Intelligent diabetic socks for foot ulcer prevention using model reduction

Vincent Luboz[t], Christelle Boichon[a], Michel Rochette[a], Francis Cannard[t], Marek Bucki[t]

Presentation

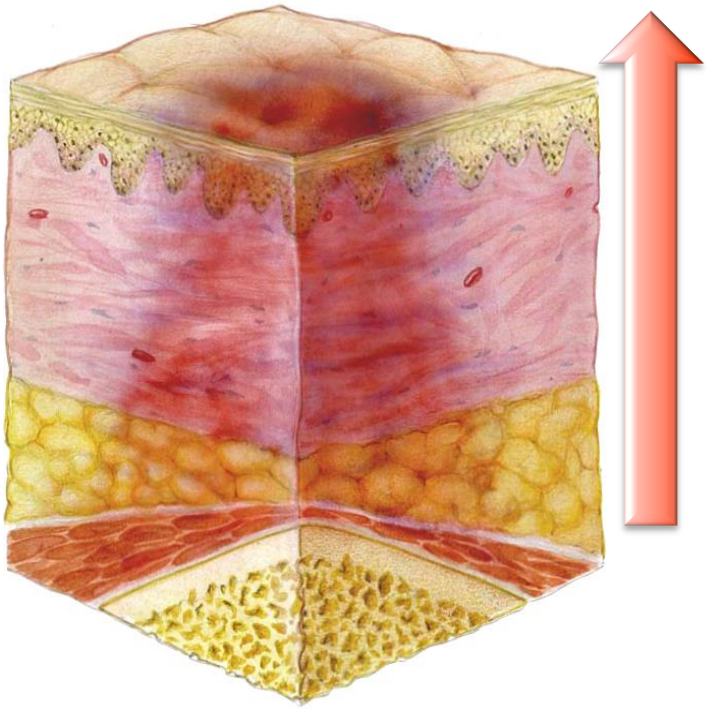
- Founded in 2011
  - Headquarters in Montceau-les-Mines
  - Research in Grenoble and Paris

- Activity: medical devices / biomechanics
  - Pressure ulcer prevention (SCI, diabetic foot, elderly, …)
  - Biomechanical modeling (surgery planning/simulation, injury prevention, comfort assessment, orthotic design, …)

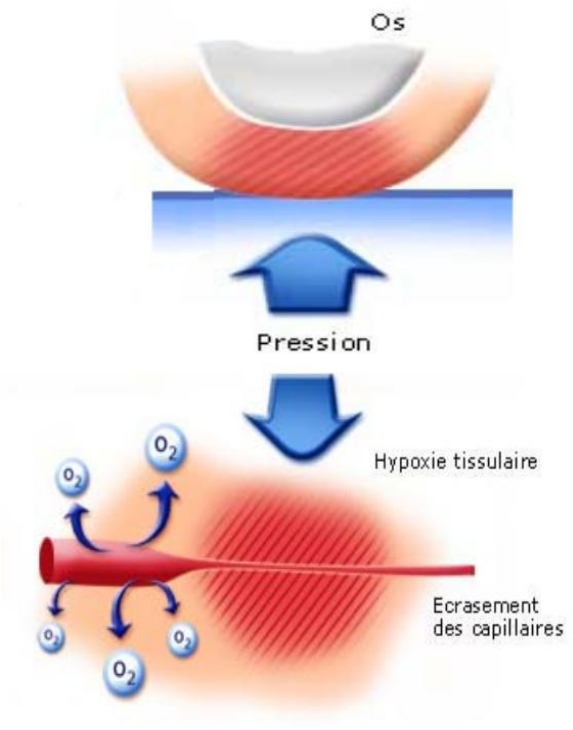
- Areas of expertise
  - Smart textile: patented pressure sensing fabric
  - Wearable technology
  - Finite Element modeling of soft/hard tissues: FE toolbox

Pressure Ulcers

- **Deep Tissue Injuries** - « *Between a bone and a hard place* »
  - DTIs appear near bony prominences:
    - Cell membranes deformation (short term effect)
    - Ischemia (long term effect)



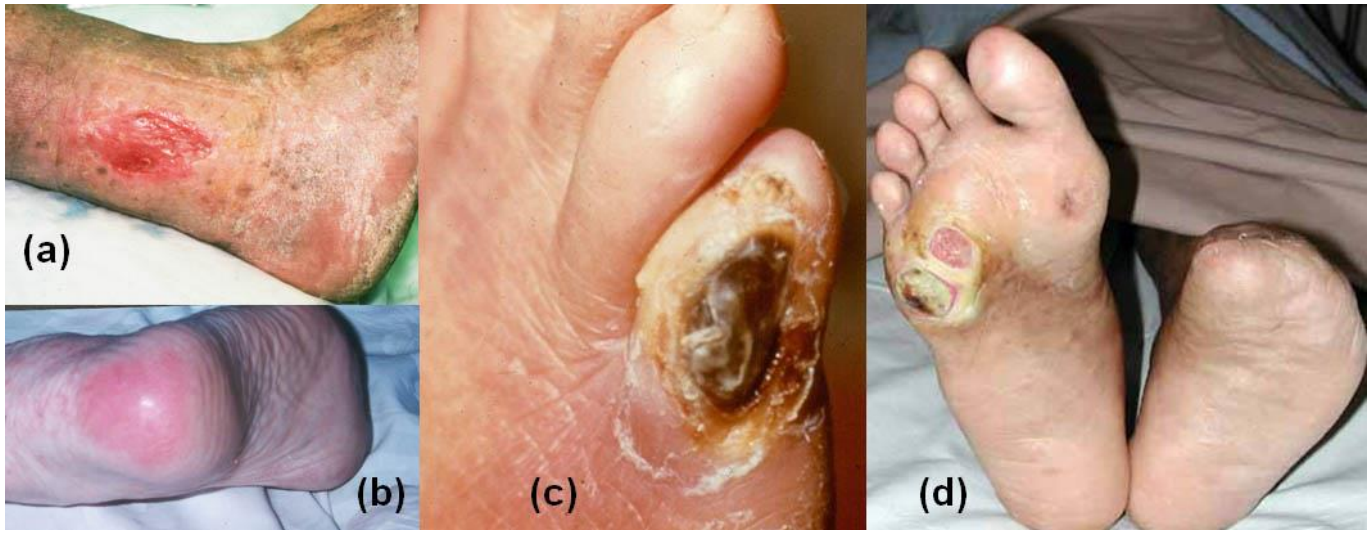
Bottom-top lesion propagation



Pressure ➔ vessels collapse ➔ necrosis

Diabetic foot

- Foot ulcer
  - Etiology: Diabetes mellitus ➔ angiopathy & neuropathy
  - Interactions foot – shoe ➔ repeated micro-traumas ➔ lesions!



Diabetic foot

- Statistics
  - **250 millions** people suffering from diabetes in the world
  - **15%** of patients will develop a **foot ulcer** at least once
  - **15%** of these ulceration will lead to an **amputation** of the foot

- Consequences
  - Diabetes causes an **amputation** of a foot every **30 seconds**
  - Public health issue

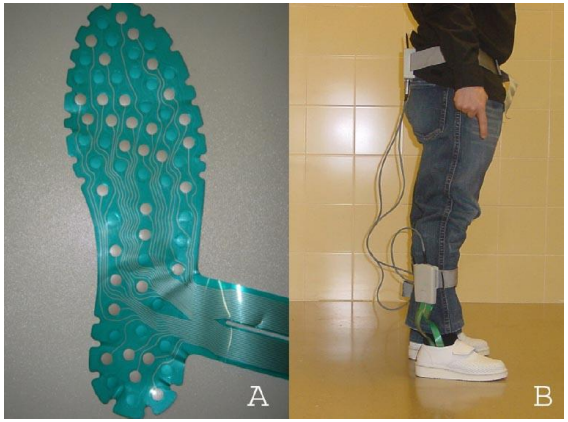
    $ **11 billions** / year in the USA

    £ **3 billions** / year in the UK

Diabetic foot

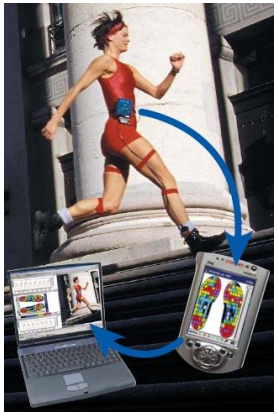
- Prevention relies heavily on the subject attention
  - **Daily inspection and palpation of the foot**
  - If necessary, prescription of custom made orthopedic shoes
  - Redness/swelling ➔ suspicion of lesion due to internal overpressure
    ➔ foot at rest

- Pressure sensing
  - Expensive devices (10k€), unpractical for daily use
  - (Possibly) affect the measurement accuracy
  - Only measures external pressures under the foot sole

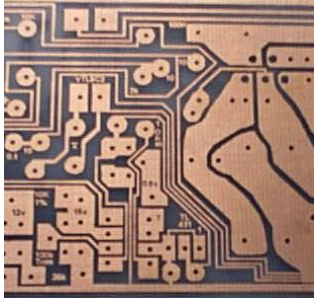


BioFoot® insoles

F-Scan®, Tekscan



Pedar shoes LilaBox



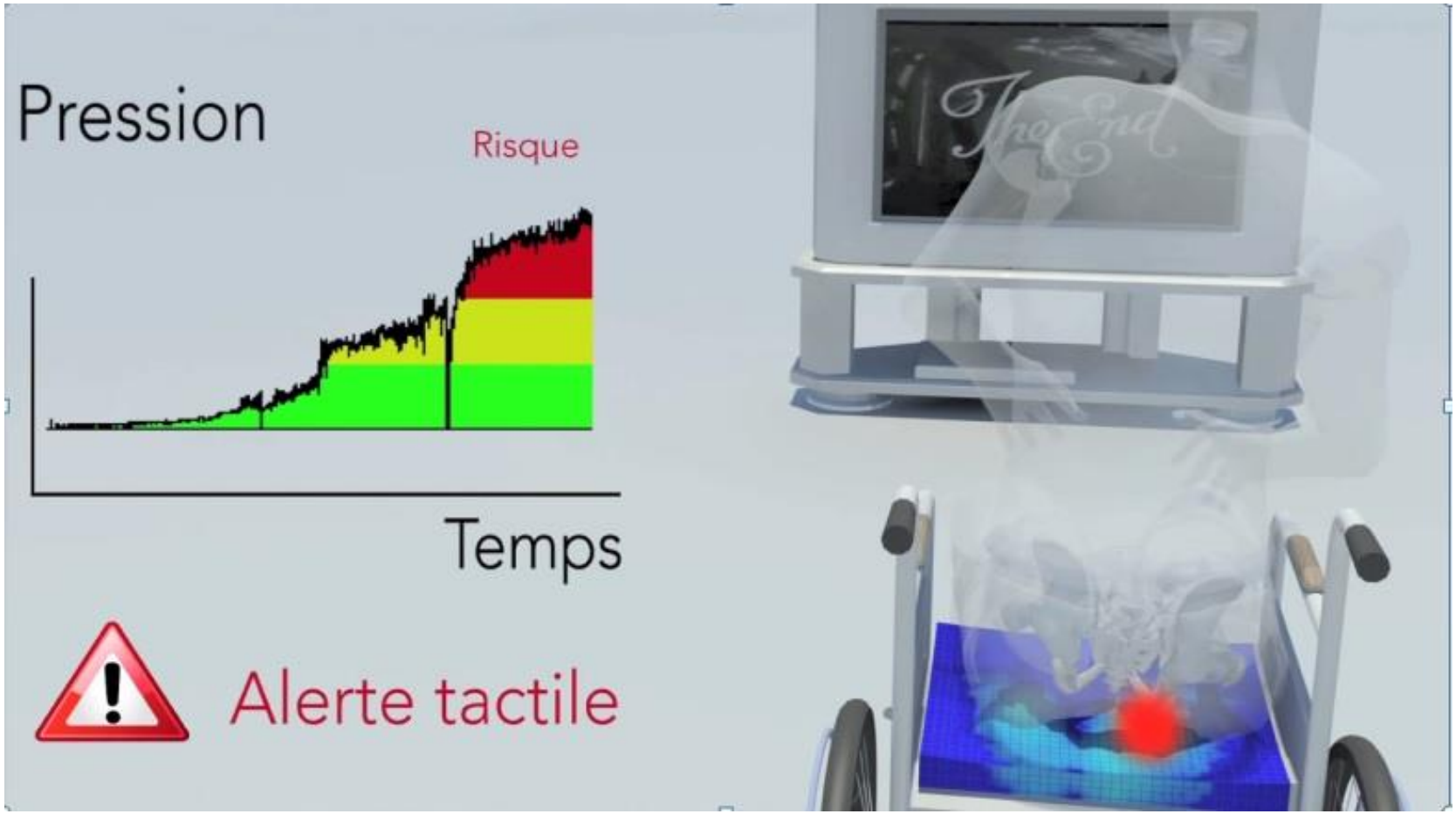
Smart Textile

- Information feed-back
  - High resolution **visual** information (smart-phone)
  - Low resolution **tactile** information (vibrating watch)

PCB 100% textile !!

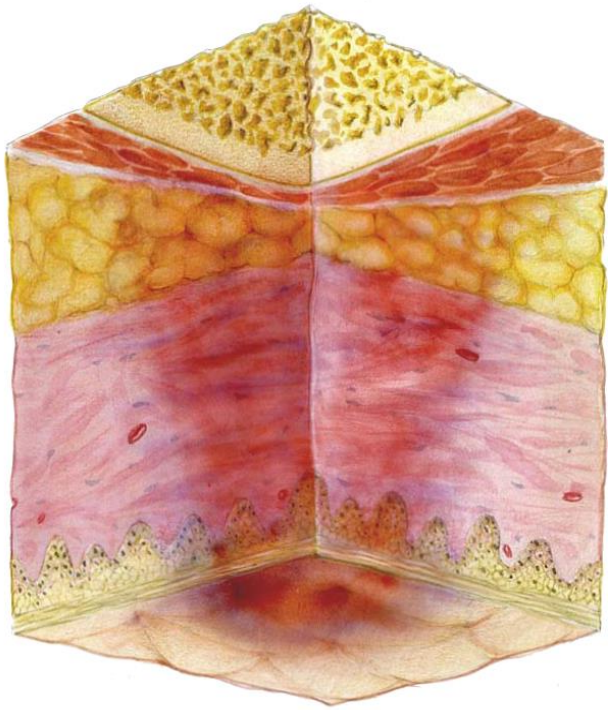
Smart Textile

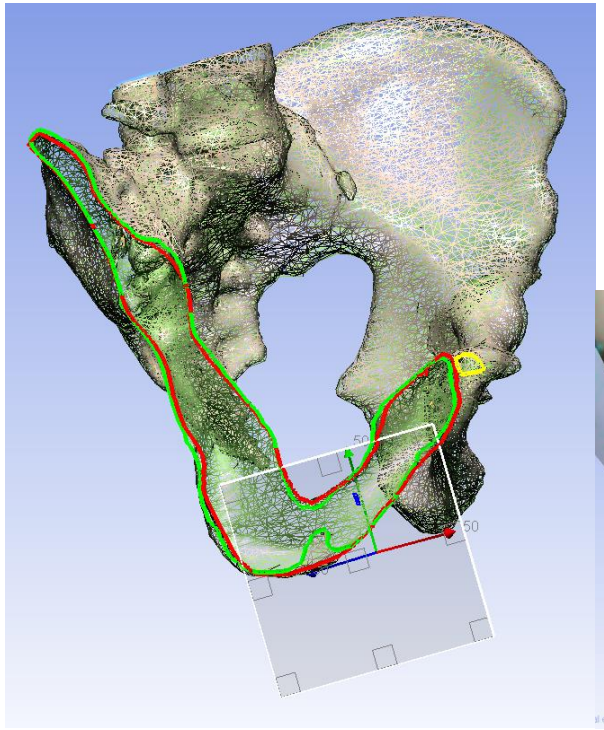
- Application to paraplegic pressure ulcer prevention

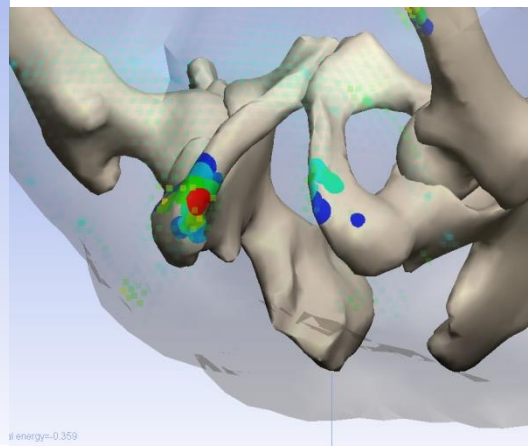


Modeling

- What for?
  - Experiment with a « hard chair » ➔ **inter-individual** variability

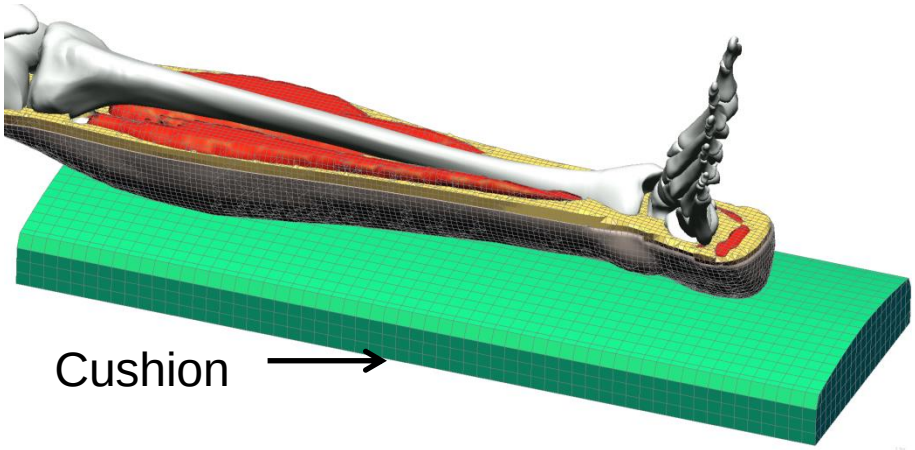






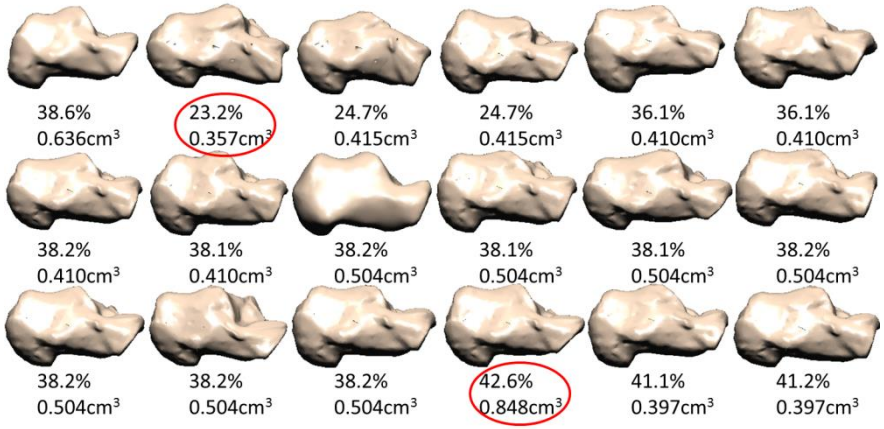
Modeling

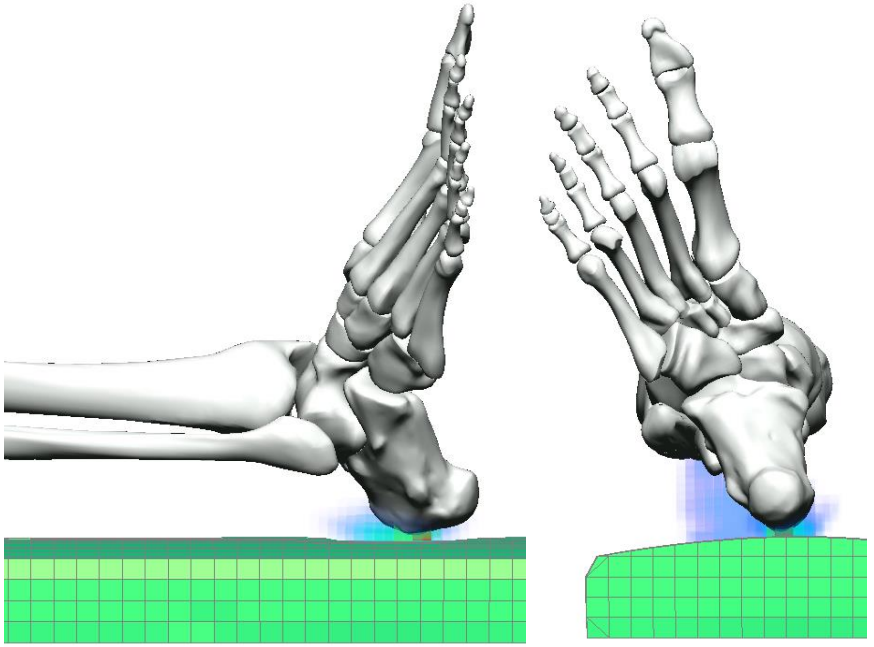
- Motivation: **morphology is key!**



3D analysis on soft cushion with mid pressure under the heel

- Max strain for the 18 patients: 36.2 % +/- 5.8pp





Result

Great variations in tissue damage levels (von Mises strains) due to the shape of calcaneum.

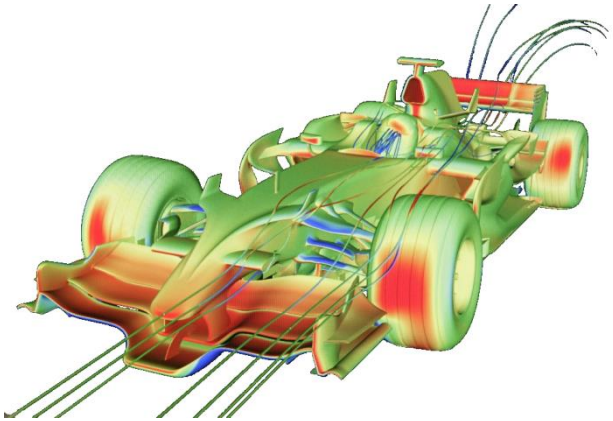
➔ Each patient is different and requires specific prevention.

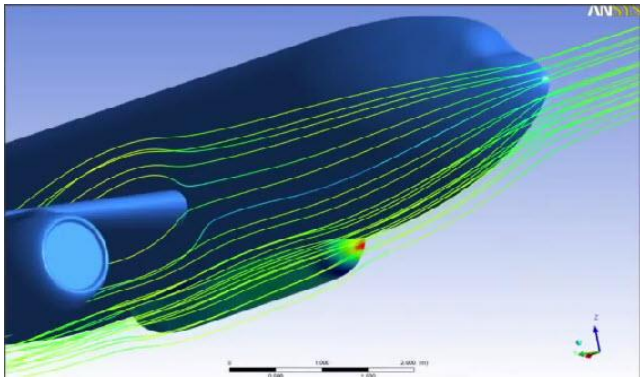
[Luboz et al., Ann Biomed Eng, 2014]

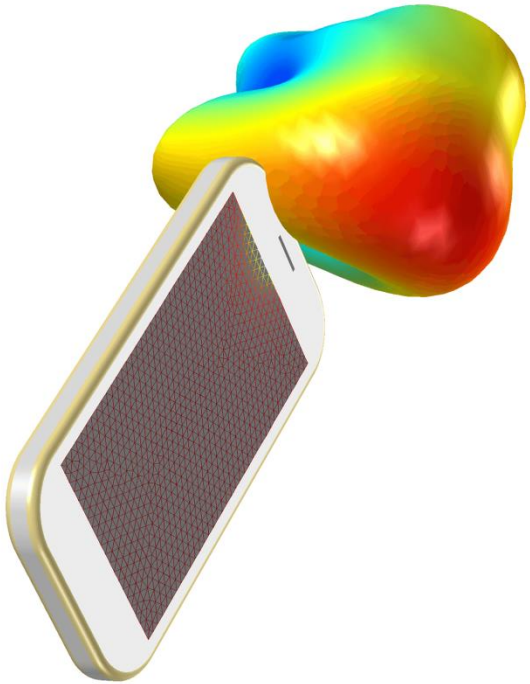
Modeling

- Mechanical engineering examples (fluid + structure), electronic.

Continuum Mechanics (tensor description + constitutive laws) ➔ PDE ➔ numerical solution







[Sources: Ansys, Comsol]

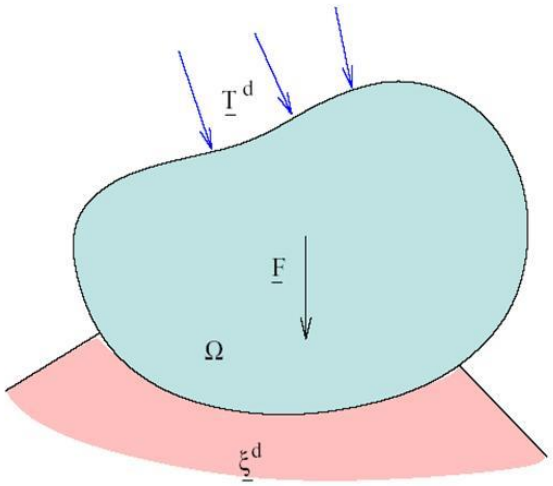
Modeling

- Mechanical engineering examples (fluid + structure), electronic.

Continuum Mechanics (tensor description + constitutive laws) ➔ PDE ➔ numerical solution

σ : stress tensor

ε : strain tensor



- Compatibility

$$\underline{\underline{\varepsilon}} = \frac{1}{2}\left(\underline{\nabla}\underline{\xi} + {}^{T}\underline{\nabla}\underline{\xi}\right),$$

- Equilibrium

$$\operatorname{div}\left(\underline{\underline{\sigma}}\right) + \underline{F} = 0,$$

- Constitutive law

$$\underline{\underline{\sigma}} = \underline{\underline{\underline{C}}} : \underline{\underline{\varepsilon}},$$

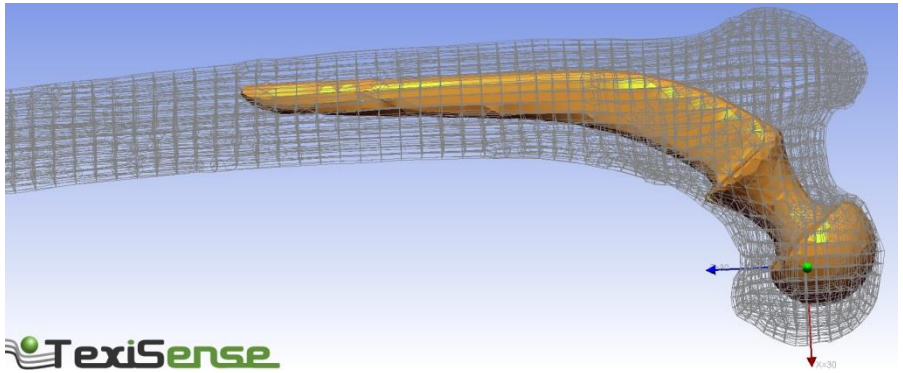
- Boundary conditions

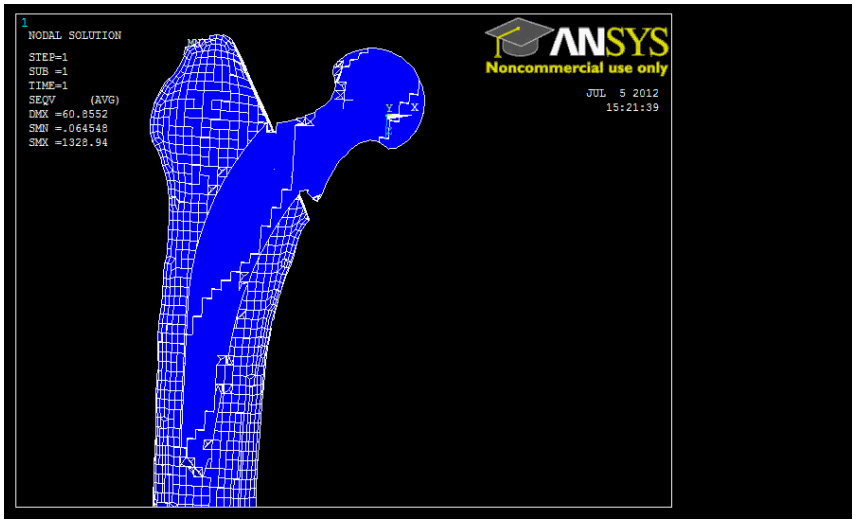
$$\underline{T} = \underline{\underline{\sigma}}.\underline{n} = \underline{T}^{d} \text{ onto } S_{\underline{T}},$$

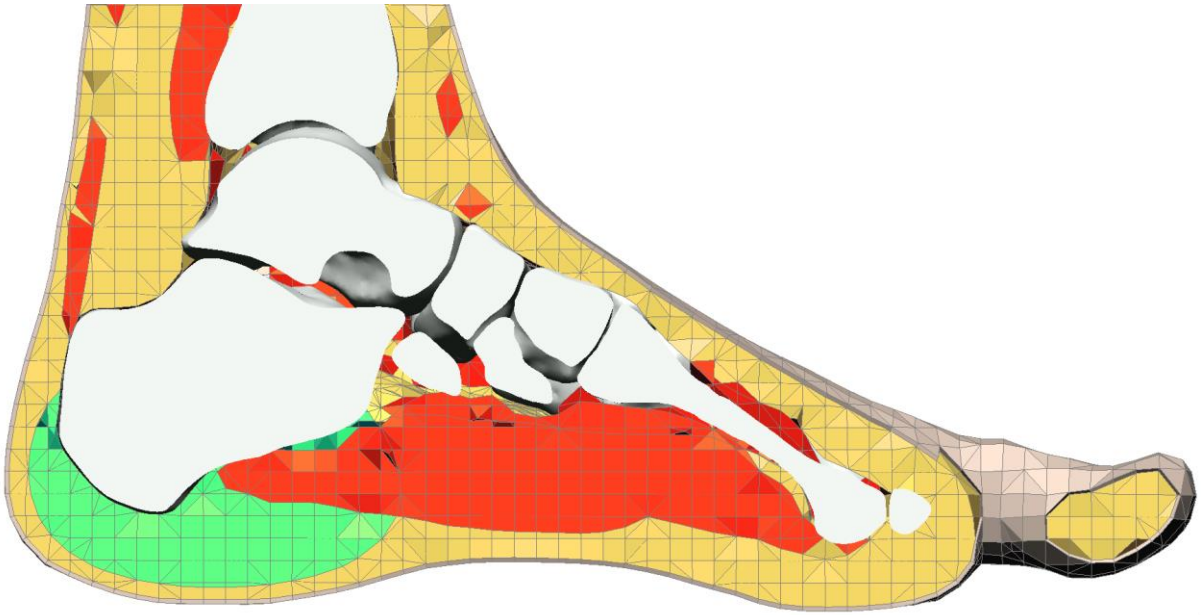
$$\underline{\xi} = \underline{\xi}^{d} \text{ onto } S_{\underline{\xi}}.$$

Modeling

- Examples from the biomedical field

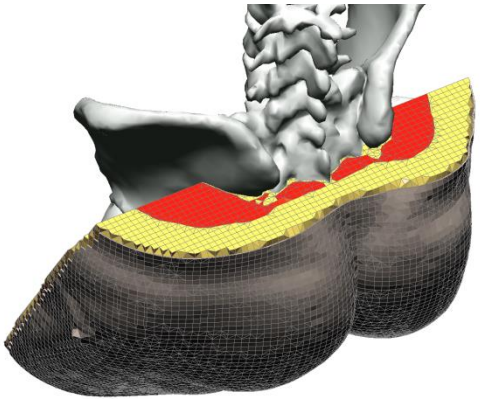






Texisense devices

+



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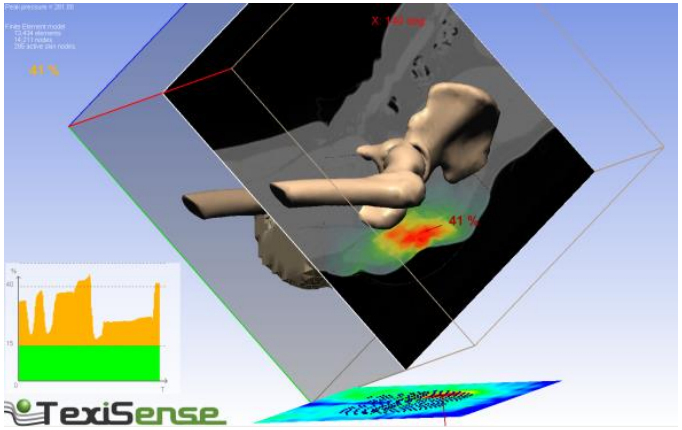

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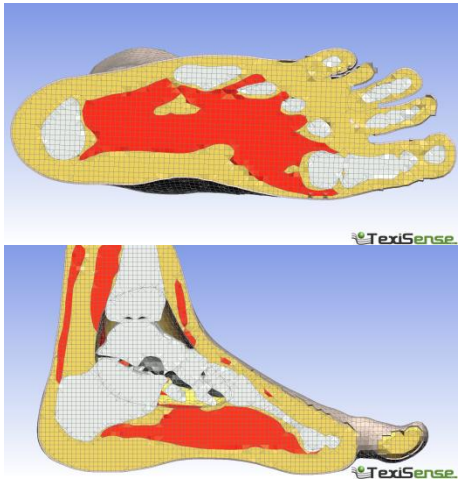

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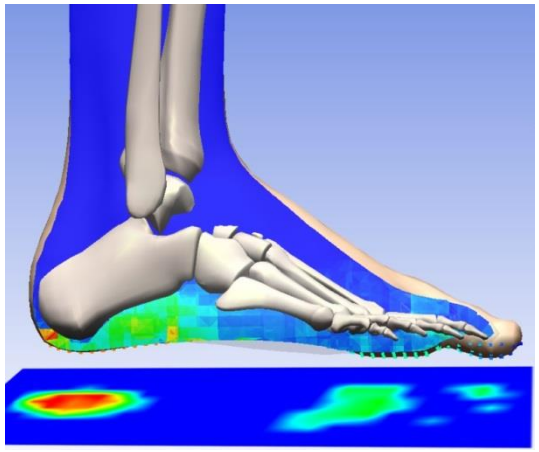
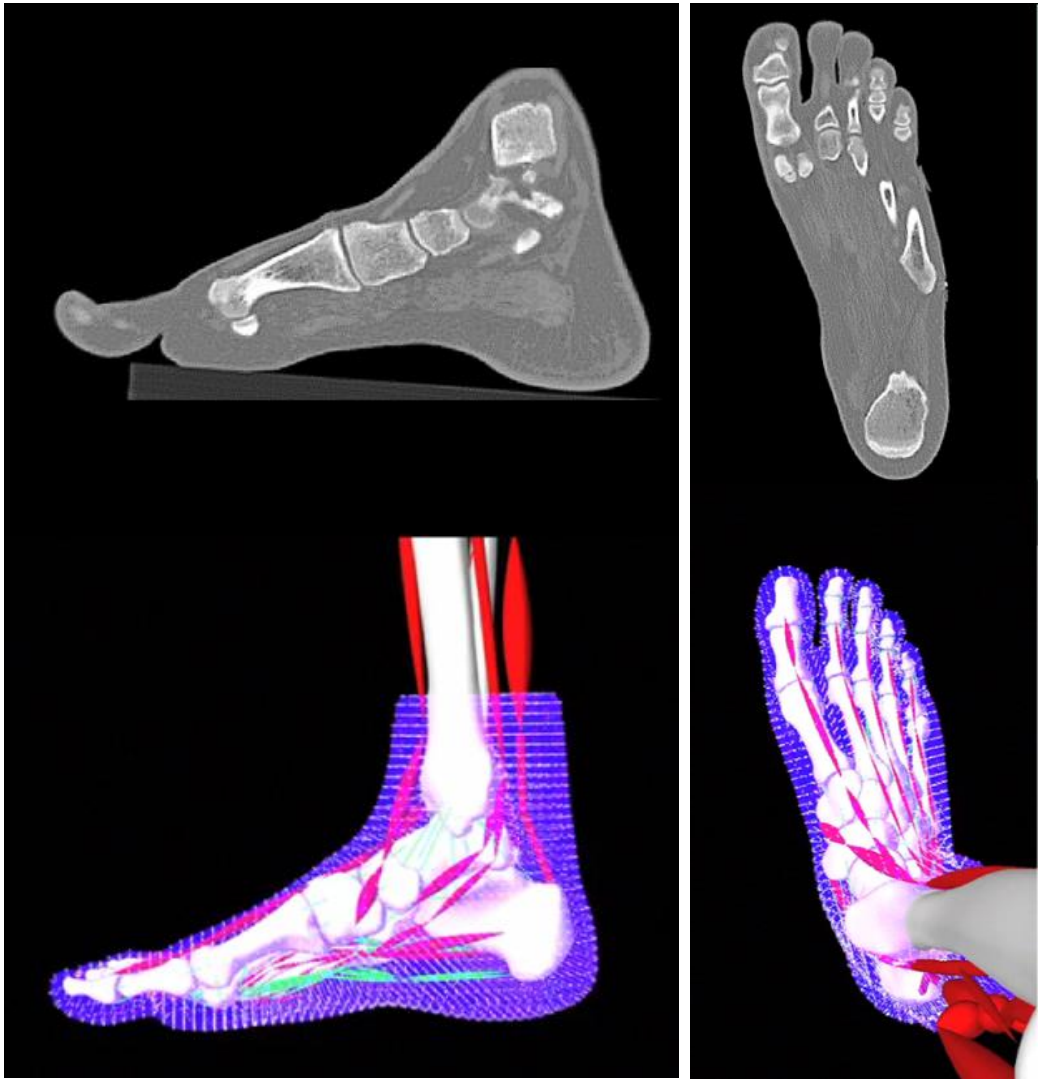


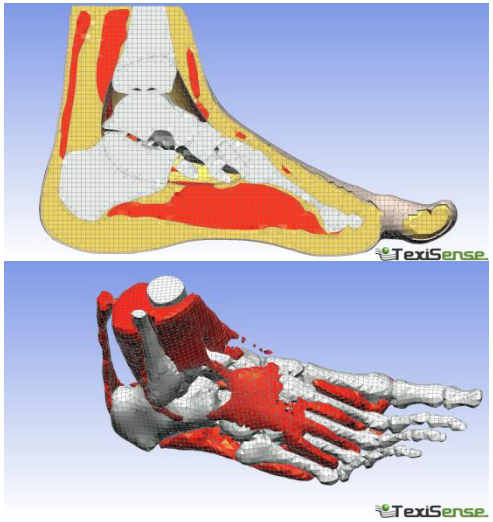
Numerical Clone

- Personalized medicine



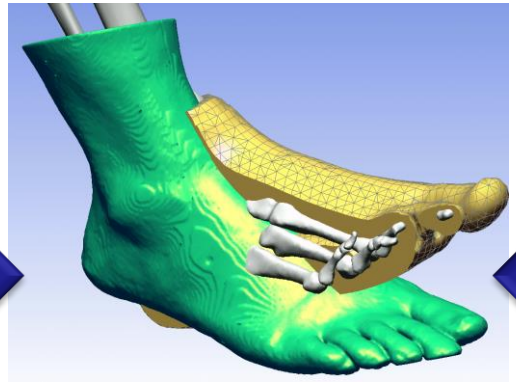
Numerical Clone

- Knowledge transfer: Atlas ➔ Patient

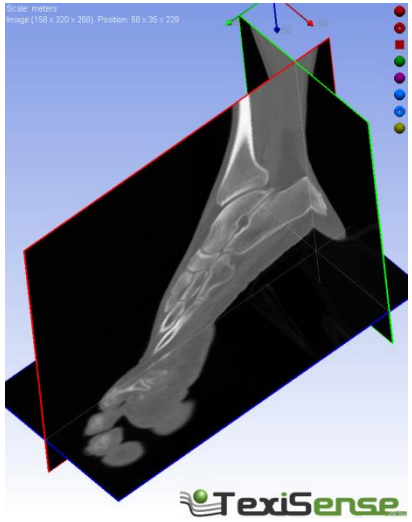


ATLAS

PRIOR KNOWLEDGE



REGISTRATION

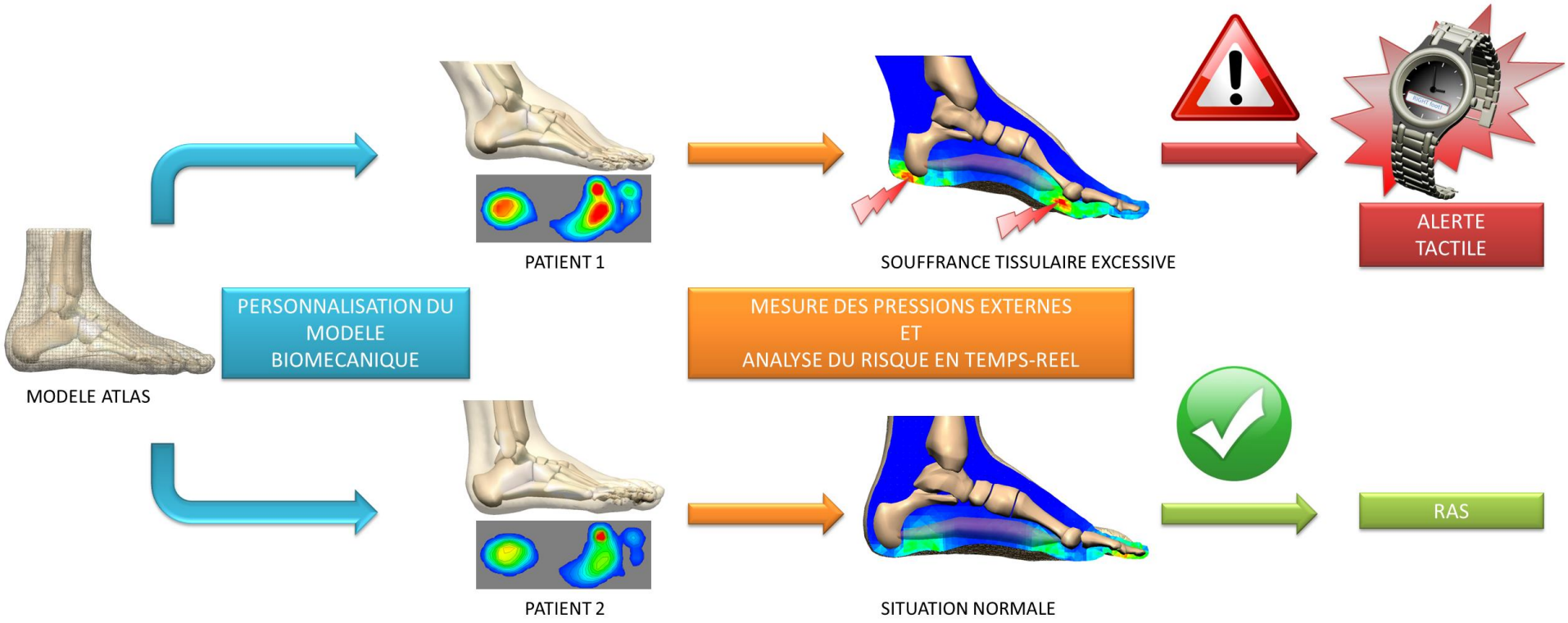


PATIENT

PATIENT SPECIFIC
BIOMECHANICAL MODEL

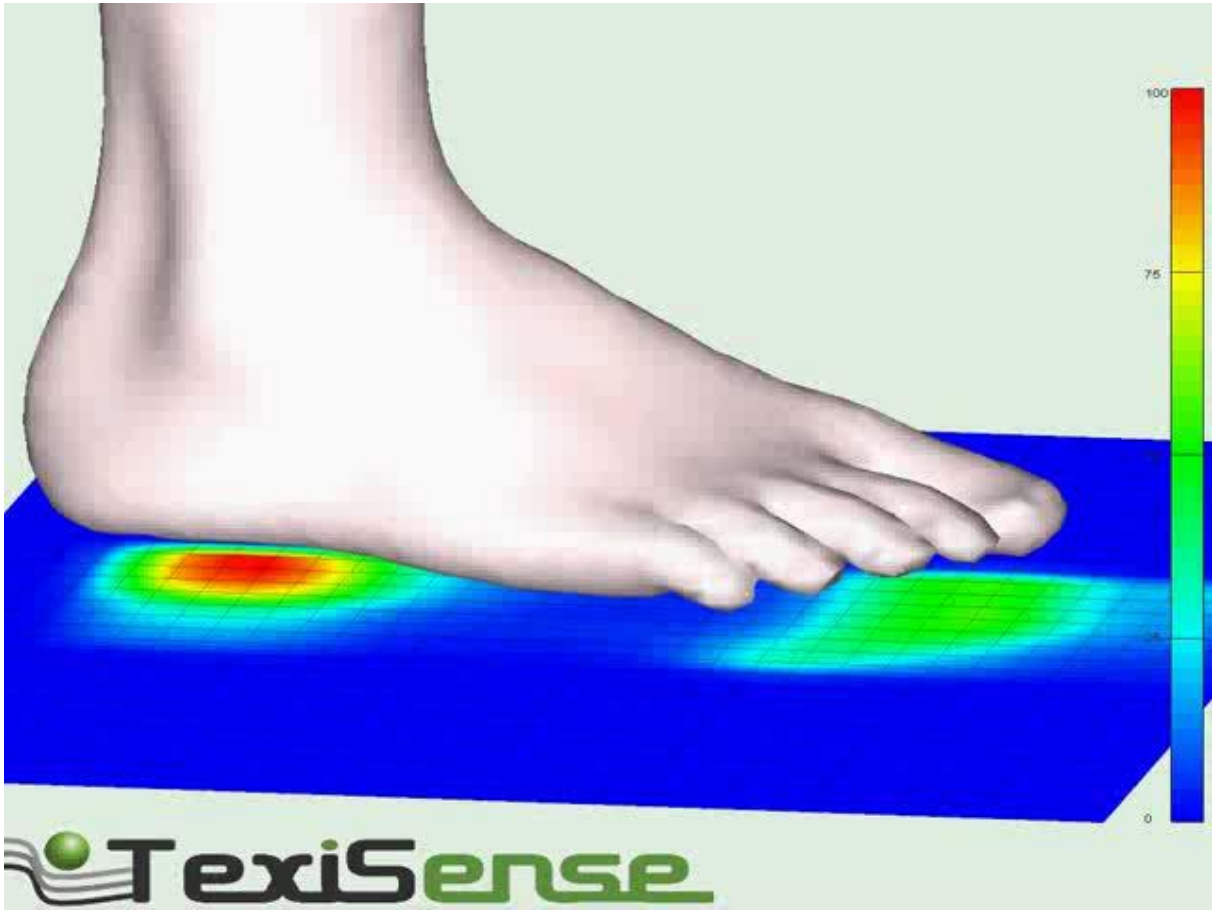
Numerical Clone

- Personnalized medecine



Texisense devices

- Biomechanical modeling: **real time** and **embedded system**
- First draft with linear PDE model:



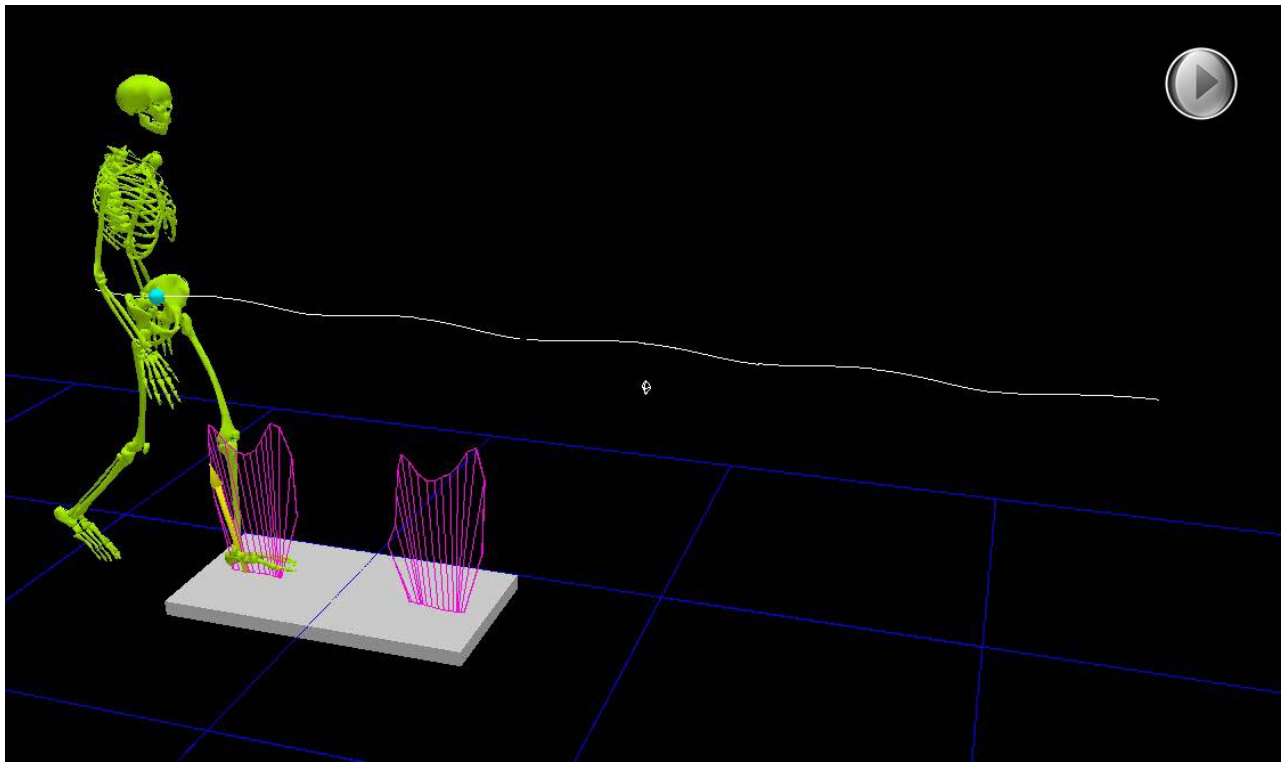
Texisense devices

- Biomechanical modeling: **real time** and **embedded system**
- Need for non linear PDE model:
  - Stepping can be divided into 75 pressure frames (from taligrade to digitigrade)
  - Each pressure frame takes about 2h30 on our simulation platform (ArtiSynth) with a powerful desktop PC
  - Too slow and too heavy for real time prevention of pressure ulcers embedded on a micro processor…

→ Need for Reduction Order Model techniques!

Model reduction process

- Offline data
  - From one patient, acquisition of the pressure below his foot

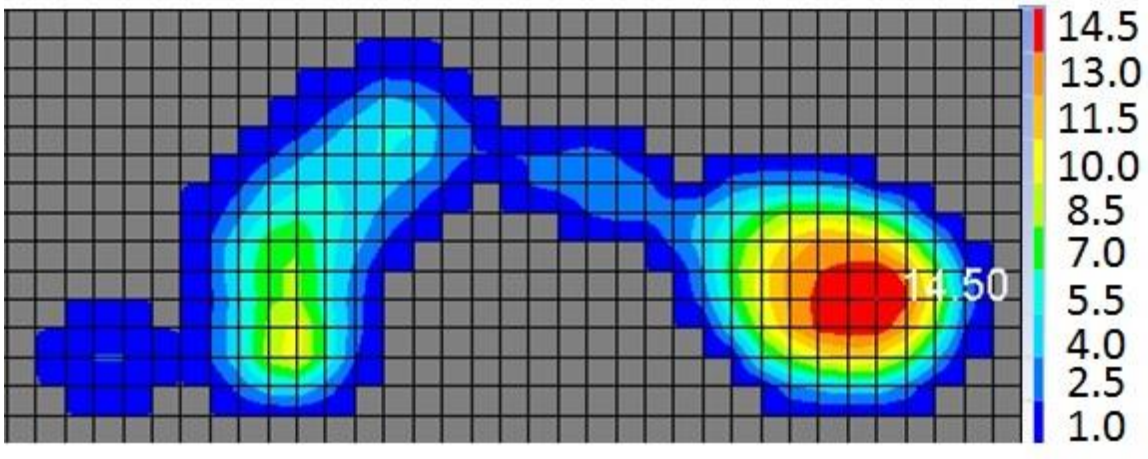


Model reduction process

- Offline data

  - From one patient, acquisition of the pressure below his foot

  - Lead to pressure fields for the 75 time steps
  - Projection of these pressure fields in a base of 5, 8, and 14 modes



Model reduction process

- Offline data

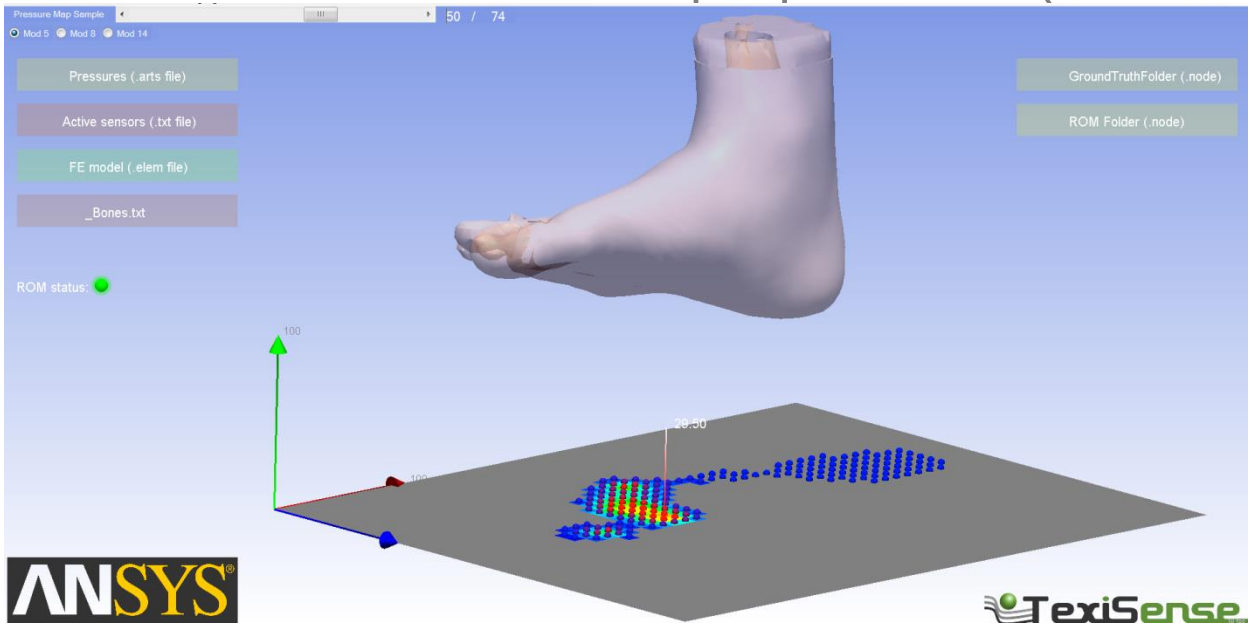
  - From one patient, acquisition of the pressure below his foot

  - Lead to pressure fields for the 75 time steps
  - Projection of these pressure fields in a base of 5, 8, and 14 modes

  - Computation of the deformation fields on the 75 time steps associated to the previous pressure fields:
    - Corresponding to the exact pressure field,
    - Corresponding to the projected pressure fields in a base of 5, 8, and 14 modes.

Model reduction process

- Online estimation
  - For any pressure field (dynamic acquisition):
    - Projection of this pressure field in the base of n modes
    - Evaluation of the ROM for this input parameter (n scalar values)



  - These 2 steps are quick and reliable
  - Quasi real time evaluation of the deformation field with respect to the pressure acquisition

Model reduction

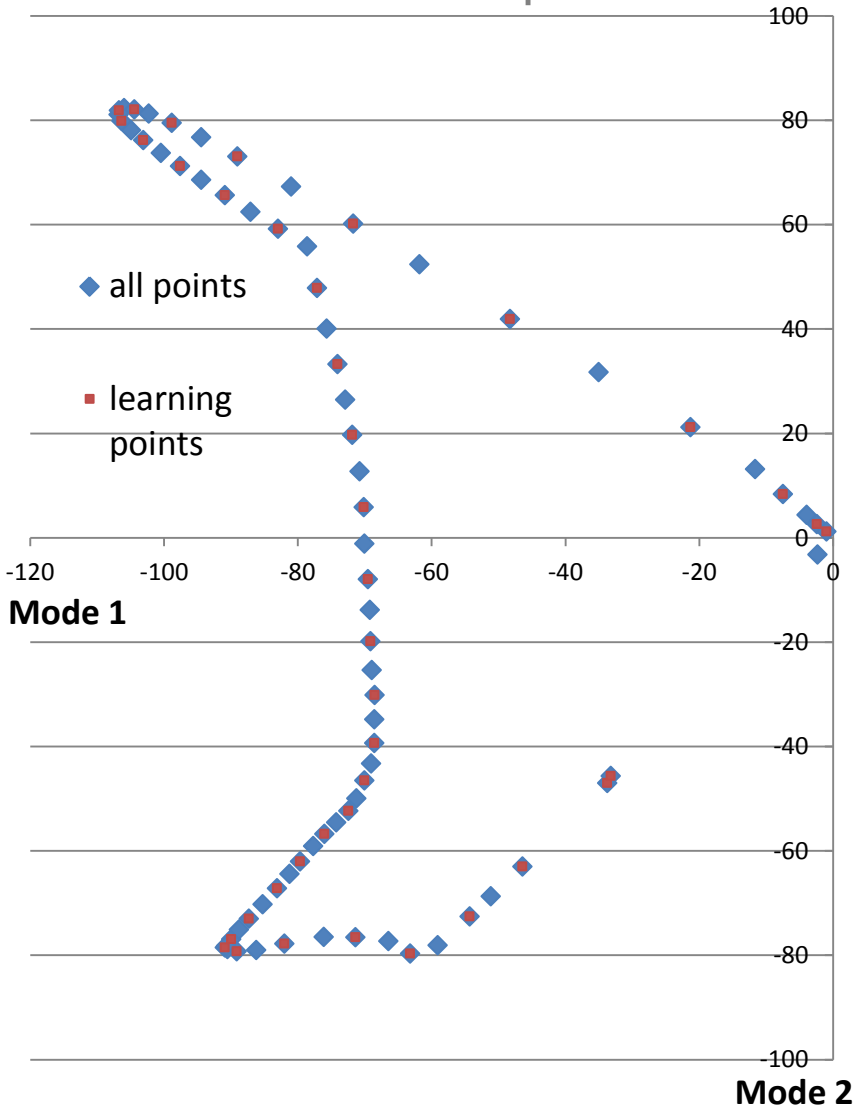
- Precision of the pressure fields projection

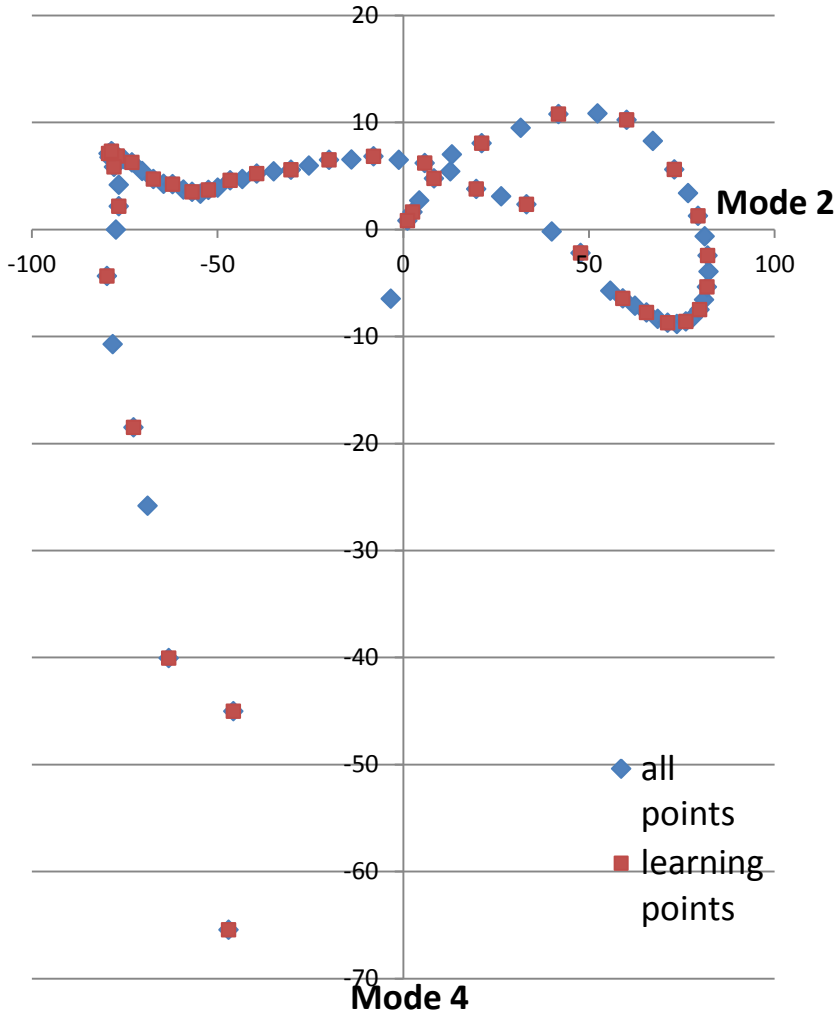
Number of modes	Precision
5	6.7%
8	2.3%
14	0.91%

- For each mode
  - 39 steps used to build the model reduction (i.e. learning points),
  - 36 remaining steps used for validation.

Model reduction

- Visualization of the pressure fields' mode coordinates





Model reduction

- Error estimation with evaluations using the model reduction:
  - In terms of displacement field, with respect to the :
    - 5 scalar parameters: Mean = 3.9 % Max = 23%
    - 8 scalar parameters: Mean = 4.6 % Max = 33%
  - In terms of deformed shape, with respect to the :
    - 5 scalar parameters: Mean = 0.45 % Max = 0.97%
    - 8 scalar parameters: Mean = 0.48 % Max = 1.33%

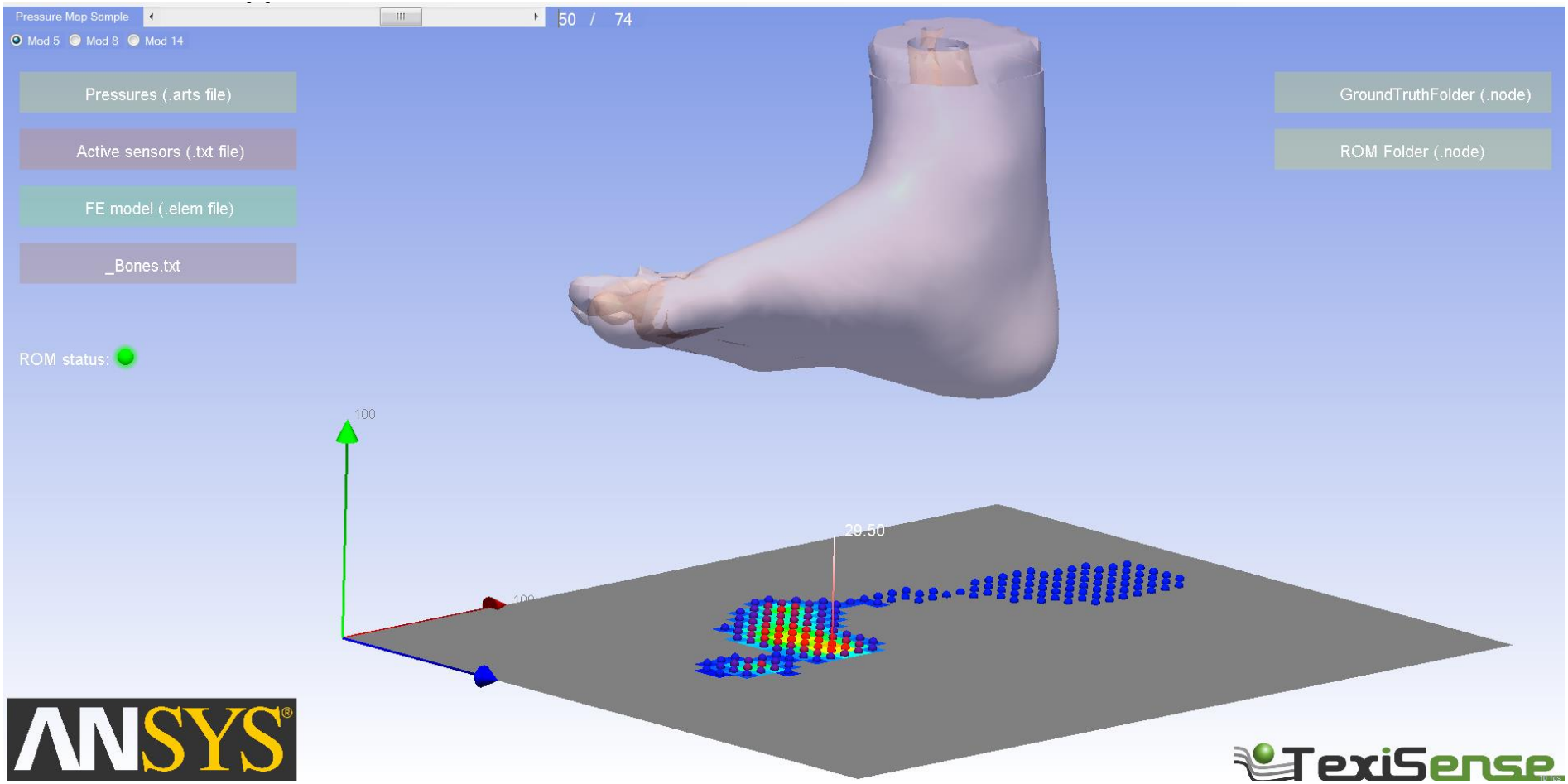
→ Better estimation with only 5 modes?

Yes, if the learning points are limited to 39 steps…

But 8 and 14 modes would become better with more learning points!

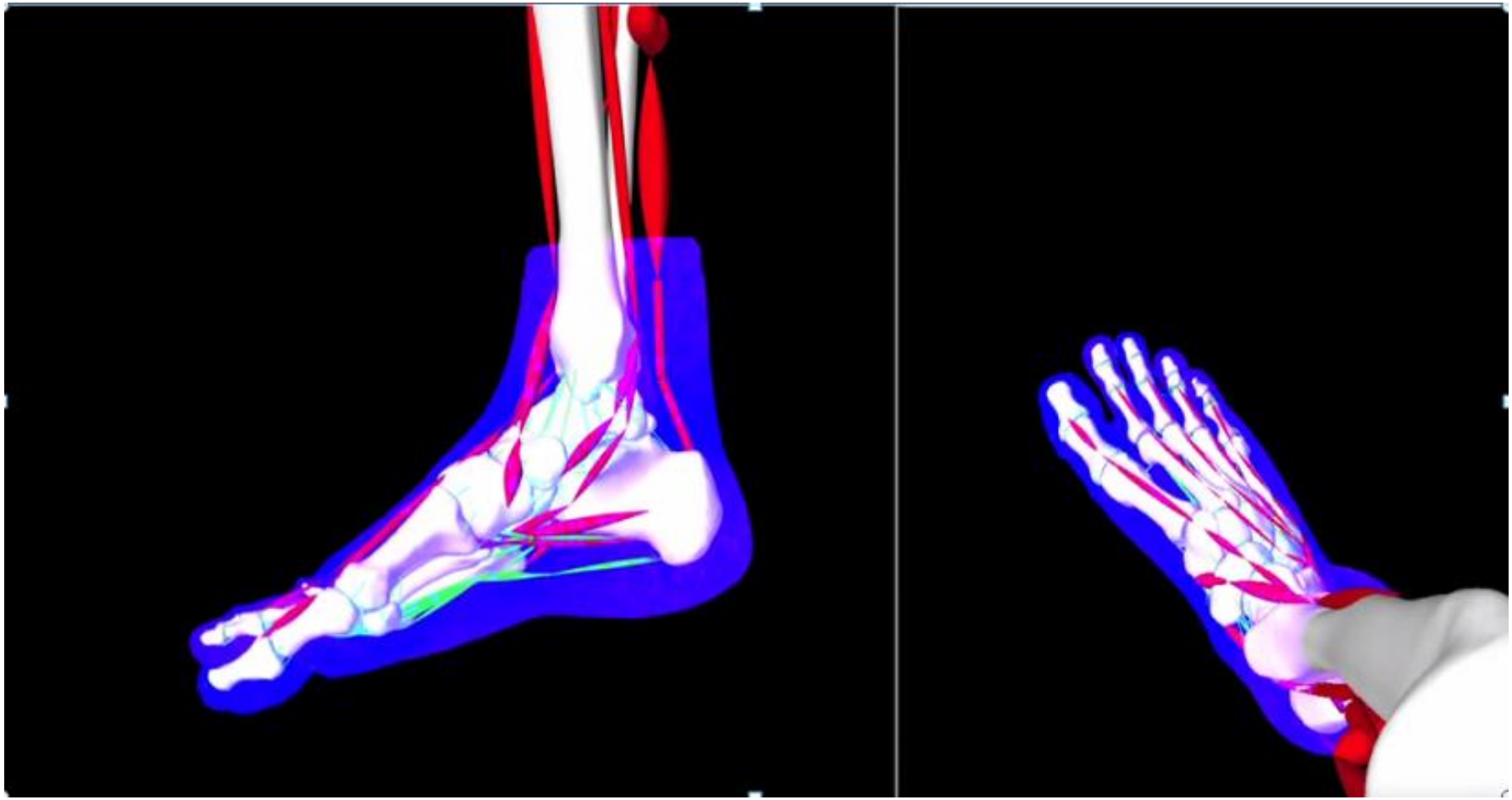
Model reduction

- Real time application to pressure ulcer prevention



Numerical Clone Extension

- Simulation of muscle activations



Prix Blaise Pascal pour la modélisation numérique médicale personnalisée, 2016

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