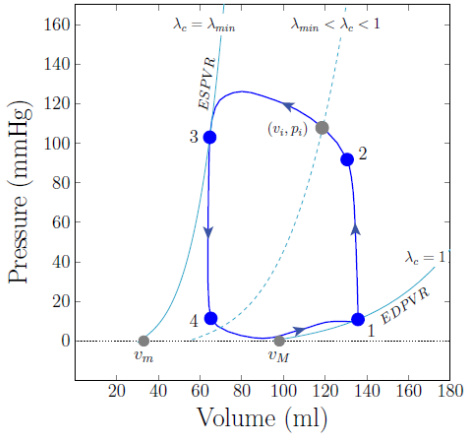


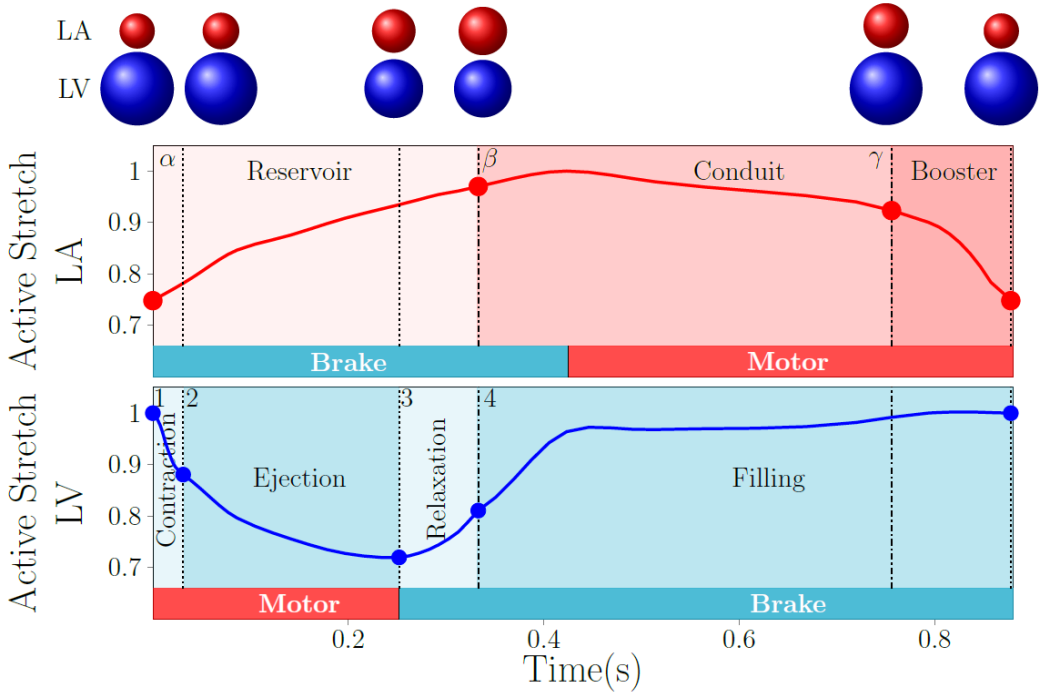
Results



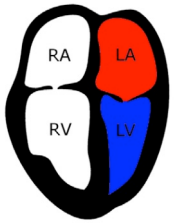
- Analysis of the time course of heart contractions







Results

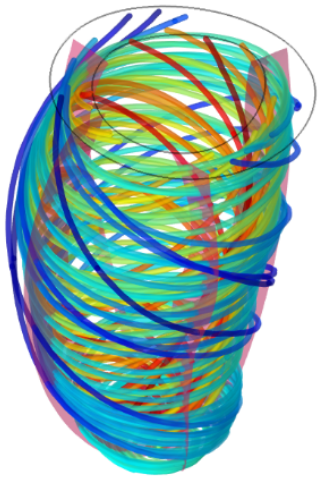


- Fiber orientation vs. Principal strain lines

Fiber orientation

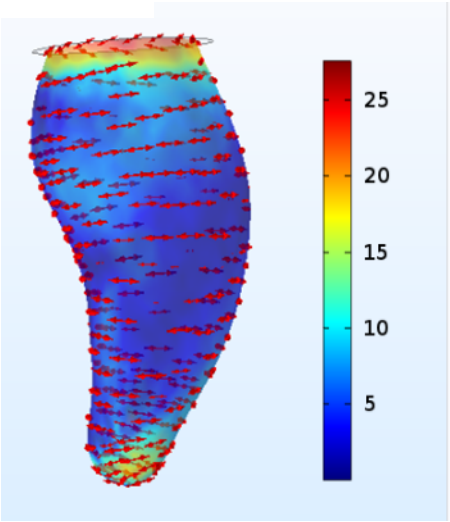
Endo: 60°

Epi: -60°

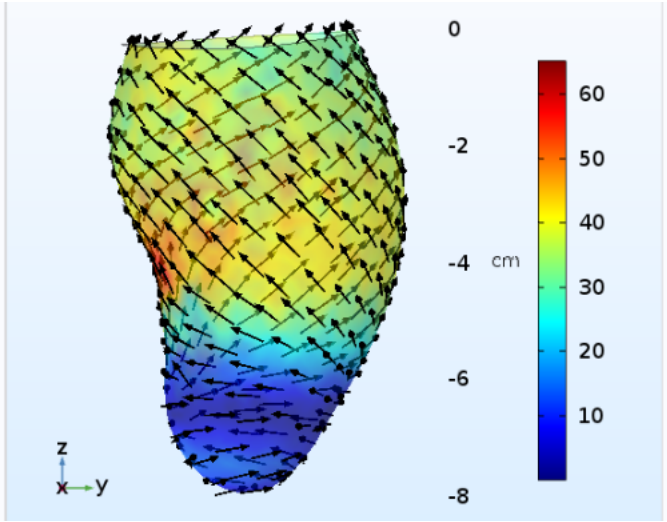


Principal strain lines

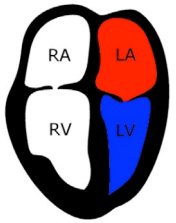
Endo



Epi



Results



- Fiber orientation vs. Principal strain lines

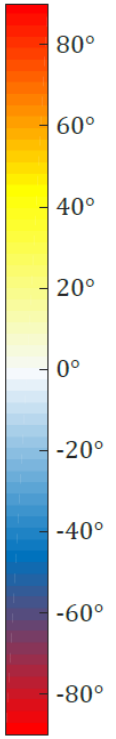
PSL angle **3DSTE** **FEM**

Endo Epi Endo Epi

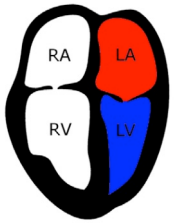
CNT

CRR

HCM

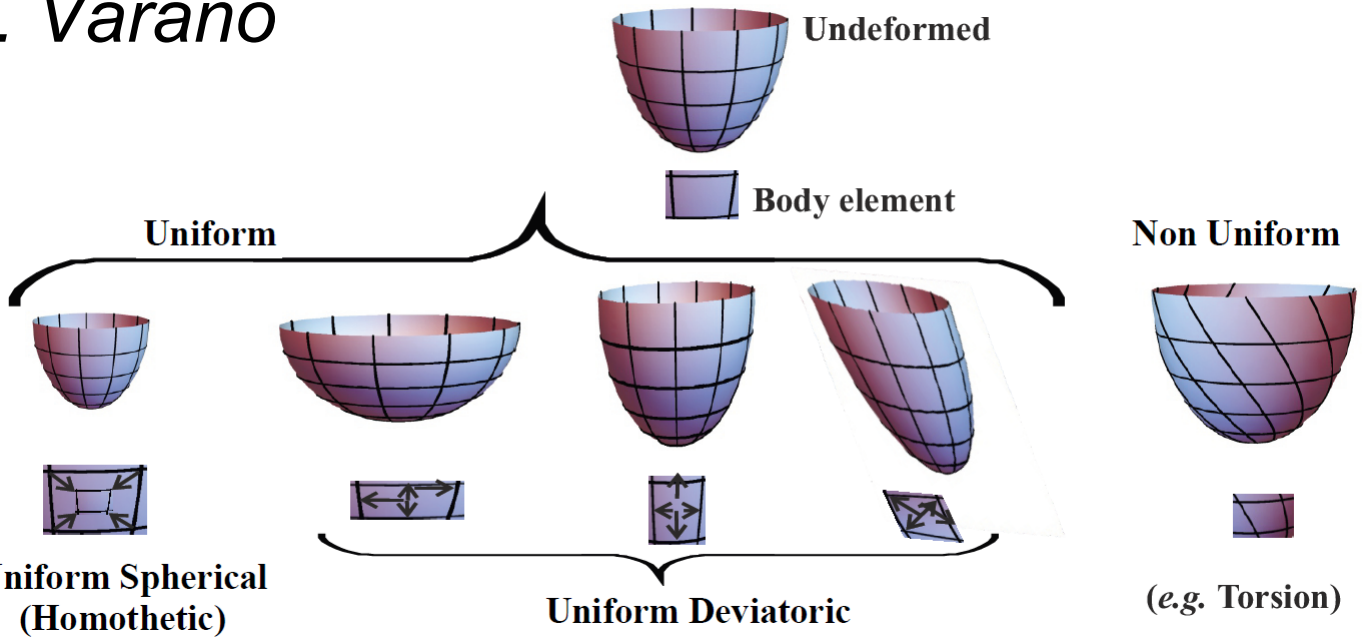


Perspectives



- *Shape analysis*: Rethinking heart deformation for early detection of heart pathologies

→ *V. Varano*



Living matter:

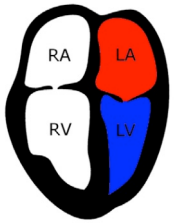
from biomechanical modeling to shape analysis

Scientific projet *Biomaterials*

V. Sansalone, V. Varano

Kick-off meeting of the IRP Coss&Vita
October 17h, 2019, École des Ponts – ParisTech, Champs sur Marne

Rome Research Team



SAPIENZA
UNIVERSITÀ DI ROMA

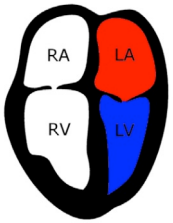
- Dep. of Structural and Geotechnical Engineering
- Dep. of Cardivascular Science and ...
  Policlinico Umberto I, Hospital
- San Giovanni Calibita Fatebenefratelli, Hospital

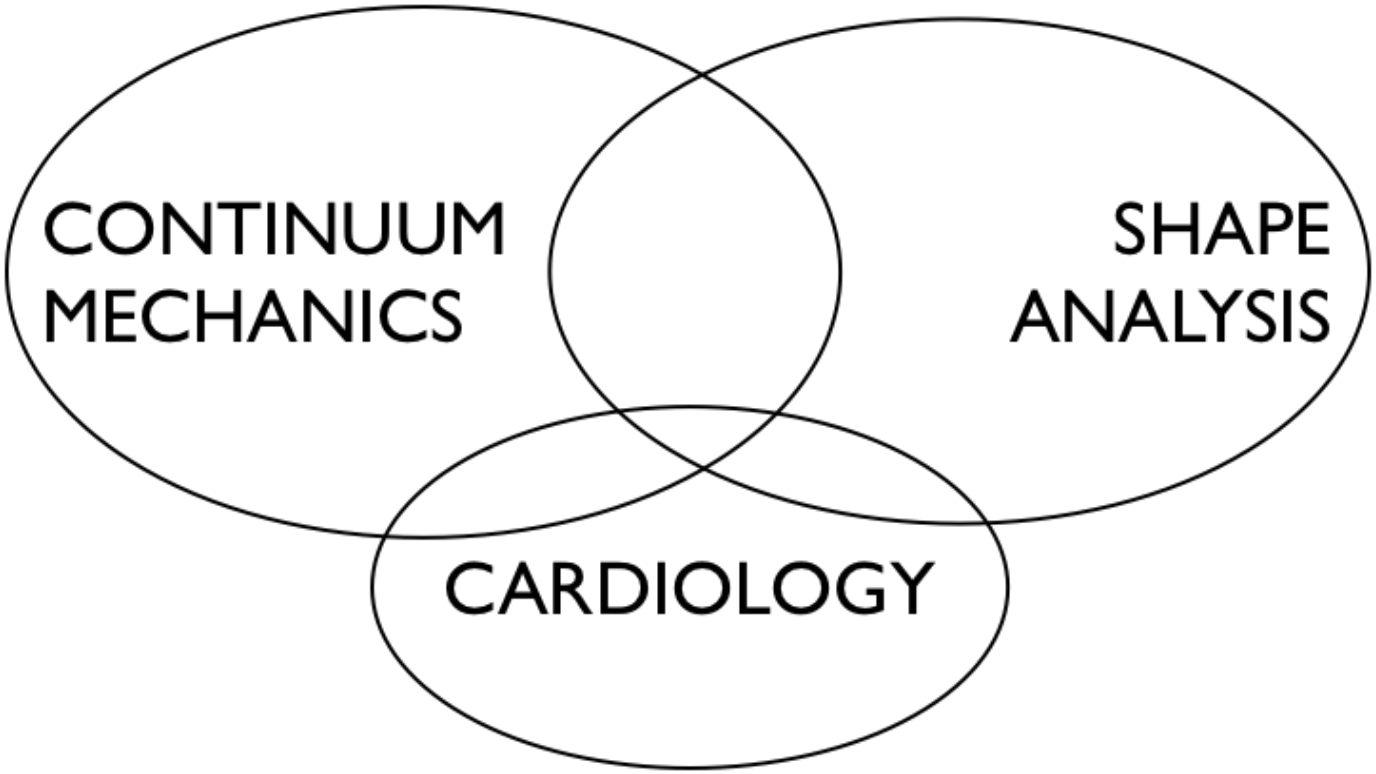
ROMA TRE
UNIVERSITÀ DEGLI STUDI

LaMS
Modelling & Simulation Lab

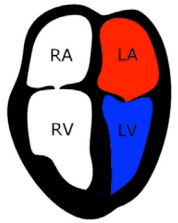
- Dep. of Mathematics and Physics
- Dep. of Architecture
- Dep. of Science

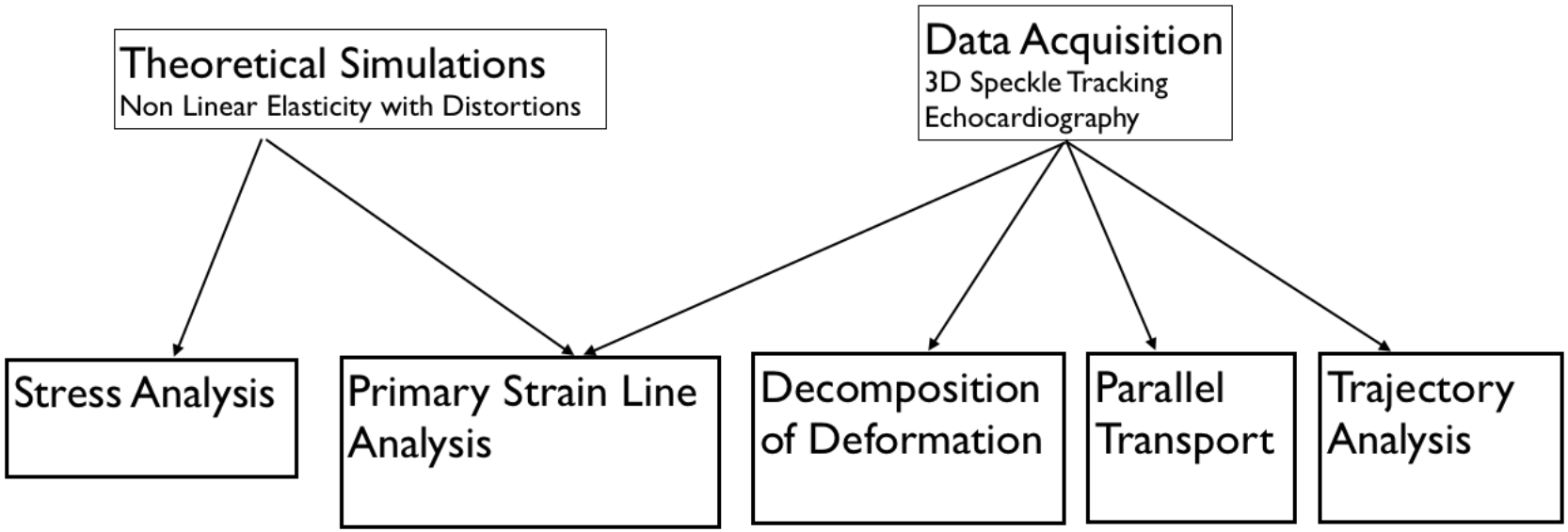
Methods





Research Project





CONTINUUM MECHANICS (Local)

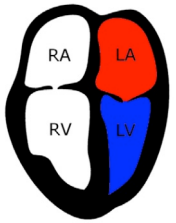
Evangelista et al. 2011 PBMB
Gabriele et al. 2015 CMBBE
Evangelista et al. 2015 J. BIOMECHANICS

x

SHAPE ANALYSIS (Global)

Varano et al. 2017 I.J.Computer Vision
Madeo et al. 2015 PLOS ONE
Piras et al. 2014 PLOS ONE

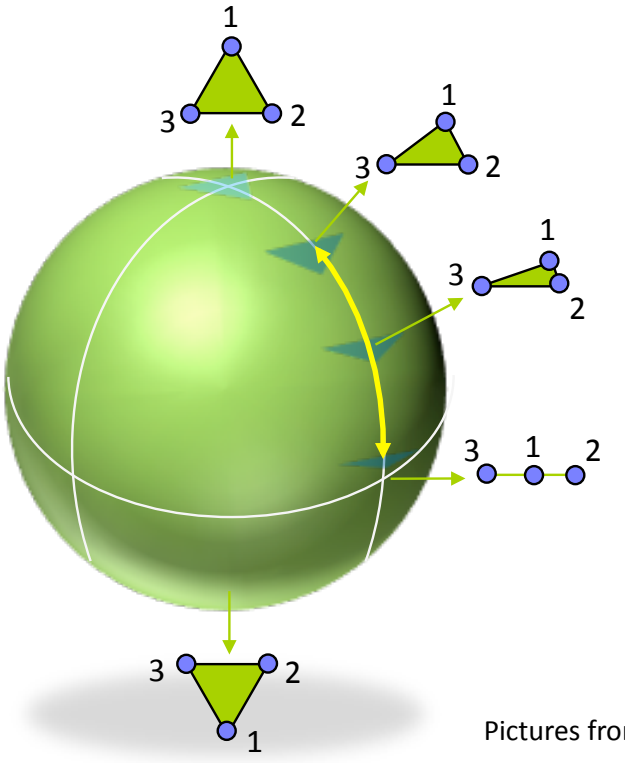
Statistical Shape Analysis



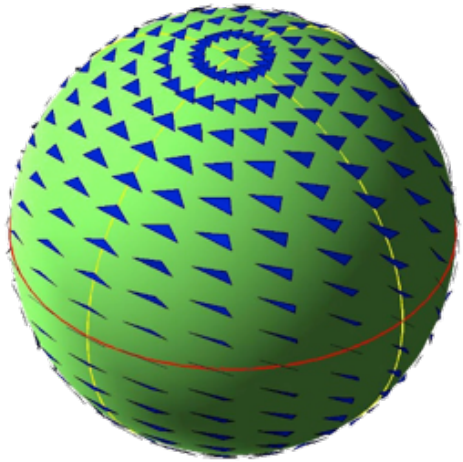
The Kendall Shape Space

The Kendall Shape Space for a set of 2D triangles is a 2D sphere:

dim(Shape Space) = dim x k - 1 - dim - dim*(dim-1)/2 = 2*3 - 1 - 2 - 2*(2-1)/2 = 2

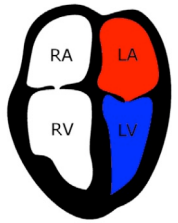


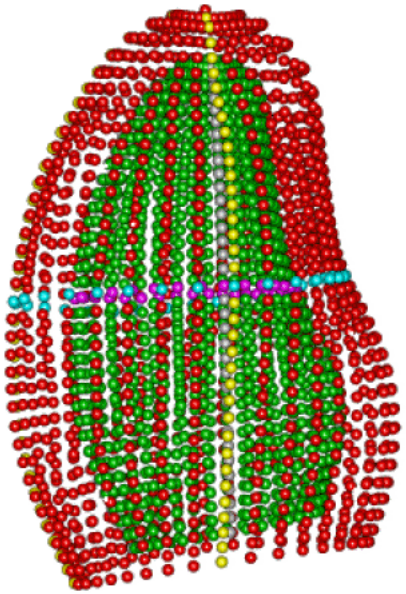
Pictures from A. Trouvé

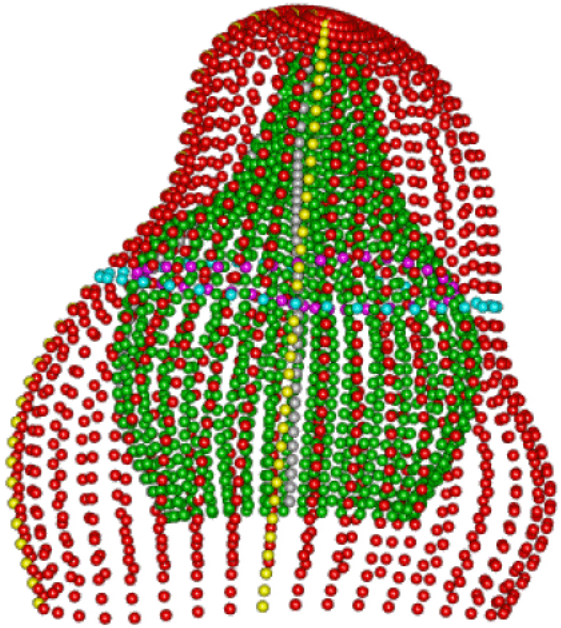


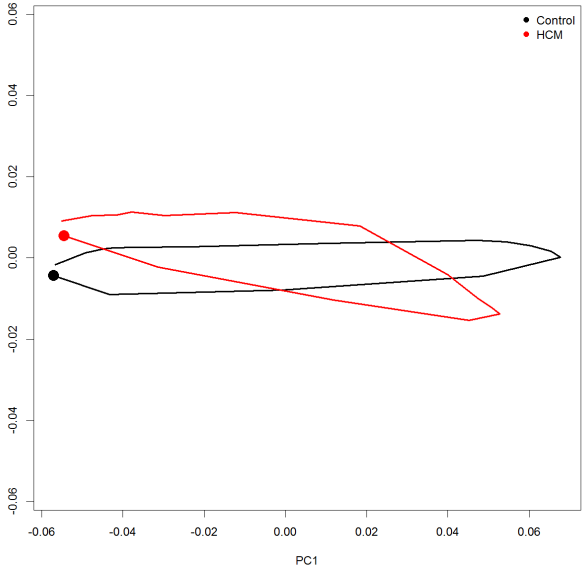
To each point of the sphere there correspond a triangle; bottom hemisphere is a reflection of top one.

Data Reduction

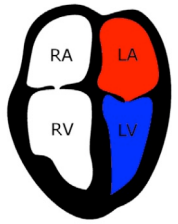




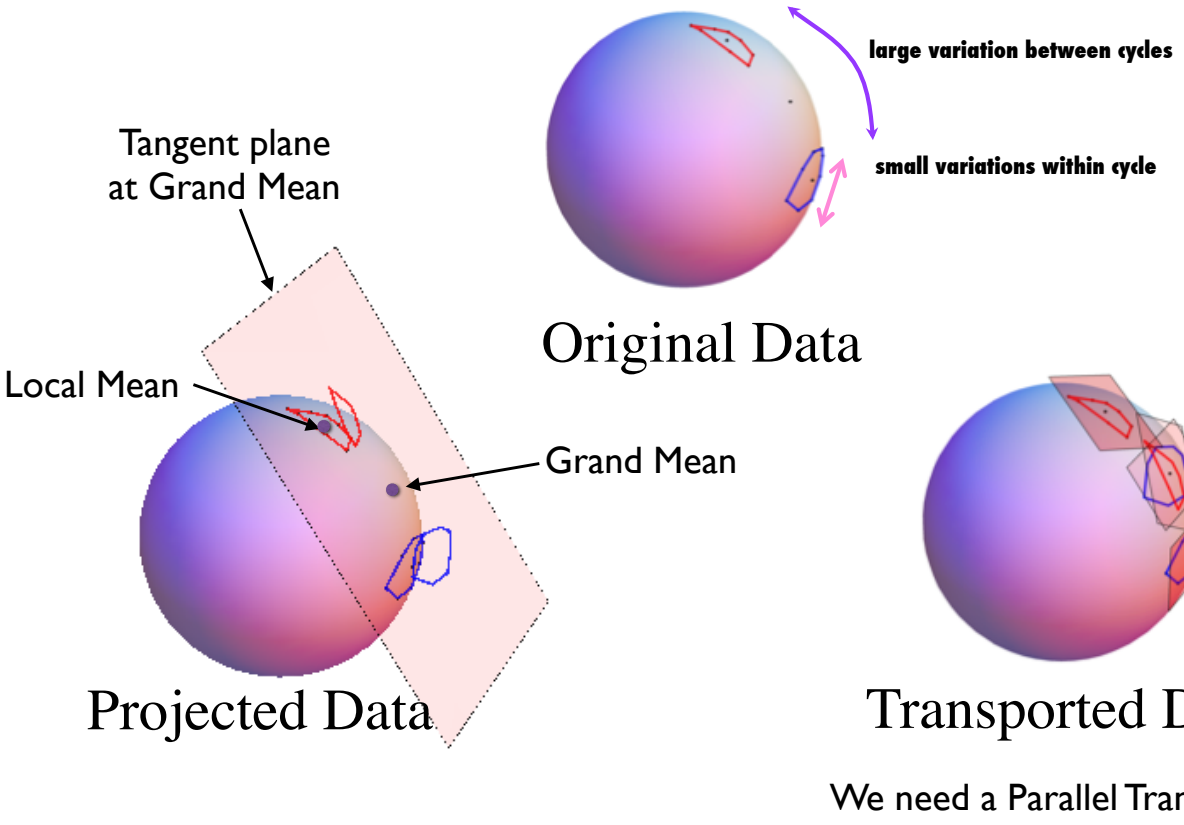




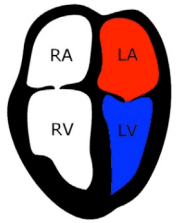
Parallel Transport of Deformations

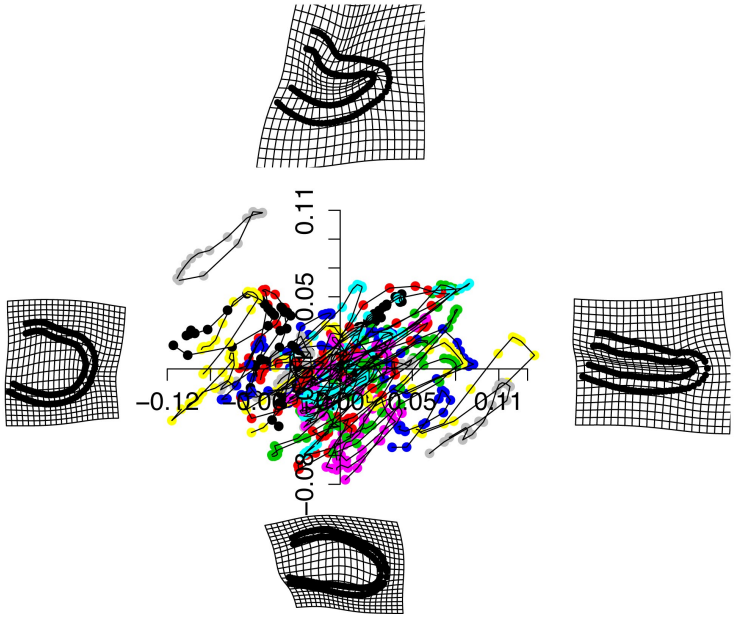


To Transport Deformations we need a Connection

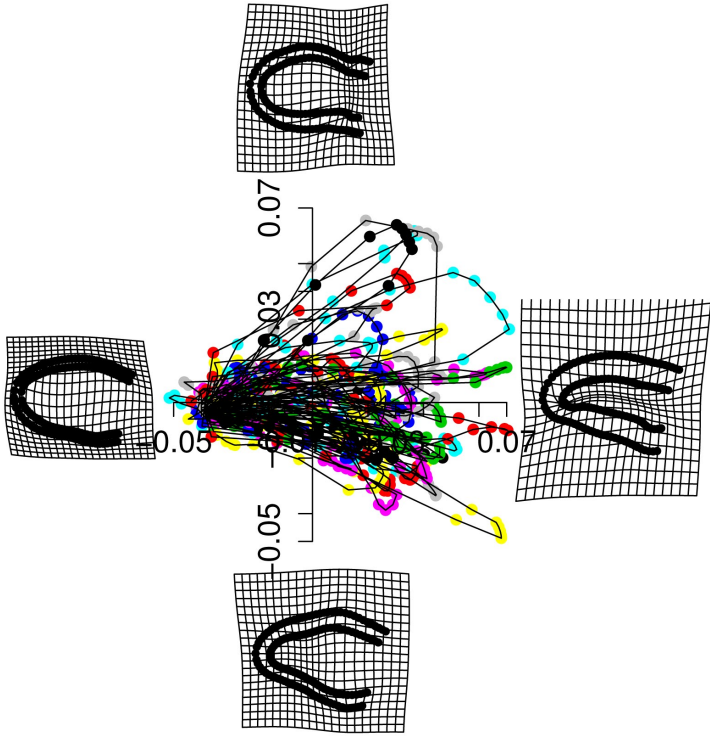


Trajectory Analysis



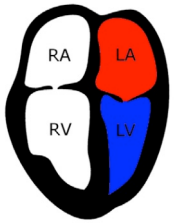


CLASSIC GPA+PCA



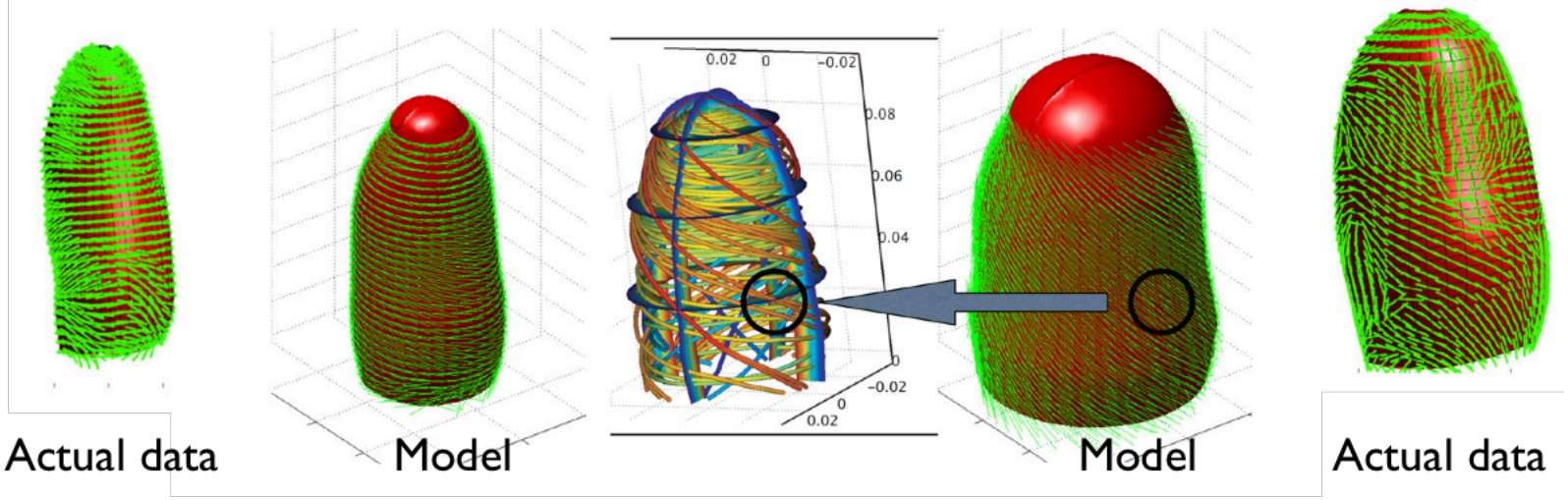
Direct Transport + GPA+PCA

Strain analysis



epicardial PSL agree with muscle fiber directions (spiralling counterclockwise toward the base) - endocardial PSL are circumferential

Epicardium

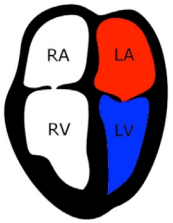


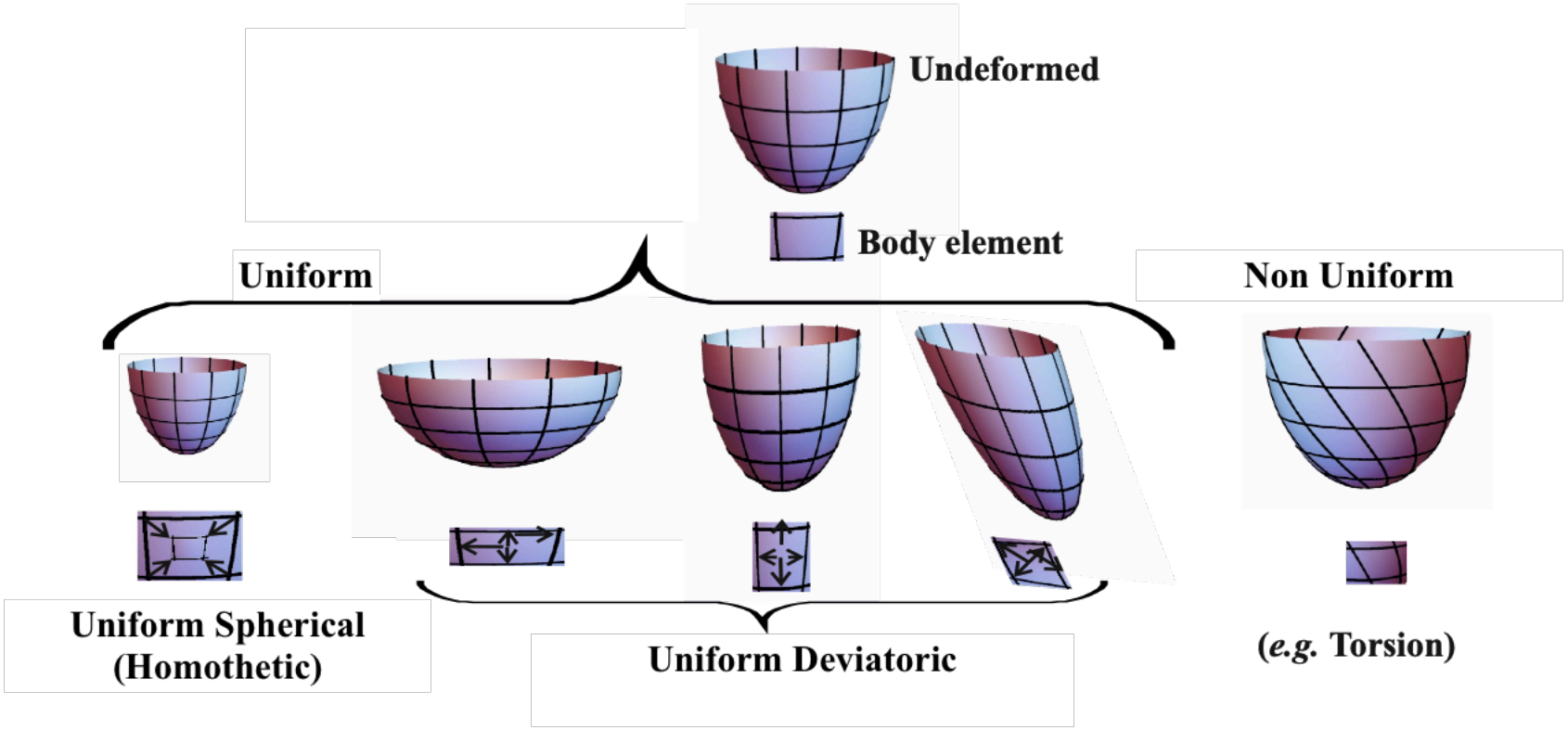
Aspect Ratio Change

Torsion

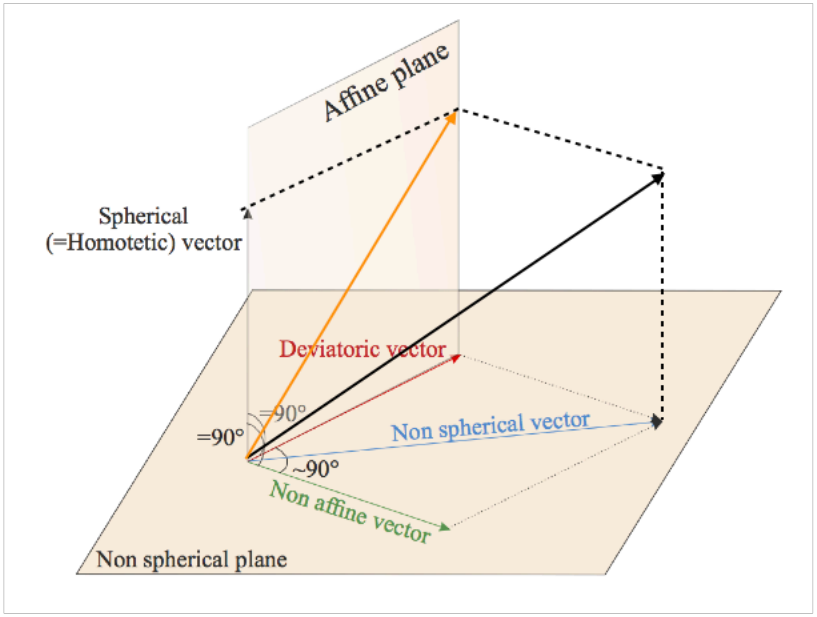
Evangelista et al. 2015 J. BIOMECHANICS

Decomposition of deformation





Decomposition of deformation



$$V = \underbrace{V_{sph} + V_{dev}}_{V_u} + V_{nu}$$

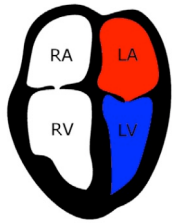
x

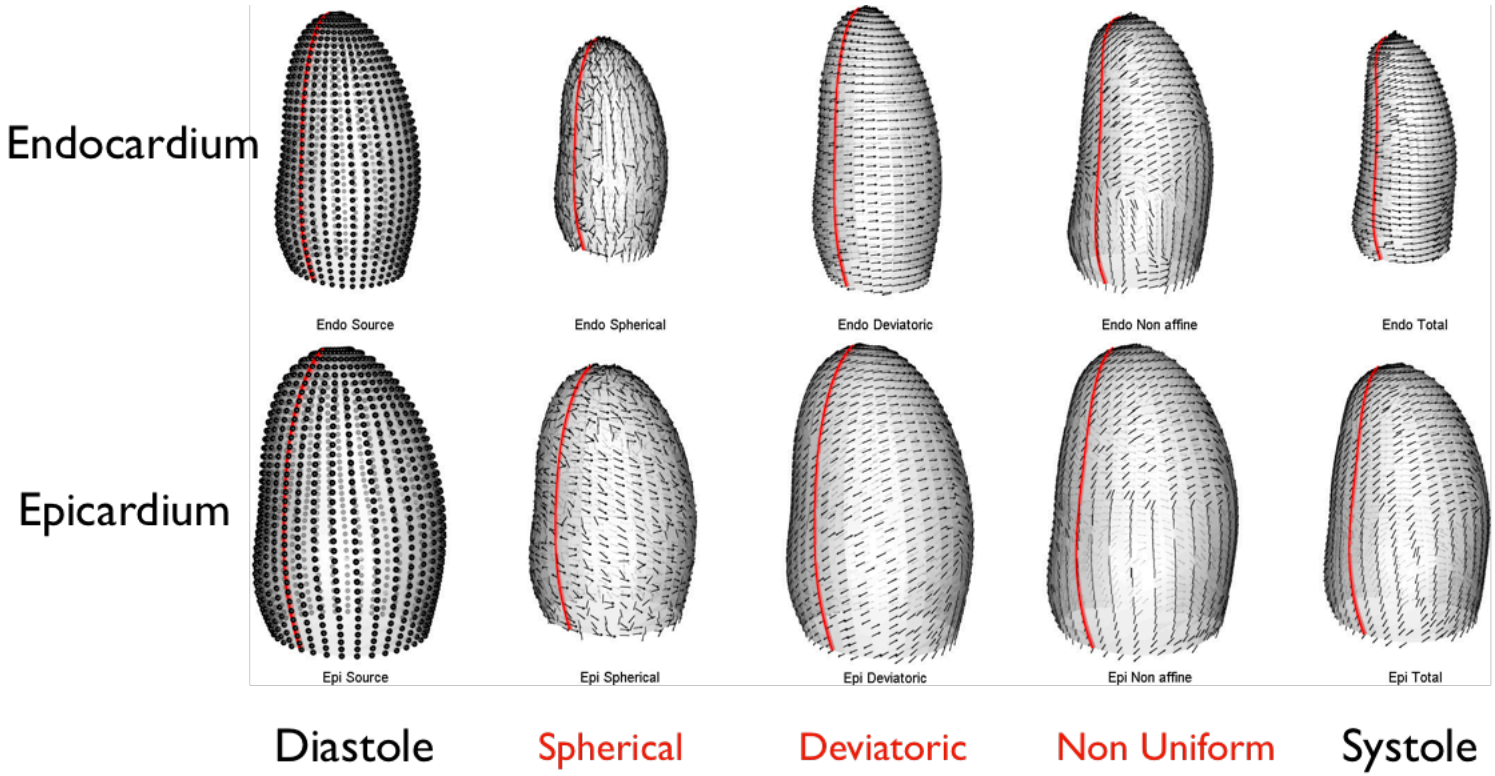
$$\mathbb{R}^{(k-1)\times m}$$

k landmarks

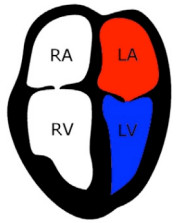
m space dimension

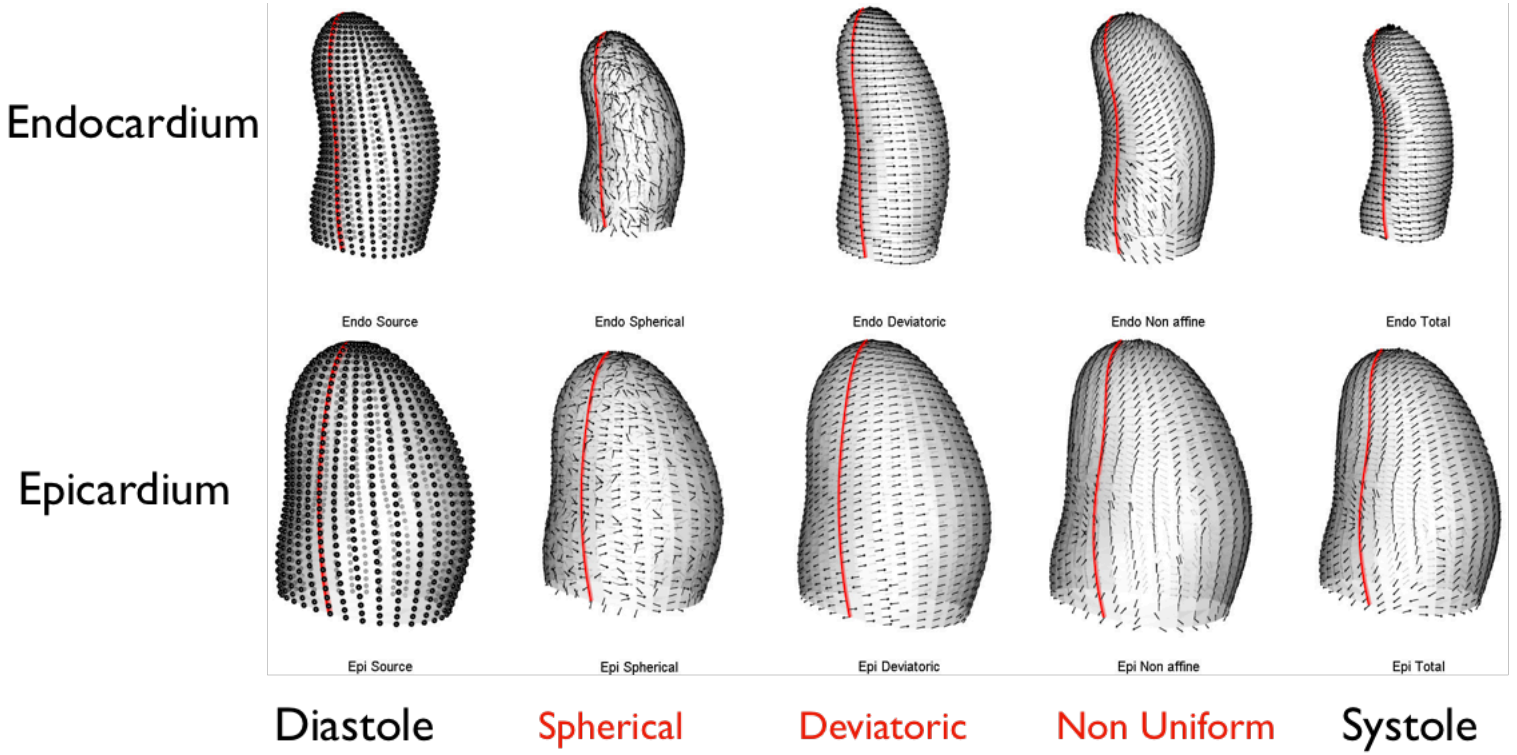
Decomposition Control
(mean of 46 individuals)



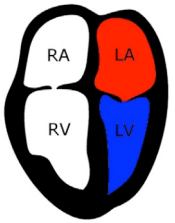


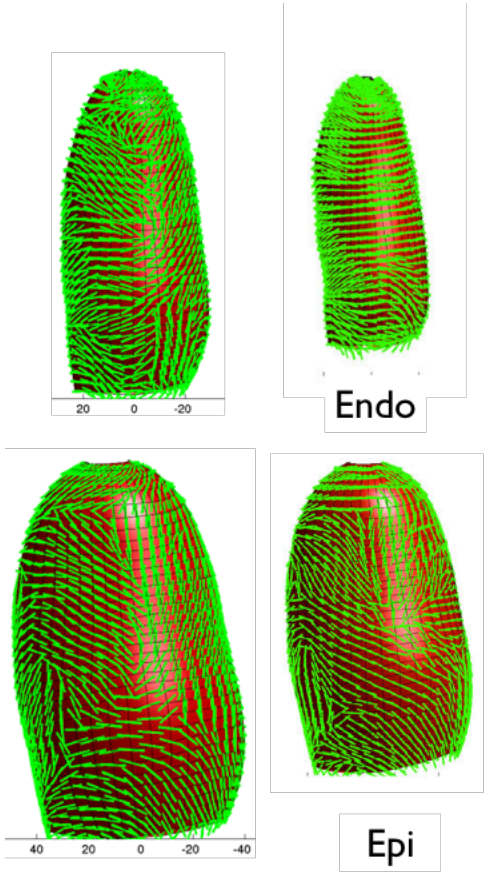
Decomposition HCM
(mean of 20 individuals)

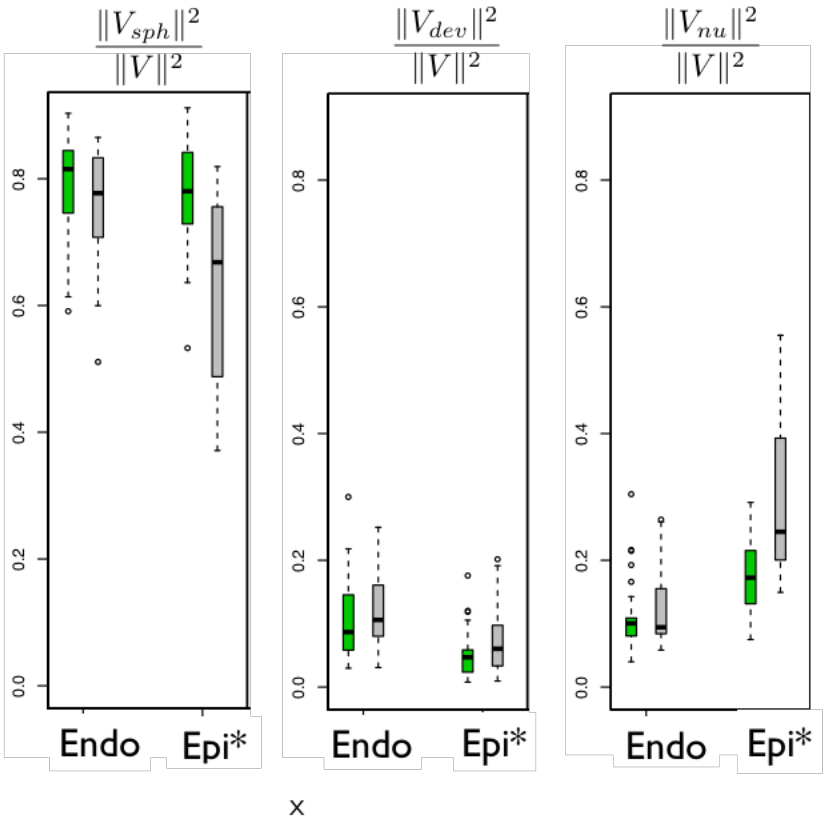




Statistical Results



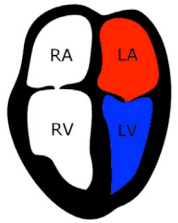




Control
HCM

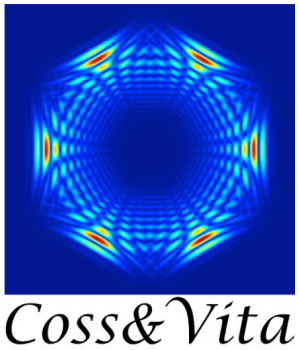
*
ANOVA
Significance

Conclusions



- **The Statistics made over the Decomposed Deformations confirms the results obtained from the Principal Strain Analysis.**
- **The obtained Components of the Deformation on epicardium allows for detection of the analysed pathology.**

Thank you for your attention



Acknoledgments: This work has been partially supported by the IRP Coss&Vita