Biomechanical Modeling to Prevent Ulcers

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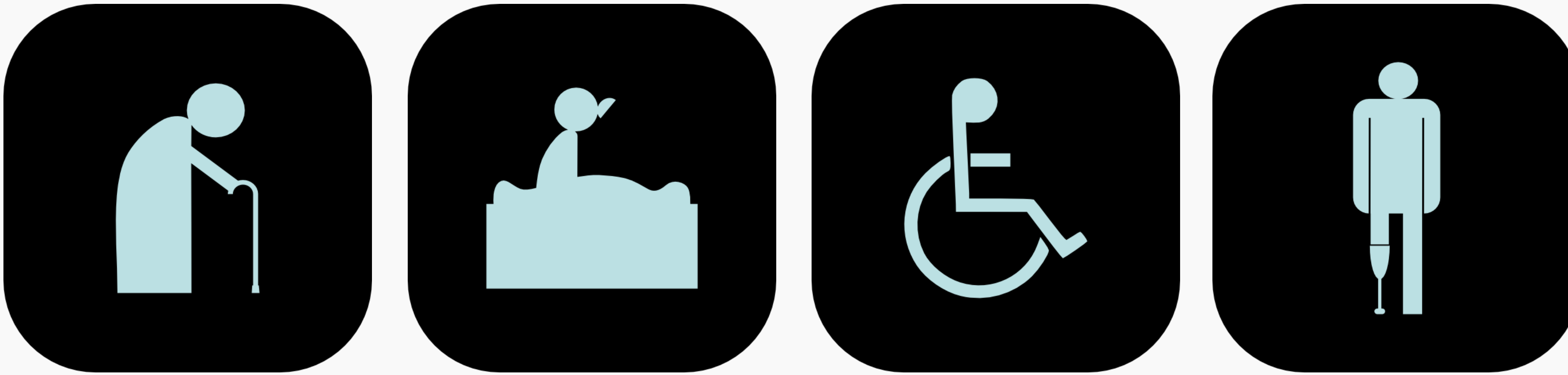
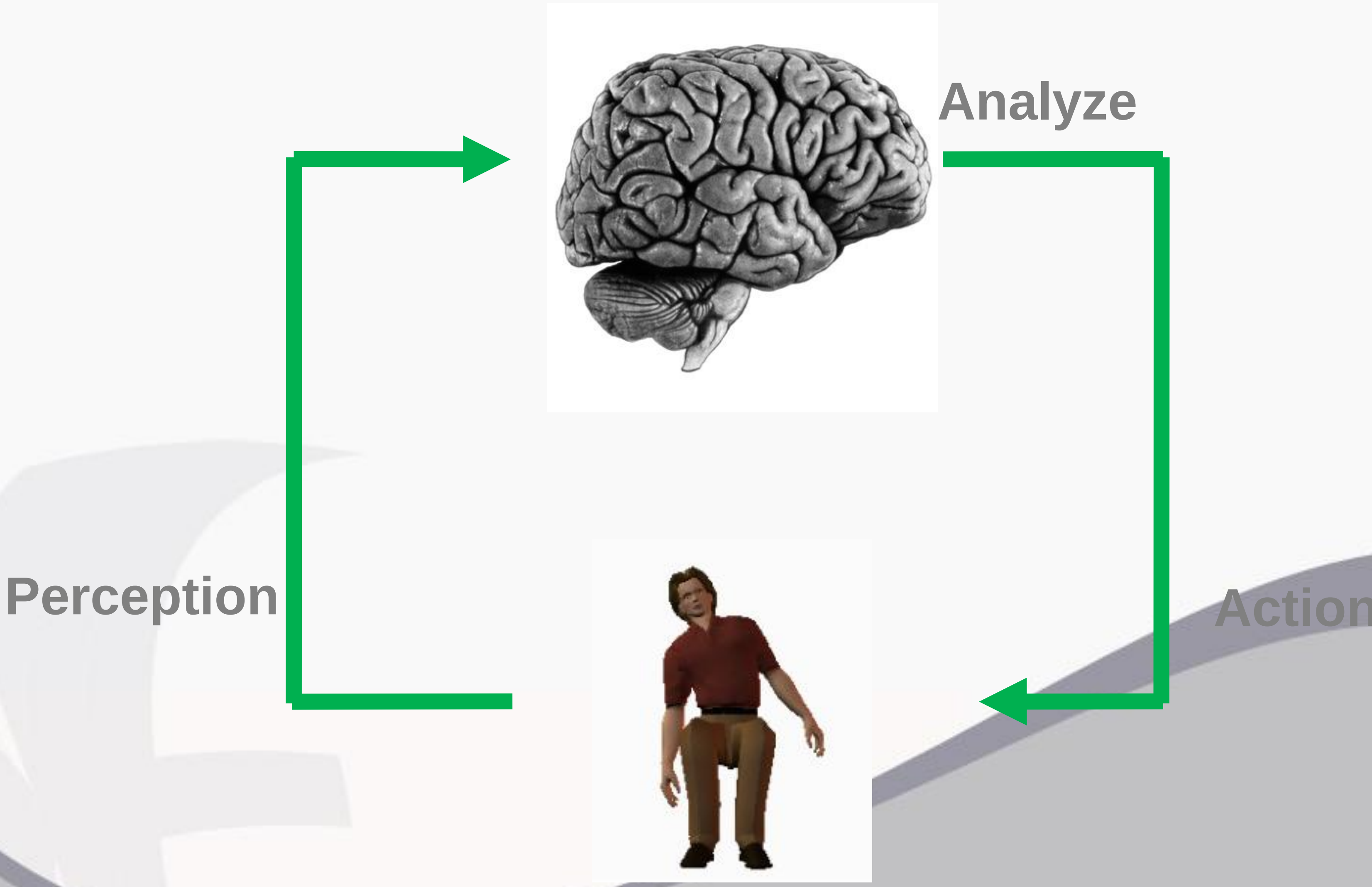
4. IDS, Montceau-les-Mines, France.

Pressure ulcers prevention

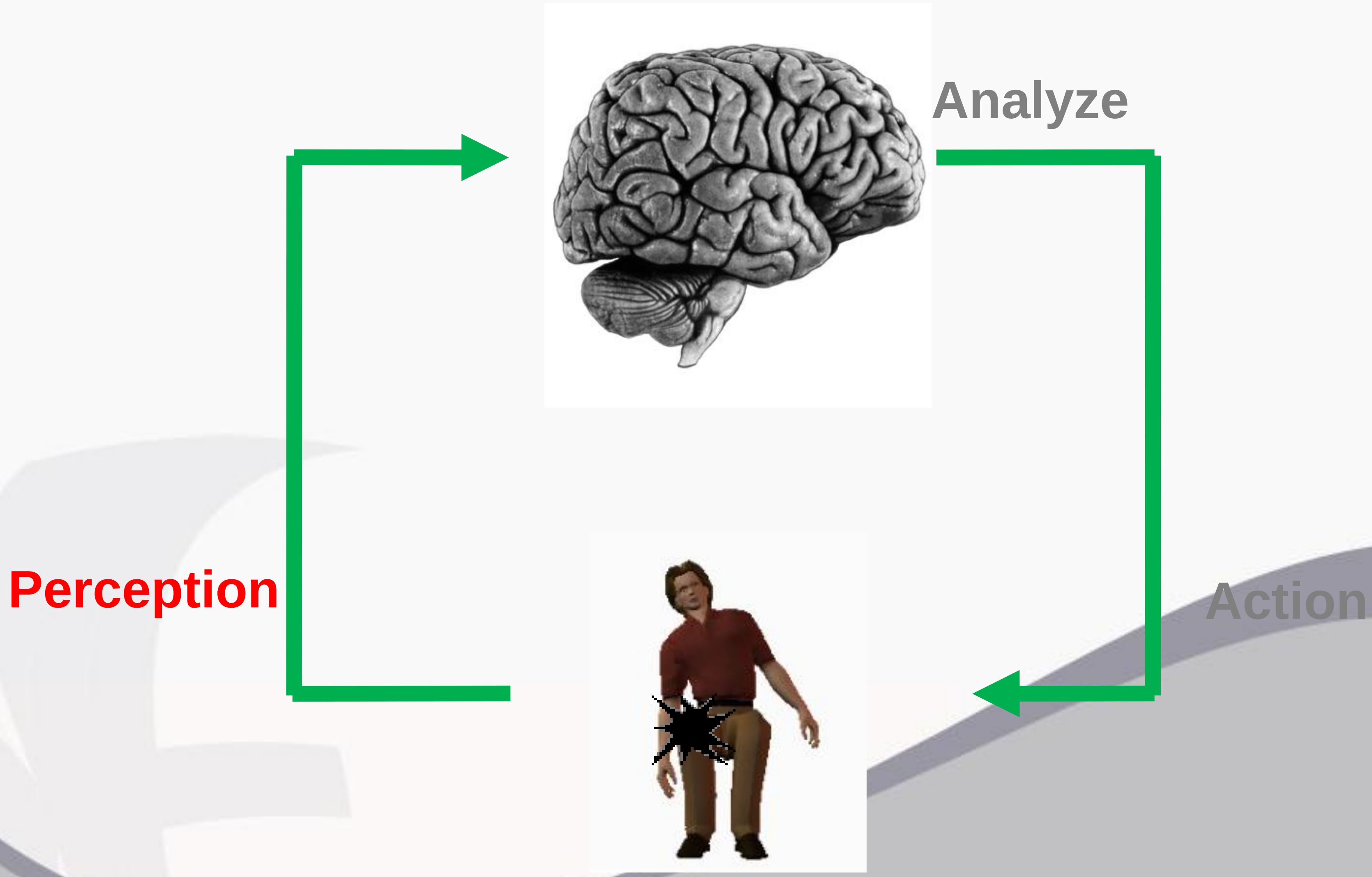


Pressure ulcers prevention for disabled, paraplegic and diabetic persons

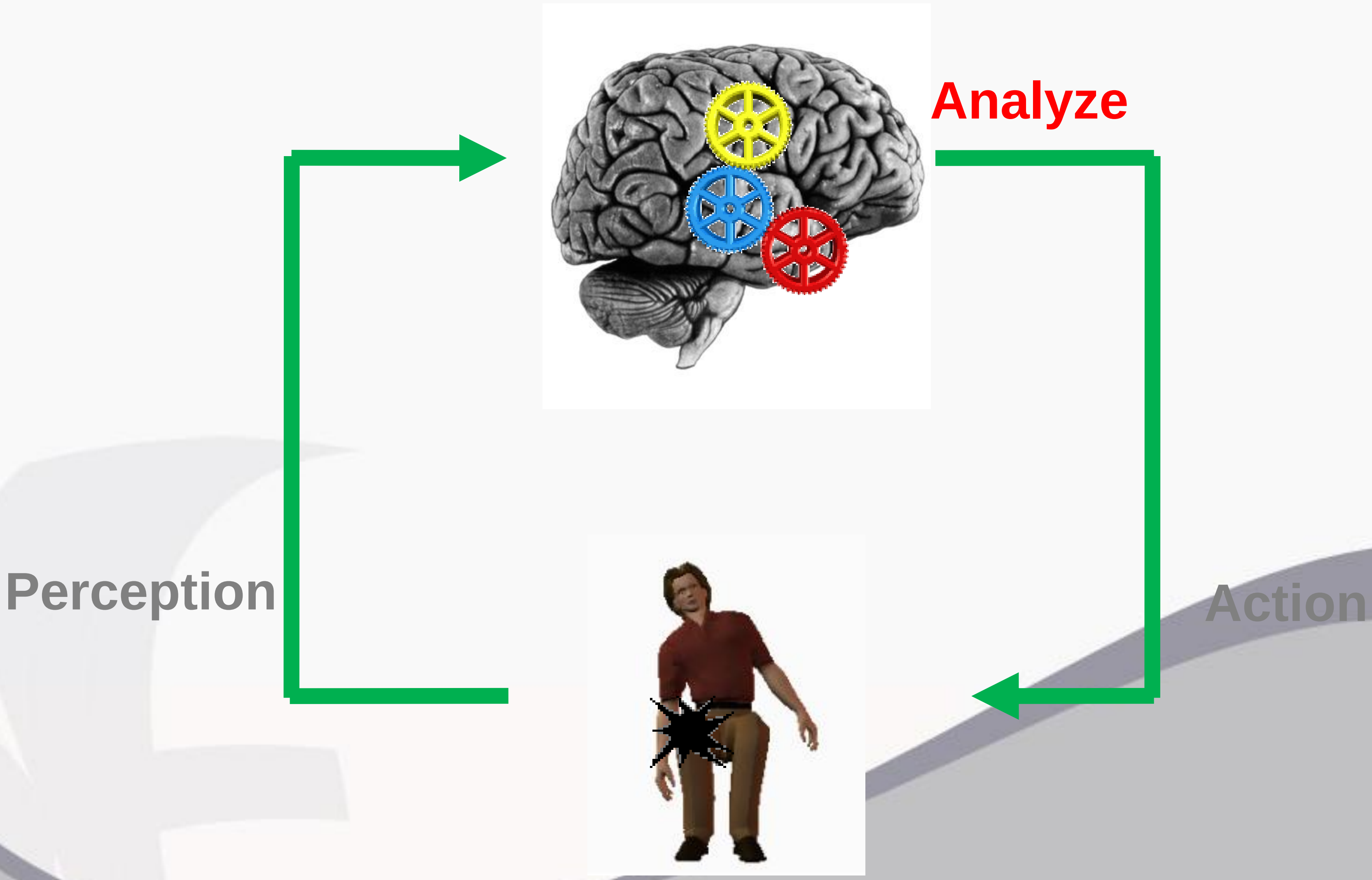
Over-pressures: healthy person



Over-pressures: healthy person



Over-pressures: healthy person



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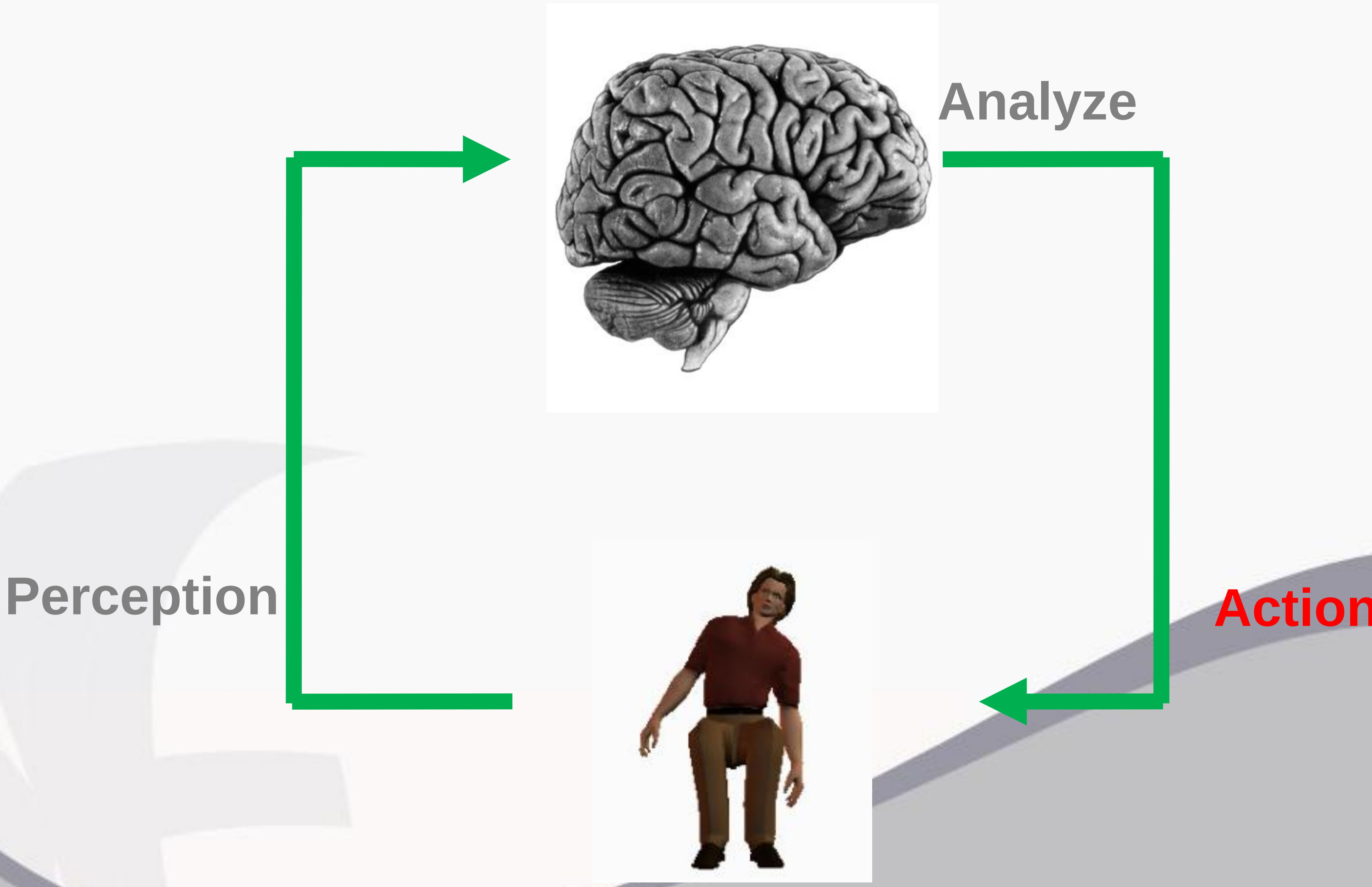
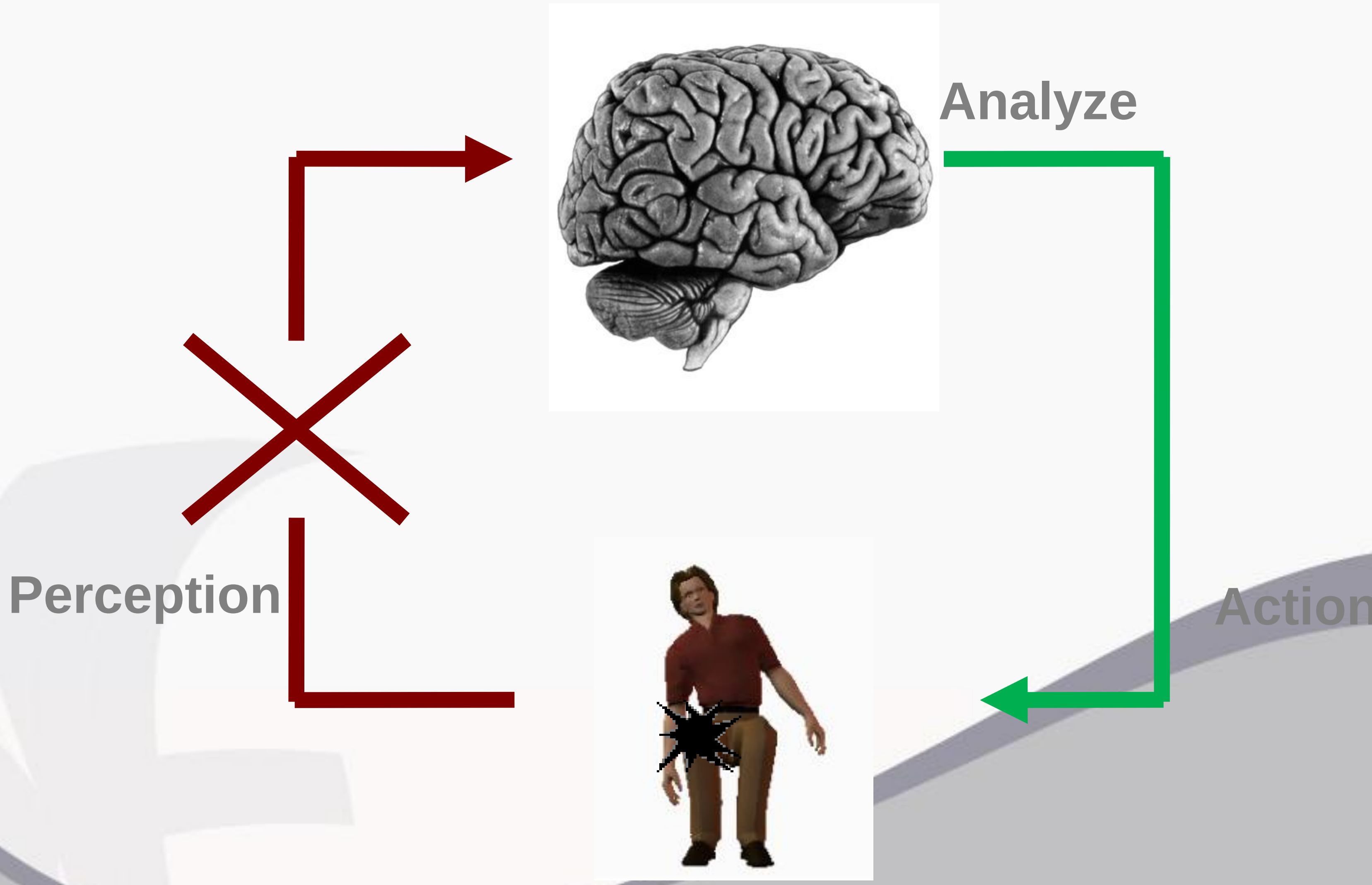
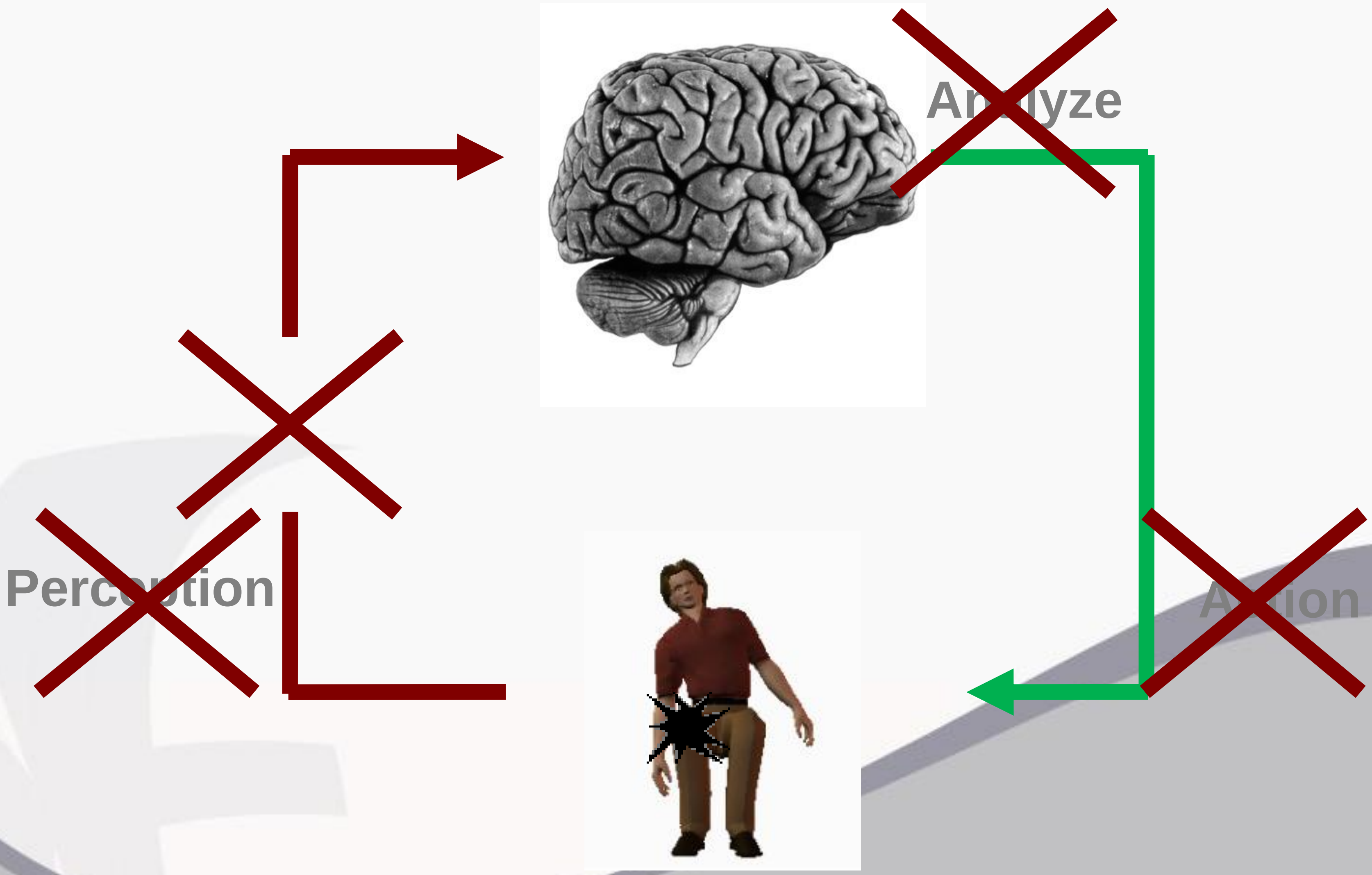
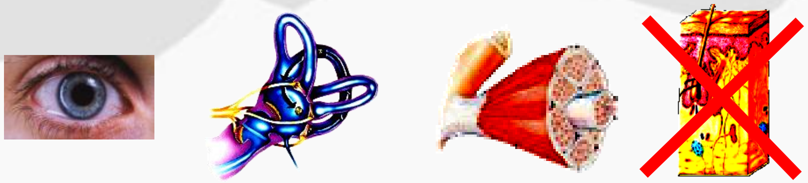


Over-pressures: paraplegics



Over-pressures: paraplegics





Artificial sensor

Coupling device

Stimulator

multi-sensory integration

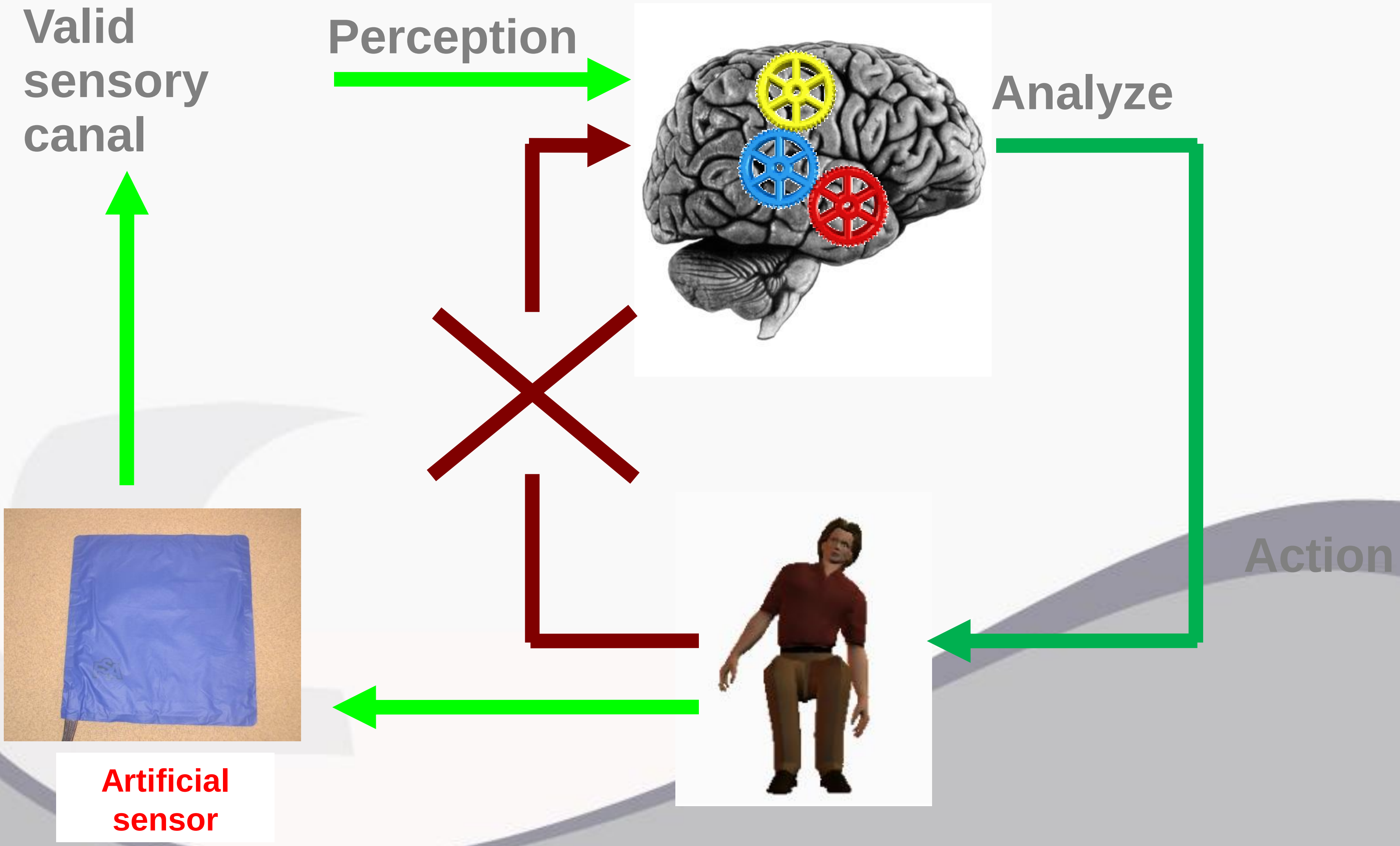
Perception

Action

Perceptual supplementation

→ provide information dedicated to one sensory modality through another modality

Over-pressures: paraplegics

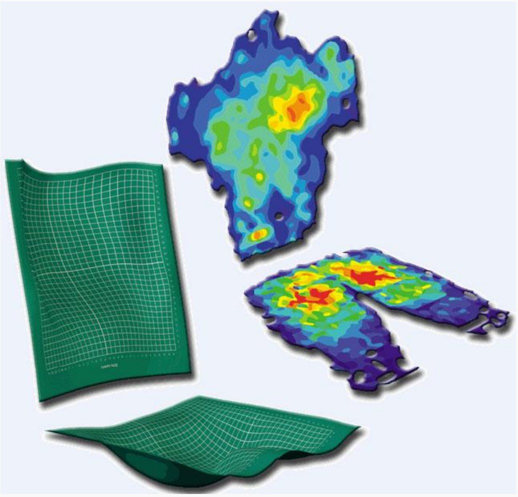


Pressure ulcer prevention

- Three questions :
  - What kind of artificial sensor for the measurement of the pressure at the buttocks / seat interface?
  - When deciding that there is a risk for pressure ulcer?
  - How to alert the person in case of a risk?

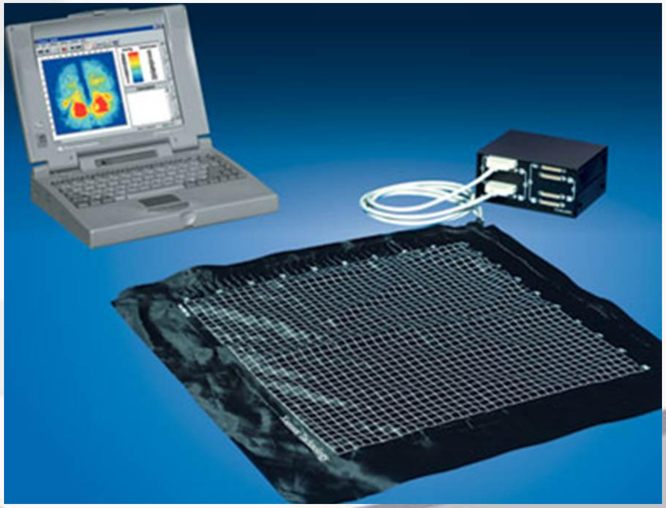
⇨ An Utility / Utilisability / Acceptability Study

What kind of artificial sensor?



Tekscan Inc.

Xsensor Inc.



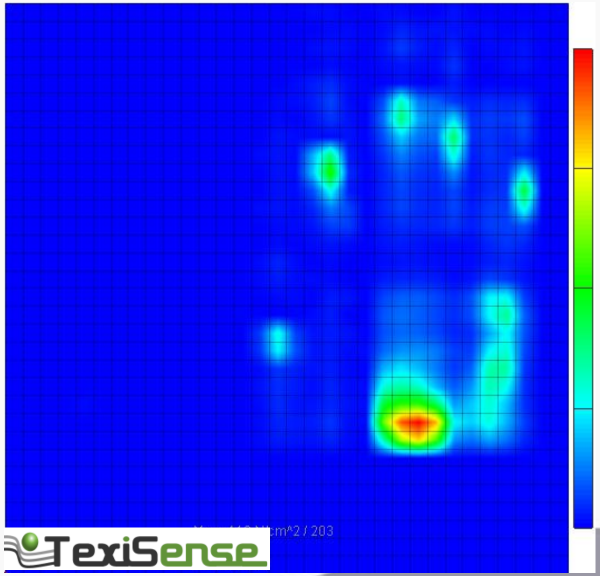
Vista Medical Inc.

What kind of artificial sensor?

- Conclusions of the Utility / Utilisability / Acceptability Study:
  - The pressure mat has to be low cost
  - The pressure mat has to be comfortable (on or around the cushion)
  - The pressure mat has to be washable

What kind of artificial sensor?

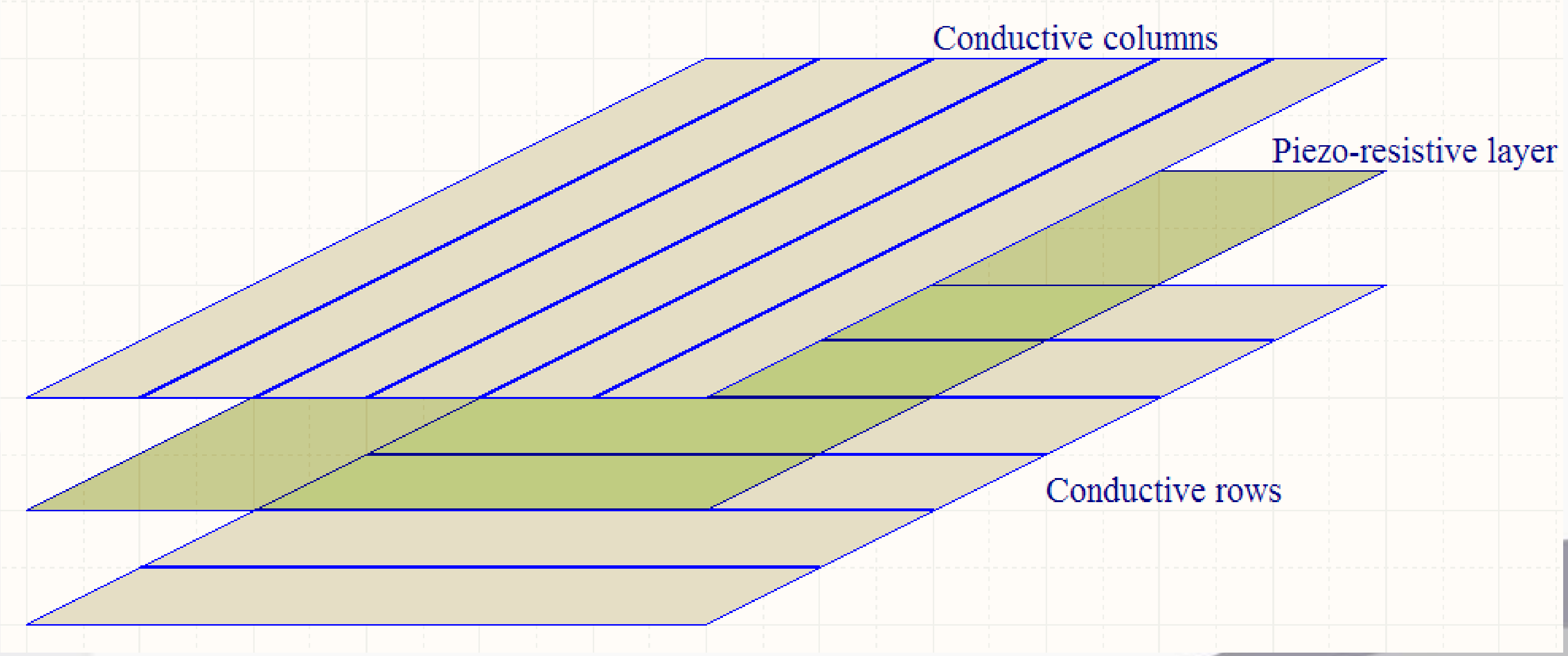
An embedded pressure mat made of textile (technology provided by Texisense company)



100% textile

What kind of artificial sensor?

An embedded pressure mat made of textile (technology provided by Texisense company)

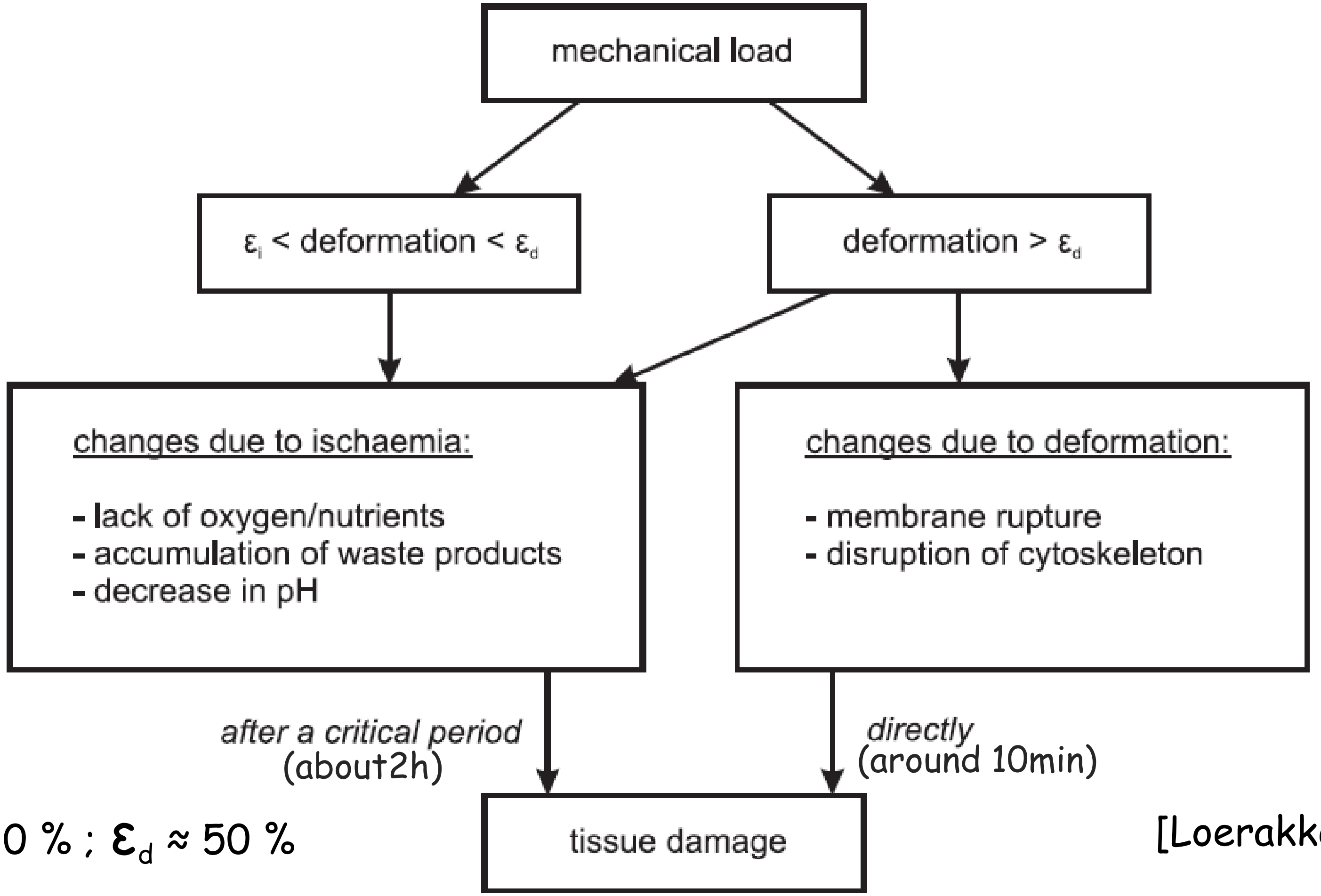


- Two outer layers form a matrix that defines the spatial resolution of the sensor: the nylon fibers coated with silver conduct current
- Any normal forces exerted onto the middle layer change the electrical resistance of the material : fibers are coated with polymers

Pressure ulcer prevention

- Three questions :
  - What kind of artificial sensor for the measurement of the pressure at the buttocks / seat interface?
  - When deciding that there is a risk for pressure ulcer?
  - How to alert the person in case of a risk?

When deciding that there is a risk for PU?



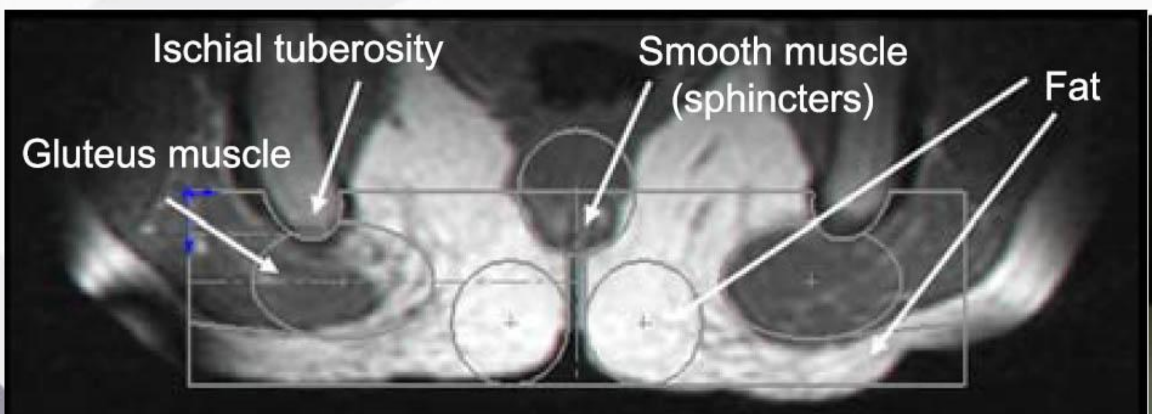
$\varepsilon_i \approx 20\ \%$; $\varepsilon_d \approx 50\ \%$

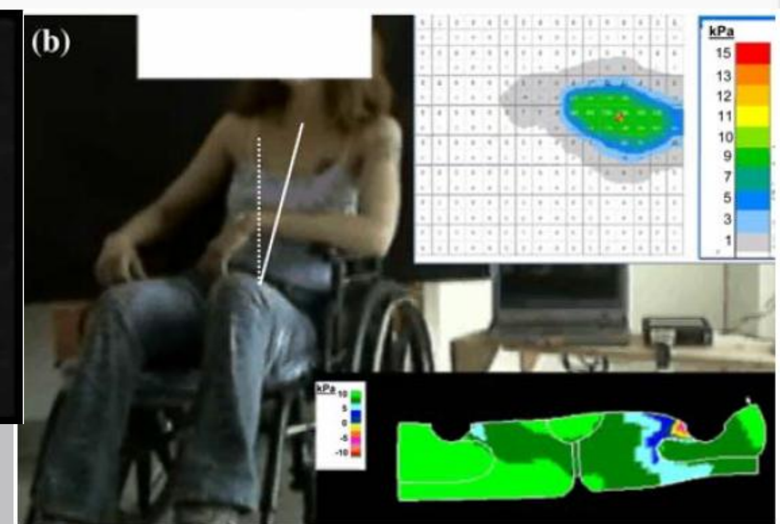
[Loerakker, 2011]

When deciding that there is a risk for PU?

- ❑ **How to estimate the deformations thresholds from the measured pressures at the buttocks / cushion interface for a given patient?**

⇨ The use of a patient-specific biomechanical model of the buttocks bone / soft tissues

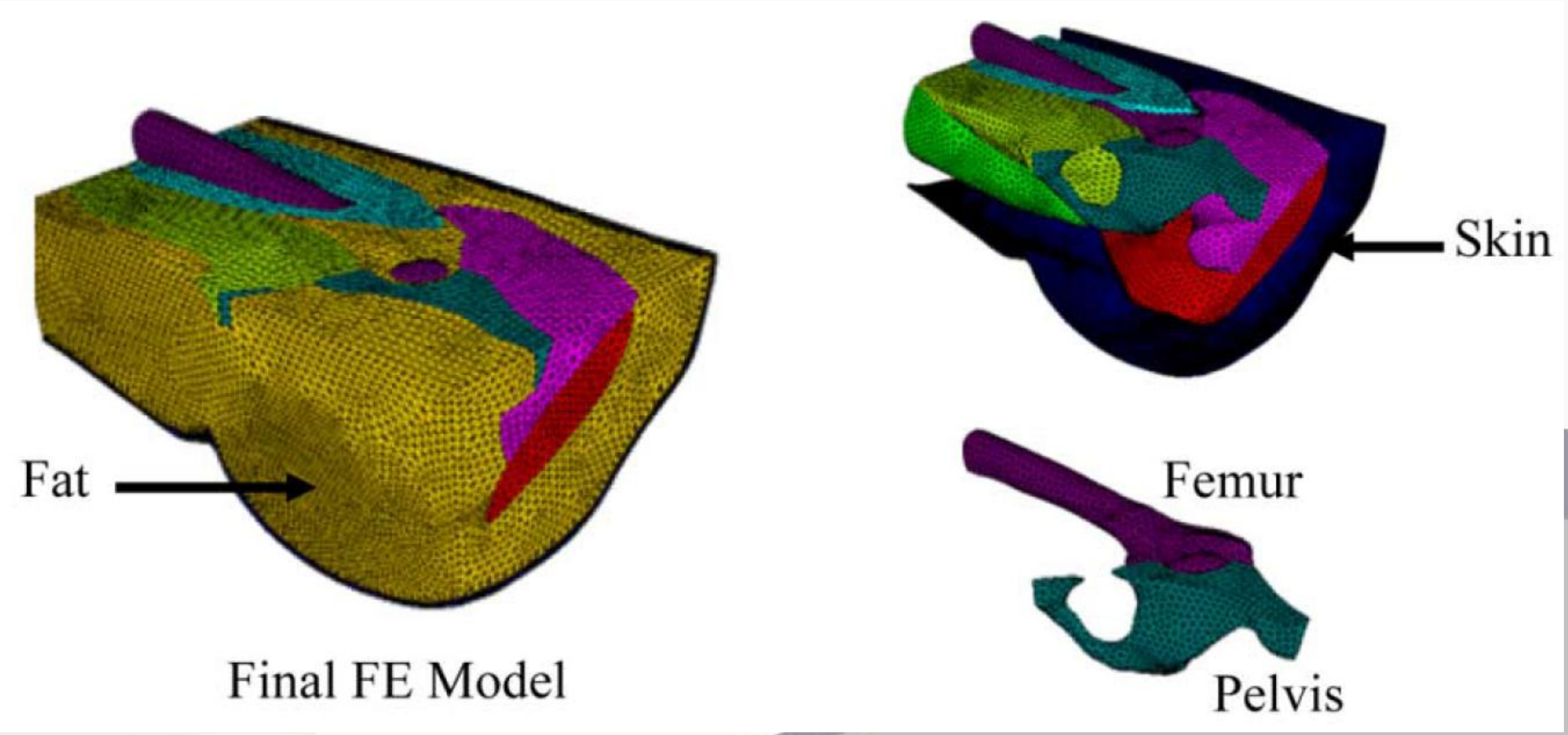




[Linder-Ganz et al., 2009]

Patient-specific biomechanical model of the buttocks

- **Explicit 3D Finite Element modeling:**
  not real time

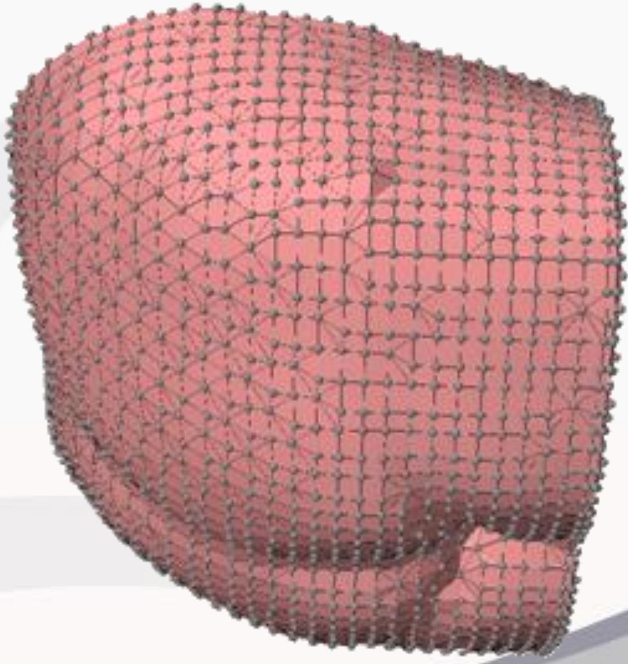


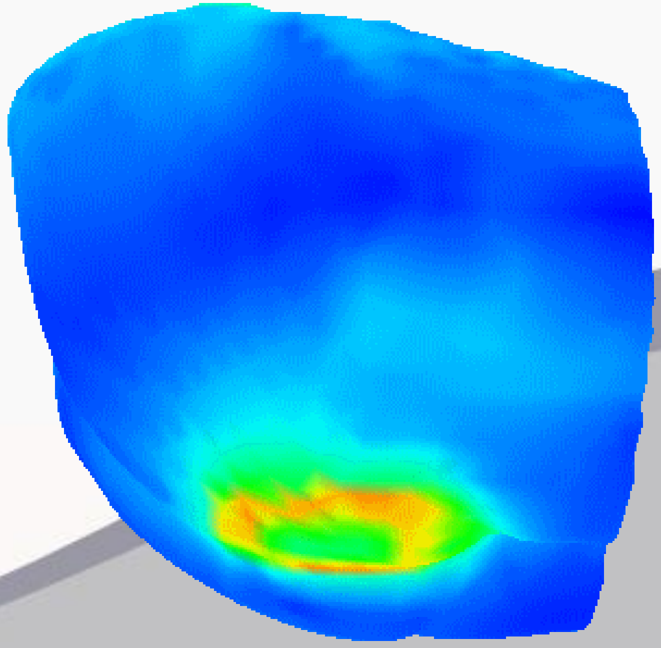
[Makhsous et al., 2007]

Patient-specific biomechanical model of the buttocks

- Semi implicit 3D Finite Element modeling:

  close to real time
- Using ArtiSynth, 3D biomechanical simulation platform (http://www.artisynth.org/) [Stavness, 2011].





Patient-specific biomechanical model of the buttocks

Acquisition of the patient morphology:

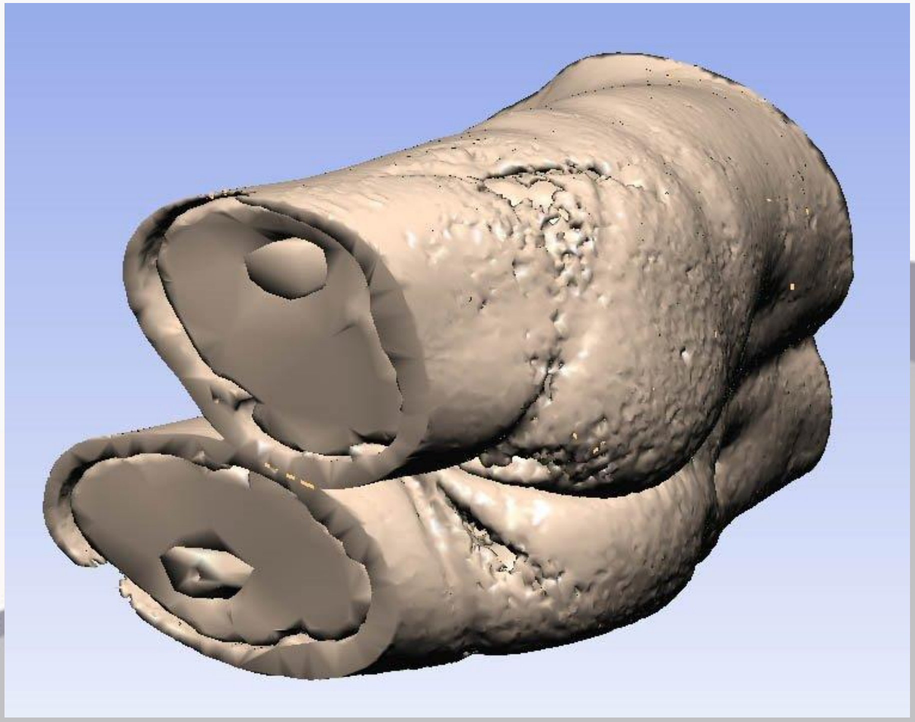
- CT scan of the patient on his back -> too much deformations of the tissues.

Patient-specific biomechanical model of the buttocks

Acquisition of the patient morphology:

- CT scan of the patient on his back -> too much deformations of the tissues.
- CT scan of the patient on his side -> only one side deformed.
- Segmented on the left side

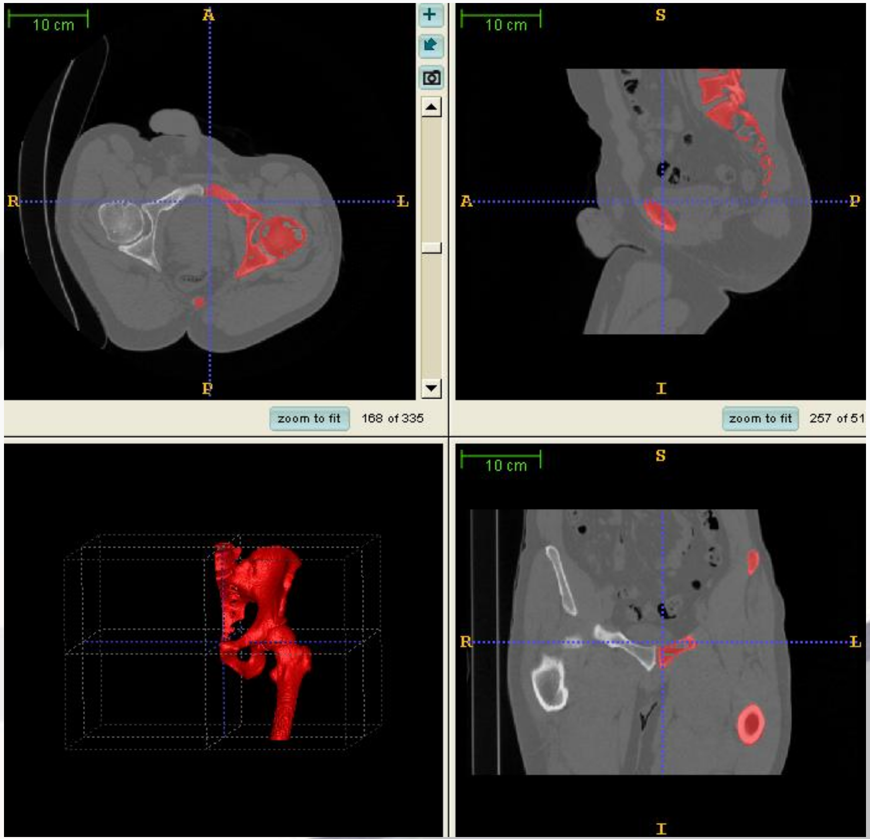
to avoid the constraints and reconstruct the morphology.

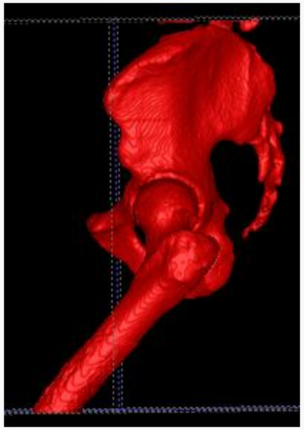


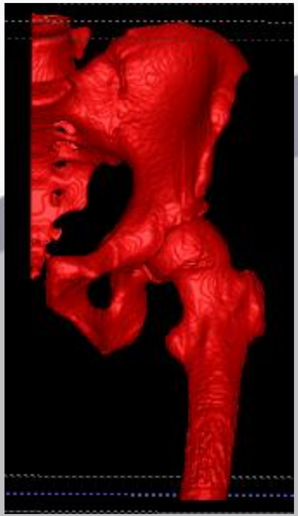
Patient-specific biomechanical model of the buttocks

Acquisition of the patient morphology:

- Using ITK-Snap
    - Segmentation of the bones



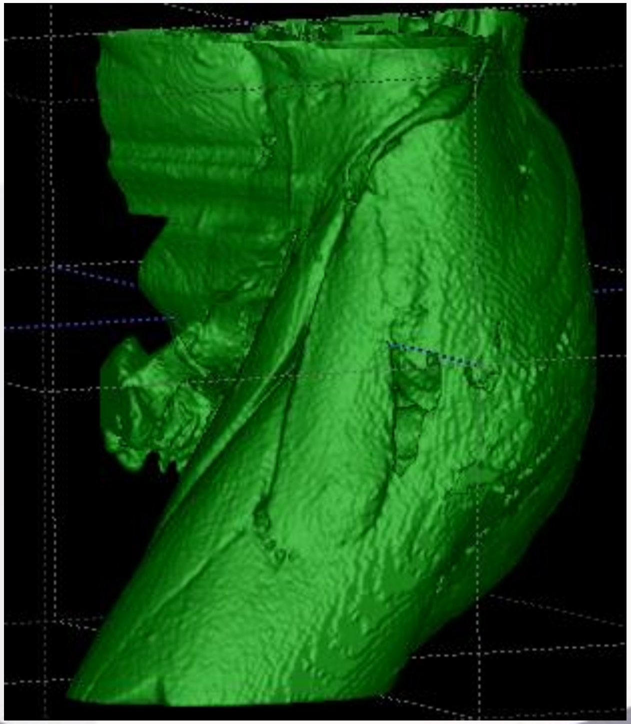




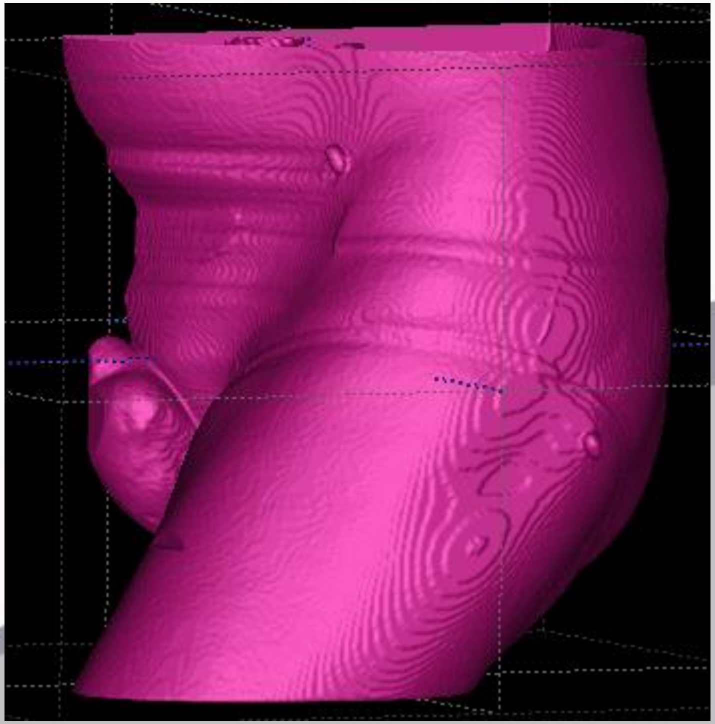
Patient-specific biomechanical model of the buttocks

Acquisition of the patient morphology:

- Using ITK-Snap
  - Segmentation of the bones
  - Segmentation of the skin and muscles



Muscles

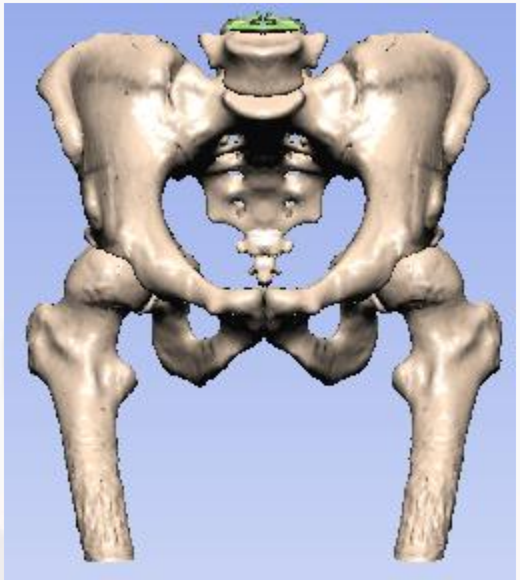


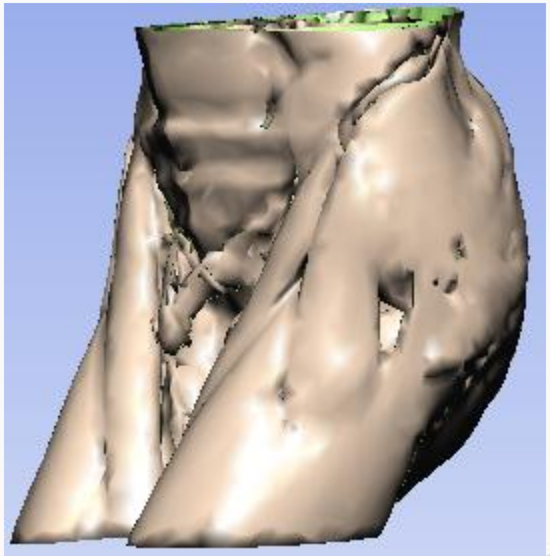
Skin

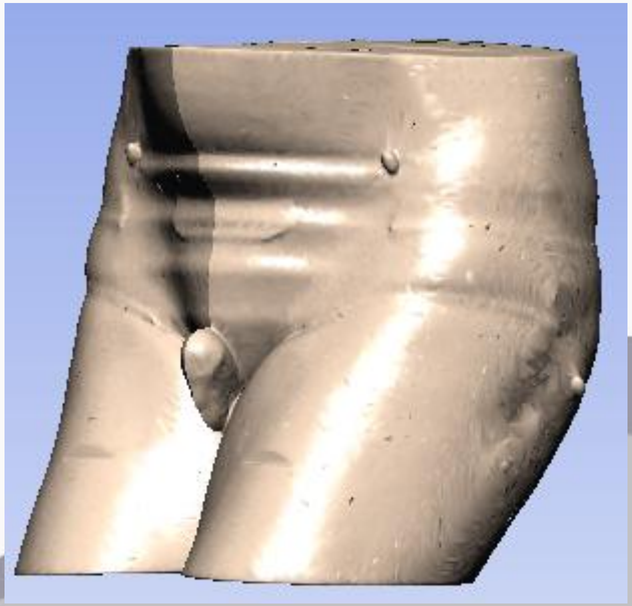
Patient-specific biomechanical model of the buttocks

Acquisition of the patient morphology:

- **Using ModelEditor (TIMC-IMAG), symetry to get the full morphology**



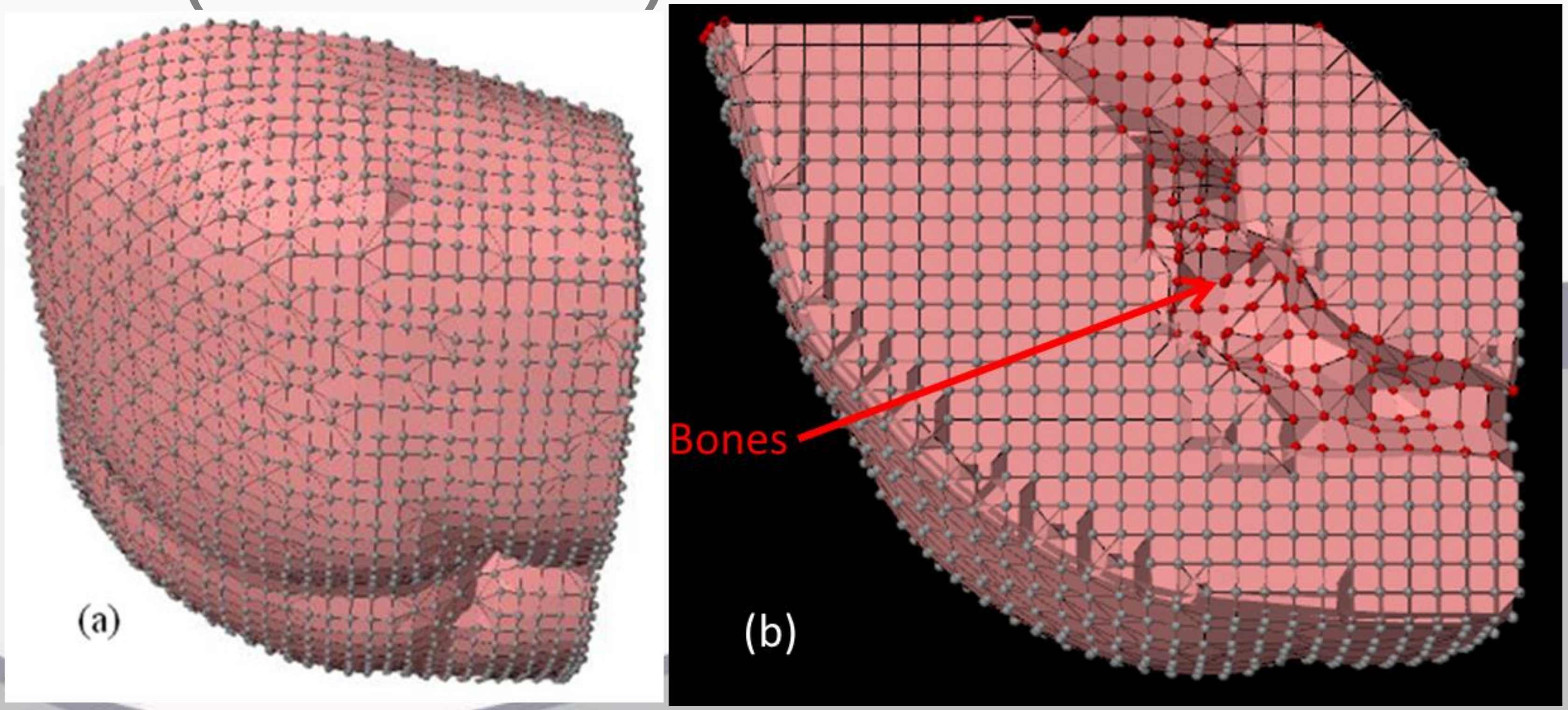




Patient-specific biomechanical model of the buttocks

Finite Element model corresponding to the patient:

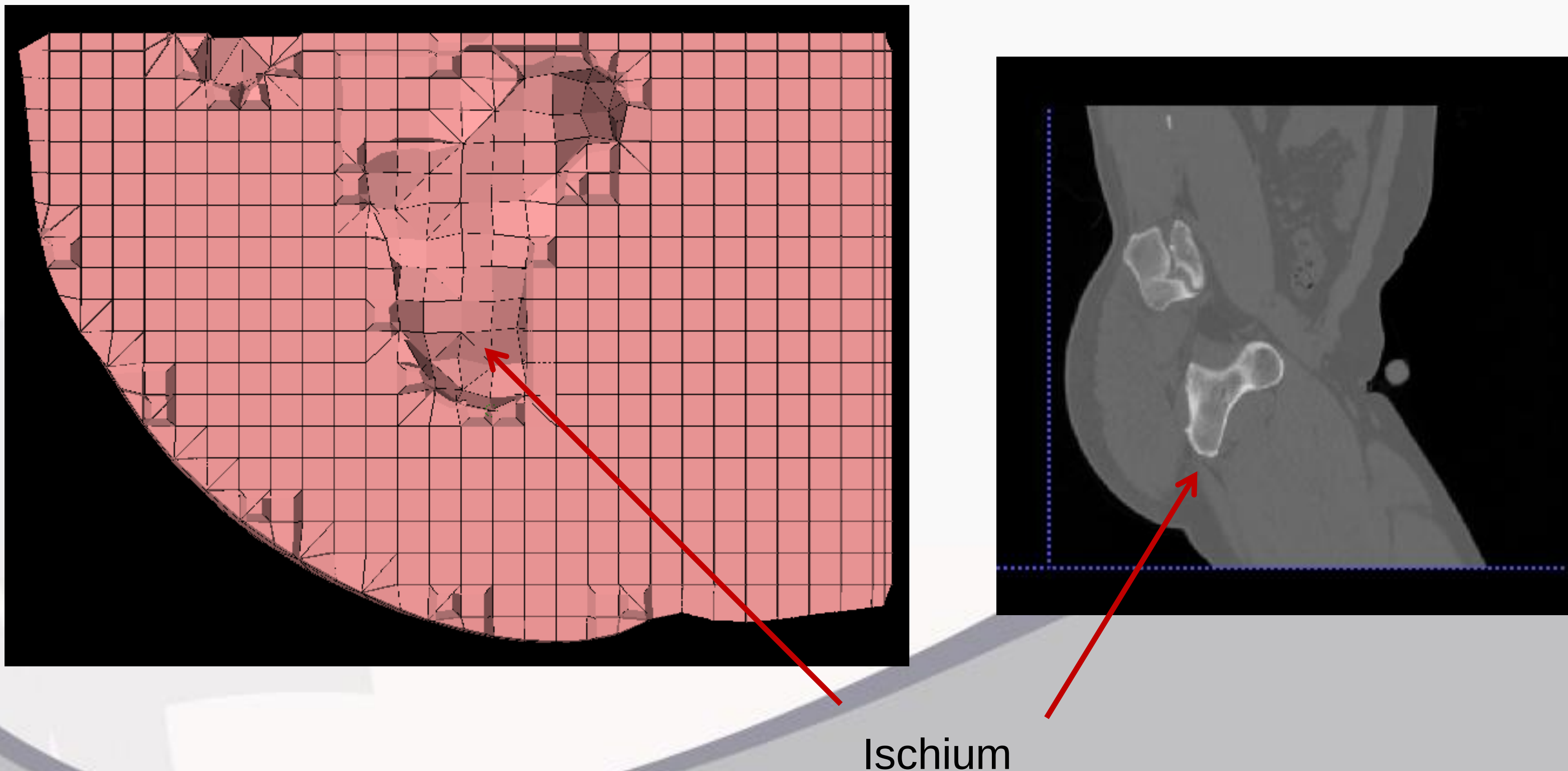
- **Using TxMesher (Texisense), filling the surfaces with hexahedrons and tetrahedrons, leaving holes for the bones (fixed red nodes).**



Patient-specific biomechanical model of the buttocks

Finite Element model corresponding to the patient:

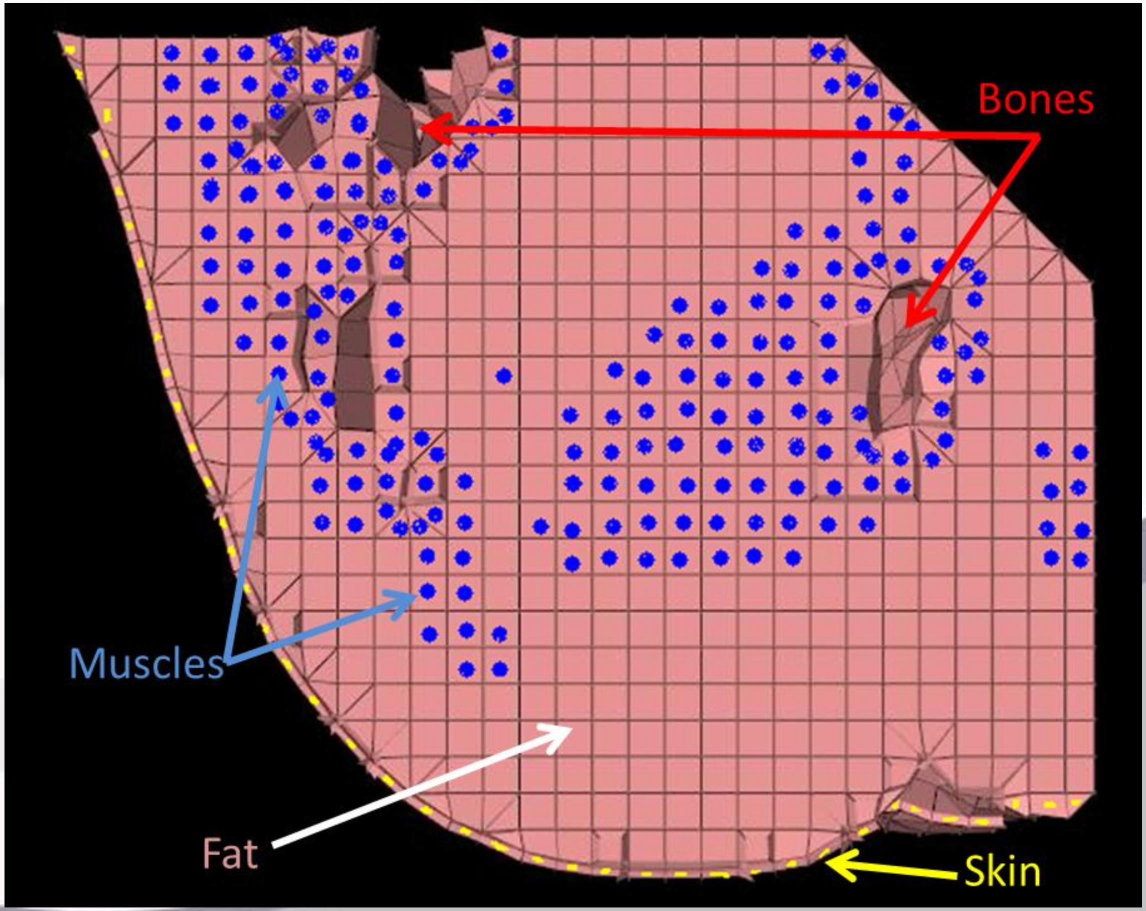
- **The role of the ischial tuberosities:**



Patient-specific biomechanical model of the buttocks

Finite Element model corresponding to the patient:

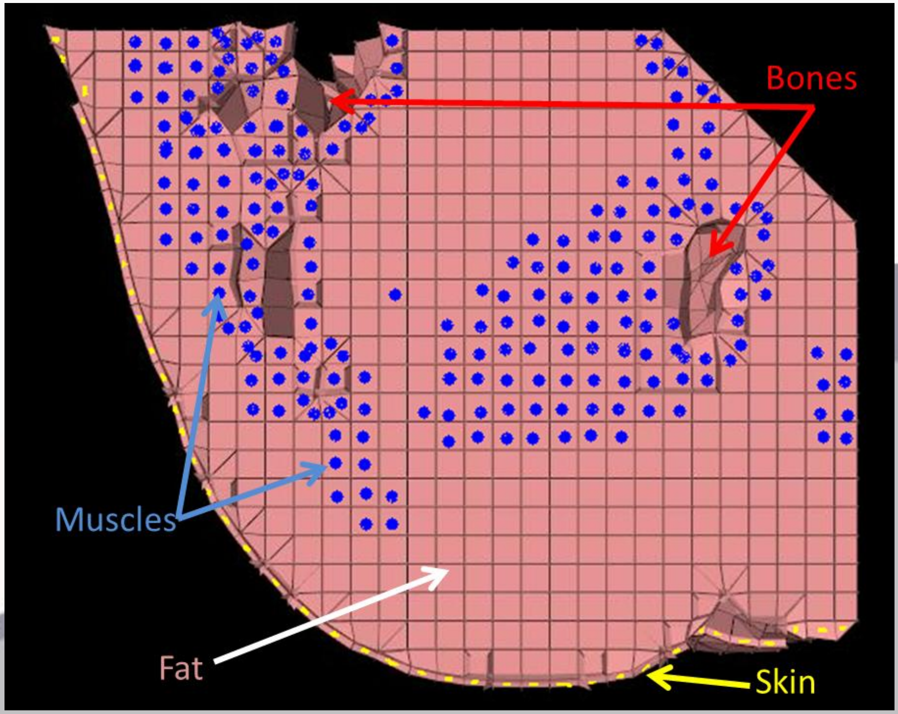
- **Separating the different soft tissues layers:**



Patient-specific biomechanical model of the buttocks

Finite Element model corresponding to the patient:

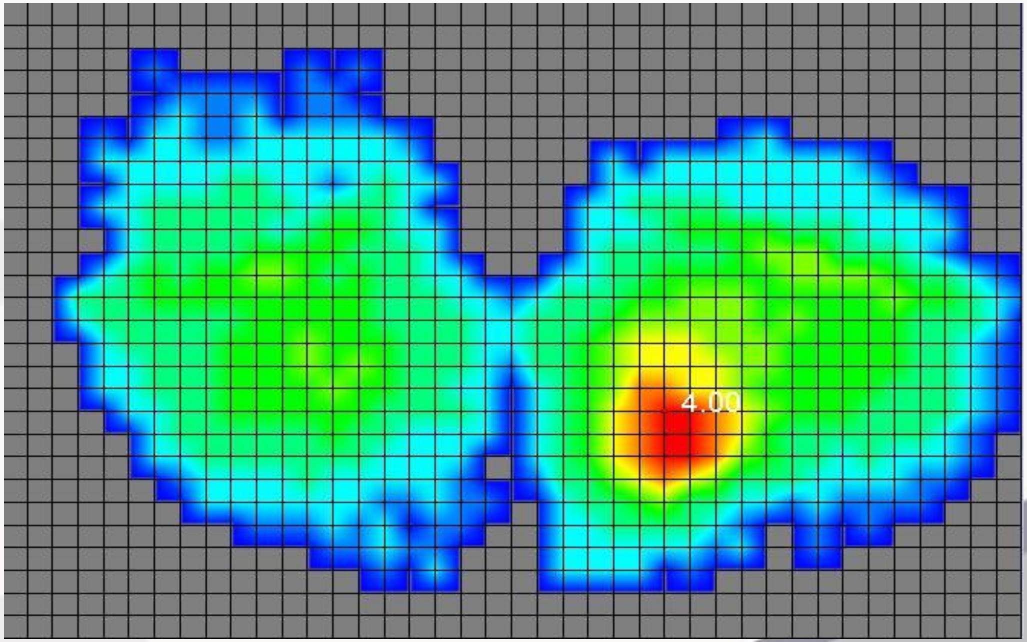
- Separating the different soft tissues layers into 3 different Neo Hookean materials:
  - Skin: E = 200 kPa, v = 0,49
  - Muscles: E = 40 kPa, v = 0,49
  - Fat: E = 10 kPa, v = 0,49



Patient-specific biomechanical model of the buttocks

Validation:

- **From pressure measurements under the patient buttocks while seating (on a zebris platform)**

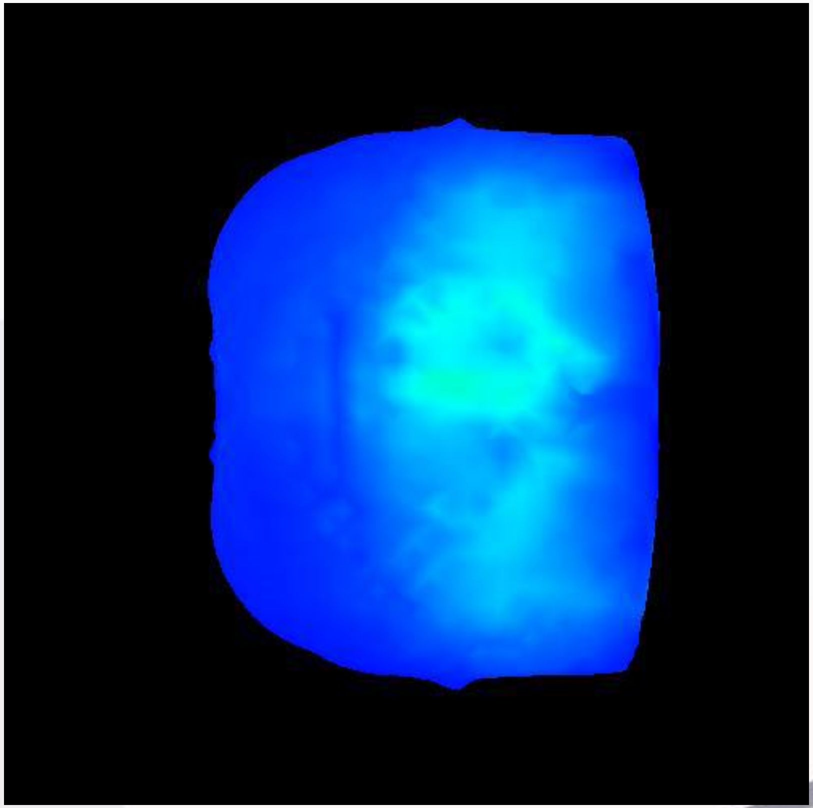


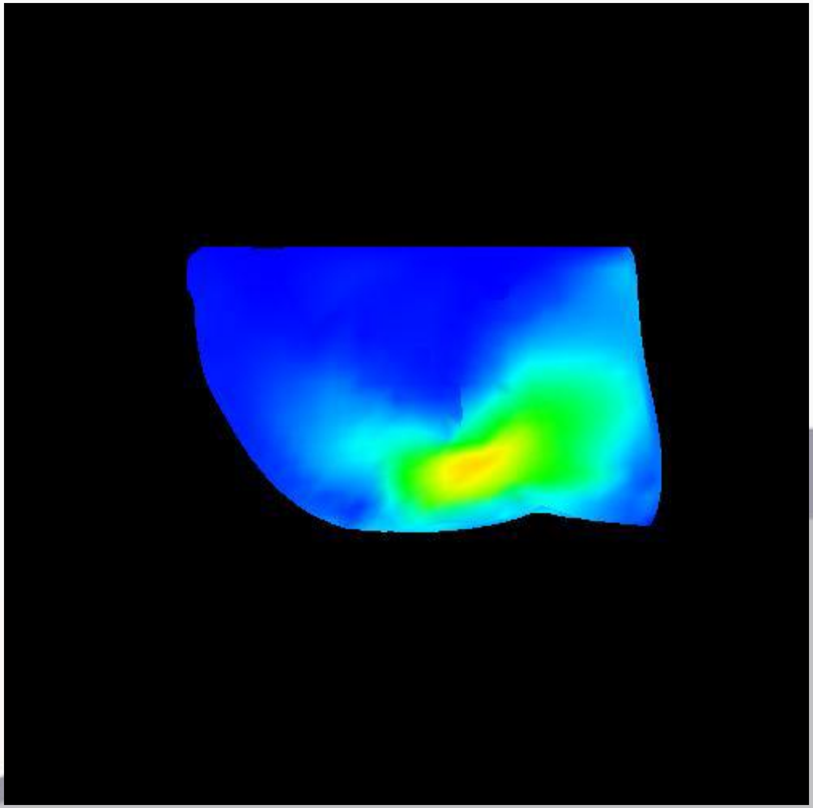
Maximum constraint = 4 N/Cm^2, in red

Patient-specific biomechanical model of the buttocks

Validation:

- Simulation results

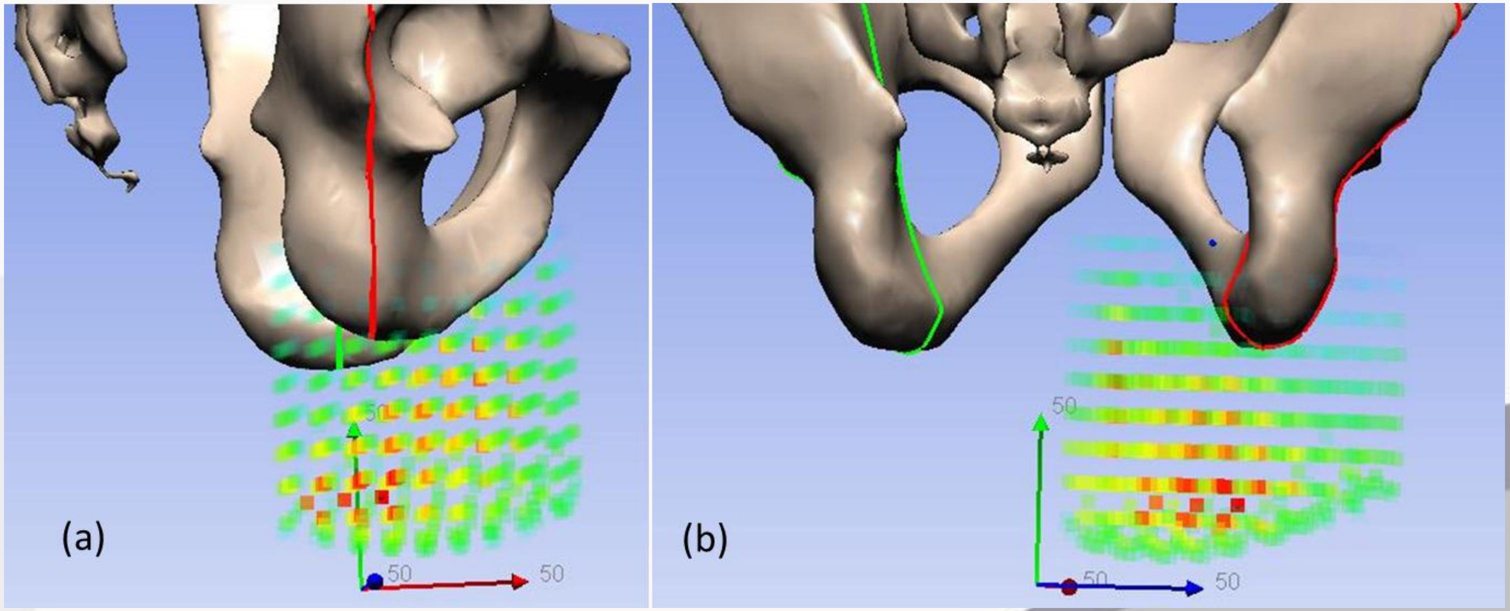




Patient-specific biomechanical model of the buttocks

Validation:

- Simulation (only measured on one side)

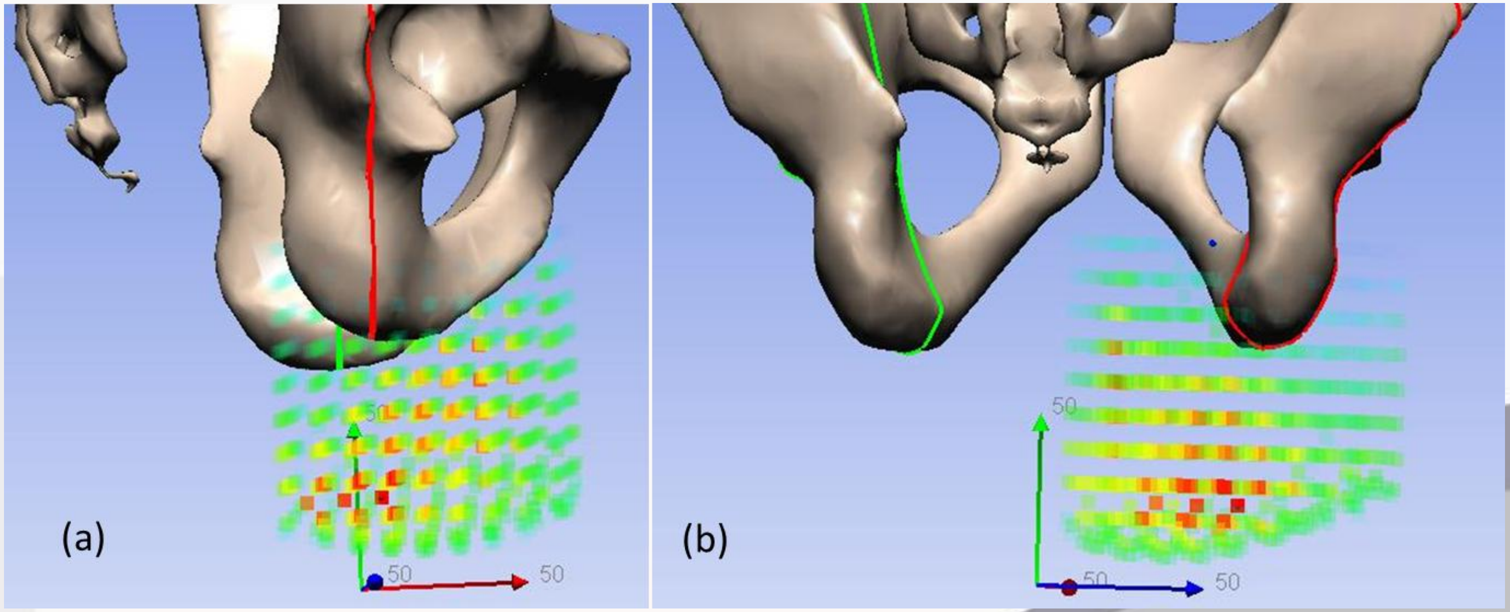


Von Mises Strain max = 66 % (in red)

Patient-specific biomechanical model of the buttocks

Validation:

- Simulation (only measured on one side)

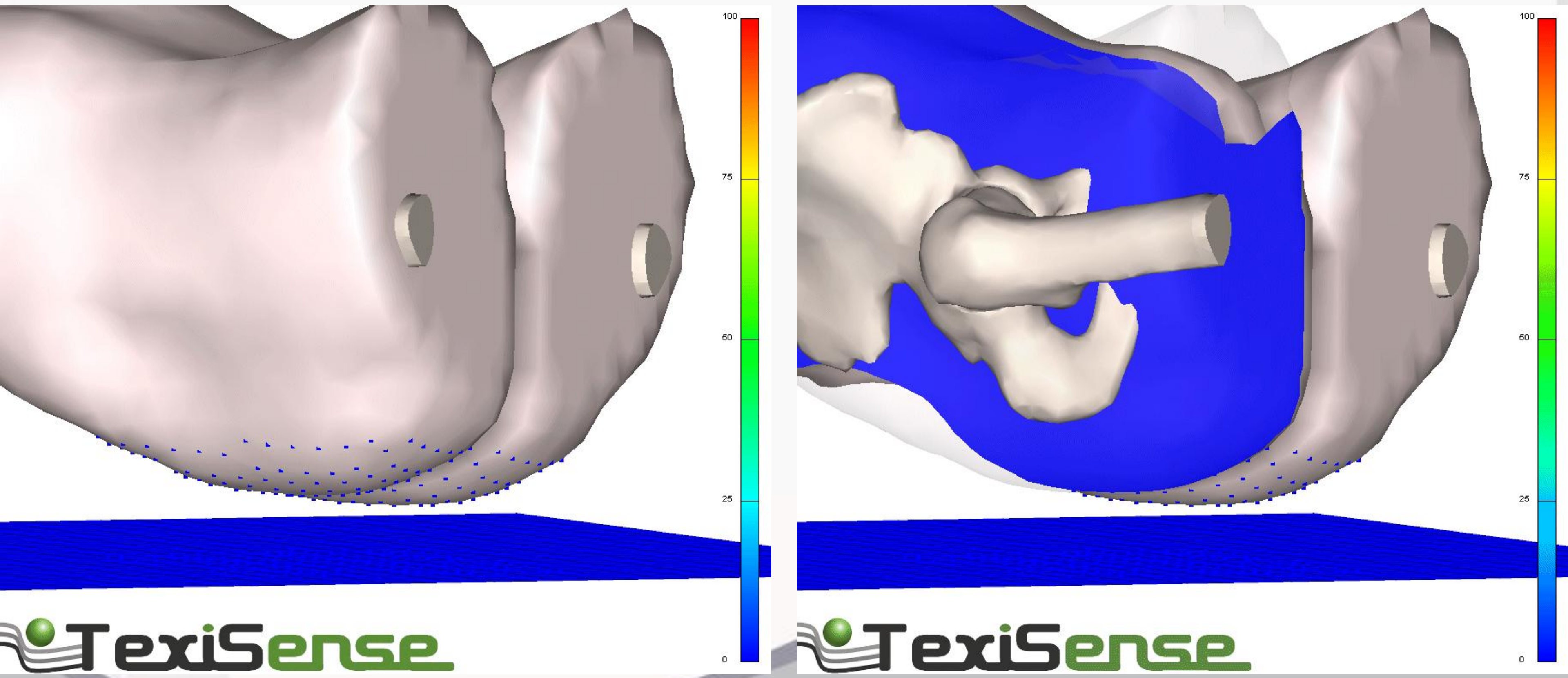


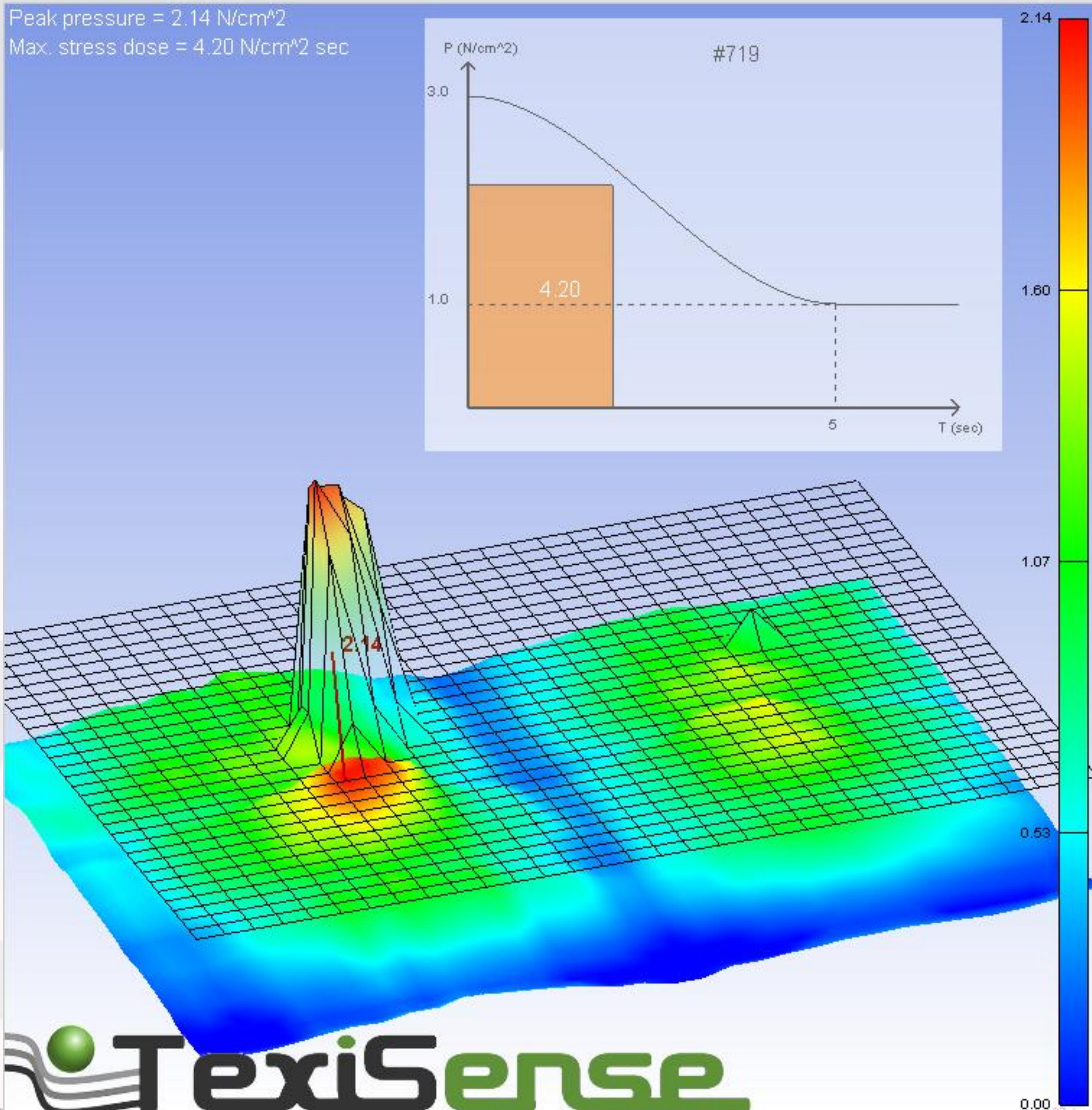
Von Mises Strain max = 66 % (in red)

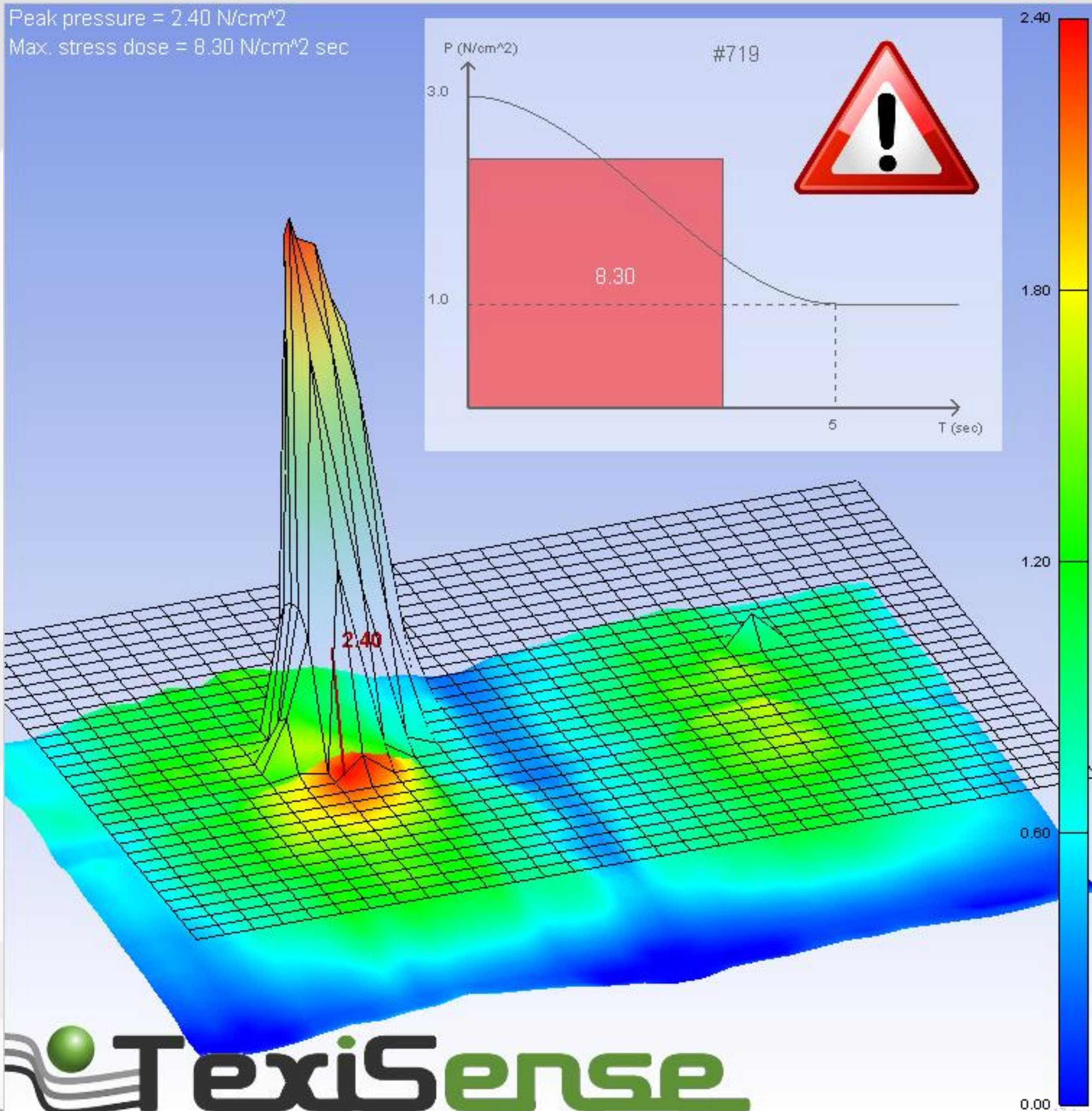
Simulation time: 8 min and 45 seconds on a INTEL CORE DUO at 3.32 GHz and 3.50 Go of RAM

Patient-specific biomechanical model of the buttocks

- Internal overpressures monitoring, in real time




Peak pressure = 2.14 N/cm^2
Max. stress dose = 4.20 N/cm^2 sec
P (N/cm^2)
#719
3.0
1.0
4.20
5
T (sec)
2.14
2.14
1.60
1.07
0.53
0.00
TexiSense


Peak pressure = 2.40 N/cm^2
Max. stress dose = 8.30 N/cm^2 sec
P (N/cm^2)
#719
3.0
8.30
1.0
5
T (sec)
2.40
2.40
1.80
1.20
0.60
0.00
TexiSense

Pressure ulcer prevention

- ❑ Three questions :
  - ❑ What kind of artificial sensor for the measurement of the pressure at the buttocks / seat interface?
  - ❑ When deciding that there is a risk for pressure ulcer?
  - ❑ How to alert the person in case of a risk?

How to alert the person in case of a risk?

- Conclusions of the Utility / Utilisability / Acceptability Study:
  - In case of risk for pressure ulcer, the alert sent to the person should:
    - be easily perceived
    - remain discrete, i.e. avoid the visual or auditory canals that are daily used

⇨ The use of the tactile modality

How to alert the person in case of a risk?

A tactilo-visual signal sent in case of alert

\+

alert: tactile vibration

simple message

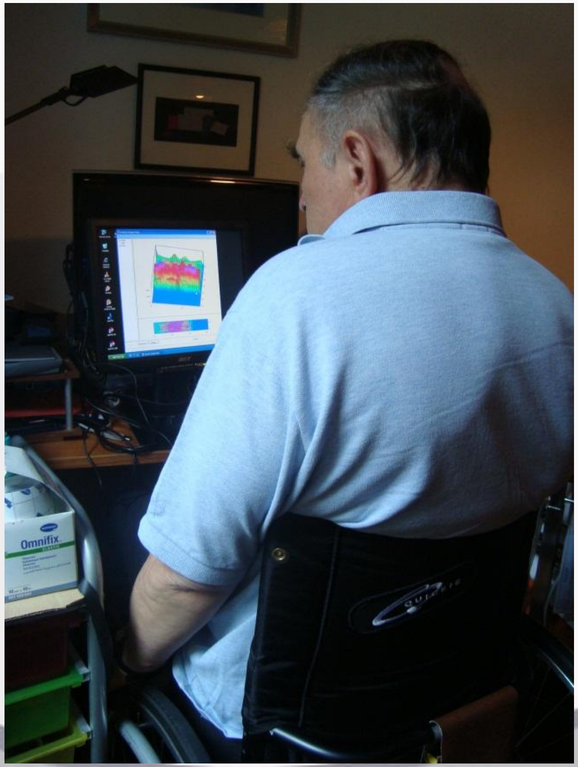
alert: tactile vibration

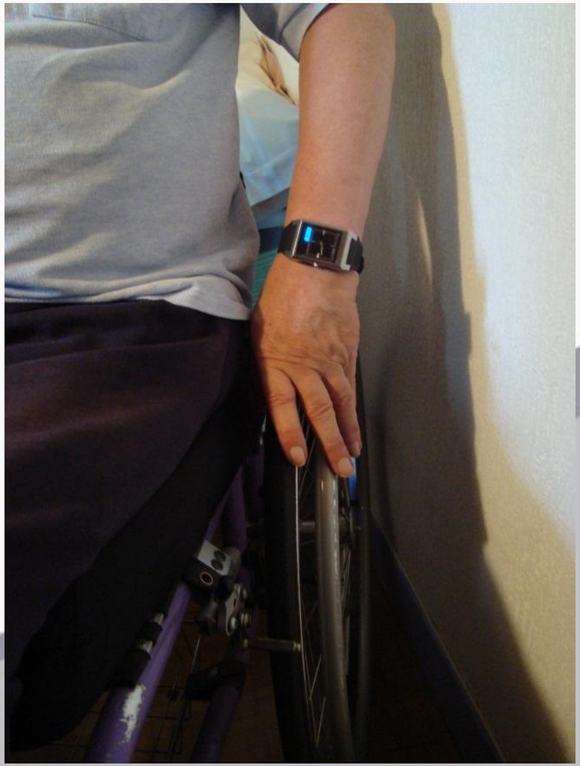
more complex messages

Clinical evaluation

On going qualitative evaluation:

- A paraplegic volunteer equipped at home with our embedded prototype + video cameras, during a recording period of six months.





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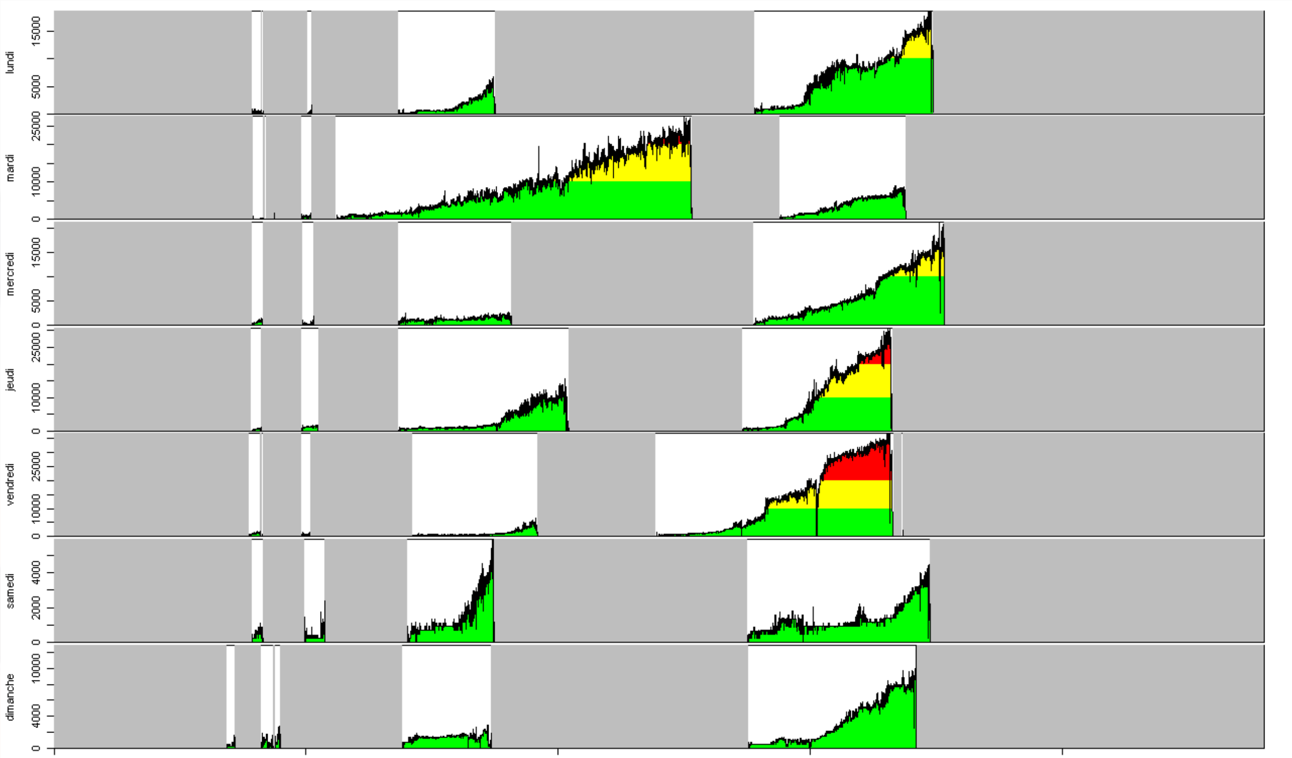

Foot and ulcers

Foot and ulcers

The "smart sock" [Bucki, 2011]:

- Developed by TexiSense (http://www.texisense.com/).
- Network of textile pressure sensors monitoring the stresses applied around the foot.
- Goals:
  - Estimate the internal strains,
  - Warn the patient when they reach a critical level.

Foot and ulcers

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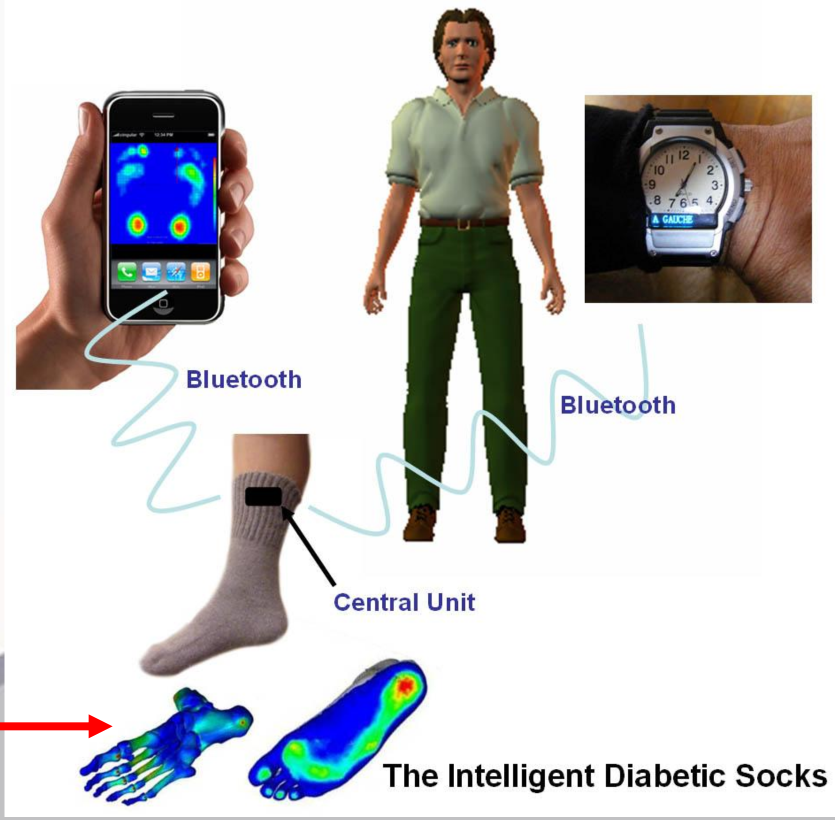
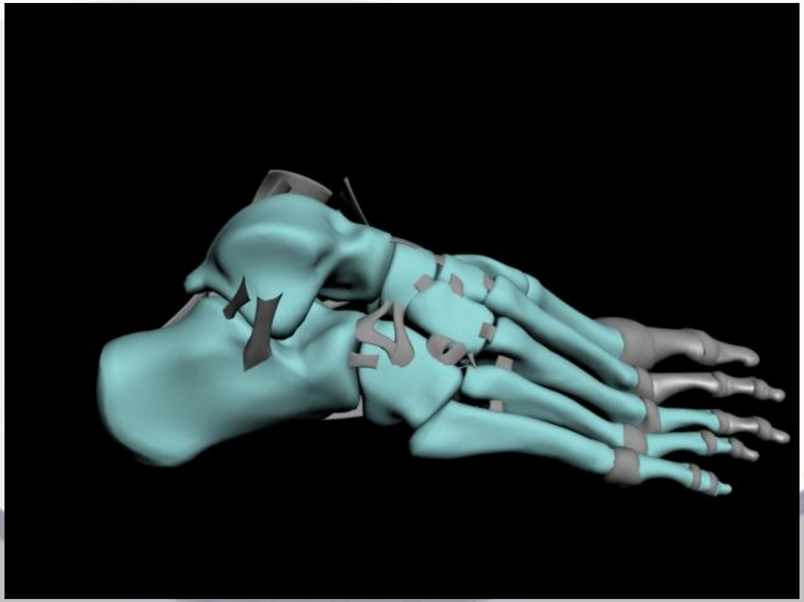
Biomechanical modeling

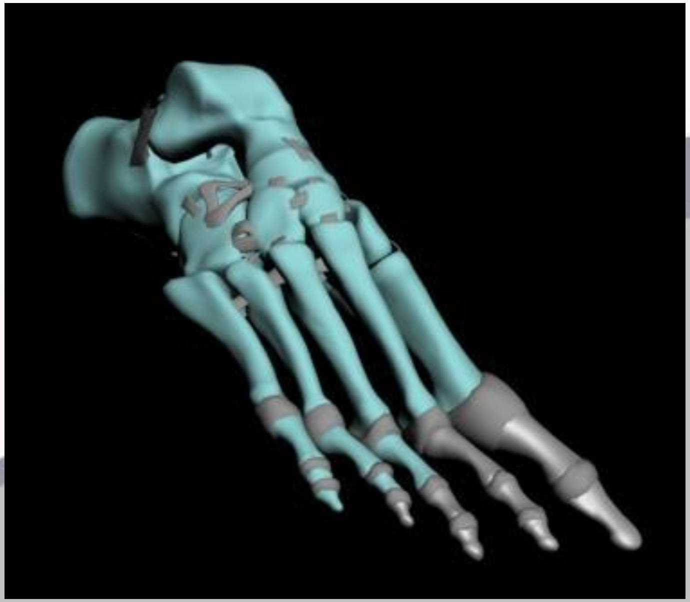


Foot and ulcers

Foot anatomy:

- 26 bones, 33 joints and more than 100 muscles, tendons and ligaments plus a network of blood vessels, nerves, skin, and soft tissues.
- Complex interactions between those structures and the external environment.

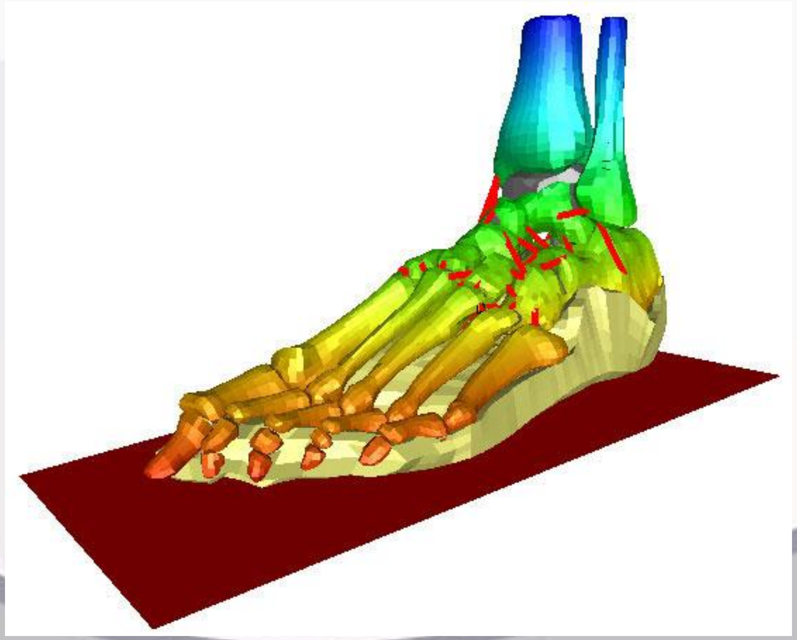


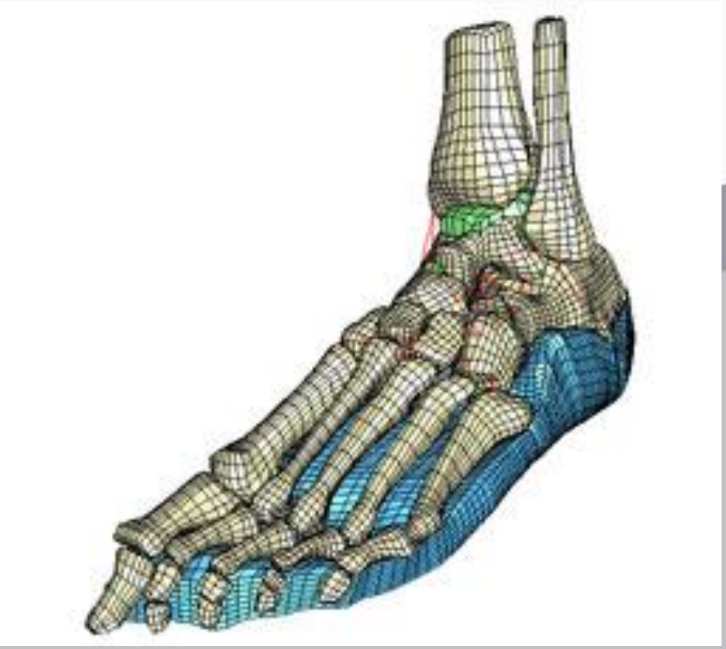


Foot biomechanical modeling

Several existing models:

- **[Ledoux, 2004] modeled:**
  - The soft tissues as a FE mesh with homogeneous elastic properties,
  - The bones as rigid FE meshes,
  - Contact between bones for the joints,
  - Ligaments for the mid foot.

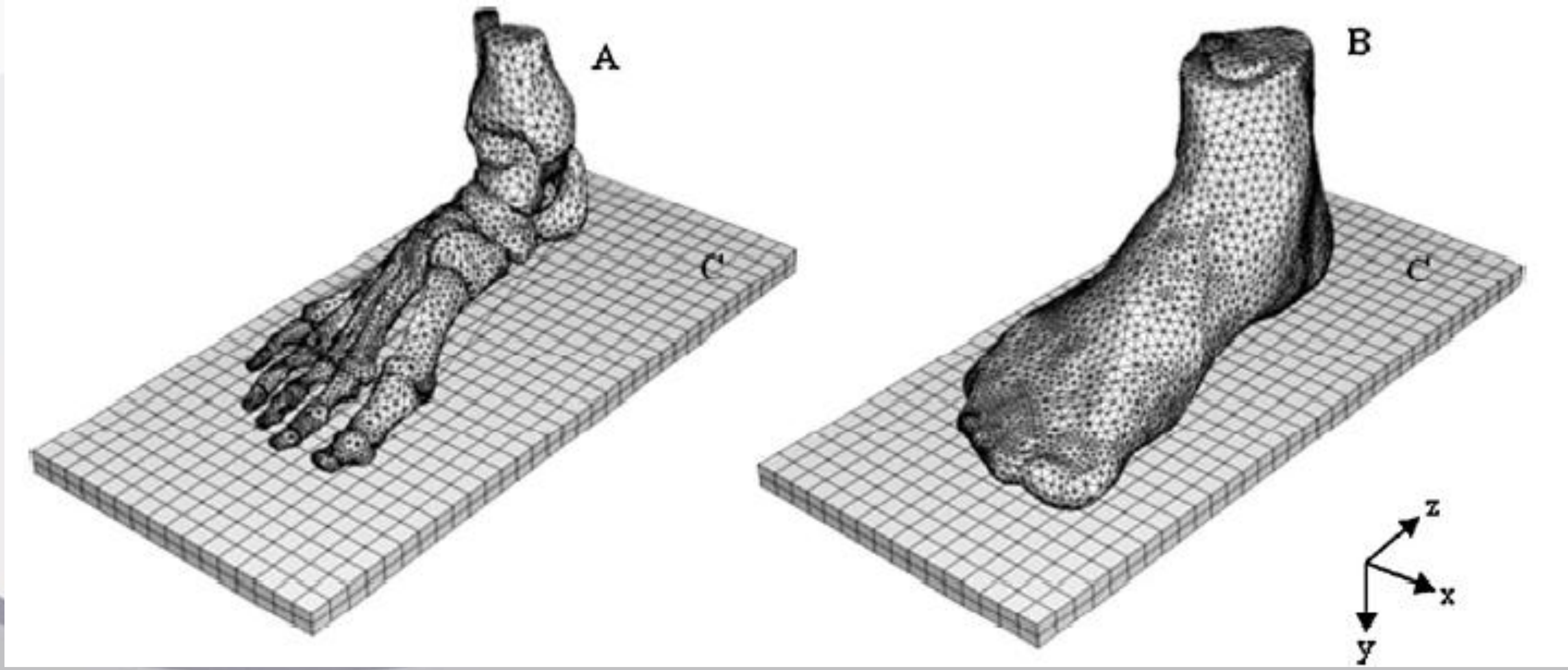




Foot biomechanical modeling

Several existing models:

- [Chen, 2010] modeled:
  - The soft tissues as a FE mesh with a Mooney Rivlin constitutive law with large deformations,
  - The bones as rigid FE meshes,
  - Main articulations modeled as contacts between bones.



Foot model

Our model proposes:

- Realistic mechanical properties,
- Light modeling,
- Computationally fast to be embedded in the “smart sock” device.

- Developed using the 3D biomechanical simulation platform, Artisynth (http://www.artisynth.org/) [Stavness, 2011].

Foot model

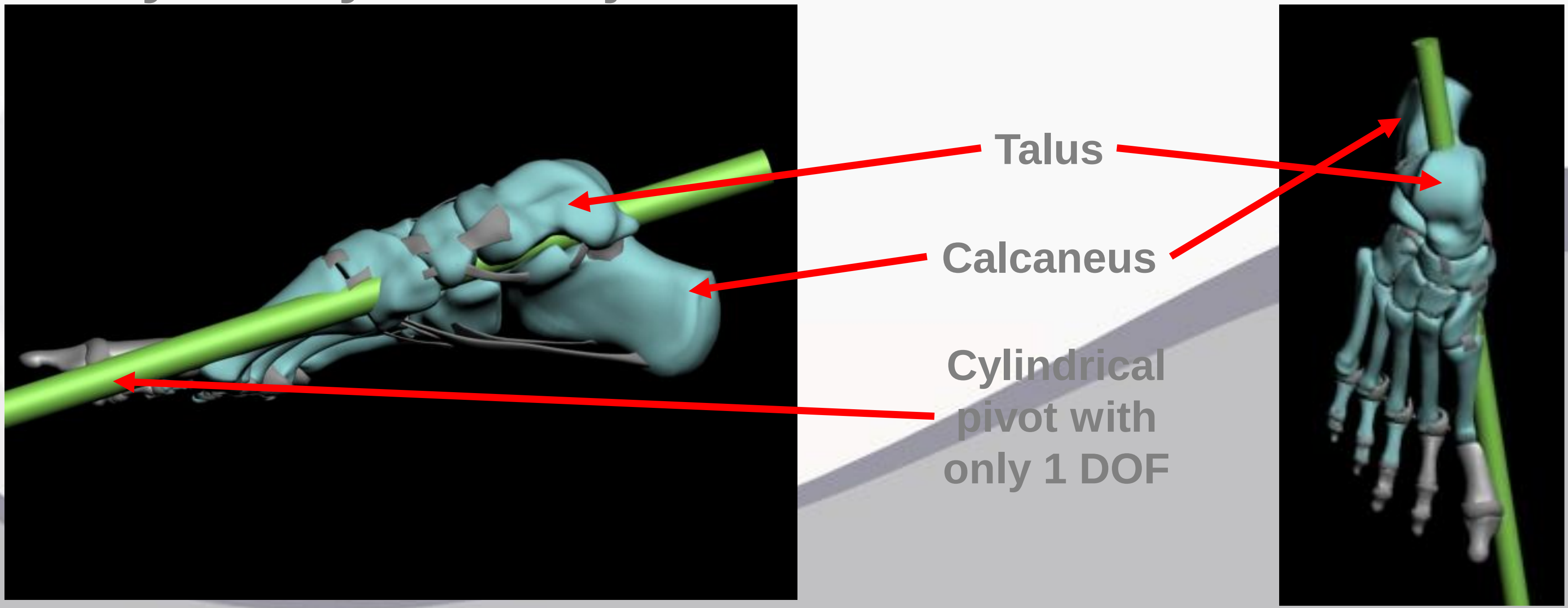
Bone and joint modeling:

- 28 bones (26 + tibia and fibula) as rigid bodies (geometry from www.zygote.com) with a density of 3000,
- 33 joints simulated by cylindrical or spherical pivots.

Foot model

Bone and joint modeling:

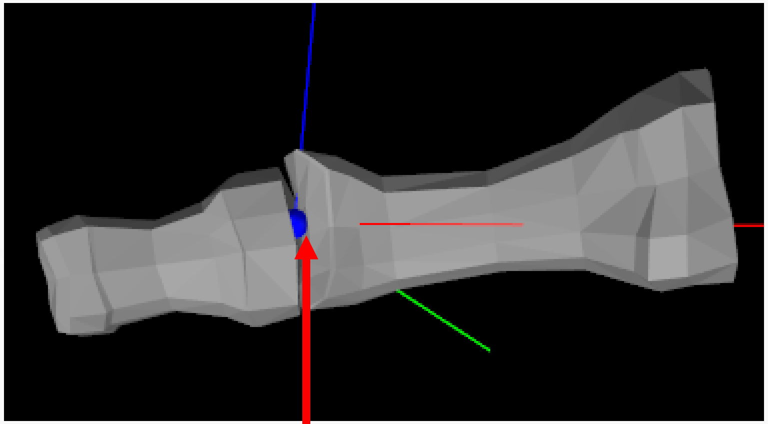
- 28 bones (26 + tibia and fibula) as rigid bodies (geometry from www.zygote.com) with a density of 3000,
- 33 joints simulated by cylindrical or spherical pivots.
- Only one cylindrical joint between talus and calcaneus:



Foot model

Bone and joint modeling:

- All other joints simulated by spherical pivots:



Spherical pivot with 3 DOFs

Foot model

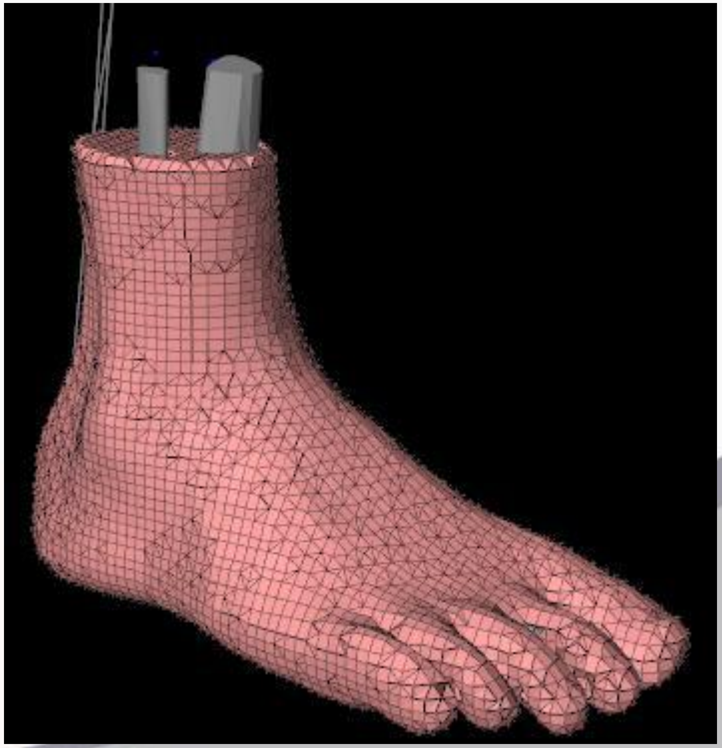
Bone and joint modeling:

- All other joints simulated by spherical pivots:
  - Phalanges: with a possible rotation angle of 45 degrees,
  - Metatarsi: with a possible rotation angle of 30 degrees,
  - Mid and back foot: with a possible rotation angle of 0-5 degrees.

Foot model

Soft tissue modeling:

- Muscles, fat, and skin modeled as 3 different layers using a Finite Element mesh adapted from the Zygote database using an automatic meshing method [Lobos, 2010].

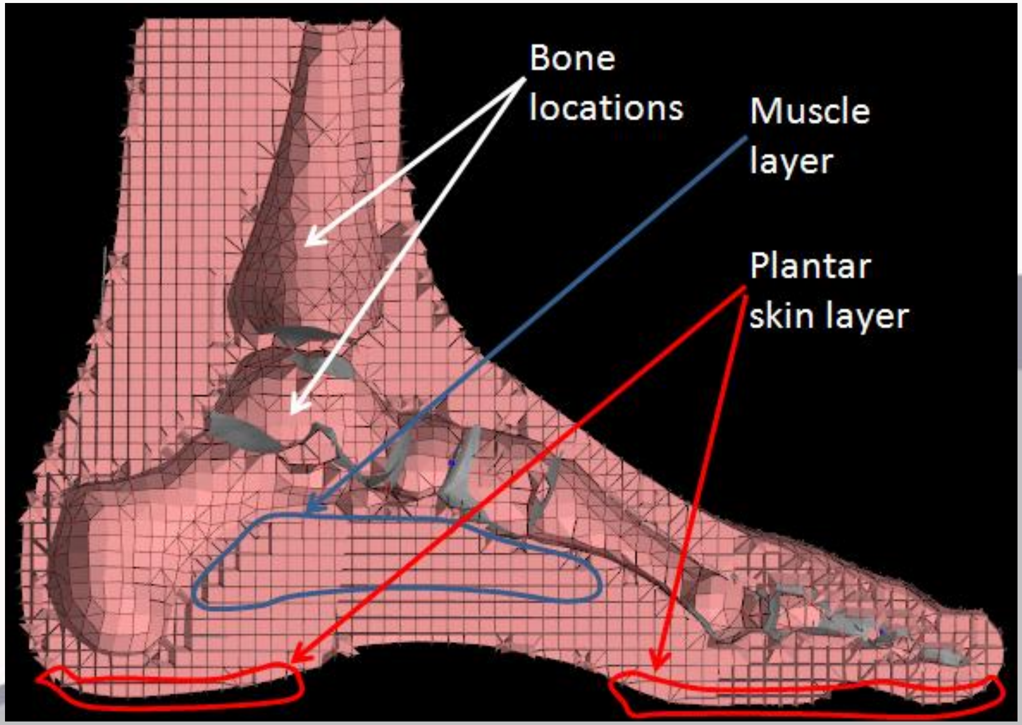


36,894 elements
and 22,774 nodes

Foot model

Soft tissue modeling:

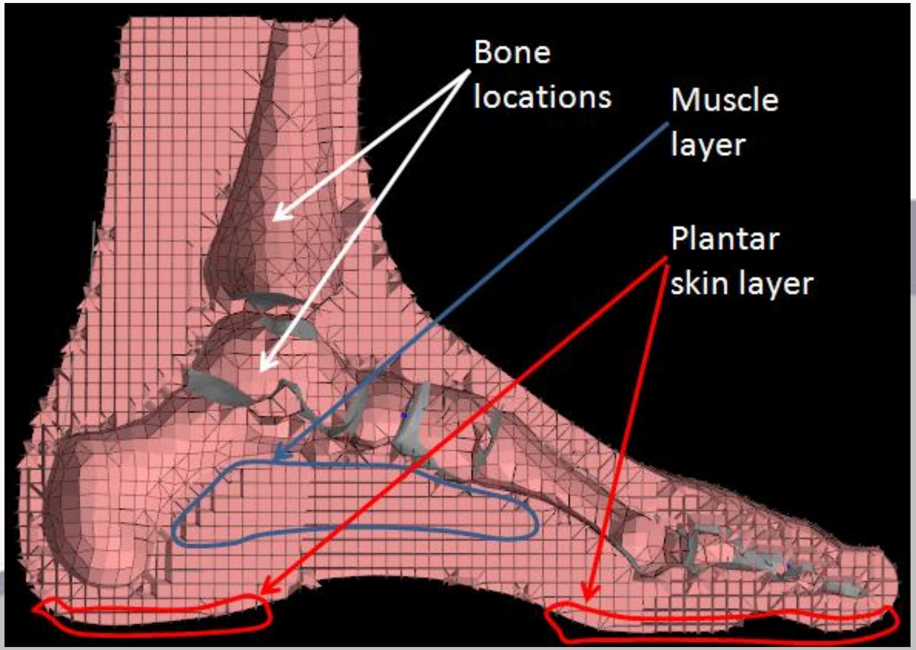
- Muscle layer limited to below the foot arch.
- Skin layer separated into 2 parts: high stiffness plantar layer and softer rest of the skin.
- Fat layer encapsulates all the other elements.



Foot model

Soft tissue modeling:

- Each layer modeled as a neo Hookean material [Sopher 2011]:
  - Muscle layer: E = 50 kPa, nu = 0.495,
  - Fat layer: E = 4 kPa, nu = 0.495,
  - Planter skin layer: E = 6 MPa, nu = 0.495.



Foot model

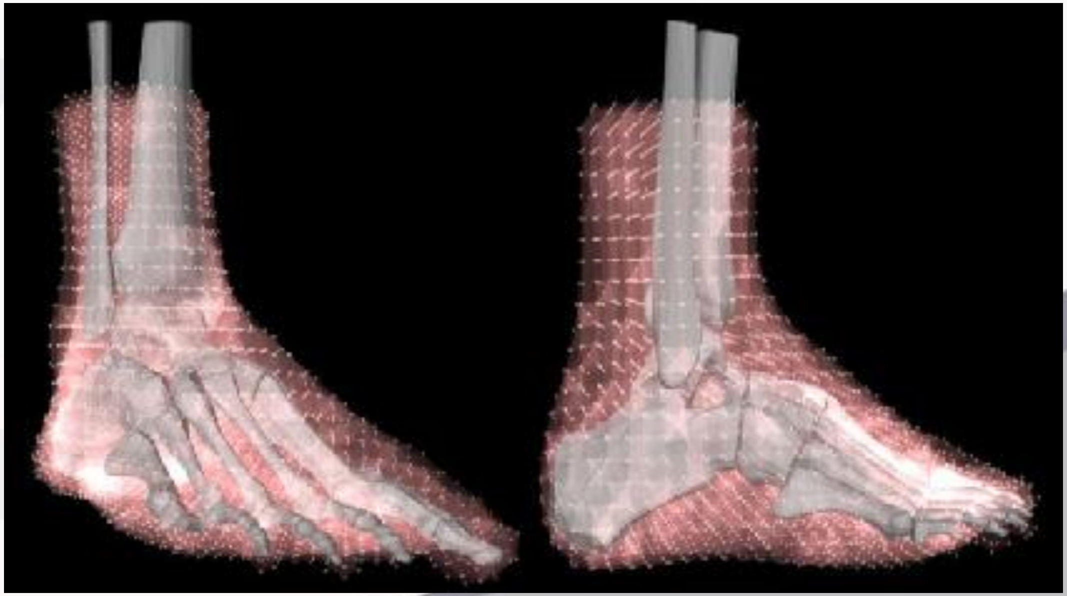
Soft tissue modeling:

- Each layer modeled as a neo Hookean material [Sopher 2011]:
  - Muscle layer: E = 50 kPa, nu = 0.495,
  - Fat layer: E = 4 kPa, nu = 0.495,
  - Planter skin layer: E = 6 MPa, nu = 0.495,
  - Skin layer (except plantar skin): E = 200 kPa, nu = 0.495, and determined by LASTIC (aspiration device for characterizing the soft tissues' elasticity) [Schiavone, 2008]:

Foot model

Soft tissue modeling:

- Bones rigidly coupled to the soft tissues.
- Realistically rigidify the foot.
- Decreases the FE matrix size and speed up the simulation.



Foot model

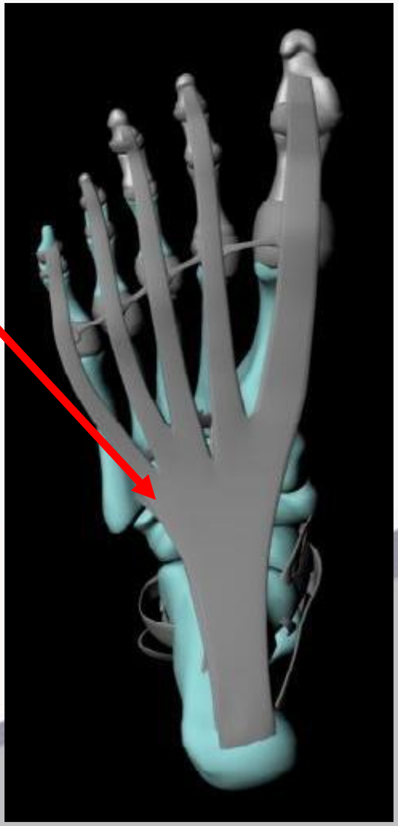
Ligaments modeling:

- Cables representing the real ligaments interconnecting the bones through the FE nodes, with a stiffness of 200 MPa in extension and of 0 MPa in compression.
- Four main ligaments integrated in the simulation:

Foot model

Ligaments modeling:

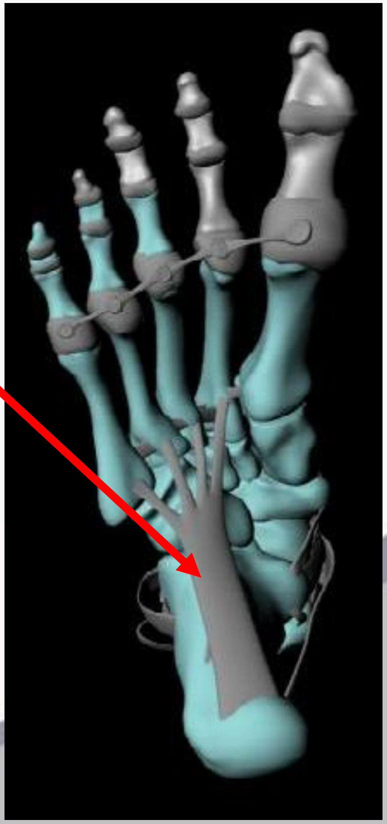
- Cables representing the real ligaments interconnecting the bones through the FE nodes.
- Four main ligaments:
  - Outer plantar fascia



Foot model

Ligaments modeling:

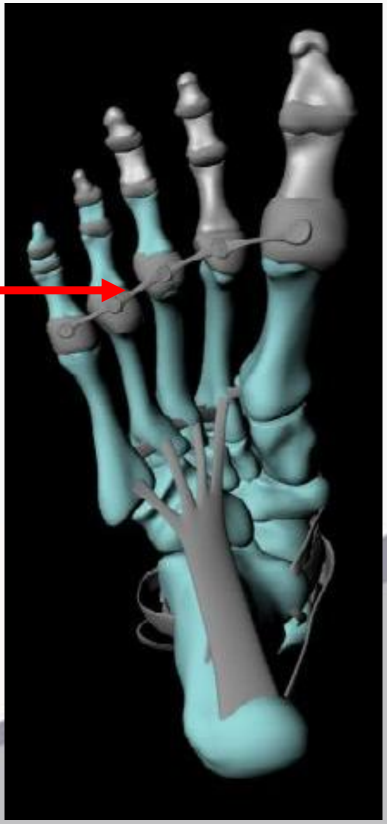
- Cables representing the real ligaments interconnecting the bones through the FE nodes.
- Four main ligaments:
  - Outer plantar fascia
  - Inner plantar fascia



Foot model

Ligaments modeling:

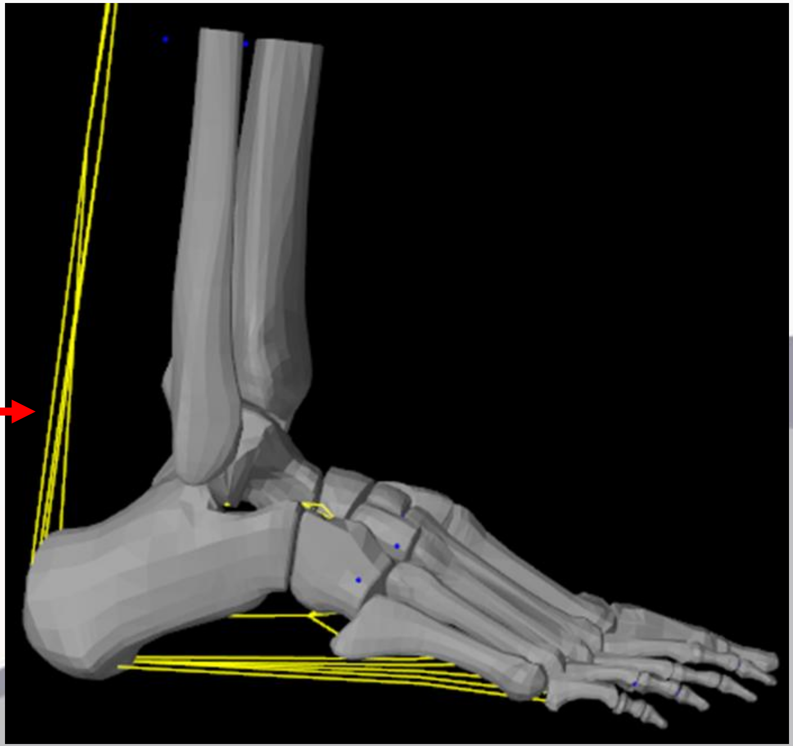
- Cables representing the real ligaments interconnecting the bones through the FE nodes.
- Four main ligaments:
  - Outer plantar fascia
  - Inner plantar fascia
  - Transversal metatarsal head ligament



Foot model

Ligaments modeling:

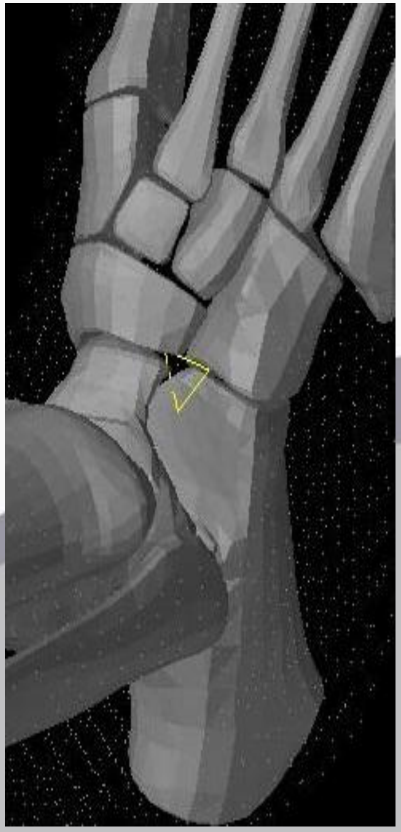
- Cables representing the real ligaments interconnecting the bones through the FE nodes.
- Four main ligaments:
  - Outer plantar fascia
  - Inner plantar fascia
  - Transversal metatarsal head ligament
  - Achilles tendon



Foot model

Ligaments modeling:

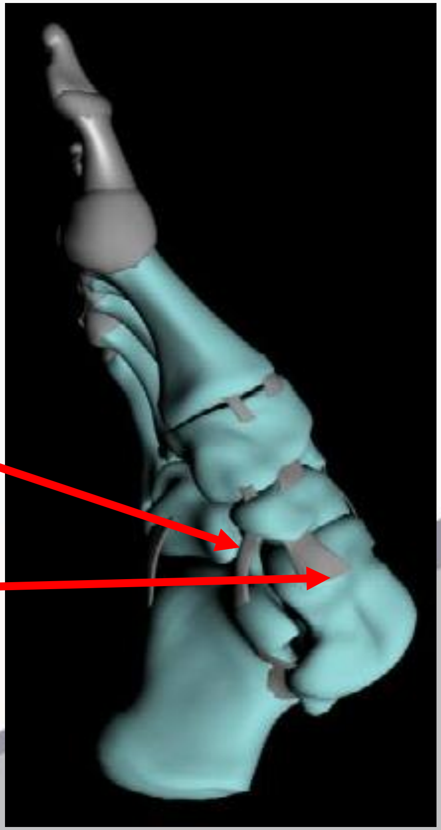
- Cables representing the real ligaments interconnecting the bones through the FE nodes.
- Three smaller ligaments:
  - Triangular ligament between navicular, calcaneus and cuboid bones

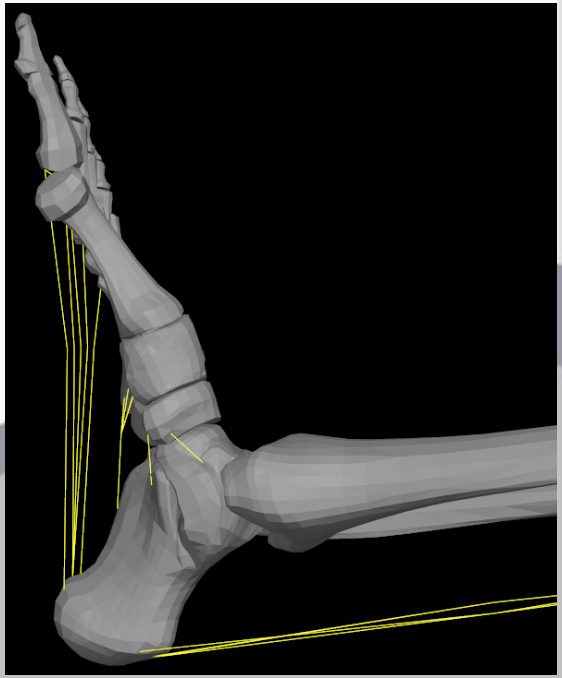


Foot model

Ligaments modeling:

- Cables representing the real ligaments interconnecting the bones through the FE nodes.
- Three smaller ligaments:
  - Triangular ligament between navicular, calcaneus and cuboid bones
  - Internal ligament between calcaneus and navicular,
  - Internal ligament between talus and navicular.

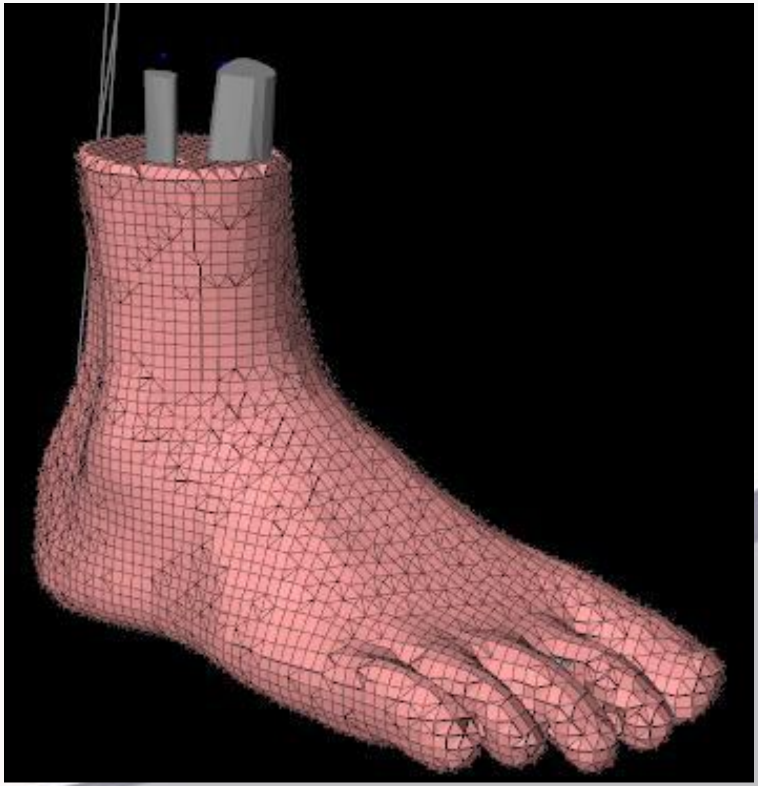




Foot model

Boundary conditions:

- Foot weight: 2 Kg, and subject to gravity.
- Tibia and fibula bones fixed to constrain the foot.

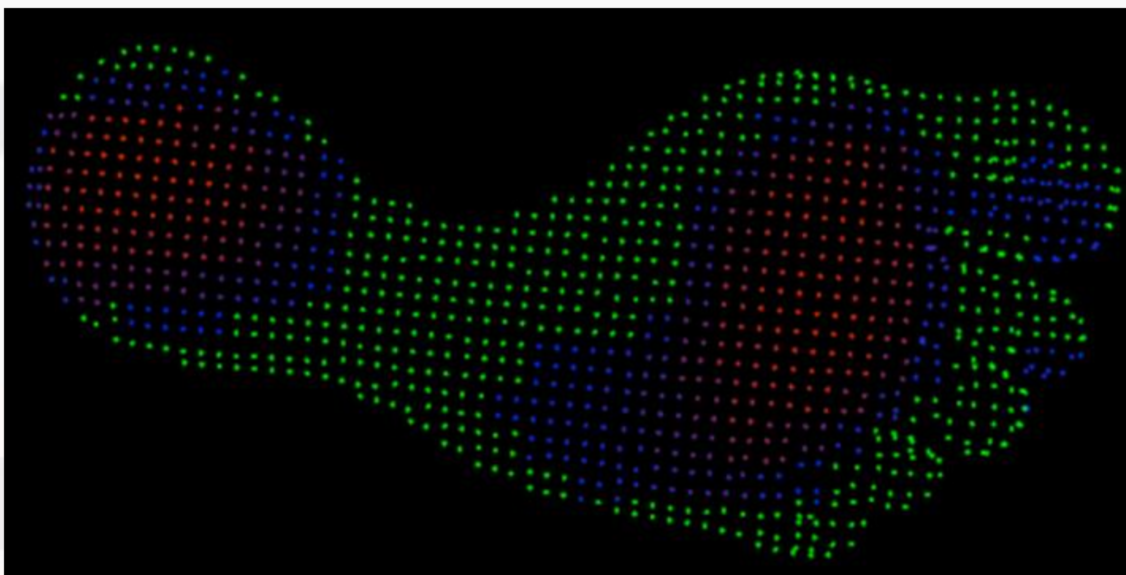


Evaluation

Evaluation

Pressure assessment

- Measuring the plantar foot pressure distribution under the right foot of a young healthy volunteer while standing on a commercially available pressure sensor system (Zebris platform, http://www.zebris.de/):



Pressures range from 0 (green) to 10.5 $N.cm^{-2}$ (red)

Evaluation

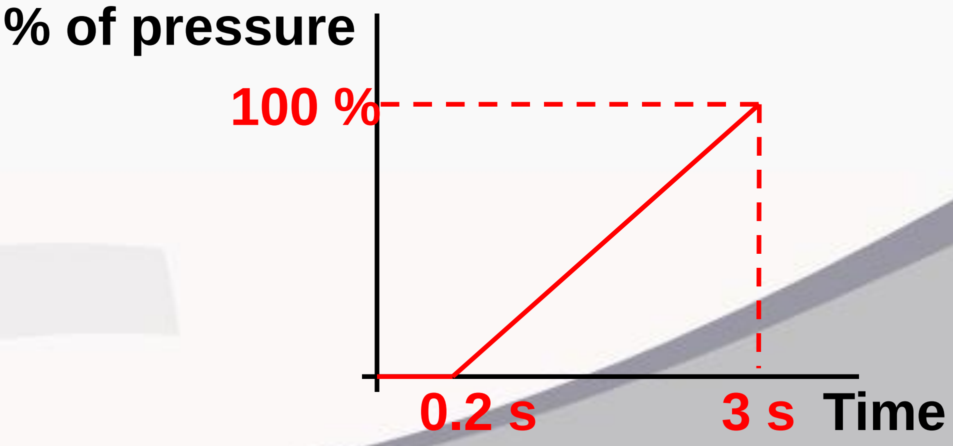
Simulation of the standing position:

- While tibia and fibula bones are fixed, the rest of the foot is let loose under the influence of gravity for 0.2 s to reach a resting position.

Evaluation

Simulation of the standing position:

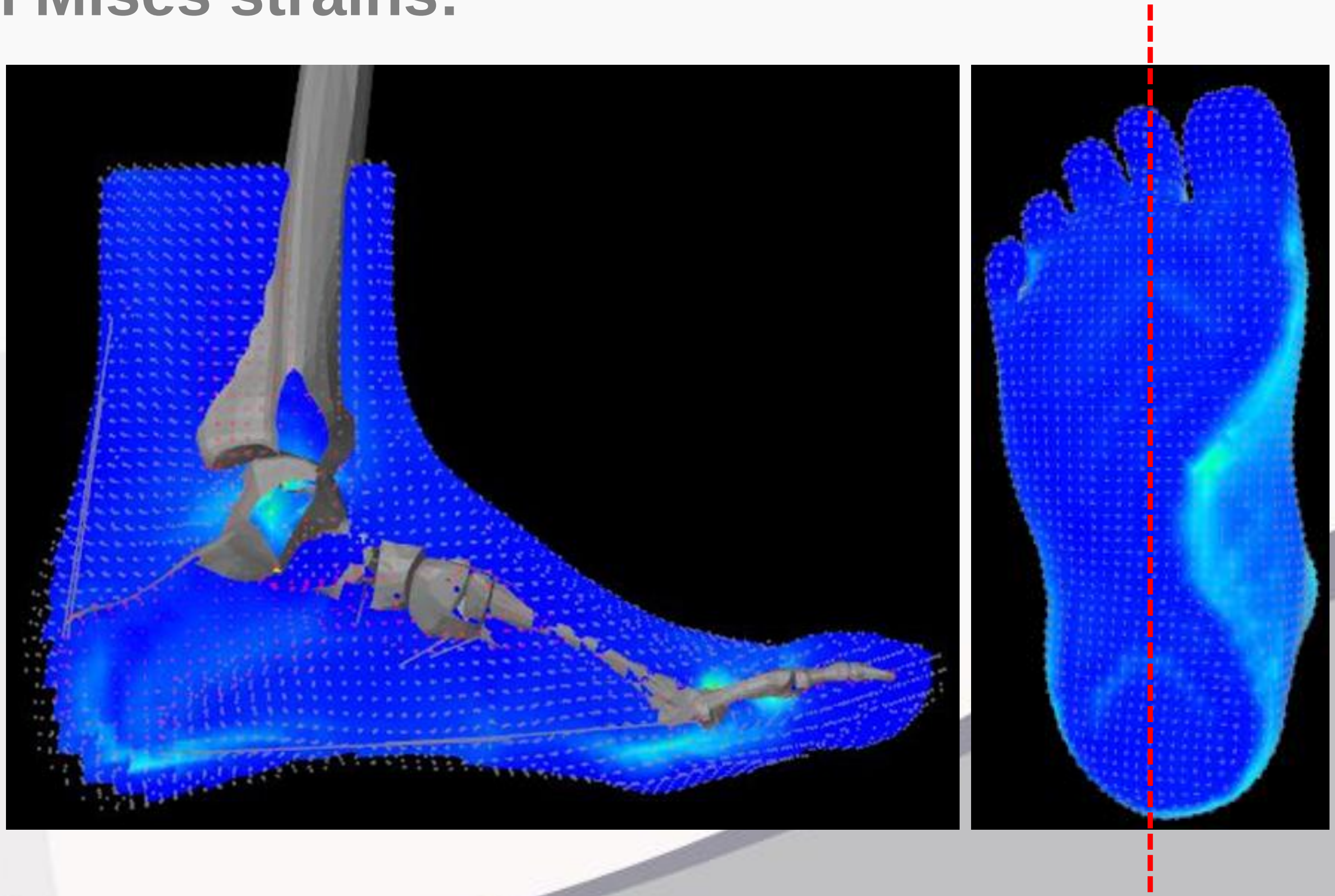
- While tibia and fibula bones are fixed, the rest of the foot is let loose under the influence of gravity for 0.2 s to reach a resting position.
- From t = 0.2 s to 3 s, application of the measured pressures to the nodes of the foot sole following a ramp (0% at 0.2 s and 100 % at 3 s) to model normal standing.



Evaluation

Observing the foot deformation at t = 3 s

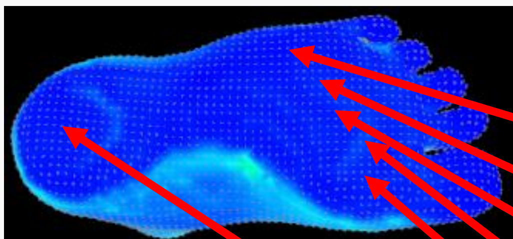
- Von Mises strains:

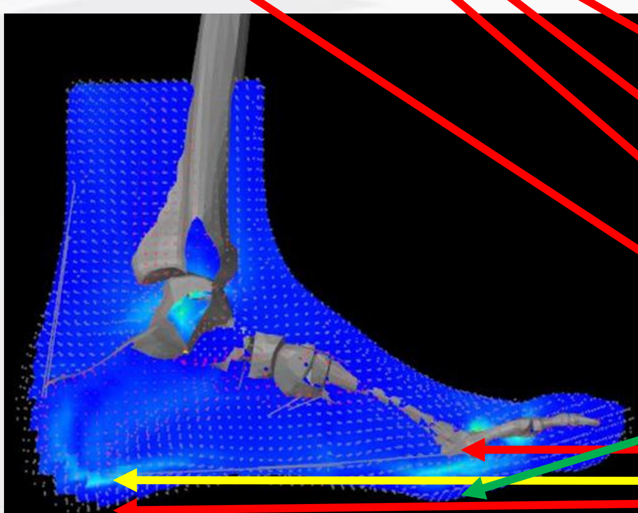


Evaluation

Observing the foot deformation at t = 3 s

- Von Mises strains on the skin surface and below the bones (internally):



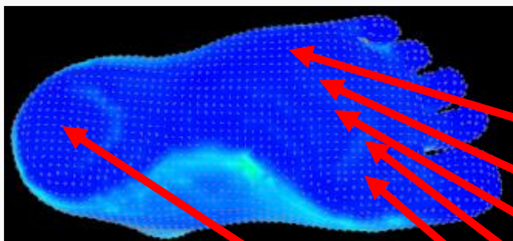


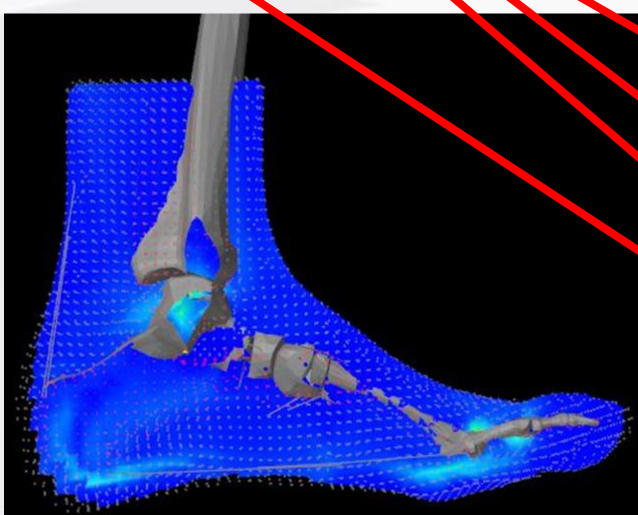
Location	Foot surface VM strain	Internal VM strain
5th toe MT	2.7 %	63.3 %
4th toe MT	5.2 %	96.8 %
3rd toe MT	8.0 %	63.0 %
2nd toe MT	4.1 %	84.2 %
1st toe MT	5.1 %	43.0 %
Heel	5.0 %	69.8 %

Evaluation

Observing the foot deformation at t = 3 s

- Von Mises strains on the skin surface and below the bones (internally):





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2nd toe MT	4.1 %	84.2 %
1st toe MT	5.1 %	43.0 %
Heel	5.0 %	69.8 %

→ **Realistic higher internal strains**

Conclusion

- New biomechanical models to prevent buttock and foot ulcer, associated with new devices (mat and sock)
- Realistic behavior in terms of external and internal strains,
- Provide tools to study the mechanical behavior of the buttock and foot and the creation of pressure ulcers.

Perspectives

- Apply pressures measured with the Texisense sensor to the buttock and foot surfaces:
  - To study their behavior when submitted to real pressures,
  - To develop a precise patient specific process to prevent pressure ulcer.
- Use a more realistic model to simulate the soft tissues (Mooney Rivlin, anisotropy…).
- Speed up the simulation to reach interactive time (for now, 8 min for the buttocks and 22 min for the foot…) and embed it in the Texisense controller for daily evaluation of the internal strains.

Biomechanical Modeling to Prevent Ulcers

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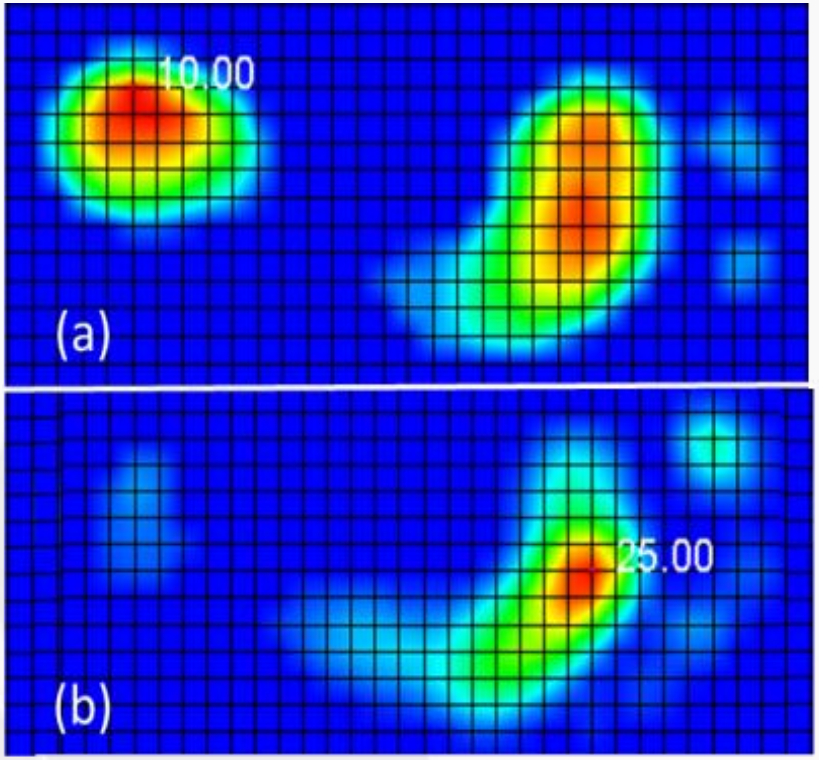
3. Laboratoire AGIM , Université Joseph Fourier, La Tronche, France ;
4. IDS, Montceau-les-Mines, France.

Perspectives

- **Dynamic analysis of subject walking:**



Location	(a) Ext. strain	(a) Int. strain	(b)Ext. strain	(b) Int. strain
5th MTT	1.8%	72.7%	3.7%	171%
4th MTT	2.8%	83.4%	6.3%	204%
3rd MTT	4.5%	81.8%	6.5%	152%
2nd MTT	3.2%	33.4%	5.1%	31.6%
1st MTT	3.3%	37.5%	7.7%	92.6%
Heel	1.8%	137%	0.6%	59.3%

Foot and ulcers

Creation of foot pressure ulcers:

Equivalent for the foot:

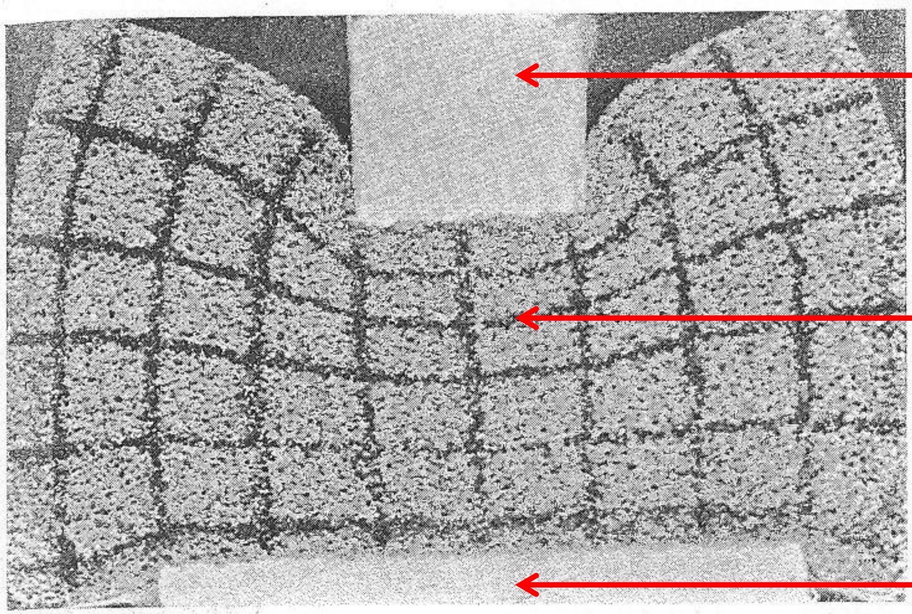


FIG. 15.—Rubber sponge compressed between two unequal rigid surfaces, showing greater distortion of the squares near the smaller surface.

[Husain, 1953]

Foot and ulcers

Creation of foot pressure ulcers:

Equivalent for the foot:

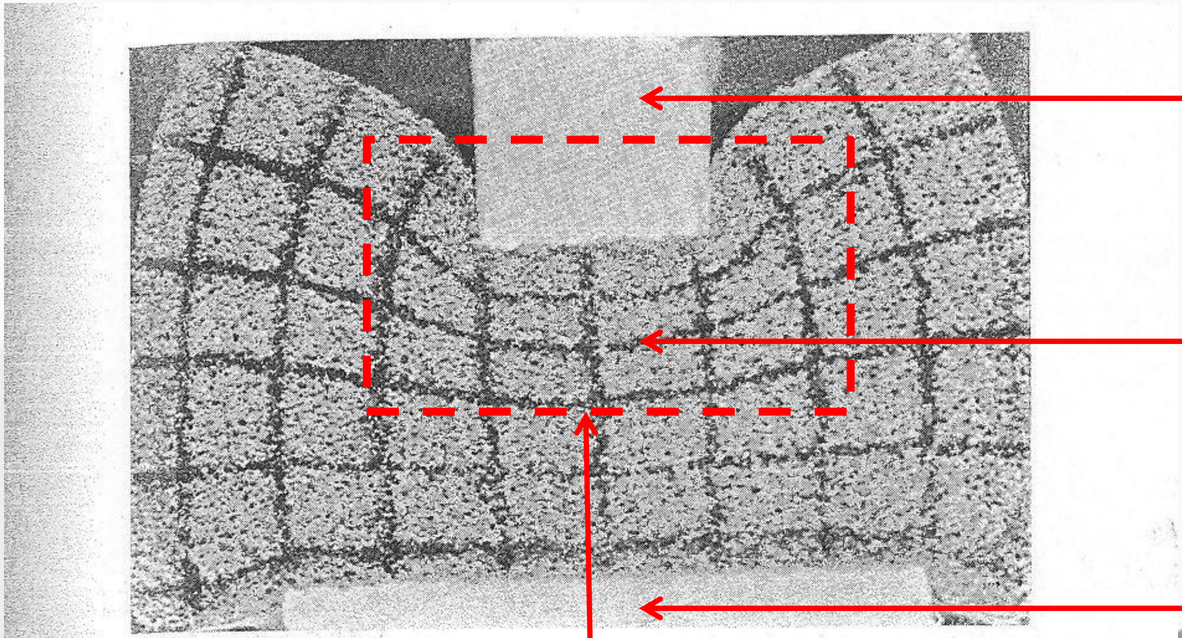
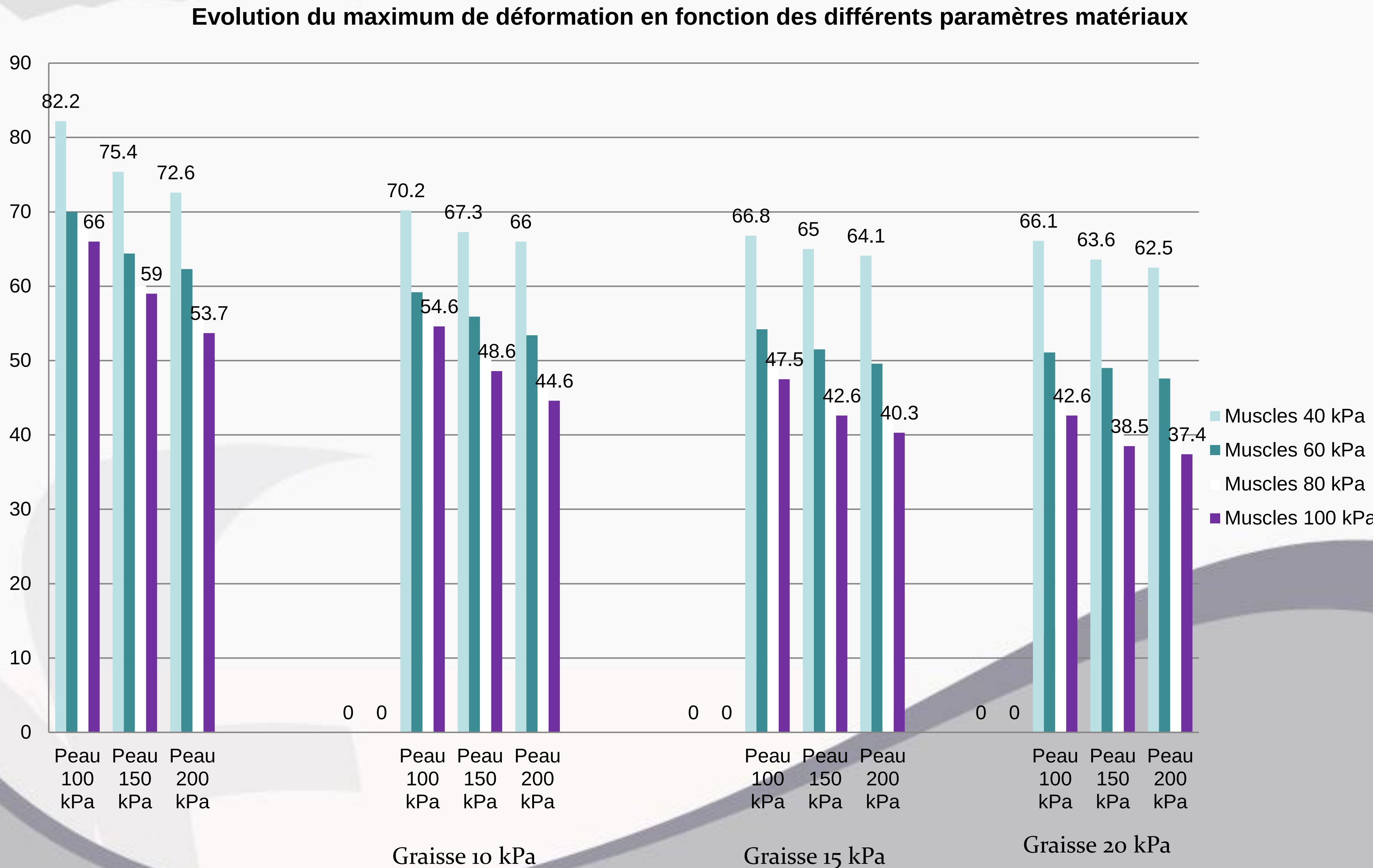


Fig. 15.—Rubber sponge compressed between two unequal rigid surfaces, showing greater distortion of the squares near the smaller surface.

[Husain, 1953]

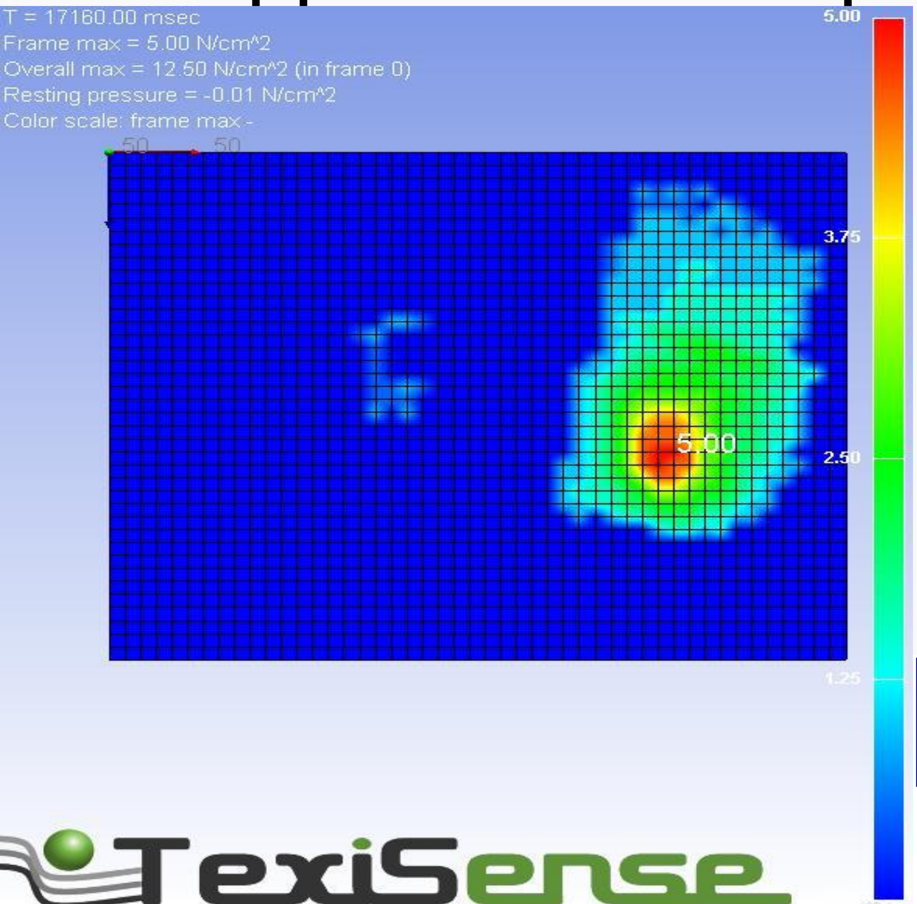
Highest deformations are internal: possibly leading to foot ulcer

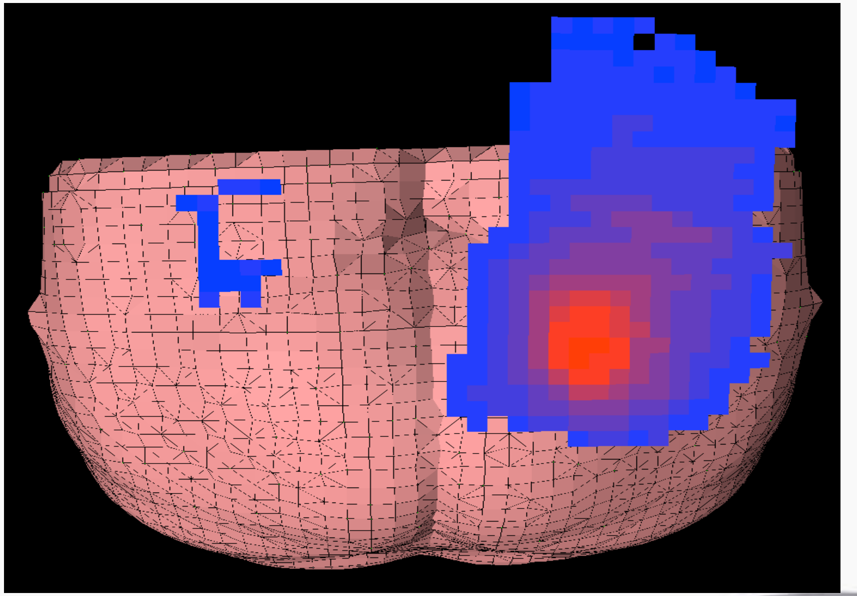
Buttocks and ulcers



Buttocks and ulcers

- Application de la pression d'un seul côté

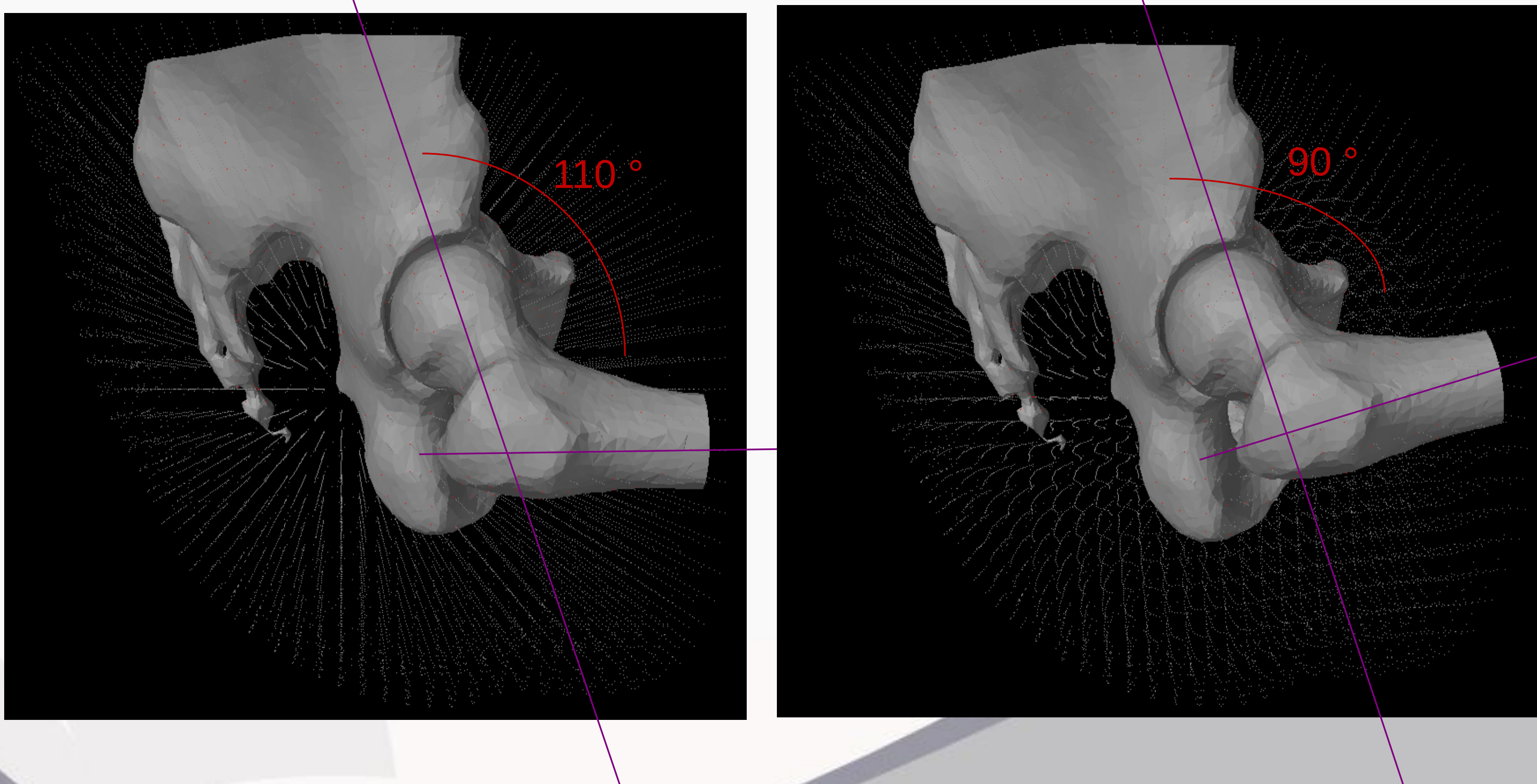




Nappes	Déformation maximum(%)
Nappe initiale zebris	57.1
Nappe unilatérale	61.6

Buttocks and ulcers

- Patient assis



Buttocks and ulcers

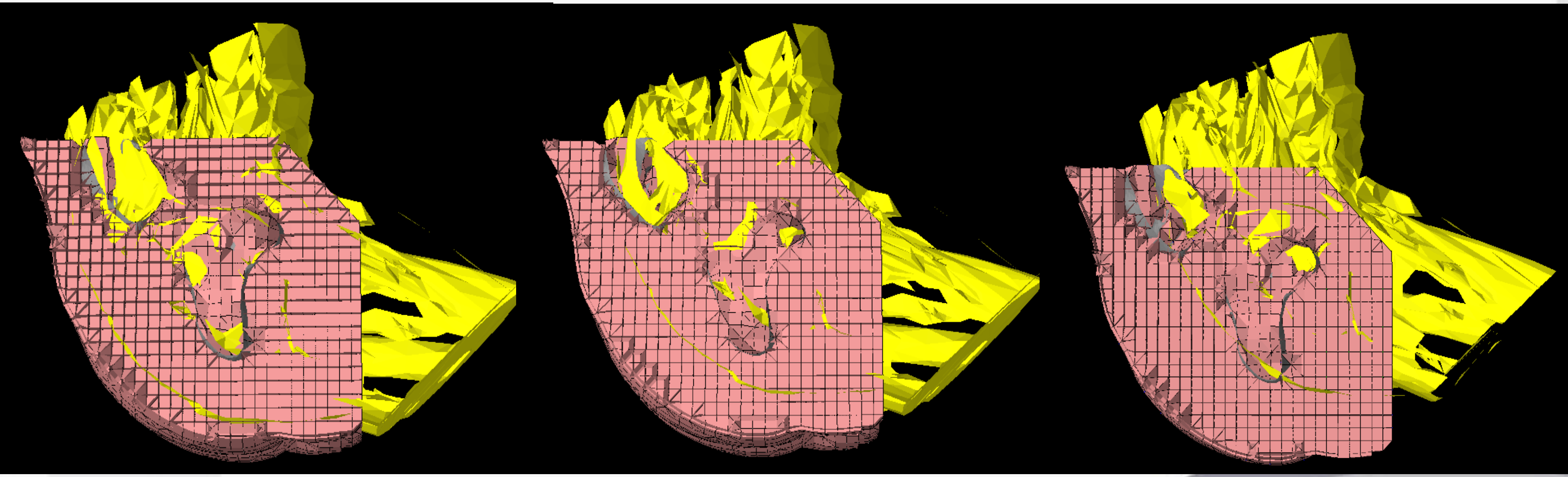
- Patient assis

Position	Déformation maximum(%)
Avachie	57.1
Assise	70.4

- Ischions plus saillants à 90 °

Buttocks and ulcers

- Influence de la diminution de l'épaisseur du muscle



Buttocks and ulcers

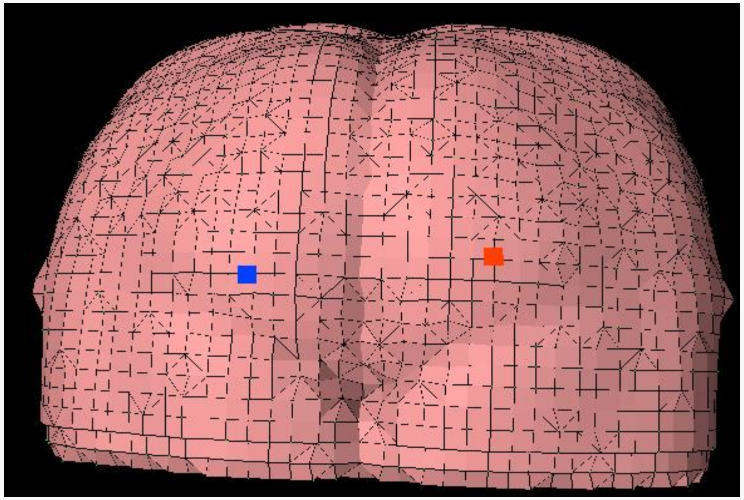
- Influence de la diminution de l'épaisseur du muscle

Epaisseur du muscle	Déformation max (%)
Initiale	57.1
Moyenne	108.9
Fine	140.9

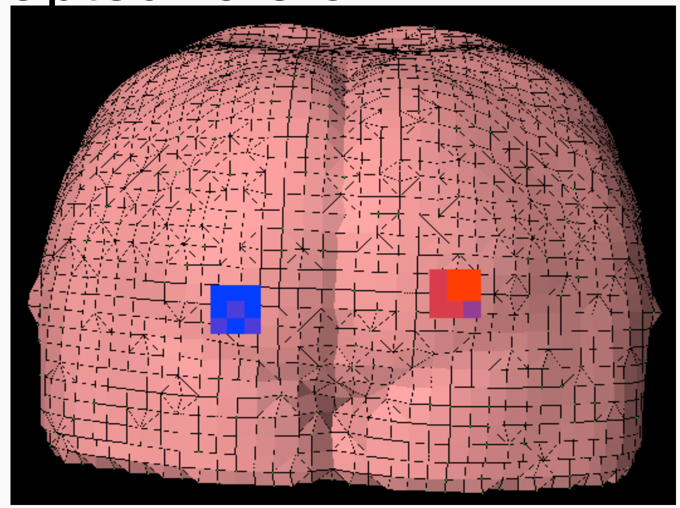
- Donc une personne qui a très peu de muscles et beaucoup de graisse a plus de chances de développer des escarres qu'une personne plus musclée.

Etude de la taille du capteur

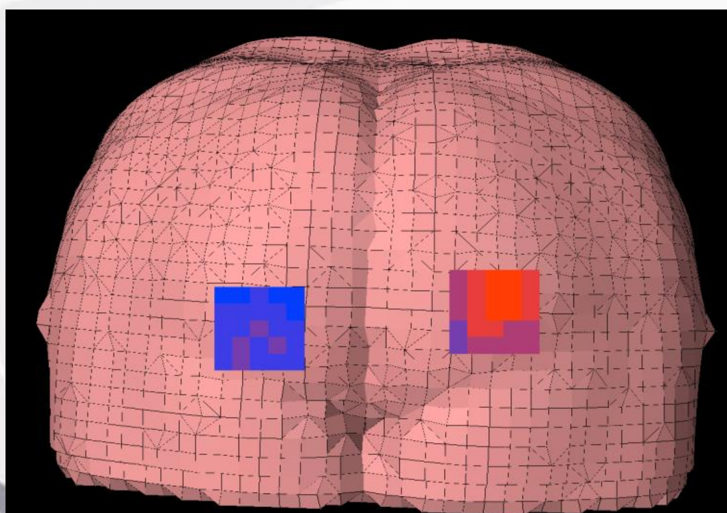
résolution d’un capteur 0.8 cm²



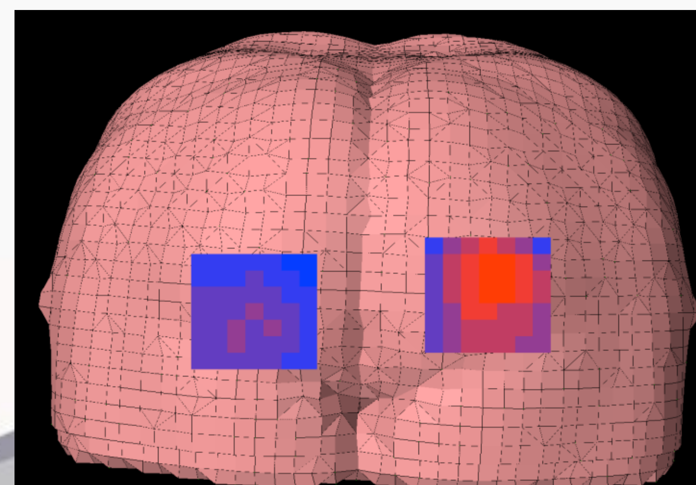
1 capteur sous chaque côté



9 capteurs sous chaque côté

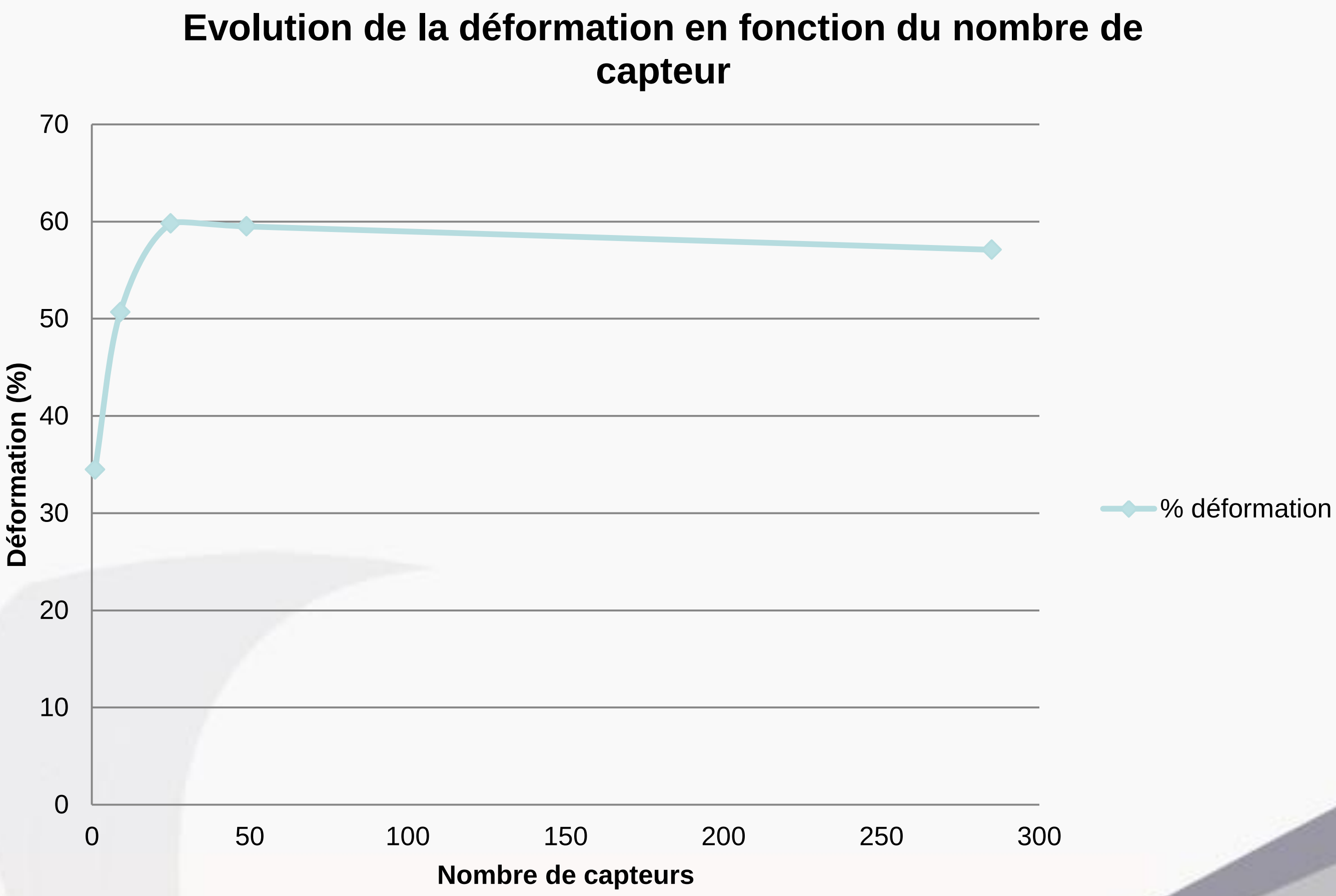


25 capteurs sous chaque côté



49 capteurs sous chaque côté

Etude de la taille du capteur



25 capteurs suffisent pour appliquer les pressions

Il suffirait d'avoir un capteur sous chaque ischion de 20 cm²

Problème : placer les capteurs exactement sous les ischions