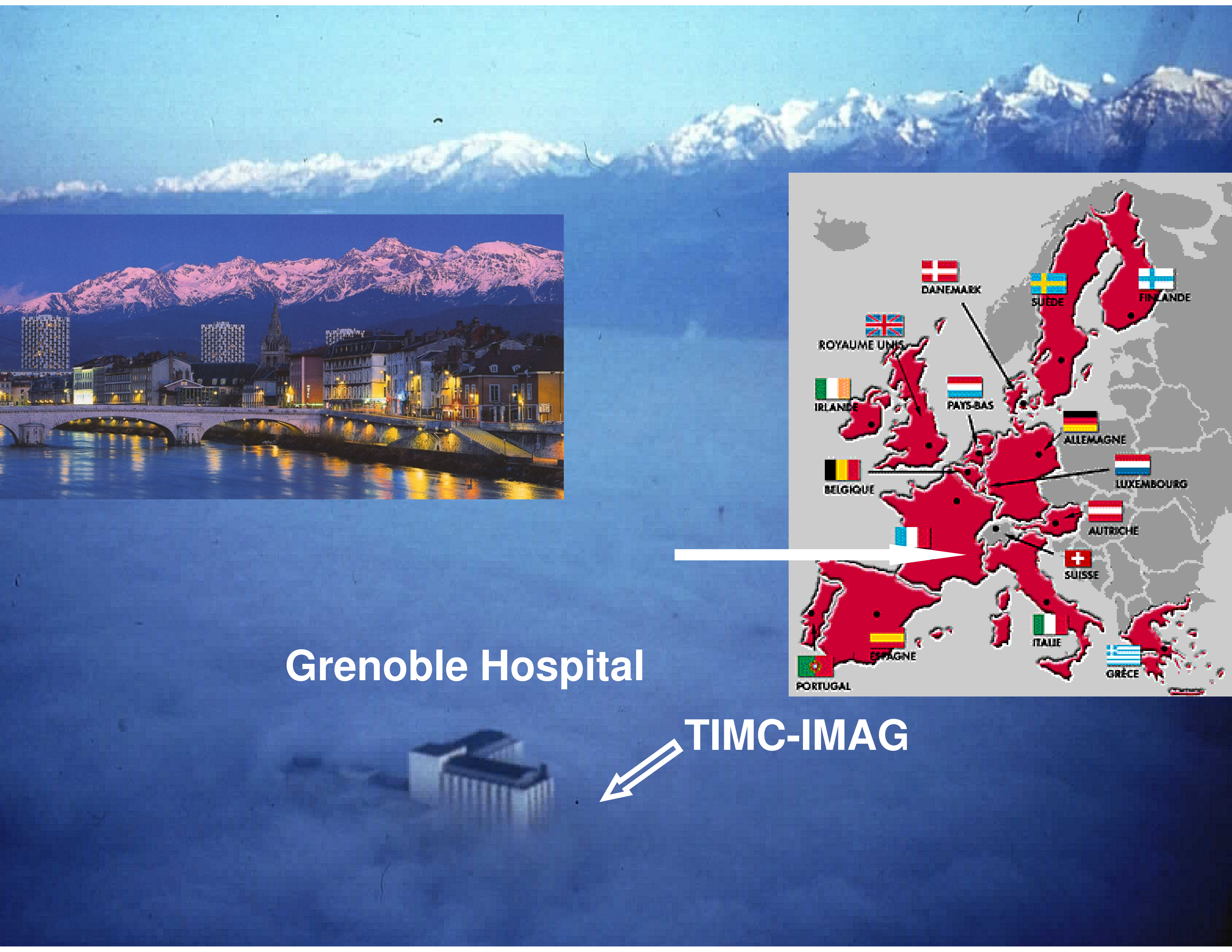
Biomechanics for computer-assisted surgery

Yohan Payan

TIMC-IMAG Laboratory
Computer Assisted Medical Intervention Group

CNRS, University of Grenoble, France

Yohan.Payan@imag.fr


Grenoble Hospital
TIMC-IMAG
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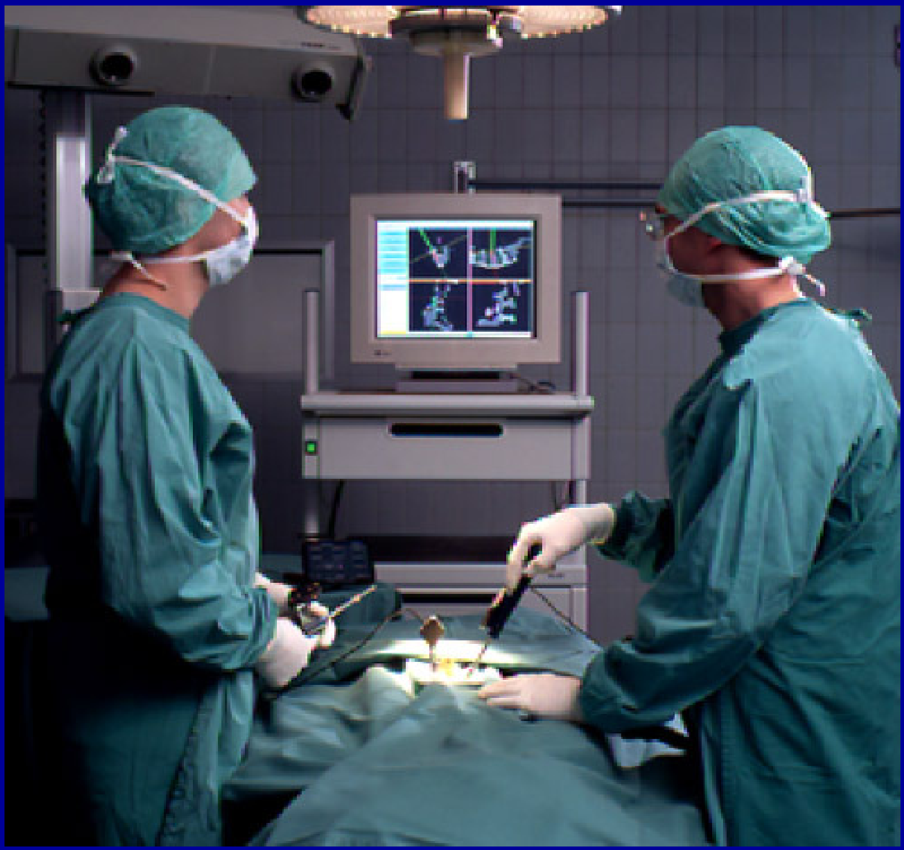
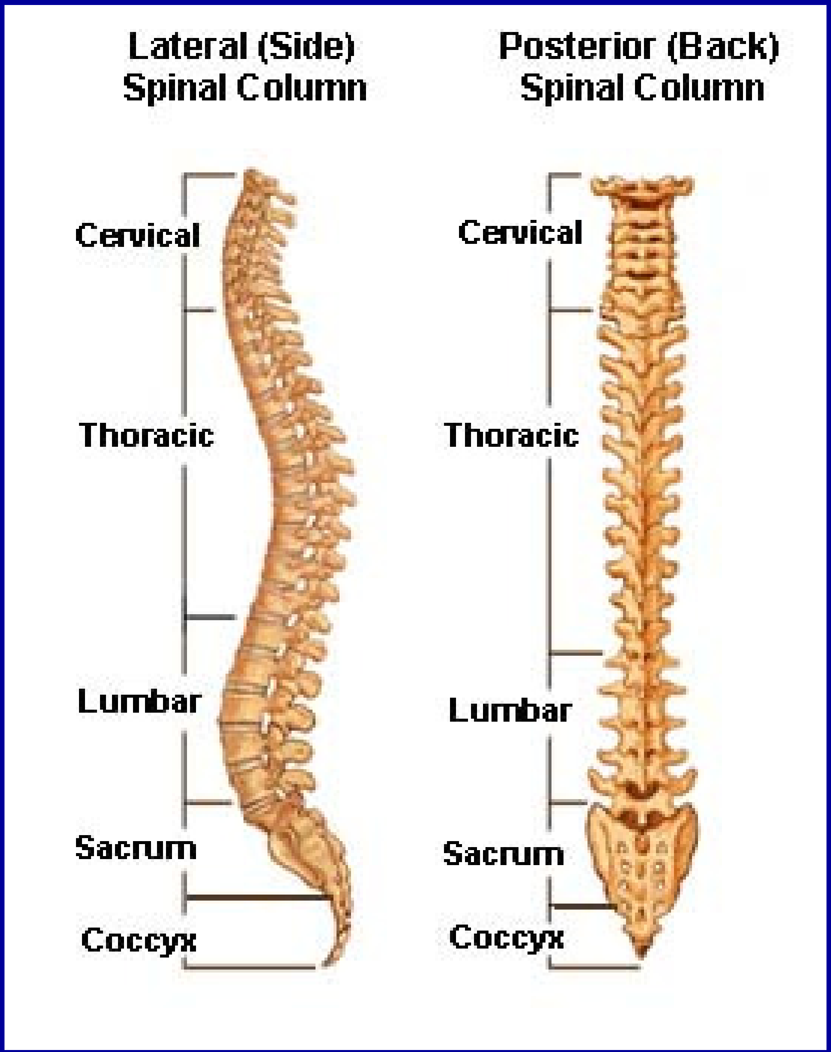
TIMC
Computer Aided Medical Intervention

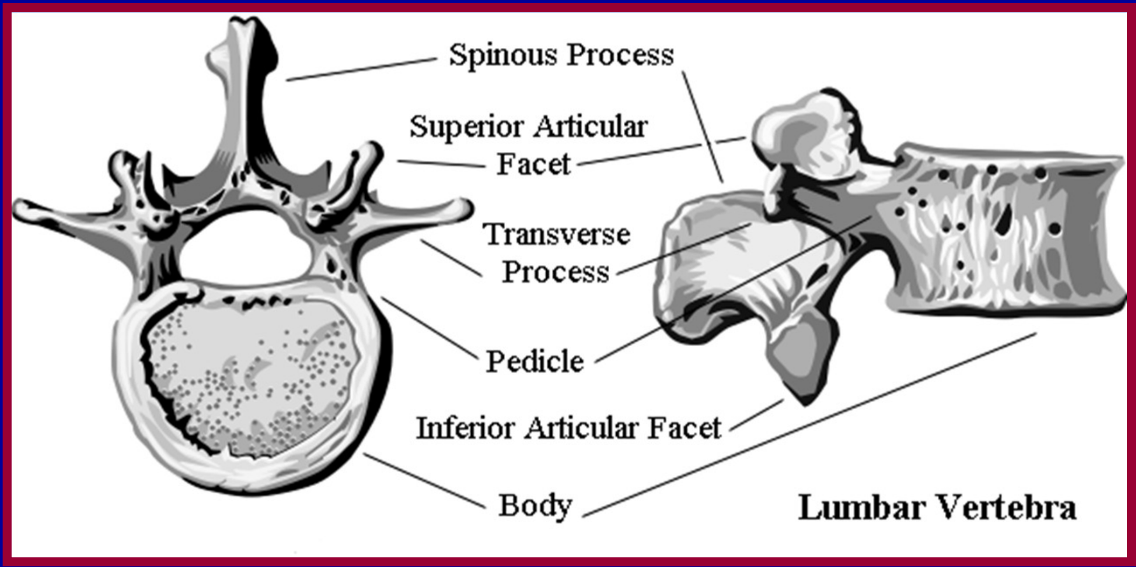


Main goal: "to assist the clinician and the surgeon in the realization of diagnostic or therapeutic intervention, in the most accurate and minimally-invasive way"

Computer Aided Medical Intervention



spinal column



vertebra
(face and sagittal view)

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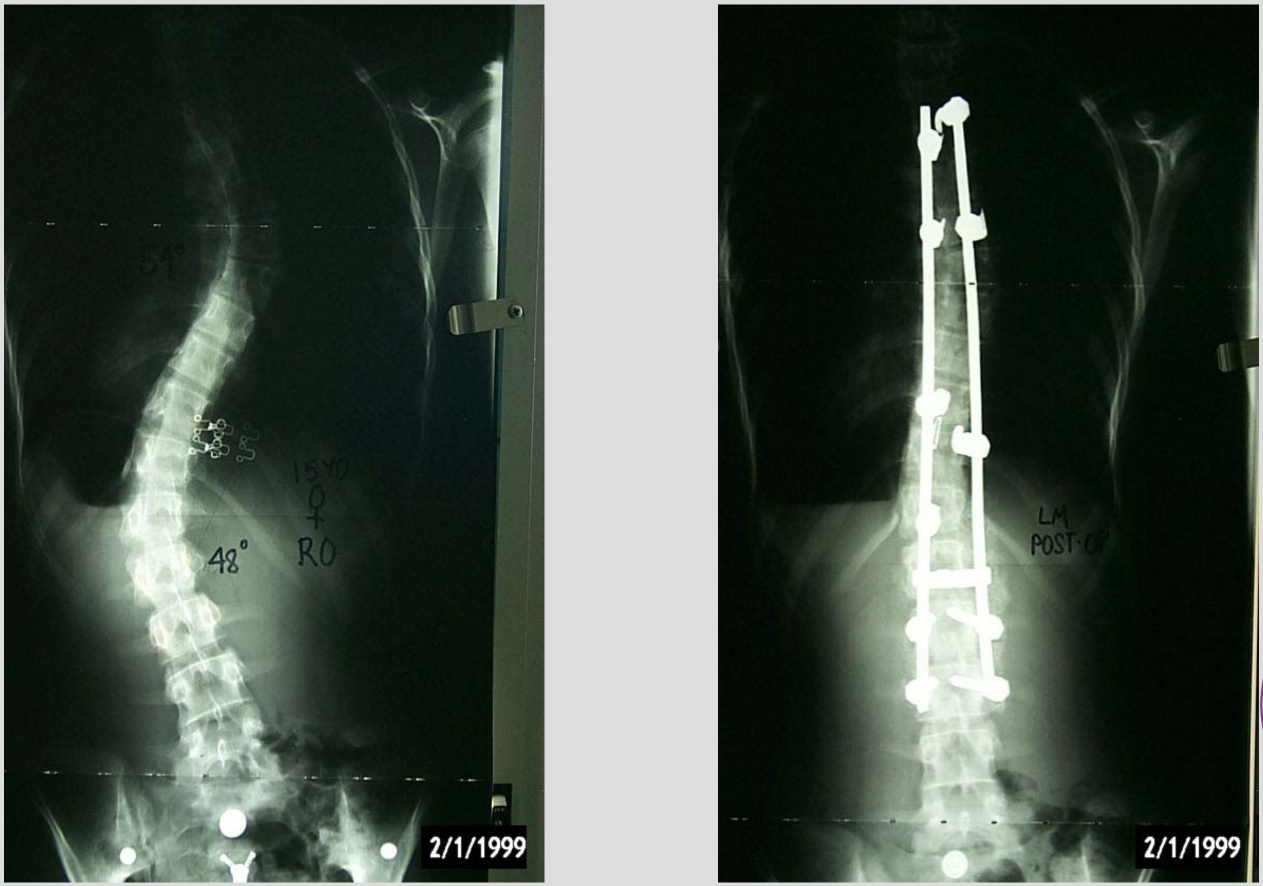
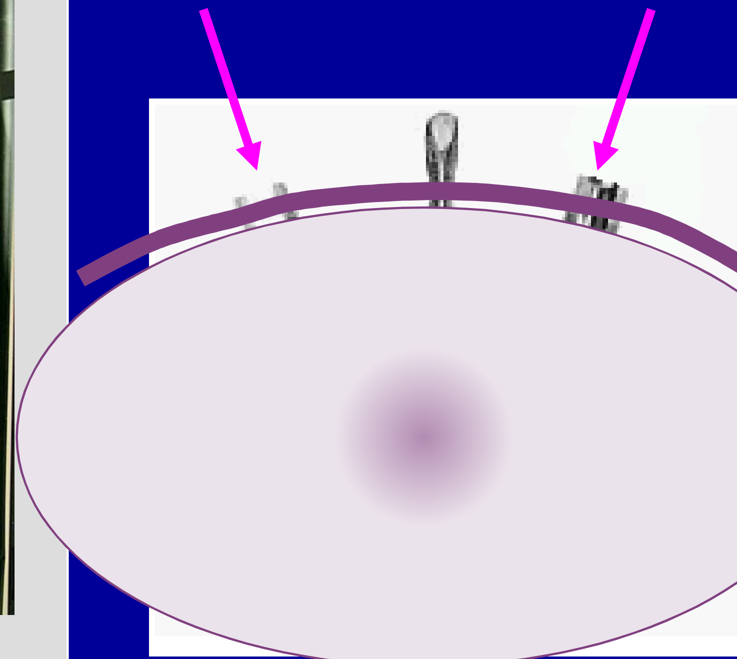


scoliosis

screws through pedicles



Spinal cord

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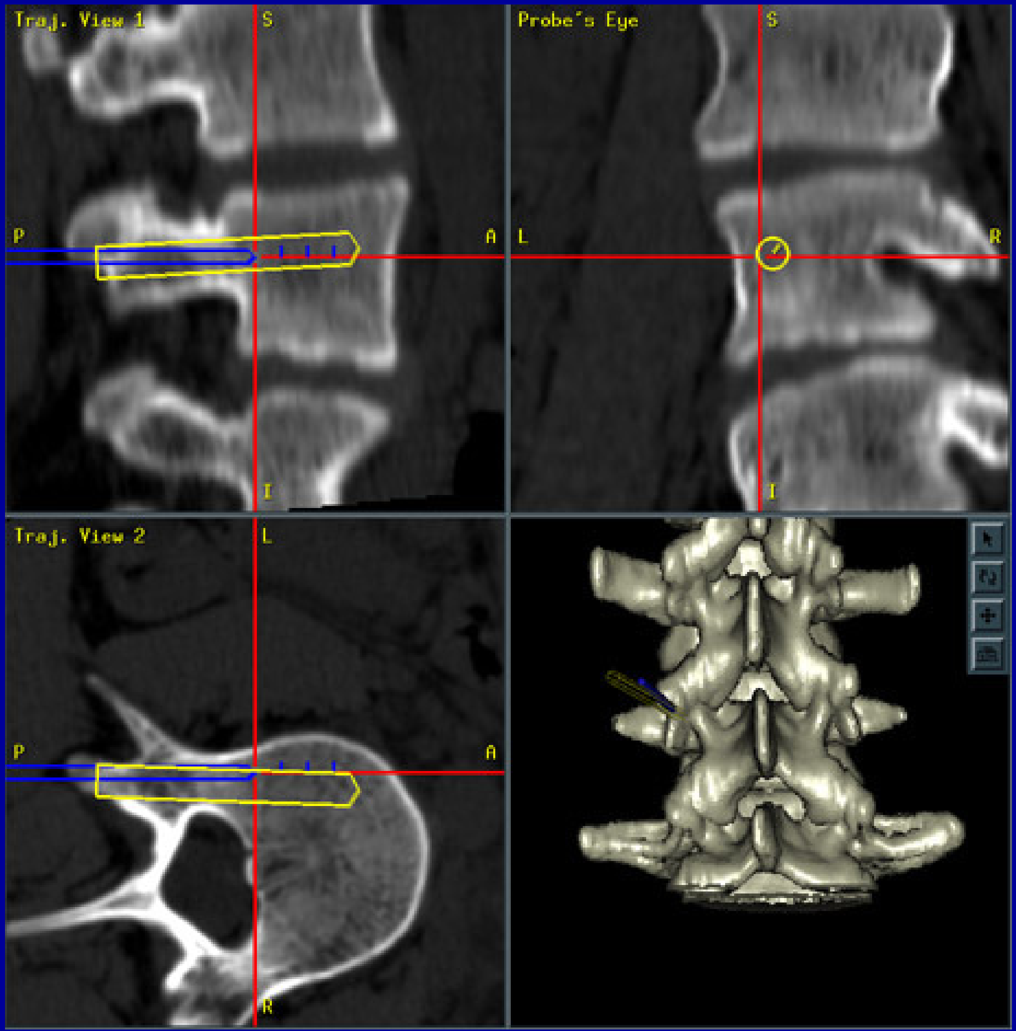
Planning onto the scanner exam



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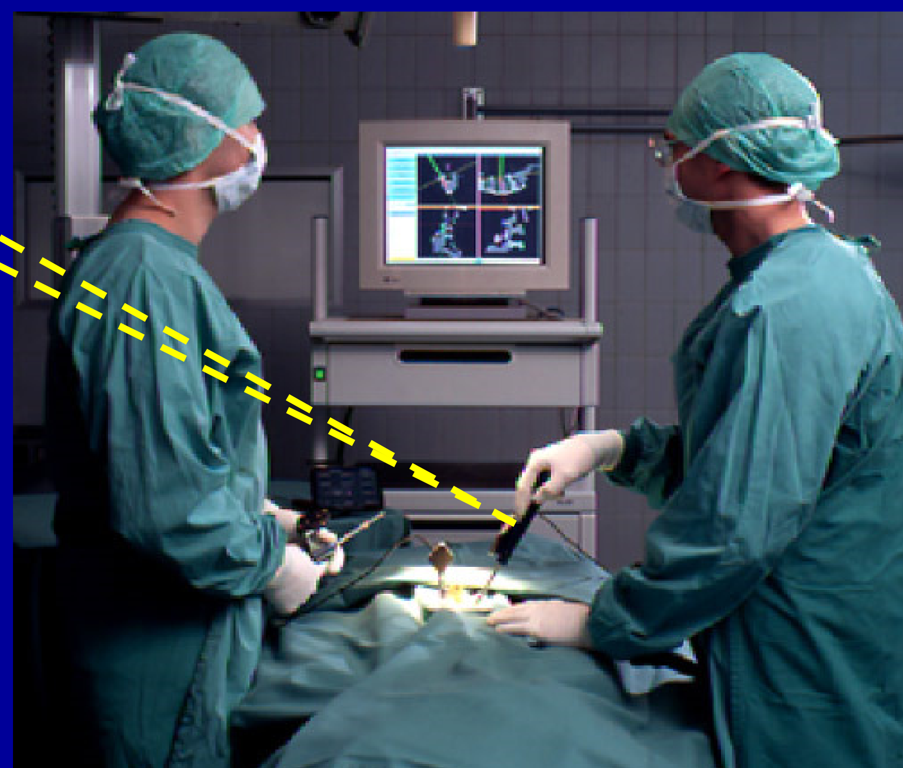
Per-operative surgical guiding :

Merloz *et al.* (1997)



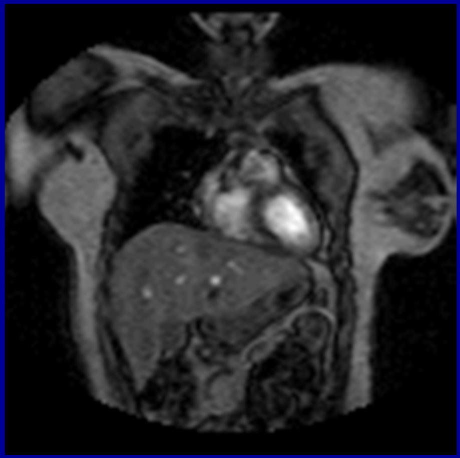
Computer Aided Medical Intervention

What about soft organs?

Computer Aided Medical Intervention

Computer Aided Medical Intervention

A computer Aided system for such a deformable organ would mean:



- A "fast" generation of the patient-specific biomechanical model of the organ
- The possibility to estimate the patient-specific constitutive behavior of the organ
- An almost real-time computation of the deformations simulated by the model

Computer Aided Medical Intervention

	Intra-operative computer Aided System
• A "fast" generation of the patient-specific biomechanical model of the organ	+++
• The possibility to estimate the patient-specific constitutive behavior of the organ	+++
• An almost real-time computation of the deformations simulated by the model	+++

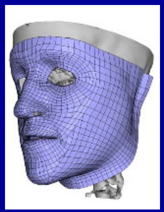
Computer Aided Medical Intervention

	Pre-operative computer Aided System
• A "fast" generation of the patient-specific biomechanical model of the organ	++
• The possibility to estimate the patient-specific constitutive behavior of the organ	++
• An almost real-time computation of the deformations simulated by the model	+

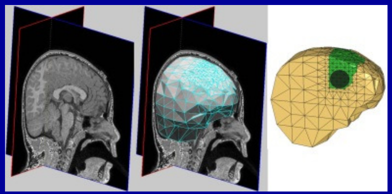
Outline

- Introduction

- Pre-operative Computer Aided Device: *maxillo-facial surgery*



- Intra-operative Computer Aided Device: *Neurosurgery*



- Discussion

Orthognatic surgery

Orthognathic surgery is directed to patients suffering from malformations of the lower part of the face

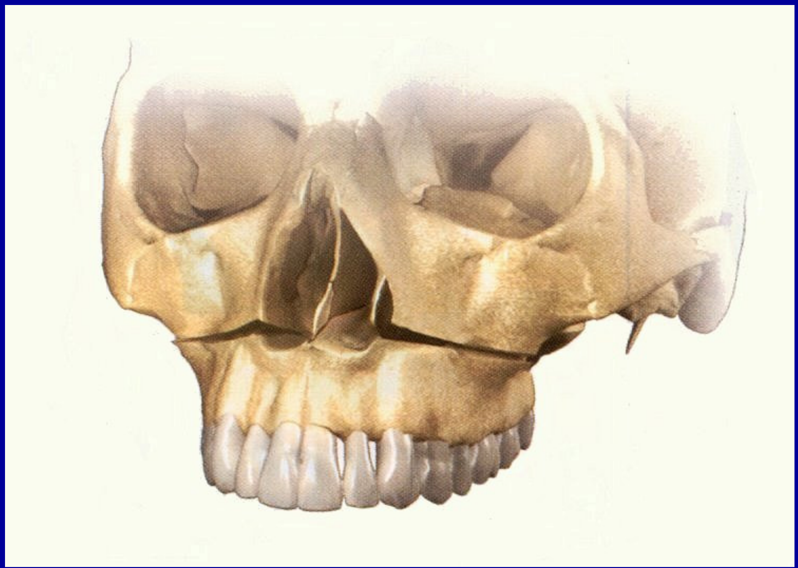
orthodontic

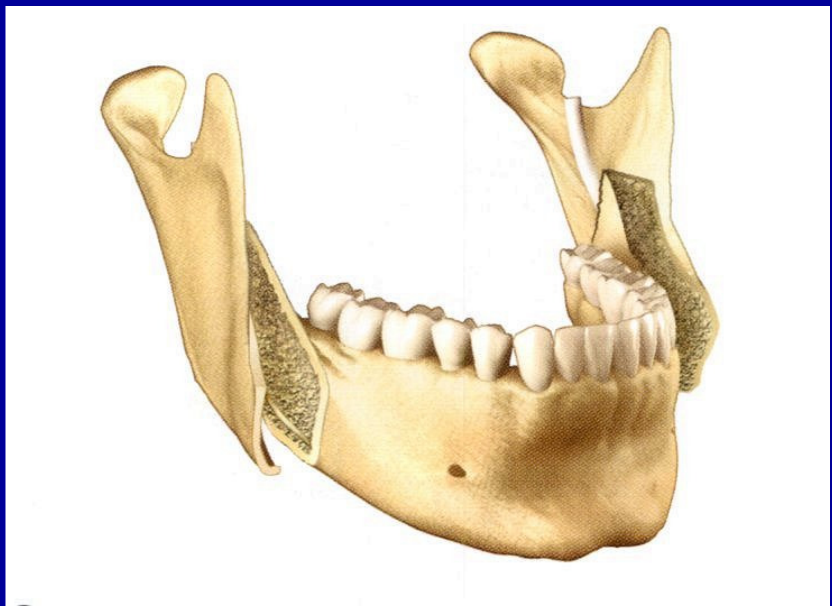
aesthetic

functionnal

Orthognatic surgery

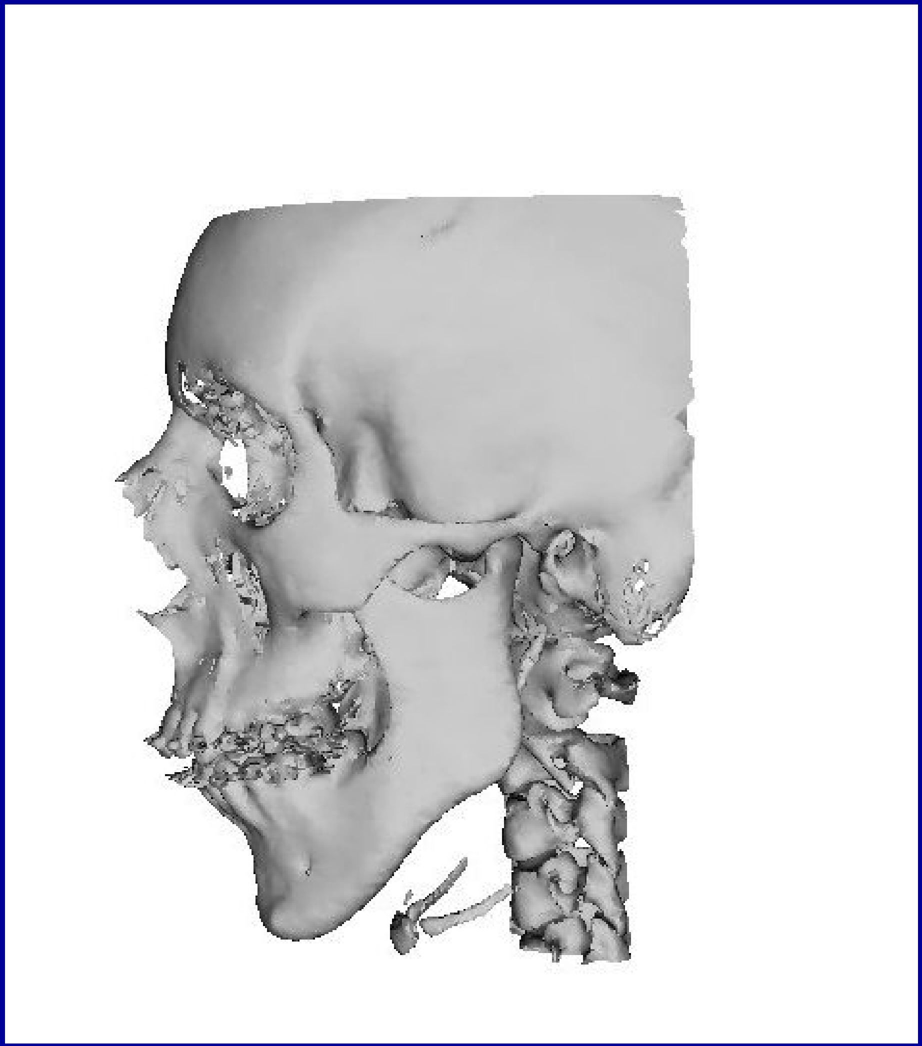
The principle of the surgical procedure is to reposition bones segments, the upper maxilla and/or the mandible, with respect to cephalometric, orthodontic and aesthetic criteria.





Orthognatic surgery

Bones cuttings and repositioning:



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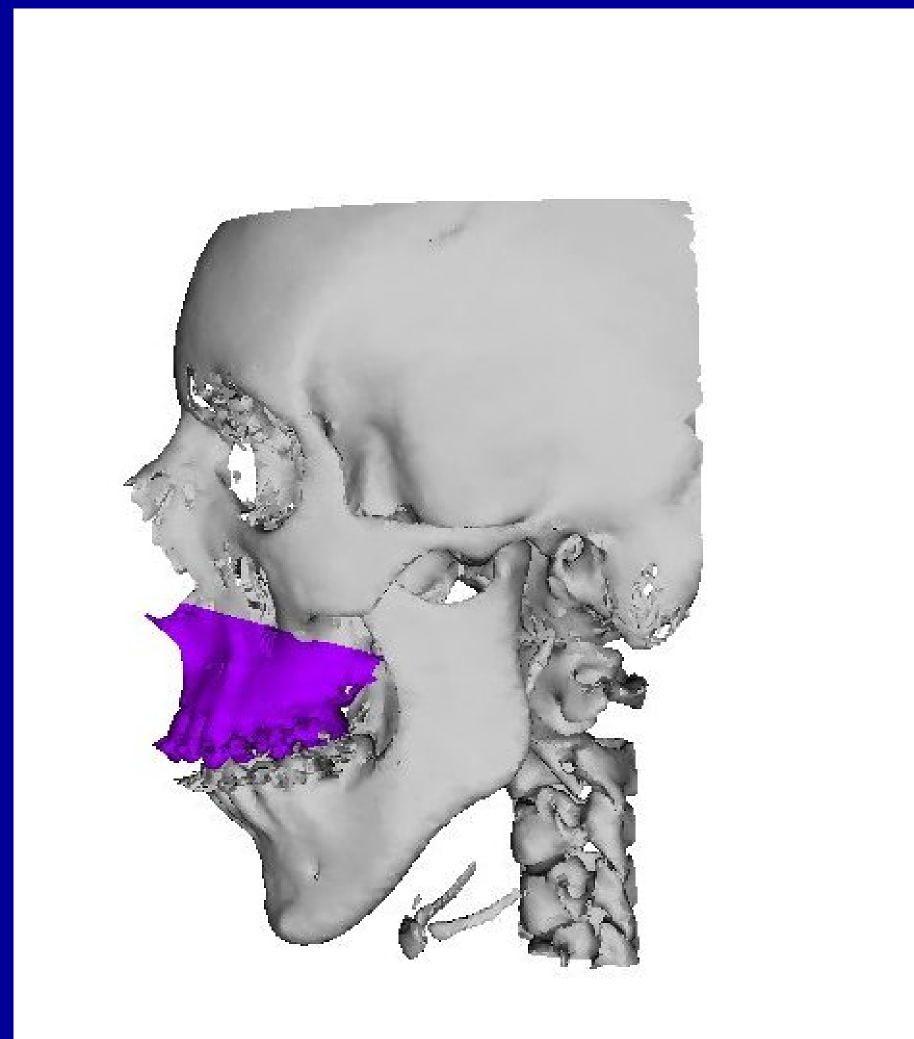

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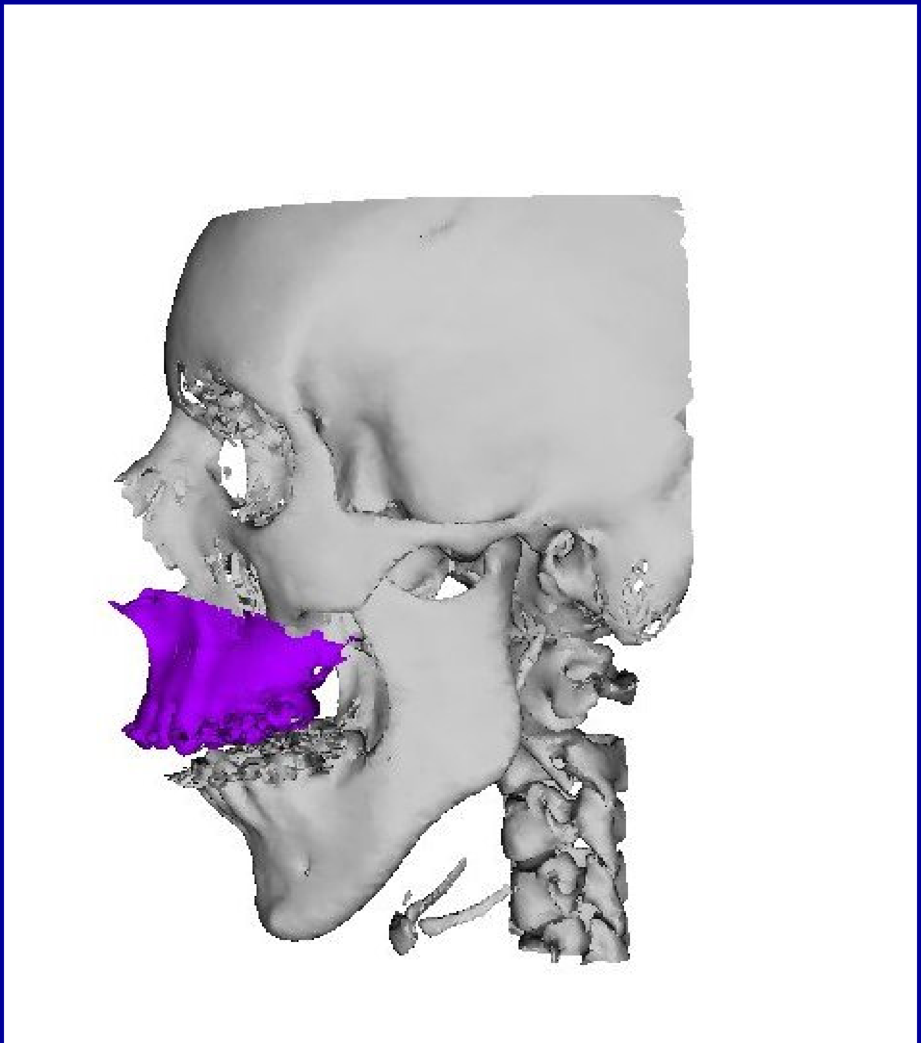

Orthognatic surgery

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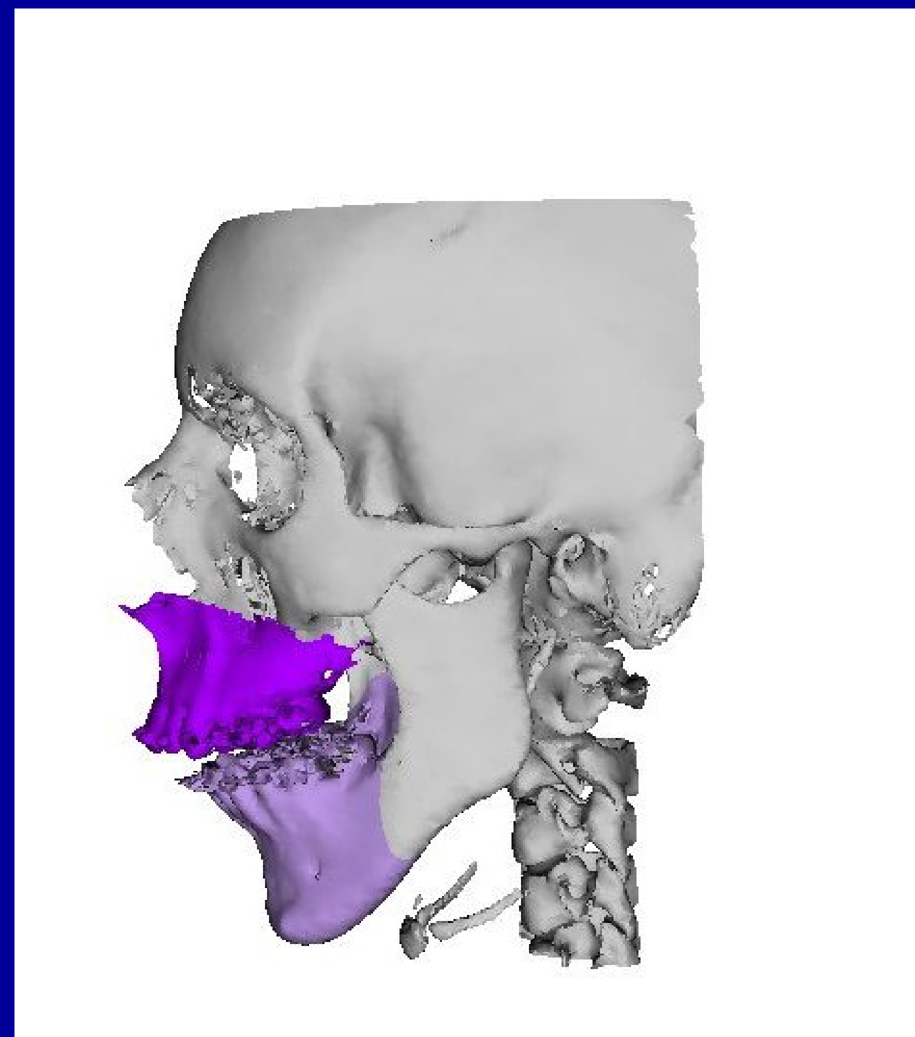

Orthognatic surgery

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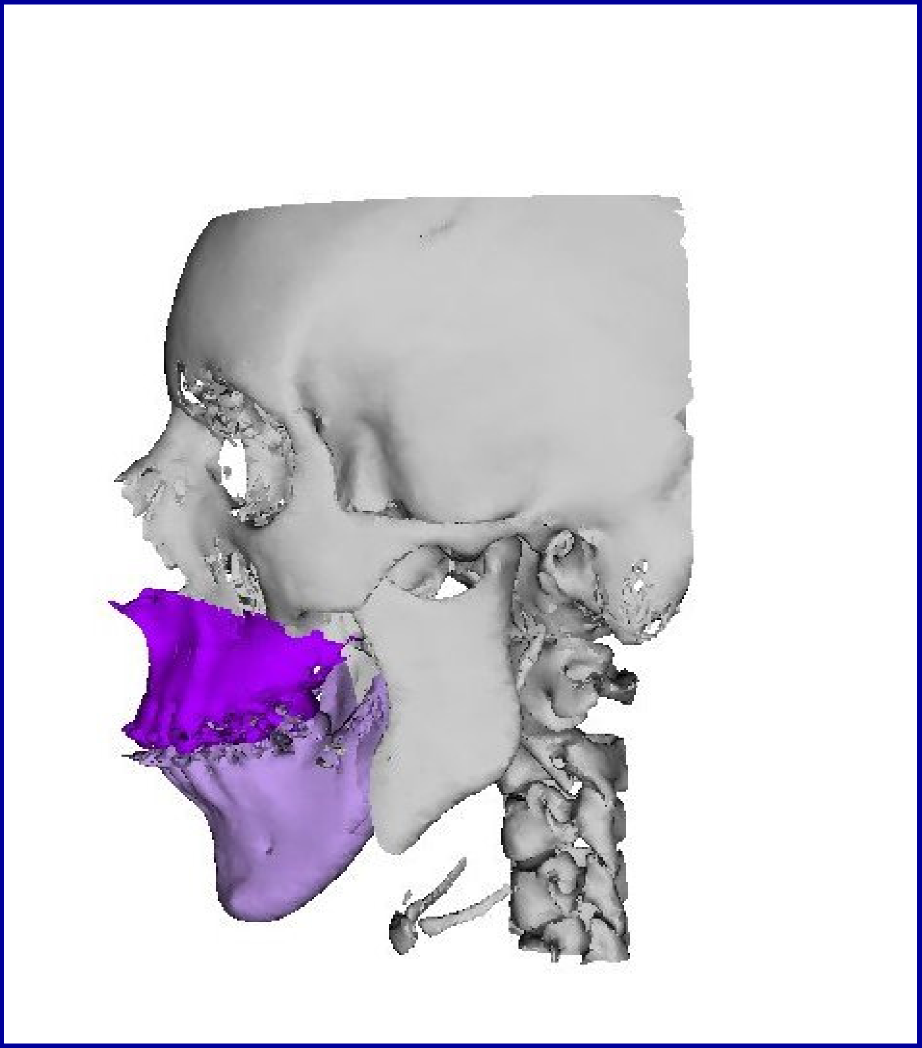

Orthognatic surgery

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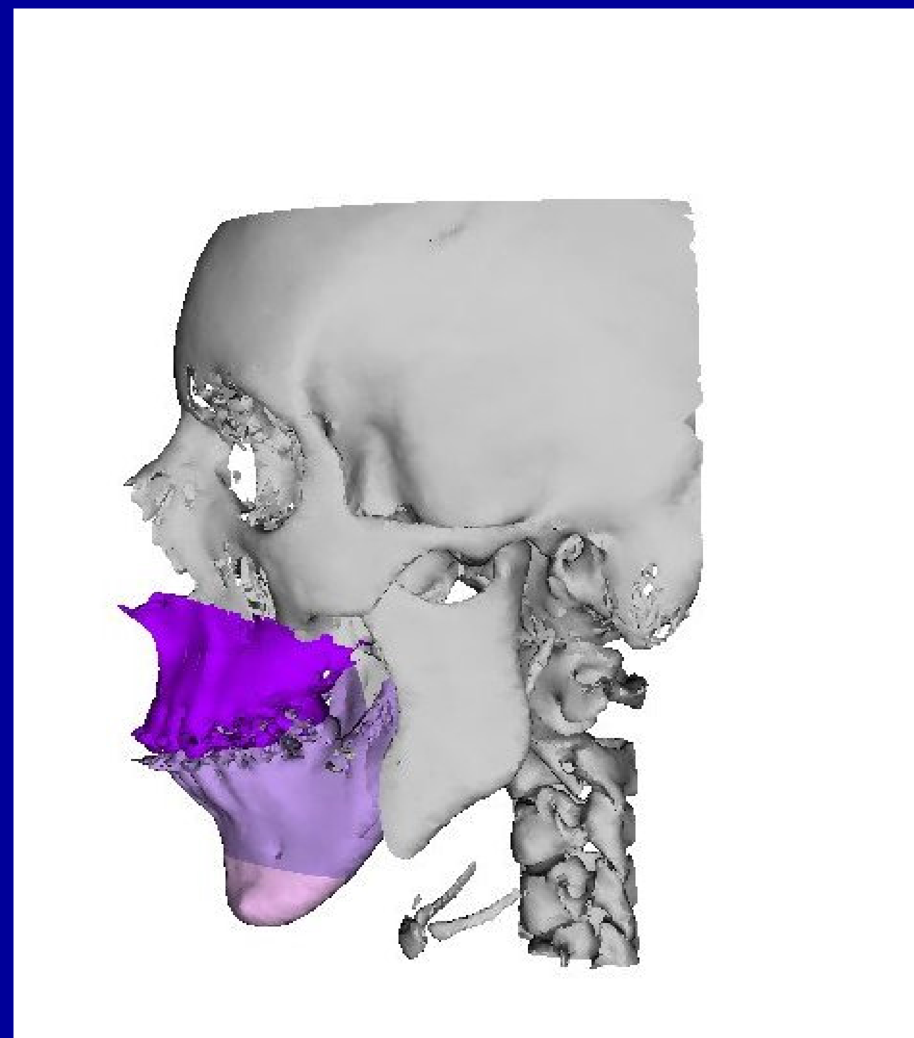
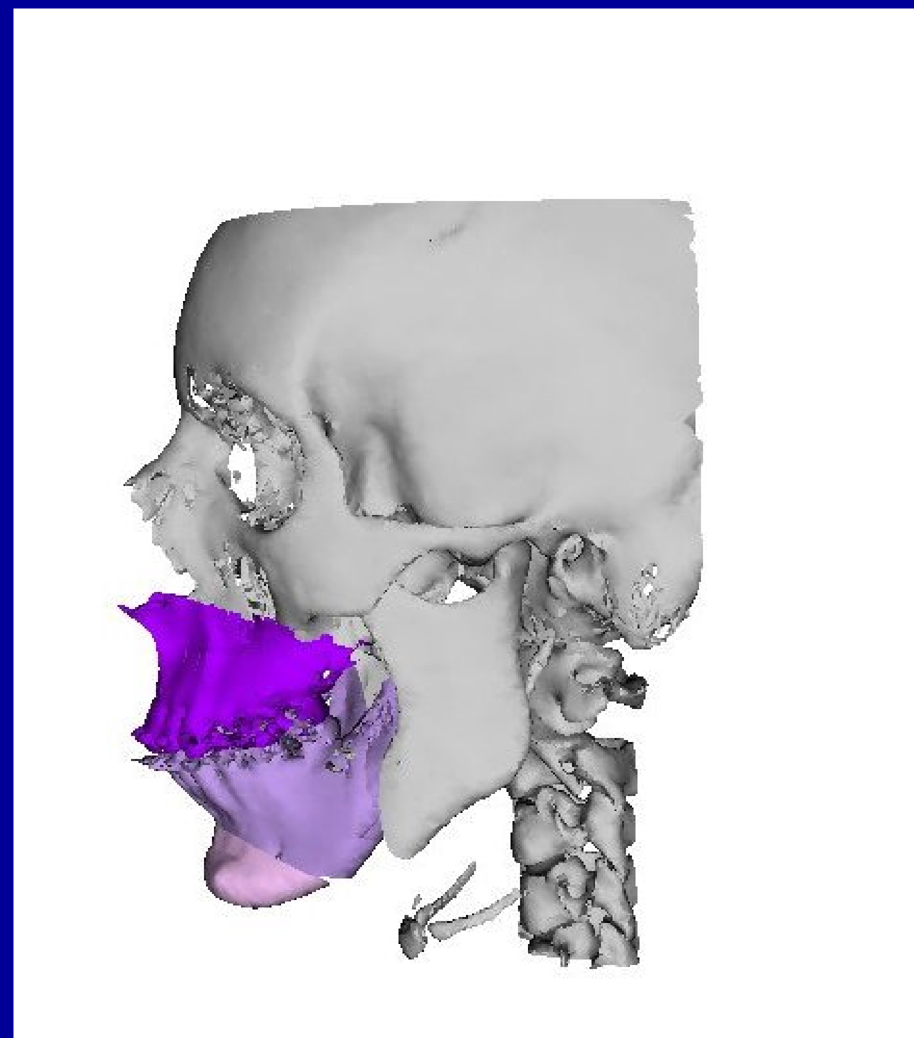
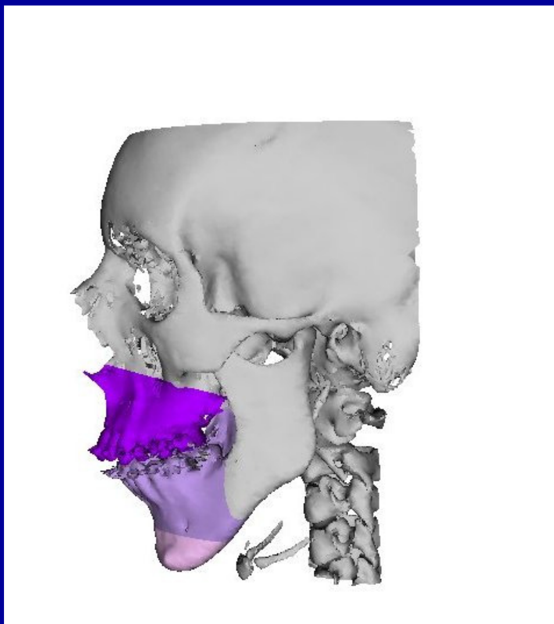


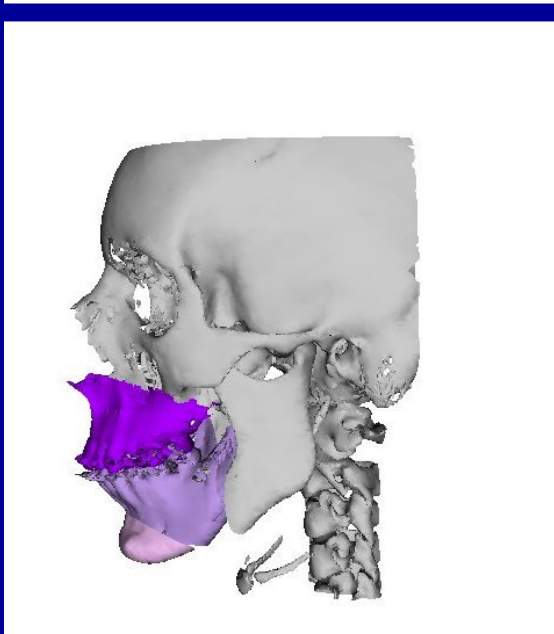
Orthognatic surgery

Bones cuttings and repositioning:



Orthognatic surgery

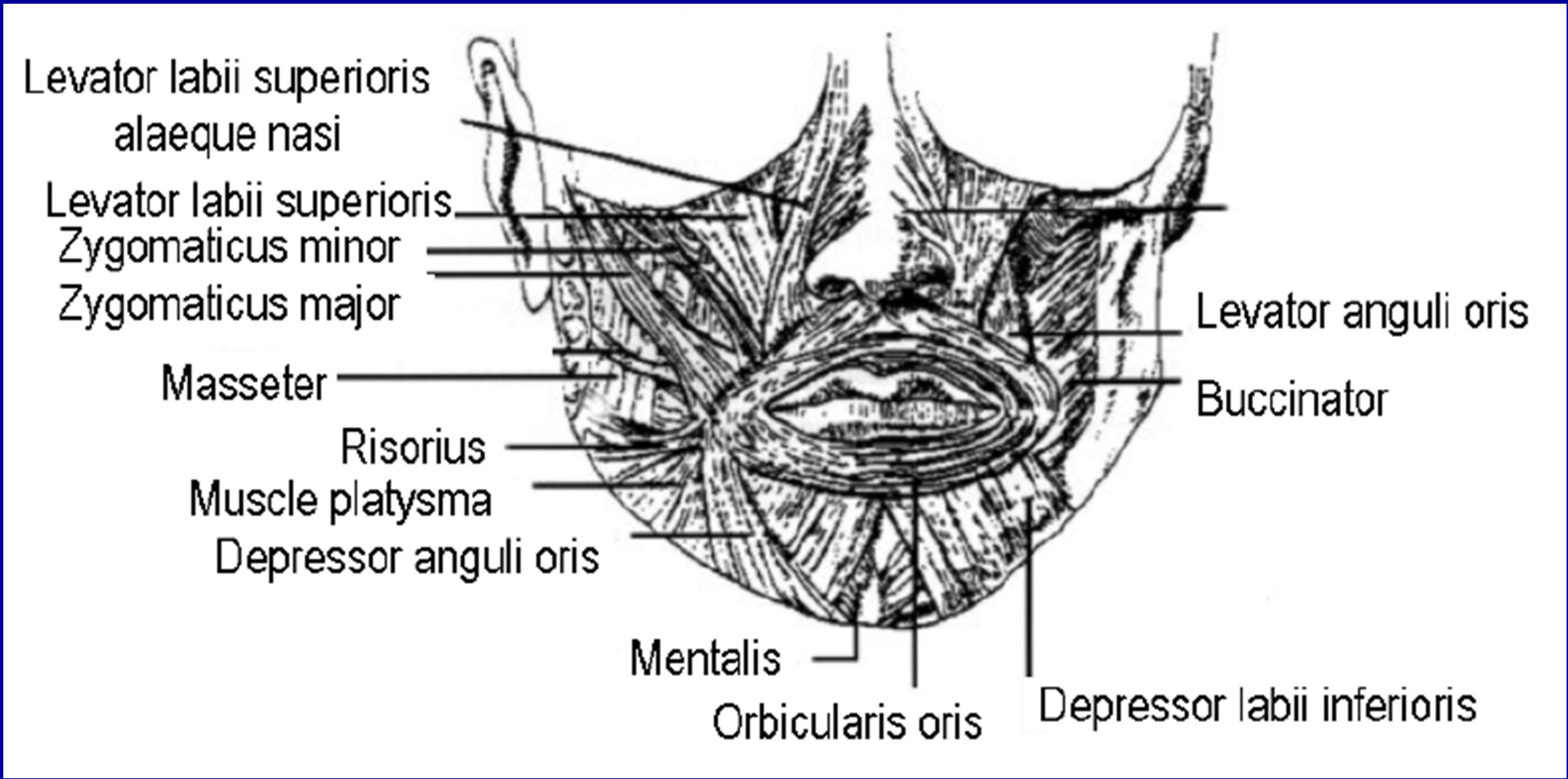




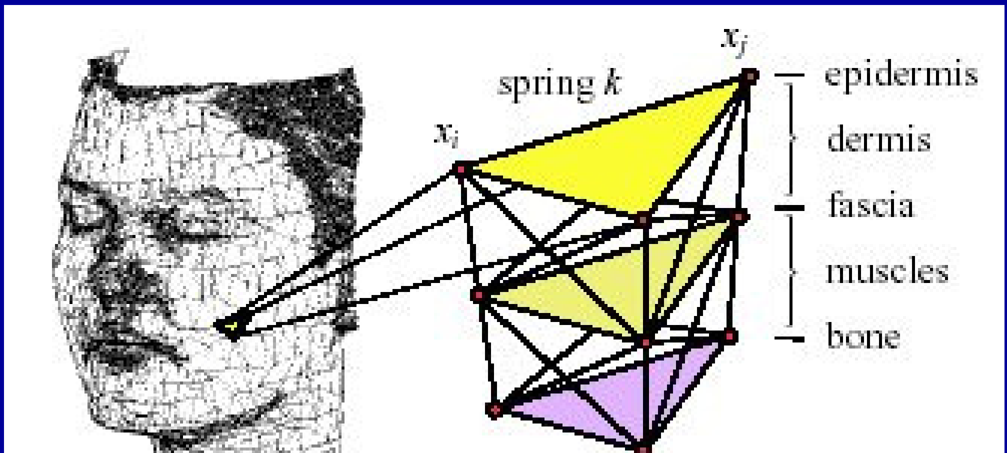
Next step: To take into account the face soft tissue deformations resulting from bone repositioning, in order to predict:

- the patient aesthetic aspect after surgery
- the functional consequences (facial mimics, mastication, speech production)

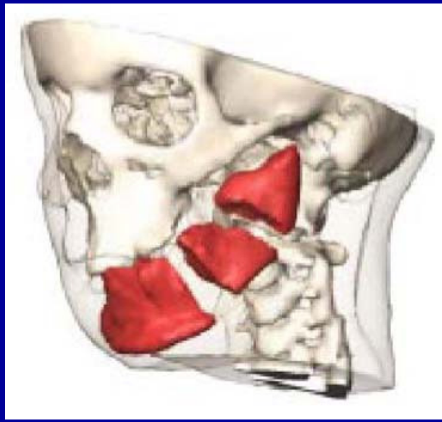
Face anatomy



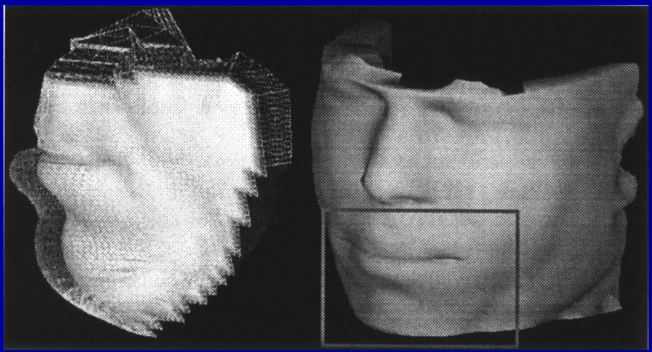
Face modeling in the maxillo-facial literature



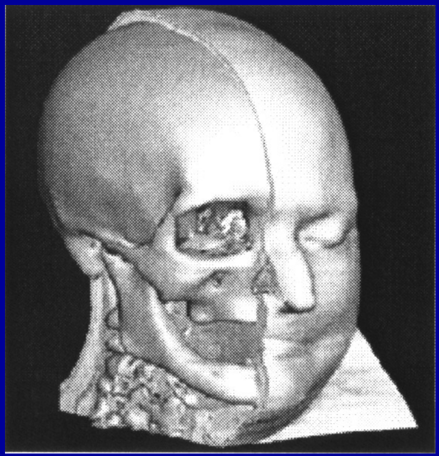
Keeve et al., 1996, 1998



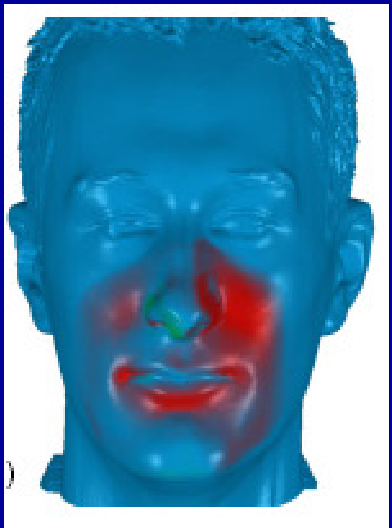
Gladilin et al., 2003



Roth et al., 1998



Zachow et al., 2000



Koch et al., 1998, 1999

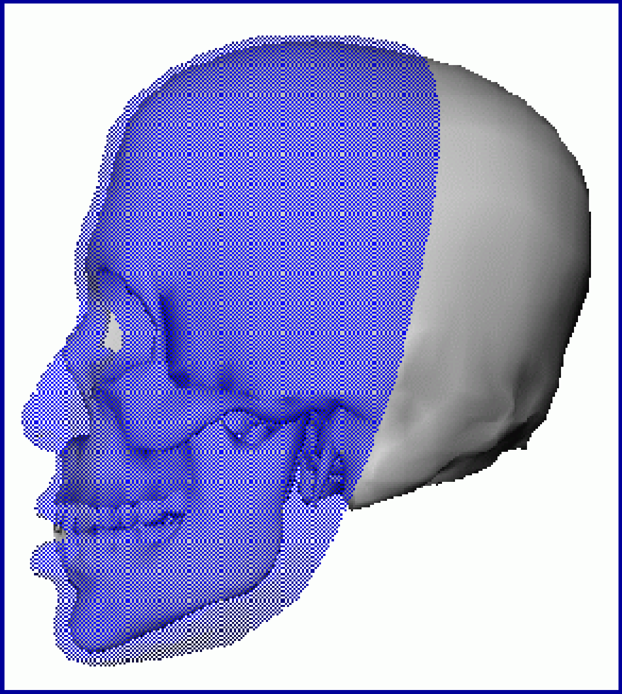
Computer Aided Medical Intervention

	Pre-operative computer Aided System
• A "fast" generation of the patient-specific biomechanical model of the organ	++
• The possibility to estimate the patient-specific constitutive behavior of the organ	++
• An almost real-time computation of the deformations simulated by the model	+

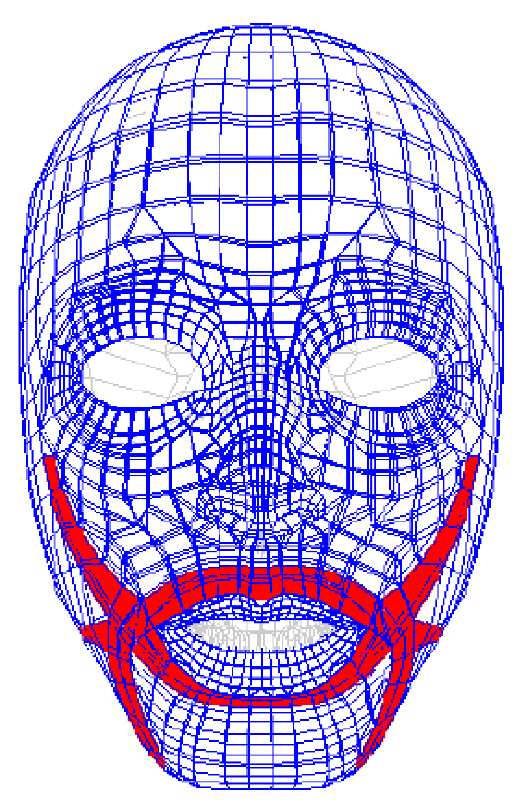
Our modeling strategy

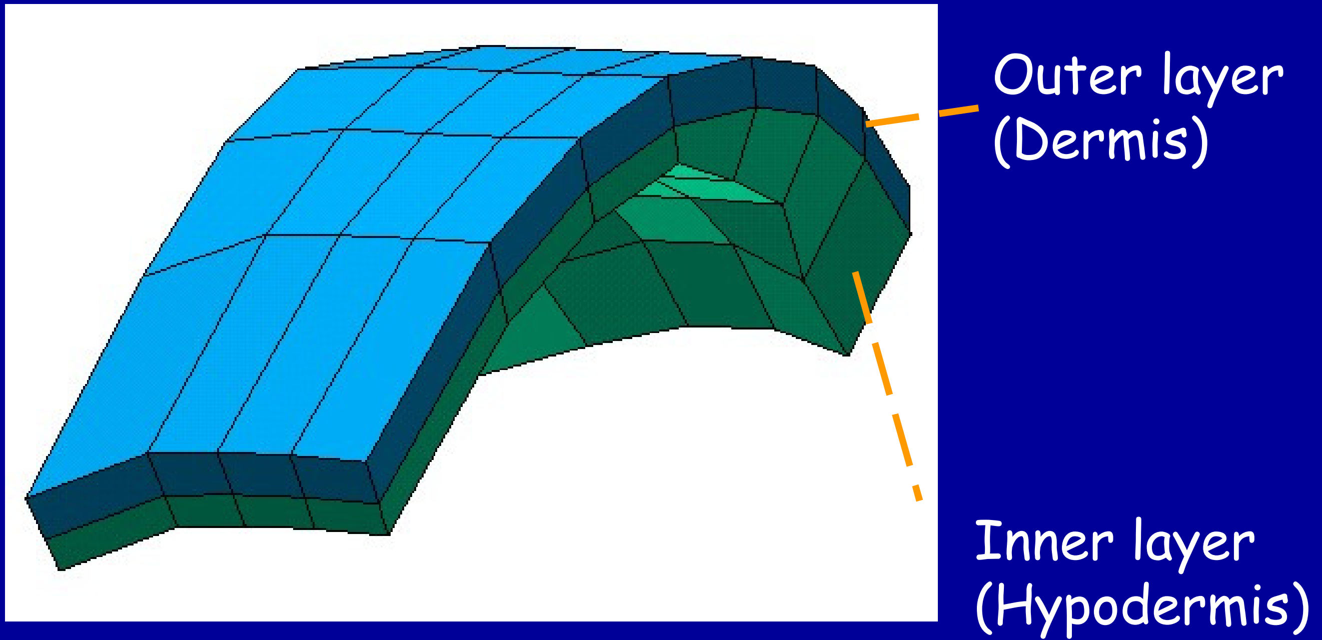
The Mesh-Matching algorithm (Couteau et al., 2000) :

1. Manual elaboration of a "generic" (atlas) Finite Element model



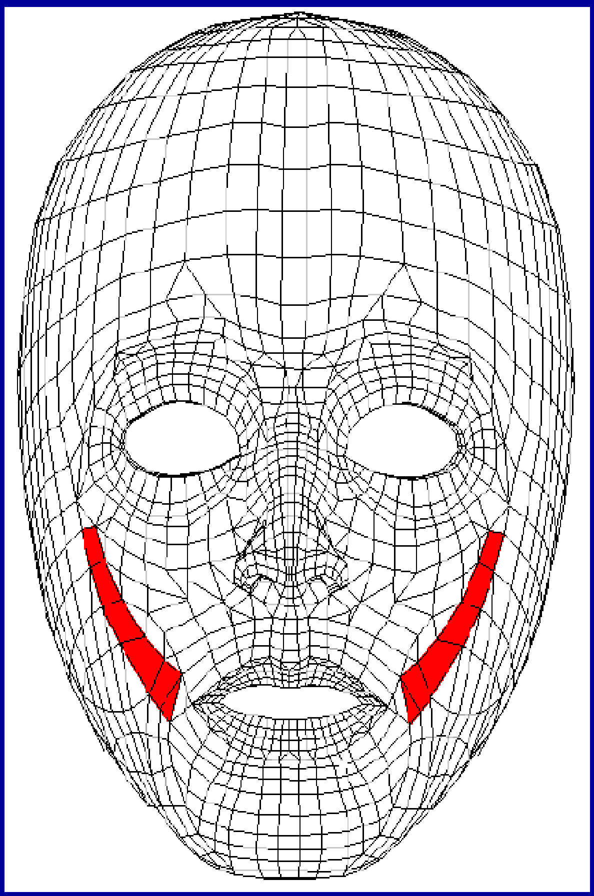
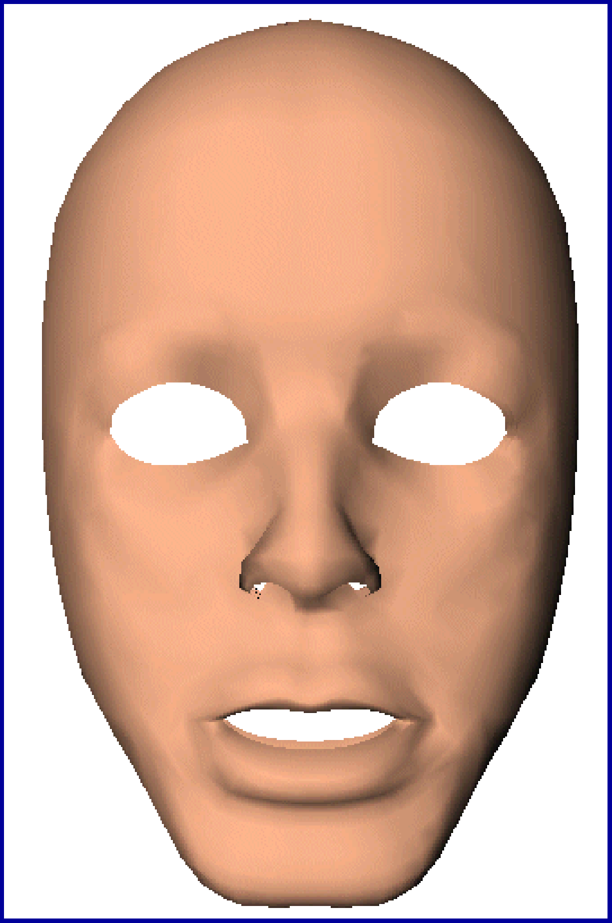
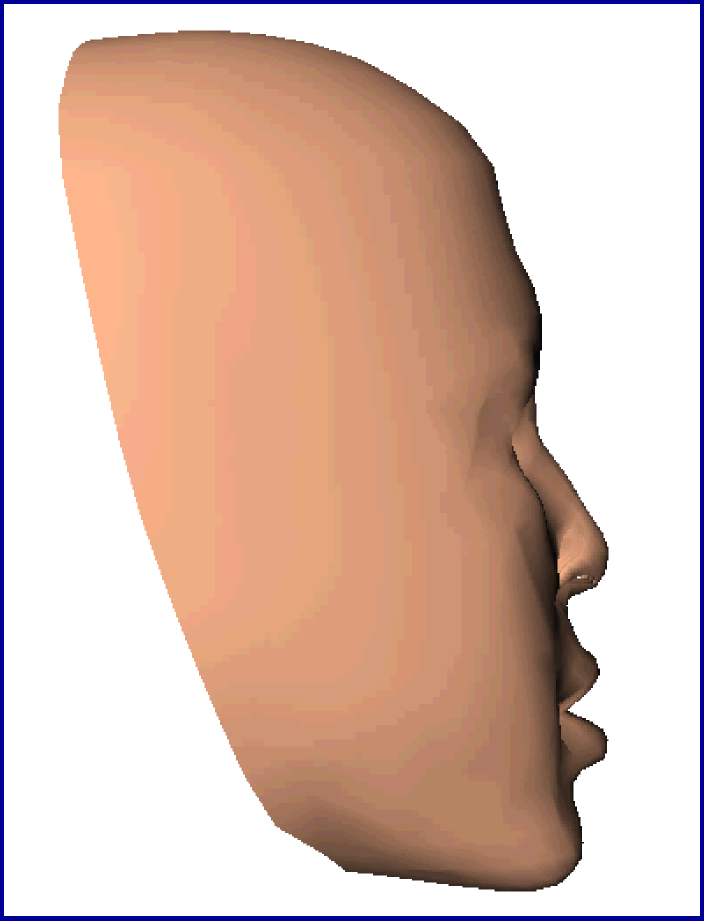
Generic Finite Element face model



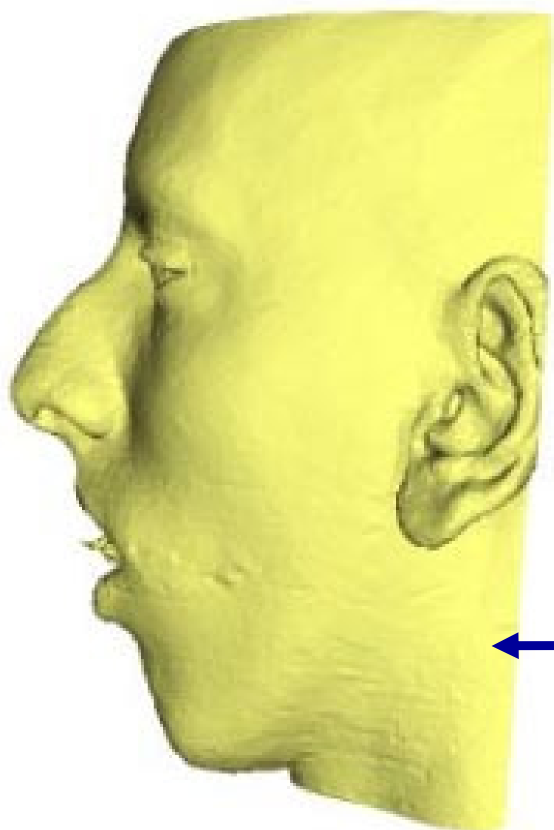


Chabanas et al. (2003), *Medical Image Analysis*

Simulation :
Activation of Zygomaticus major

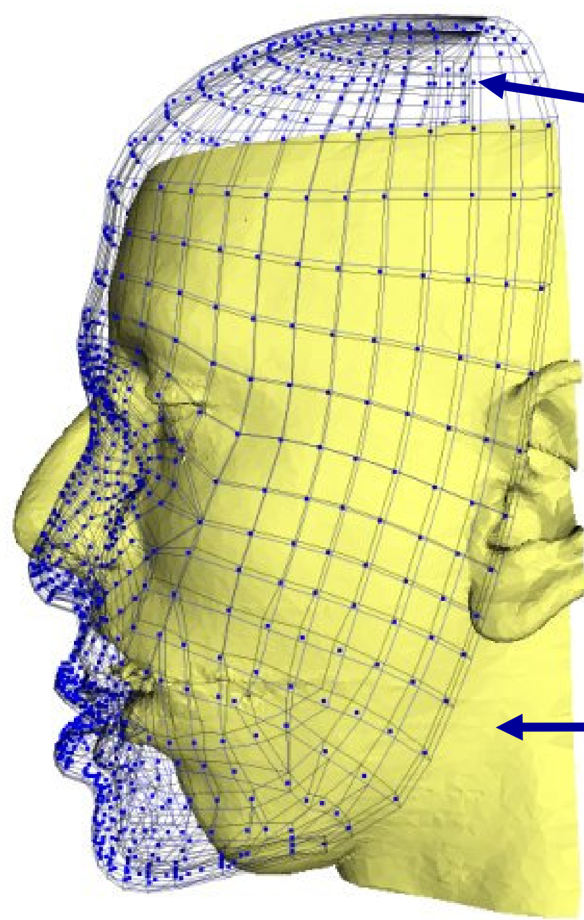




Confromation of the generic model to patient morphology



Patient skin surface segmented from CT (Marching cube)

Confromation of the generic model to patient morphology



Our modeling strategy

The Mesh-Matching algorithm (Couteau et al., 2000) :

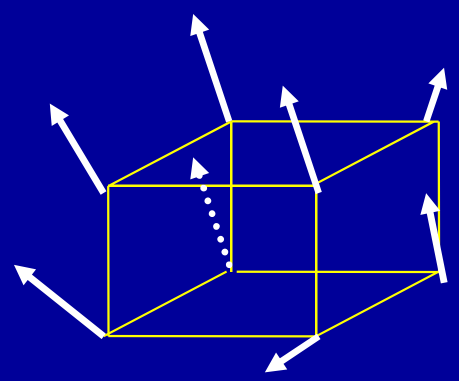
1. Manual elaboration of a "*generic*" (atlas) Finite Element model

2. Local non-linear elastic registration of this generic FE mesh to automatically match patient morphology.

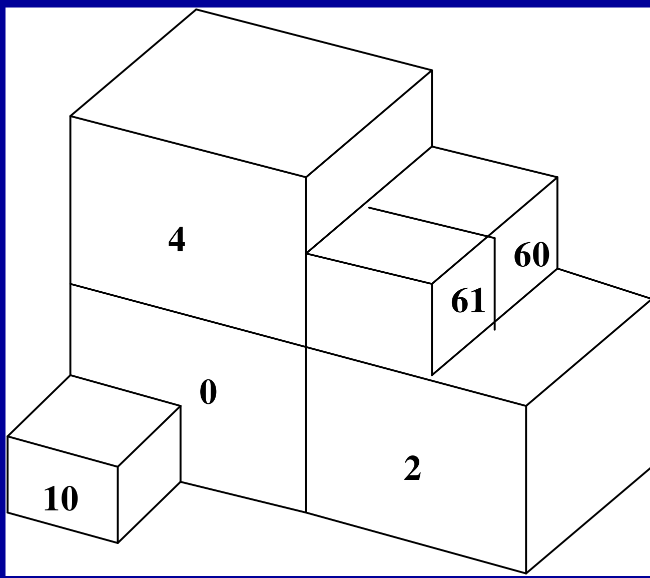
Our modeling strategy

The registration algorithm (Szeliski & Lavallée, 1996):

- Octree Spline method
- Adaptative deformation function
  - rigid matching
  - global elastic transformation
  - local elastic transformations

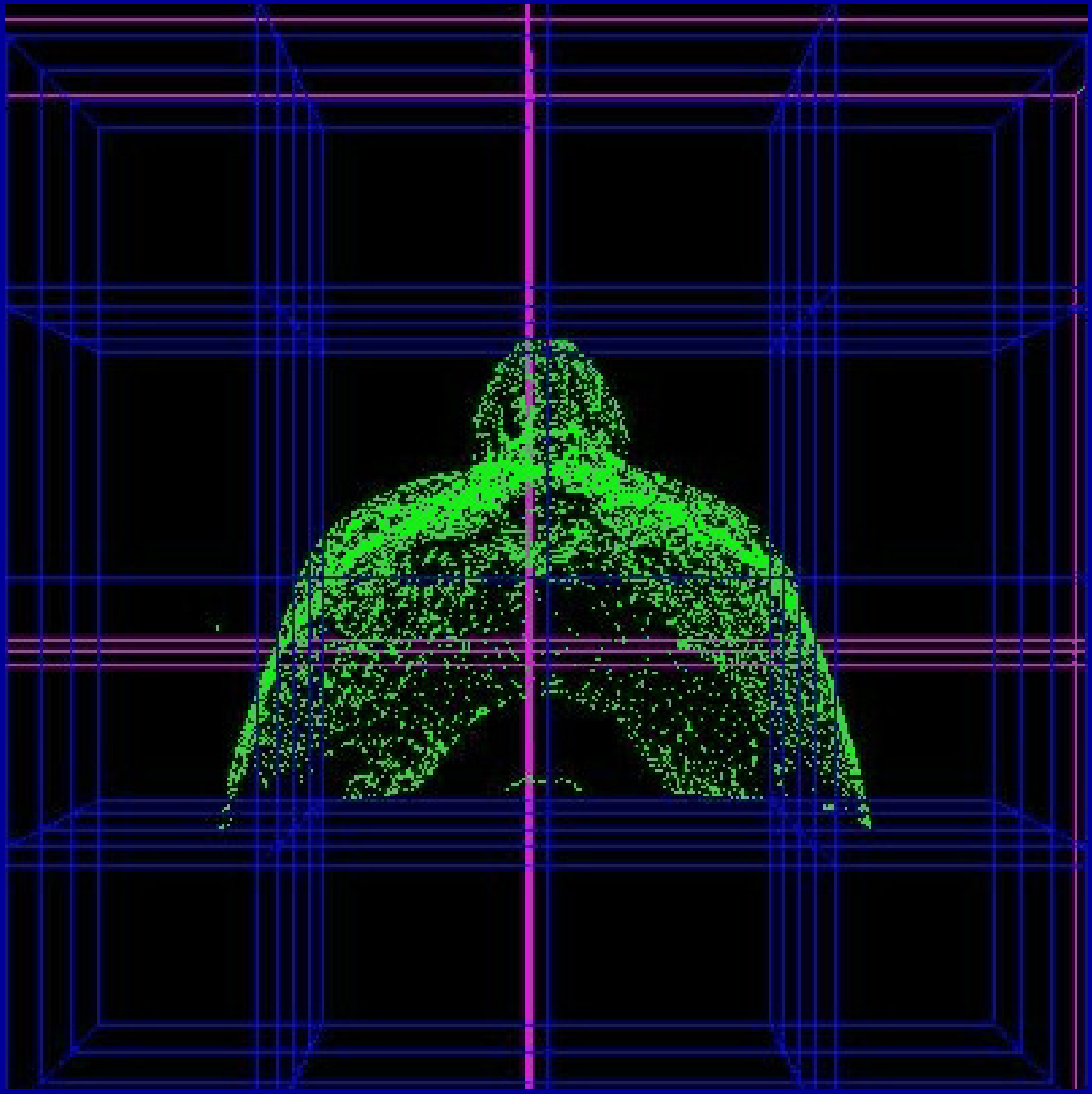


Displacement vectors on each cube vertex



- Minimization : distance + regularity criteria

Confromation of the generic model to patient morphology



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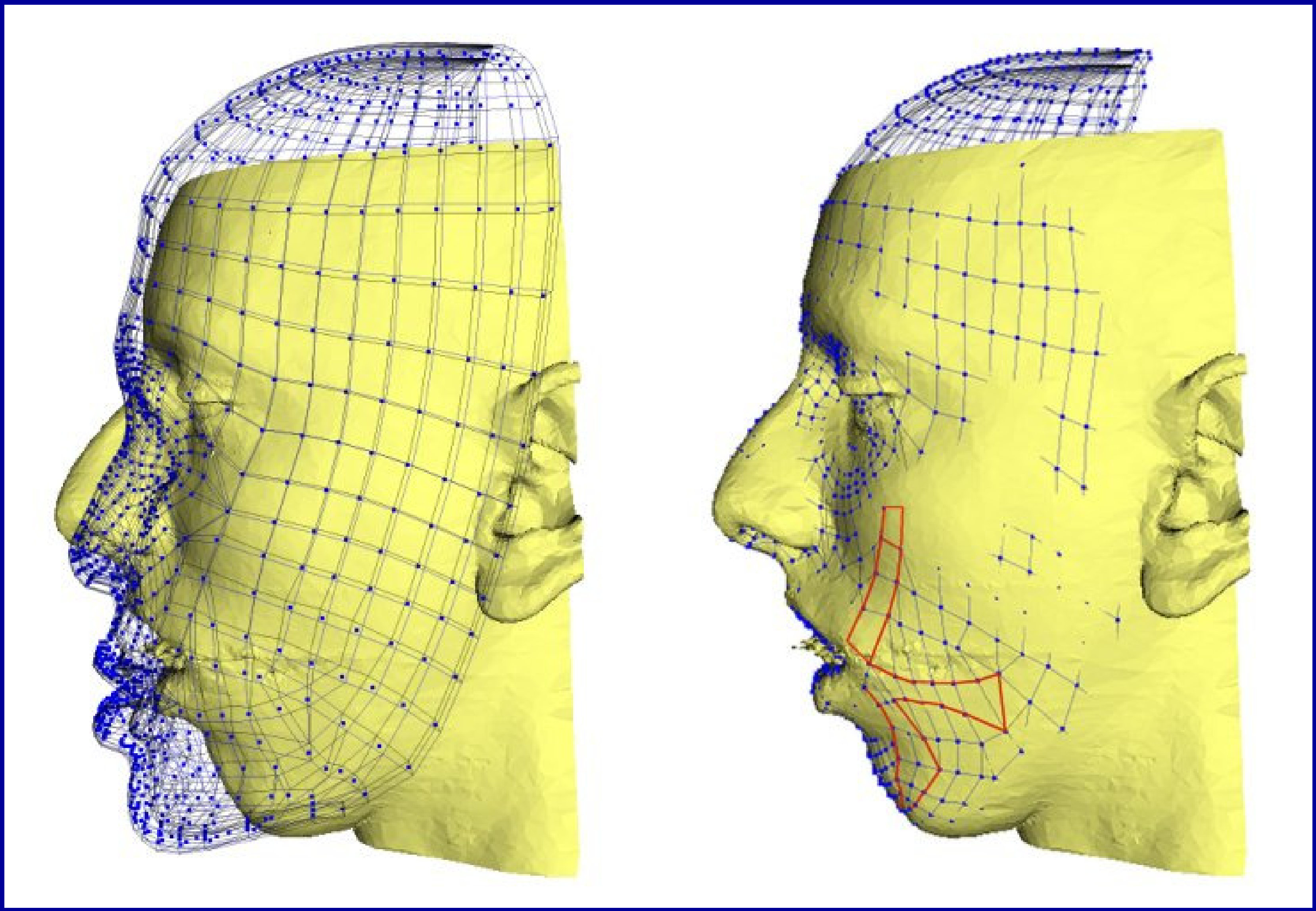

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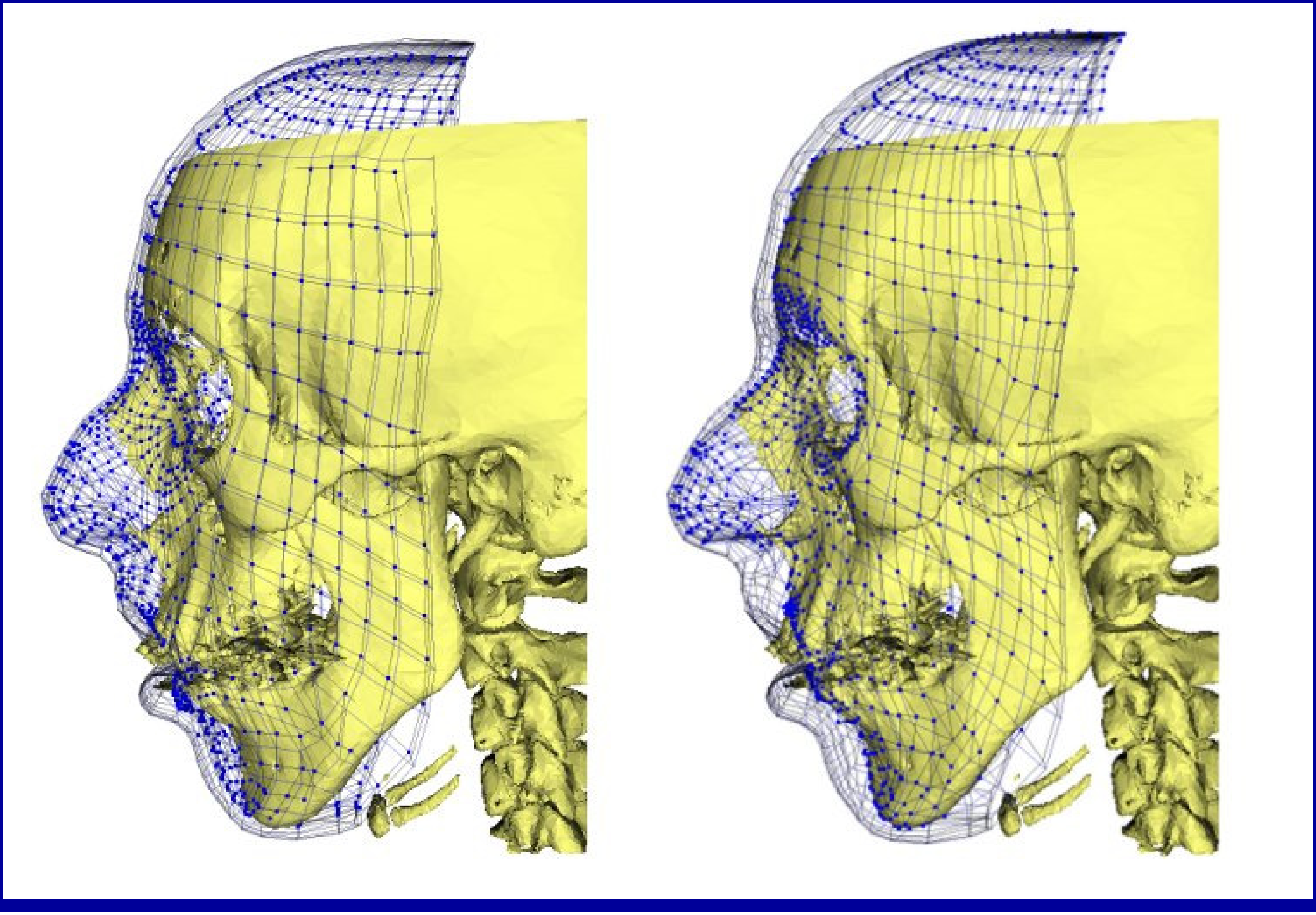
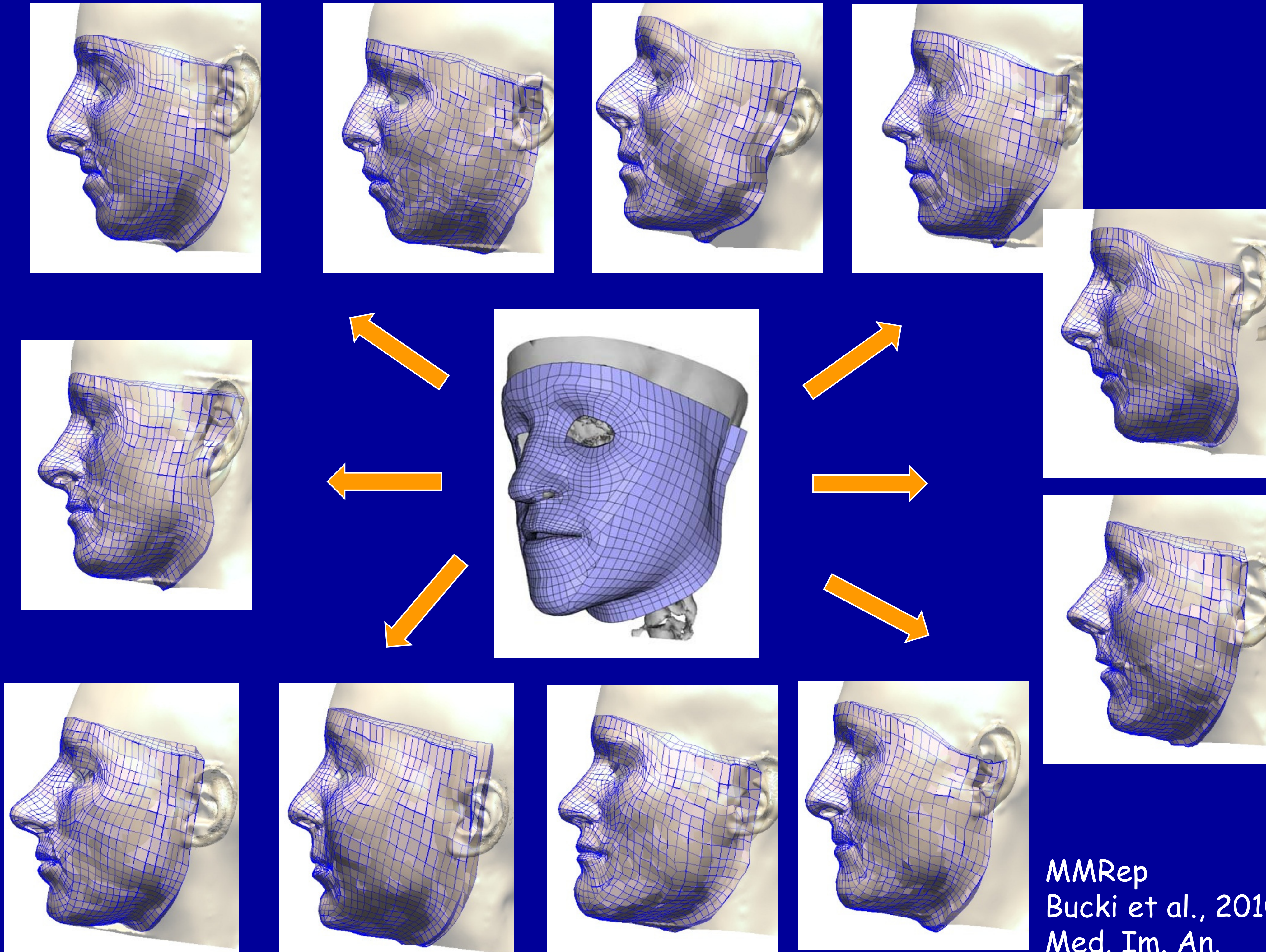


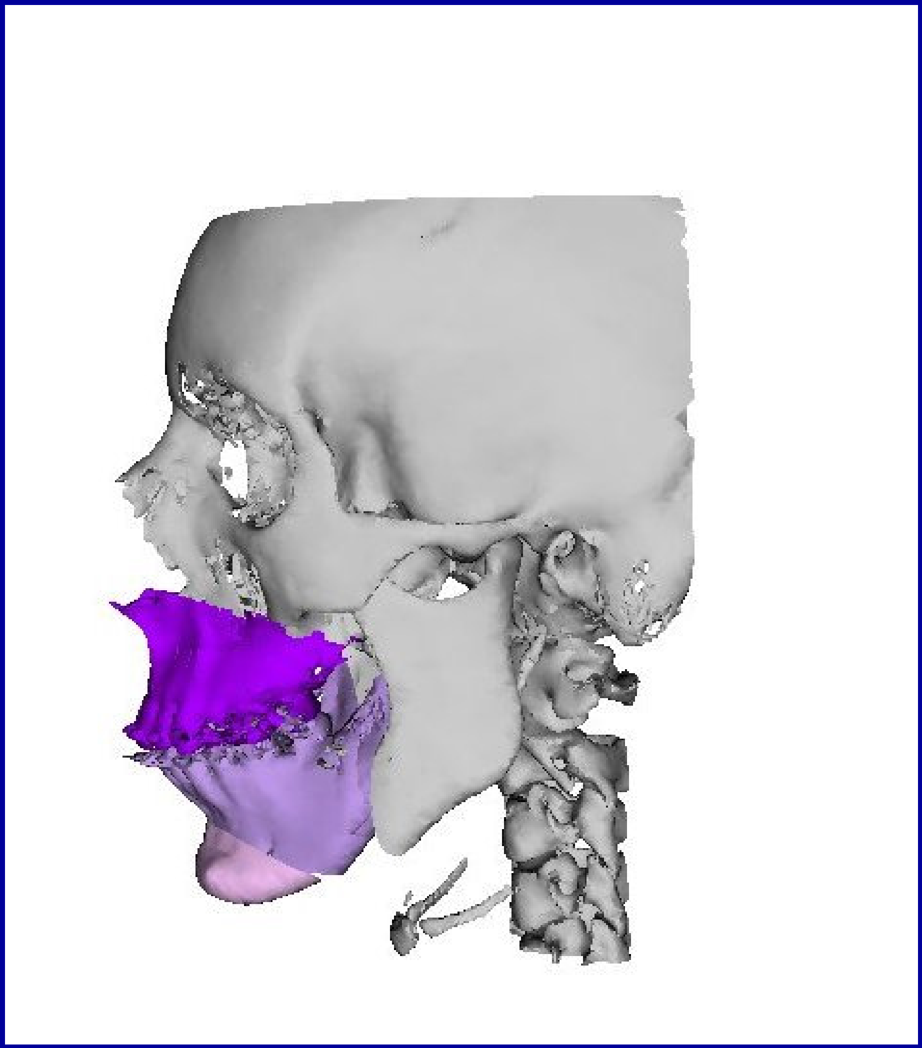
Computer Aided Medical Intervention

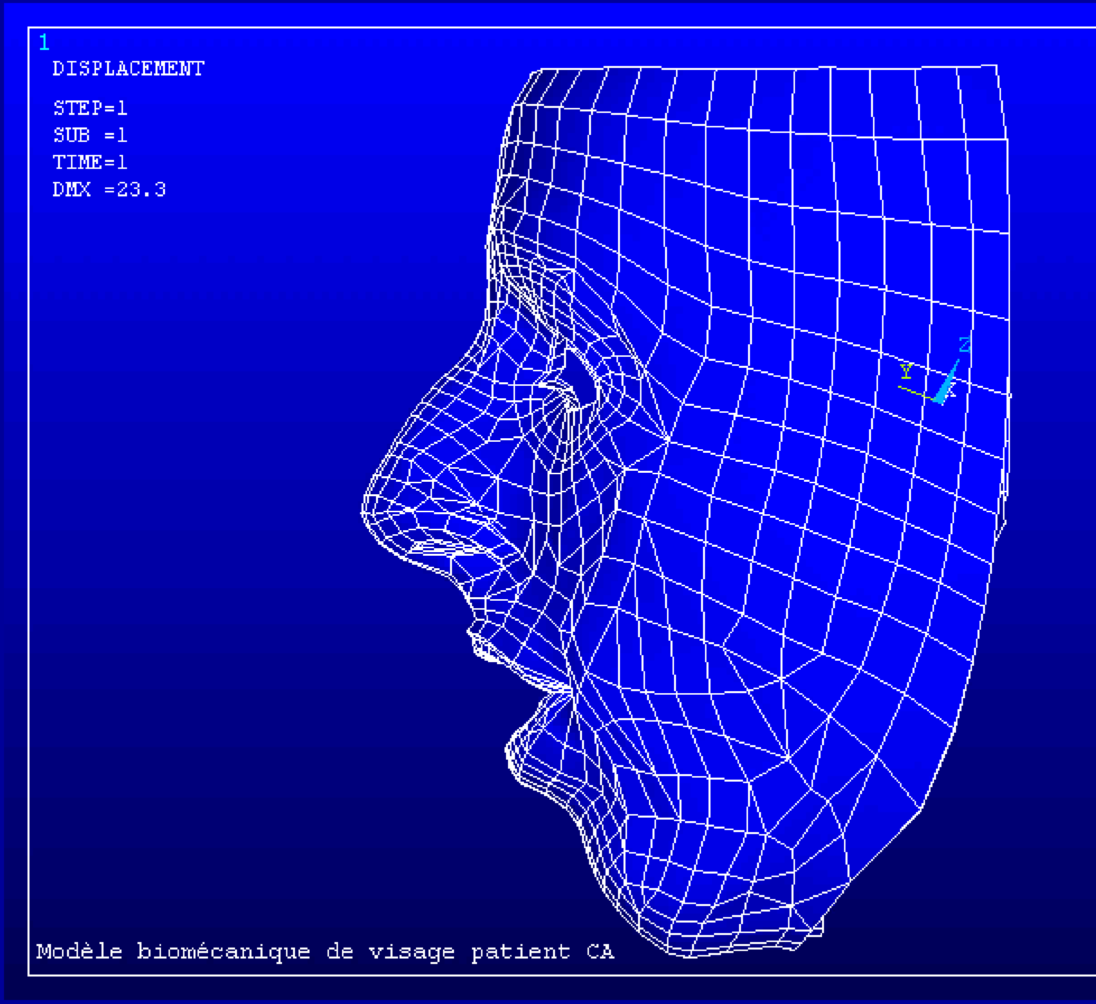
	Pre-operative computer Aided System
• A "fast" generation of the patient-specific biomechanical model of the organ	++
• The possibility to estimate the patient-specific constitutive behavior of the organ	++
• An almost real-time computation of the deformations simulated by the model	+



MMRep
Bucki et al., 2010
Med. Im. An.

Finite Element Simulations of the bone repositioning consequences





Chabanas, Luboz & Payan (2003)
Medical Image Analysis.

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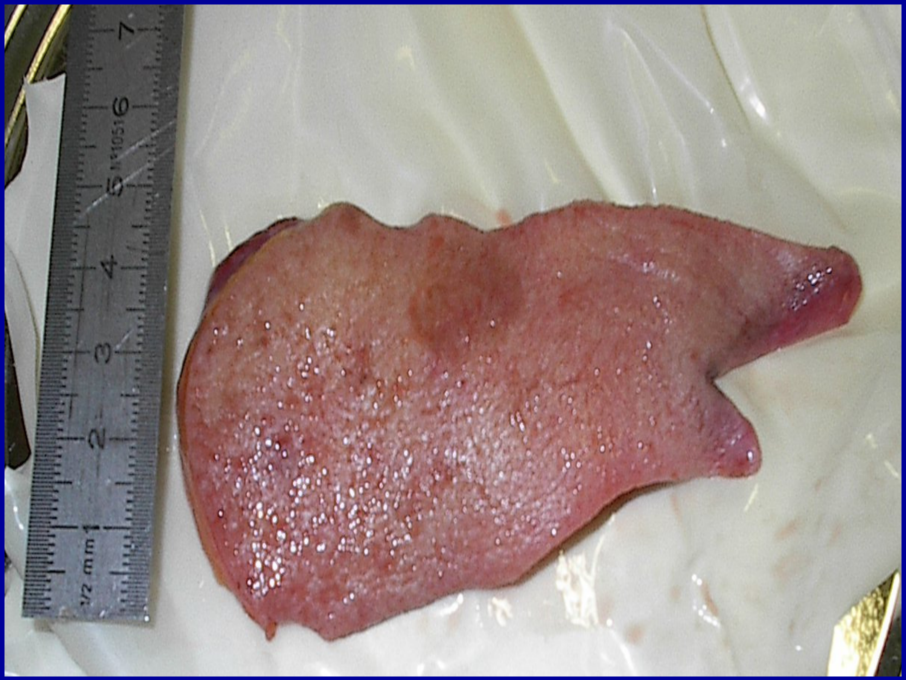
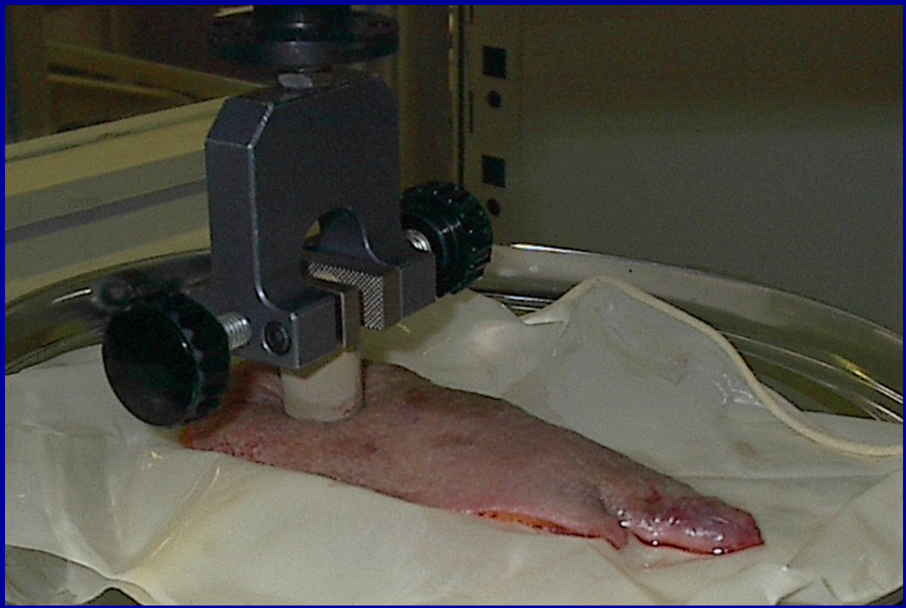
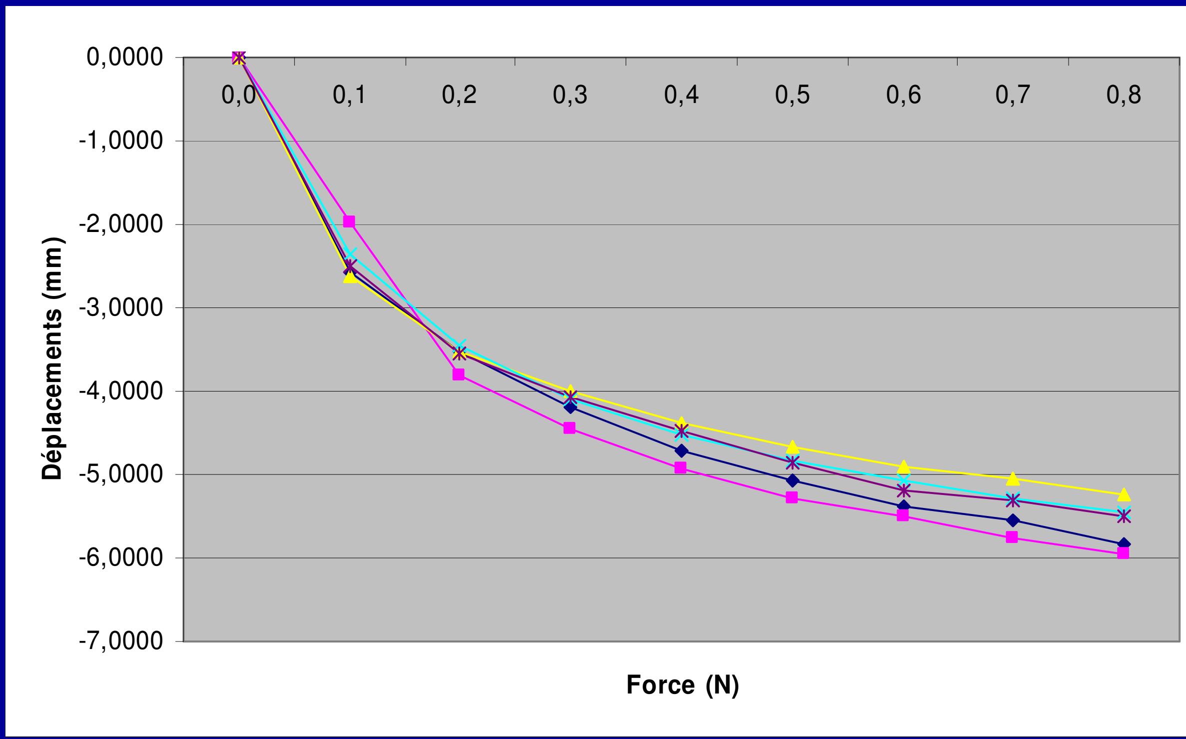
Trying to characterize the face rheology





In vitro
indentation experiment

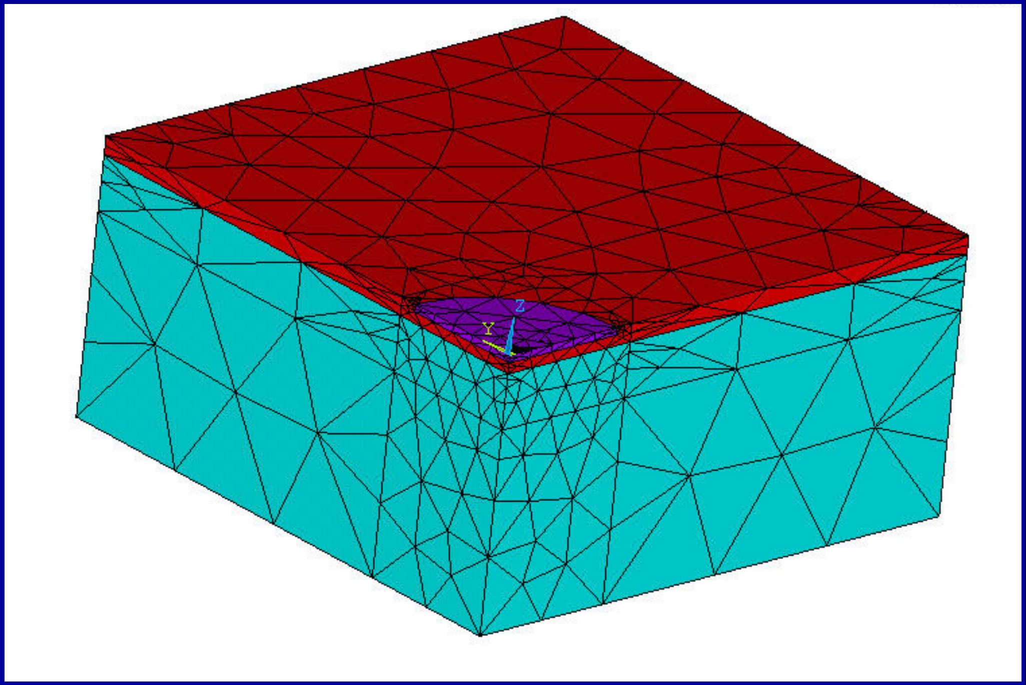


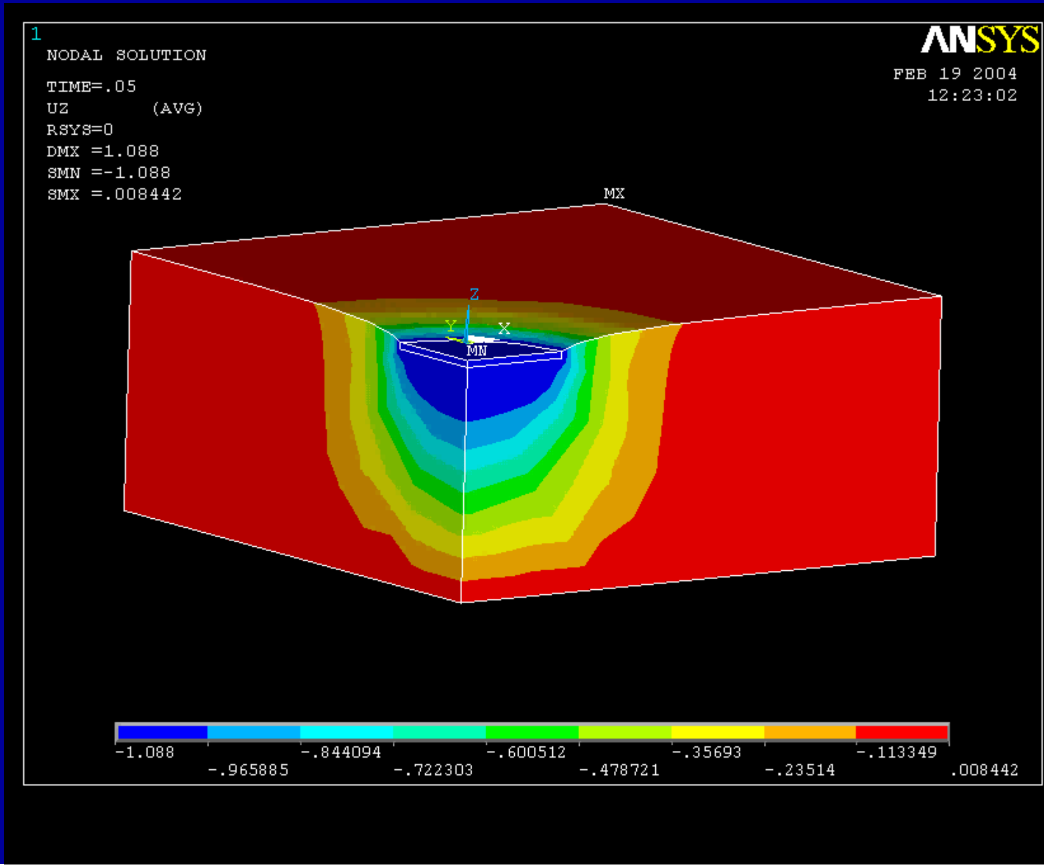
Trying to characterize the face rheology

Modeling assumptions: *Yeoh strain energy*

$$[\sigma] = \frac{\partial W}{\partial E}$$

$$W = a_{10}\,(I_1 - 3) + a_{20}\,(I_1 - 3)^2$$





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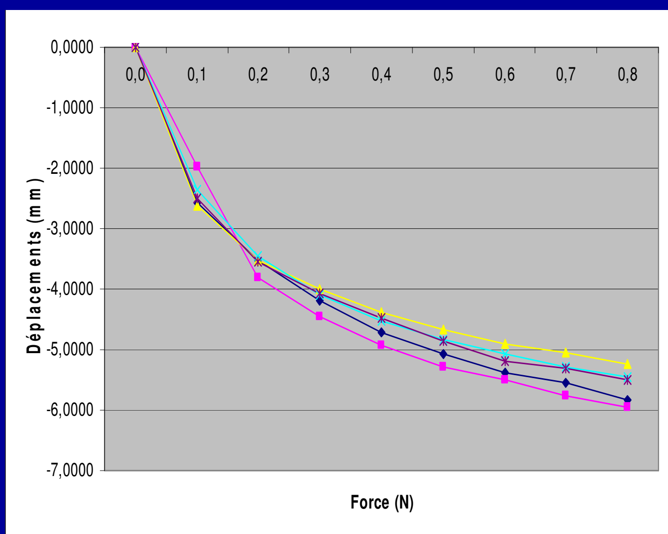
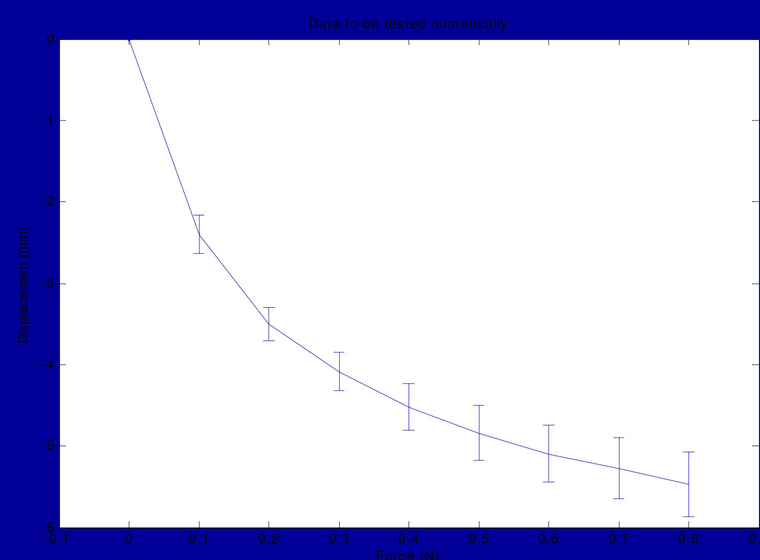


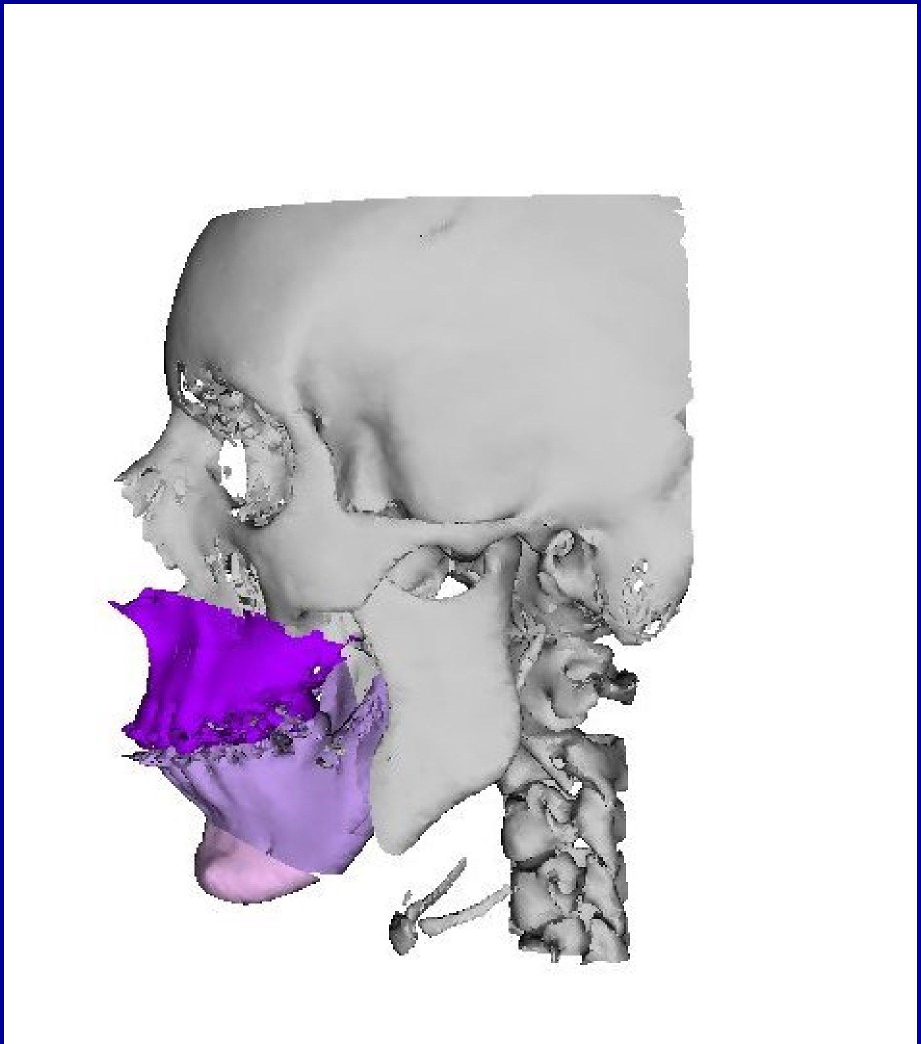
data

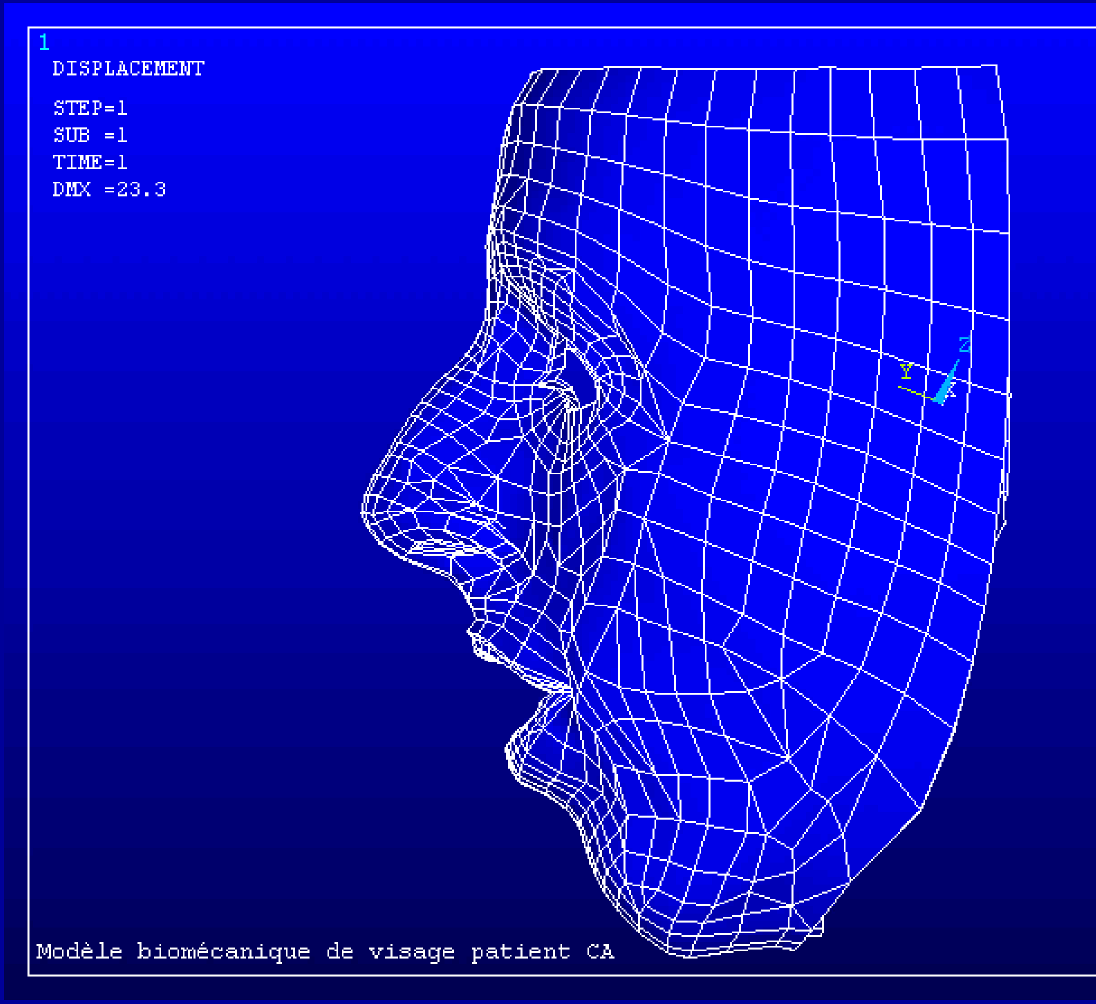


$$a_{10} = 190 Pa$$
$$a_{20} = 90 Pa$$

Gerard J.M., Ohayon J., Luboz V., Perrier P. & Payan Y. (2005), *Medical Engineering & Physics*

Finite Element Simulations of the bone repositioning consequences





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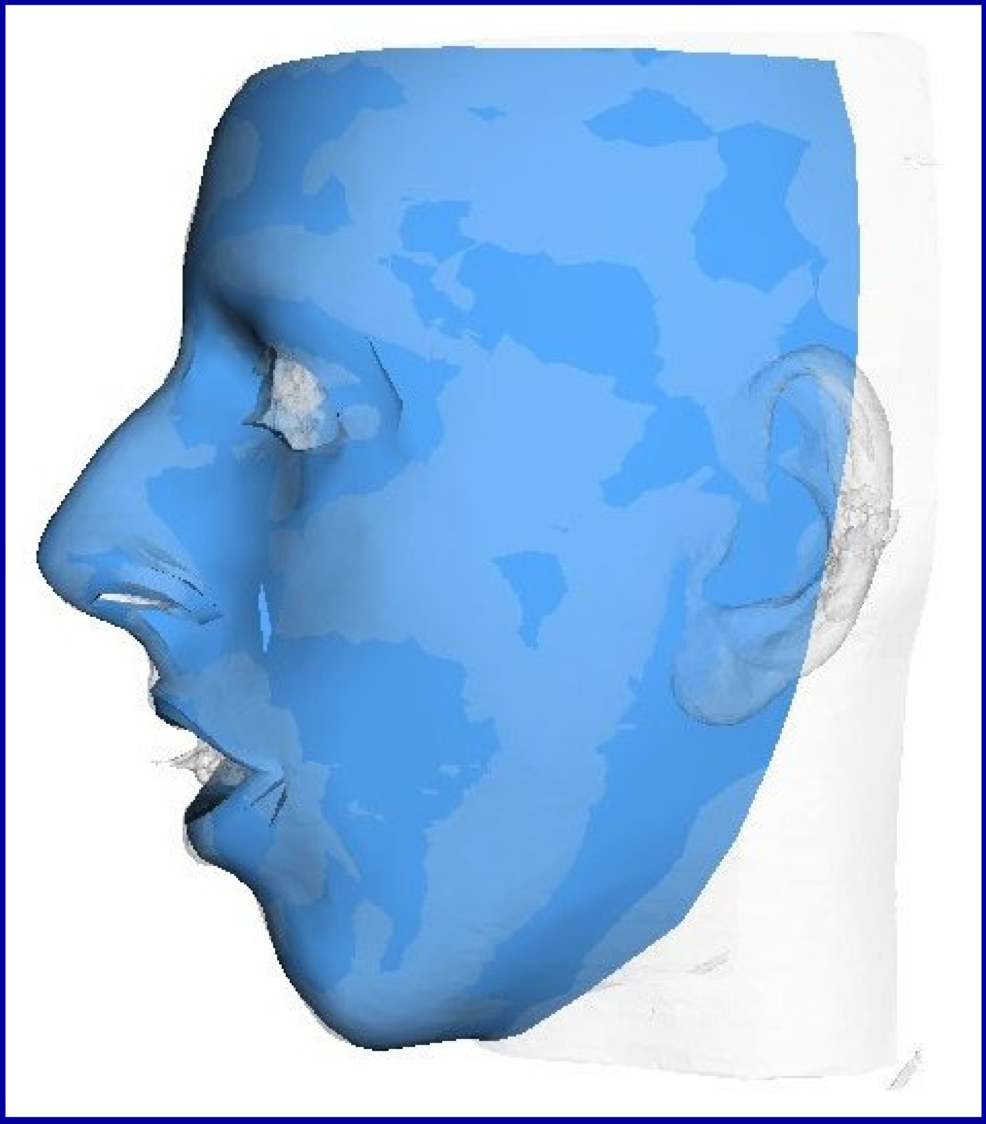

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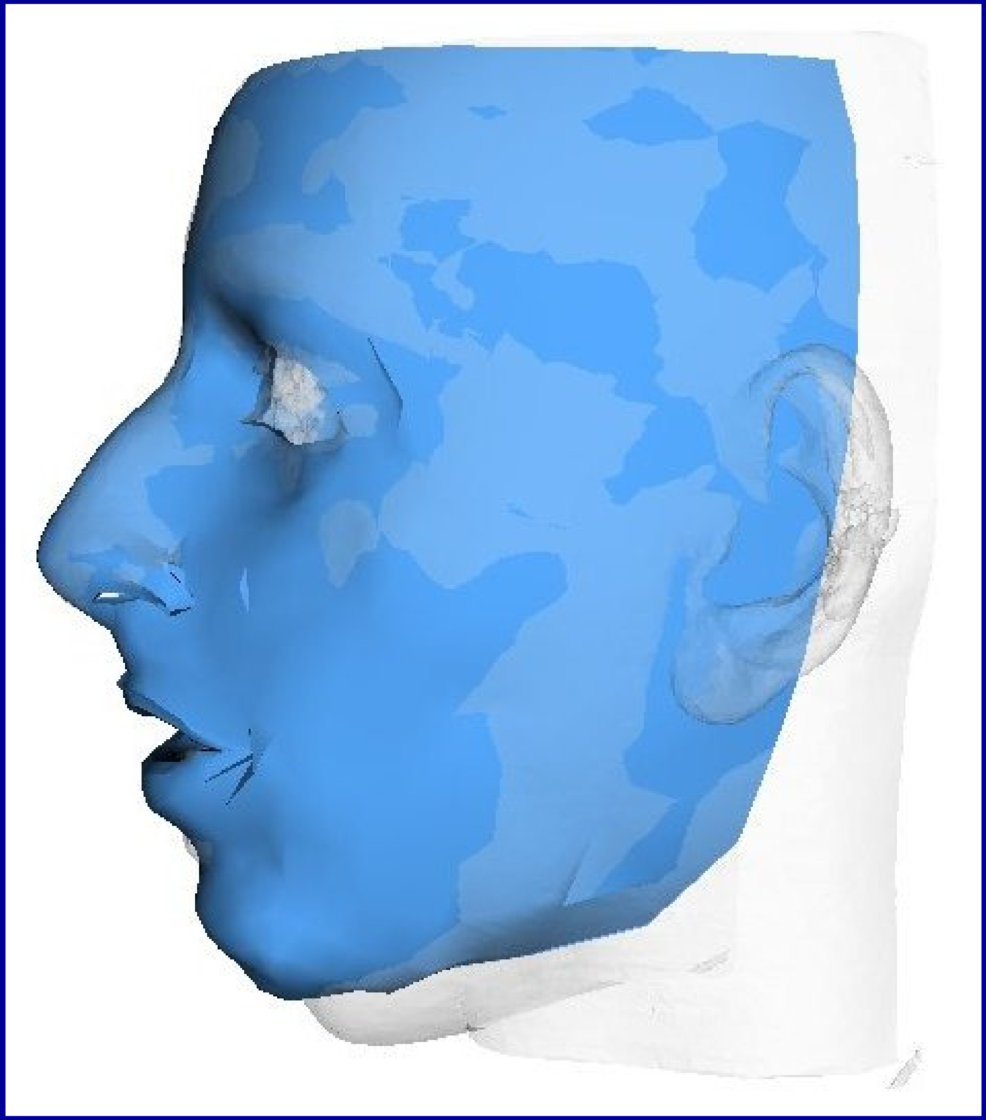
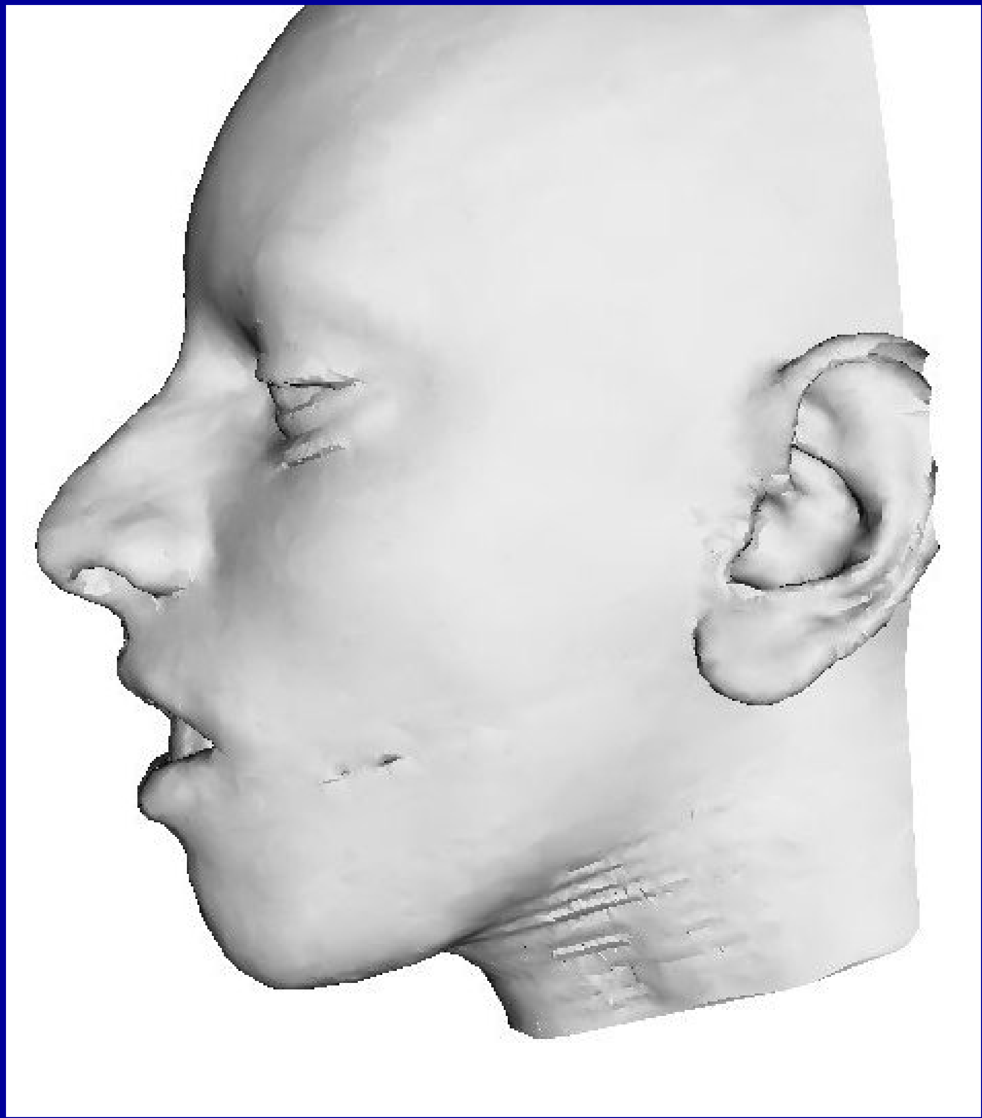


Simulations validations: comparisons with post-operative CT data



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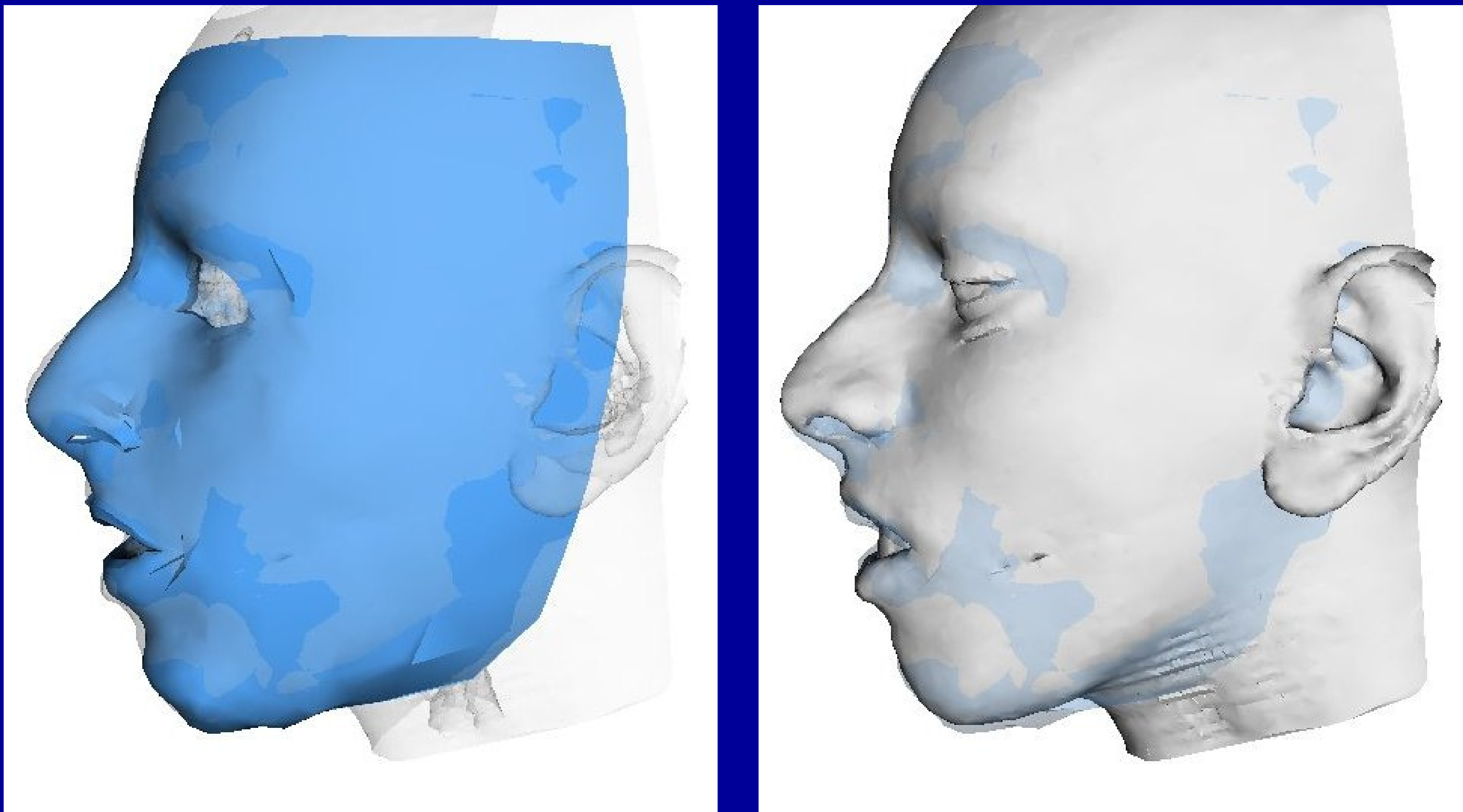
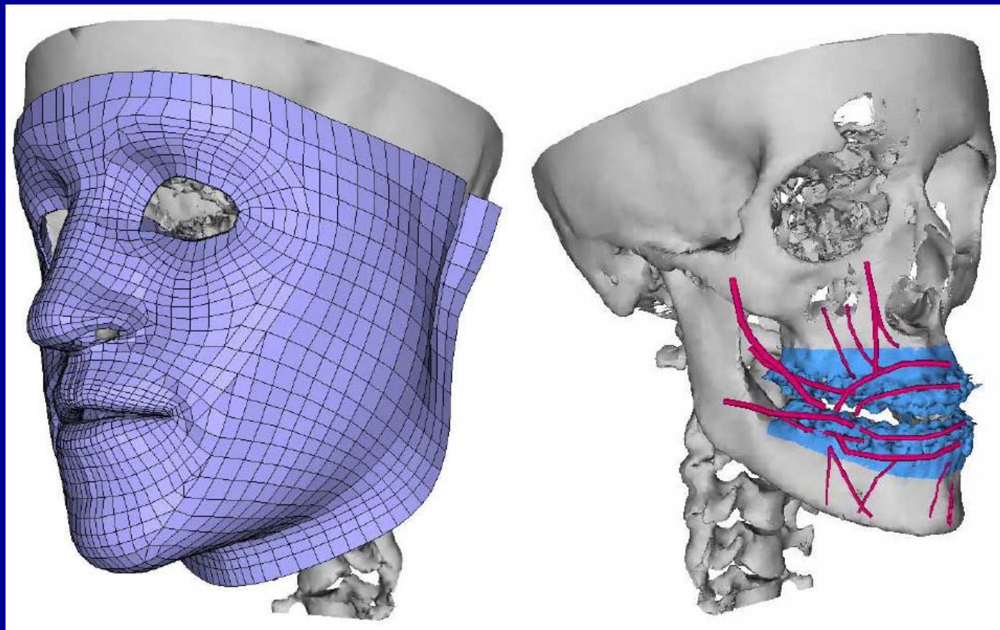
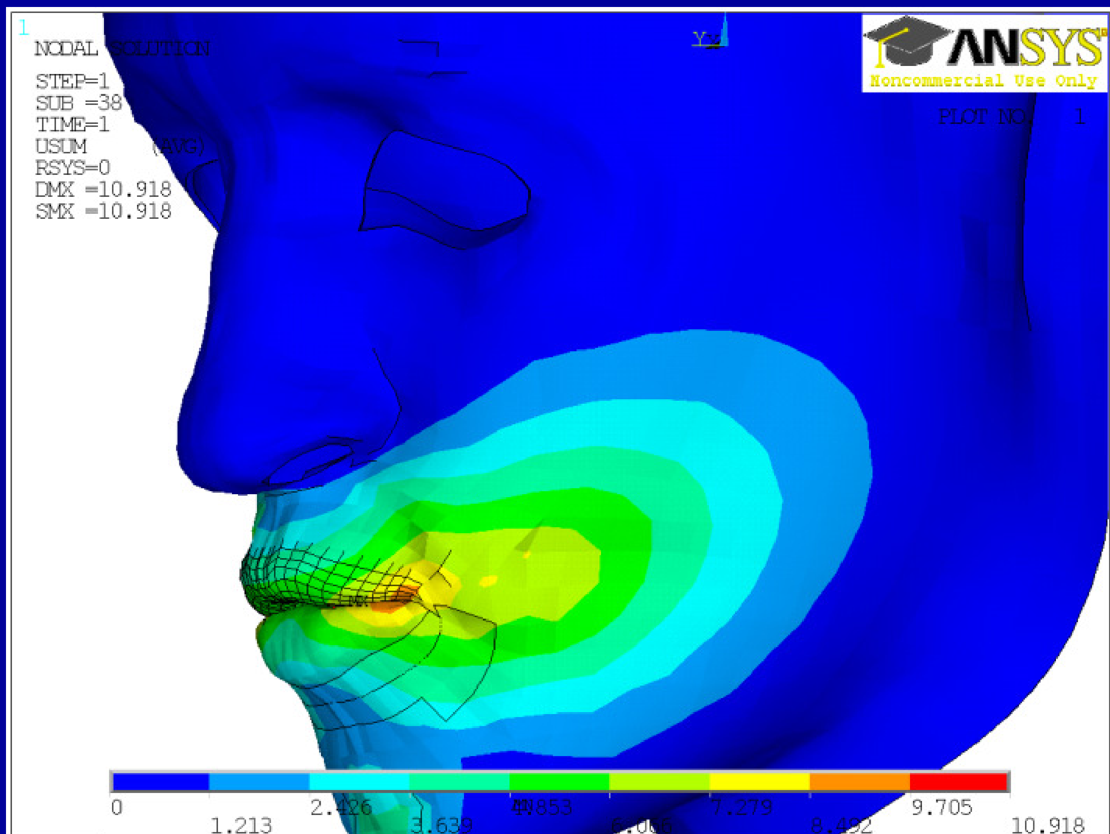




Face modeling for the study of speech production



Nazari *et al.* (2010)

Computer Aided Medical Intervention

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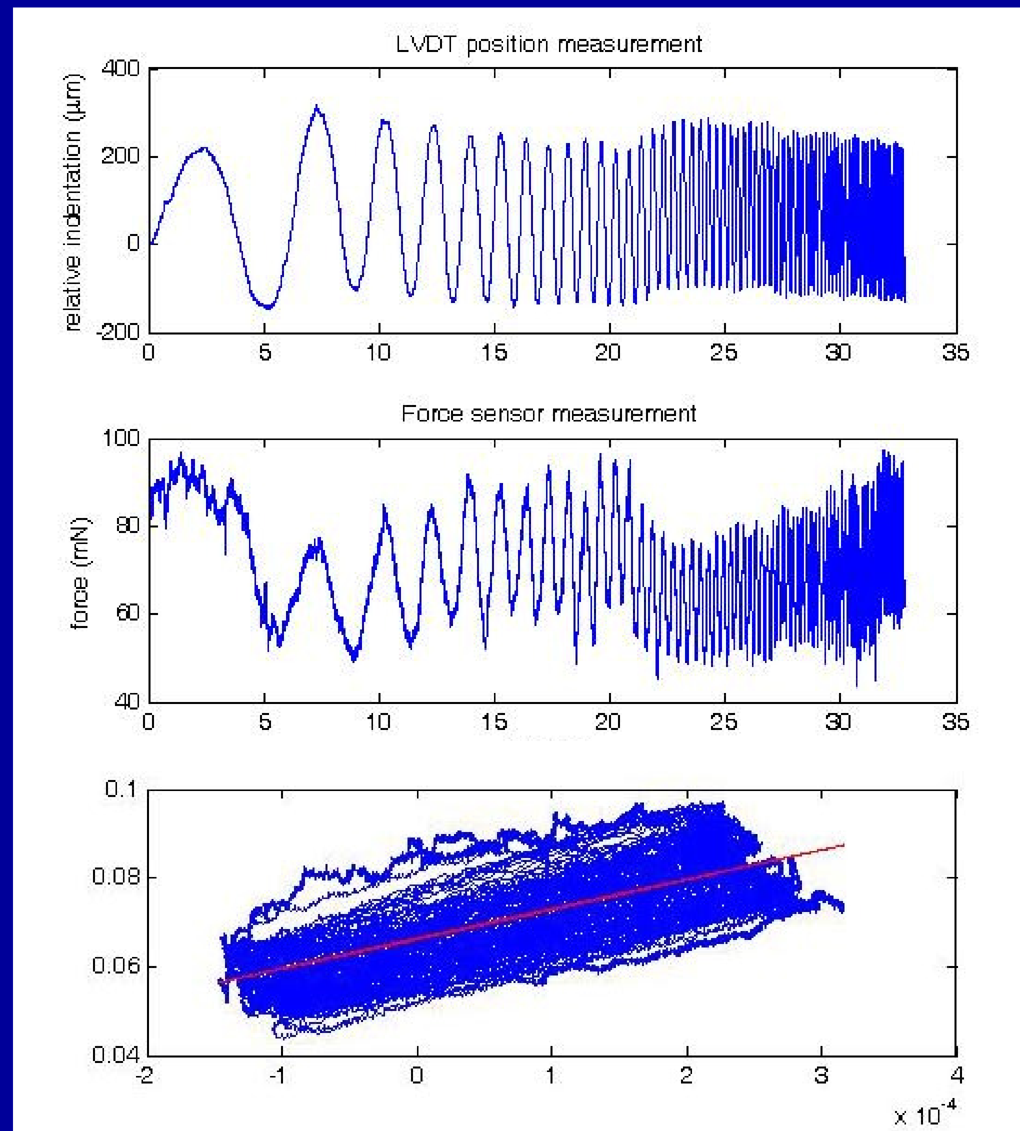
Trying to characterize the face rheology

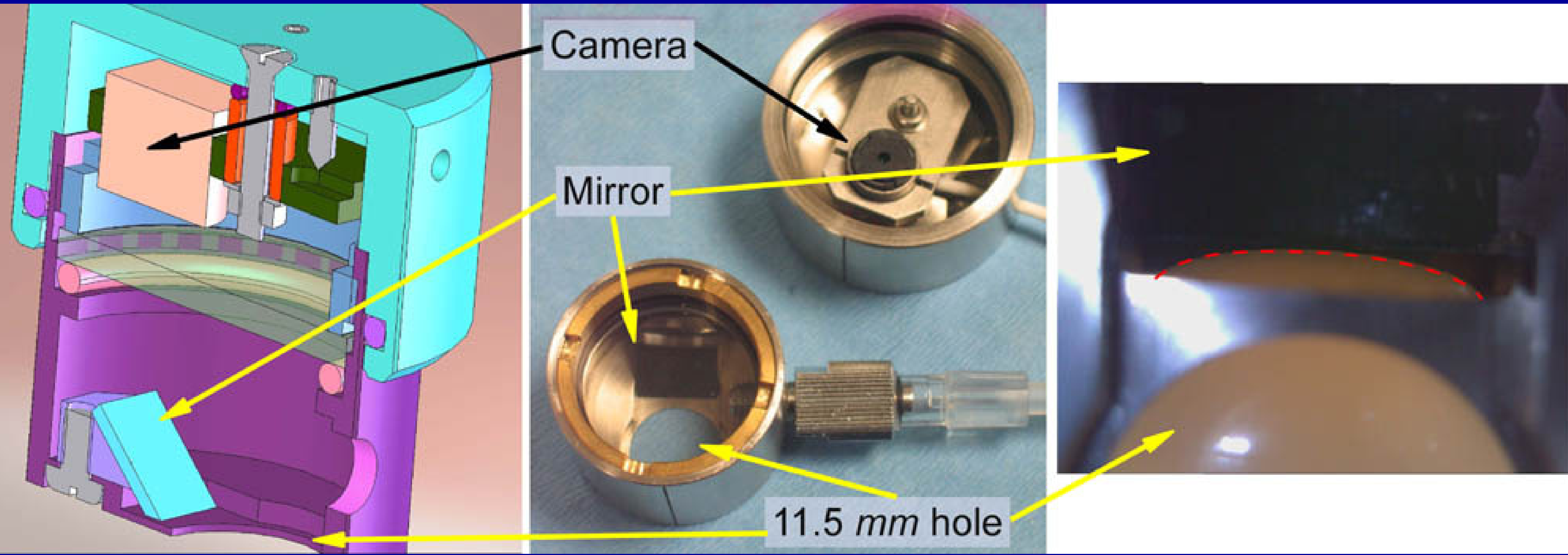
In vivo

indentation experiment



TeMPeST: Ottenmeyer, 2002

Light Aspiration Device: LASTIC



Use of micro-camera ST Microelectronics 2MPixels (1600x1200), < 1 cm^3

Schiavone et al., 2010

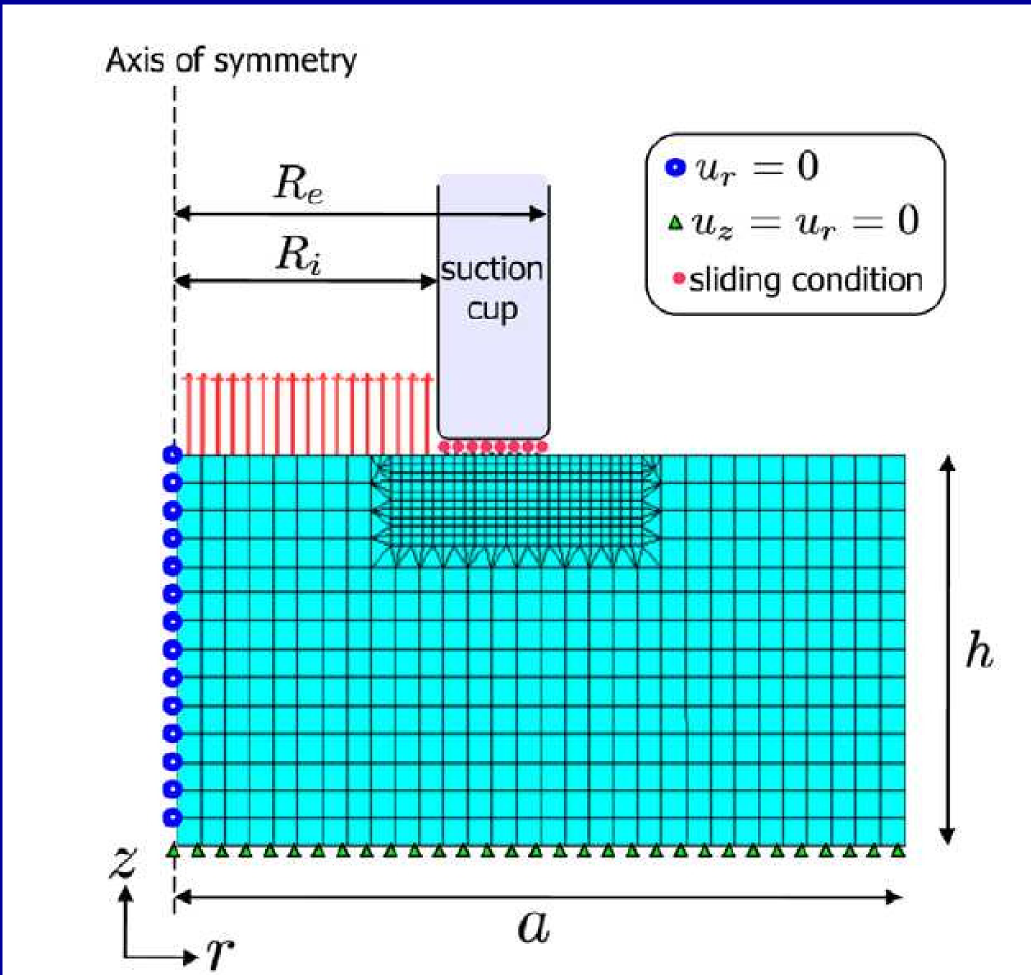
LASTIC

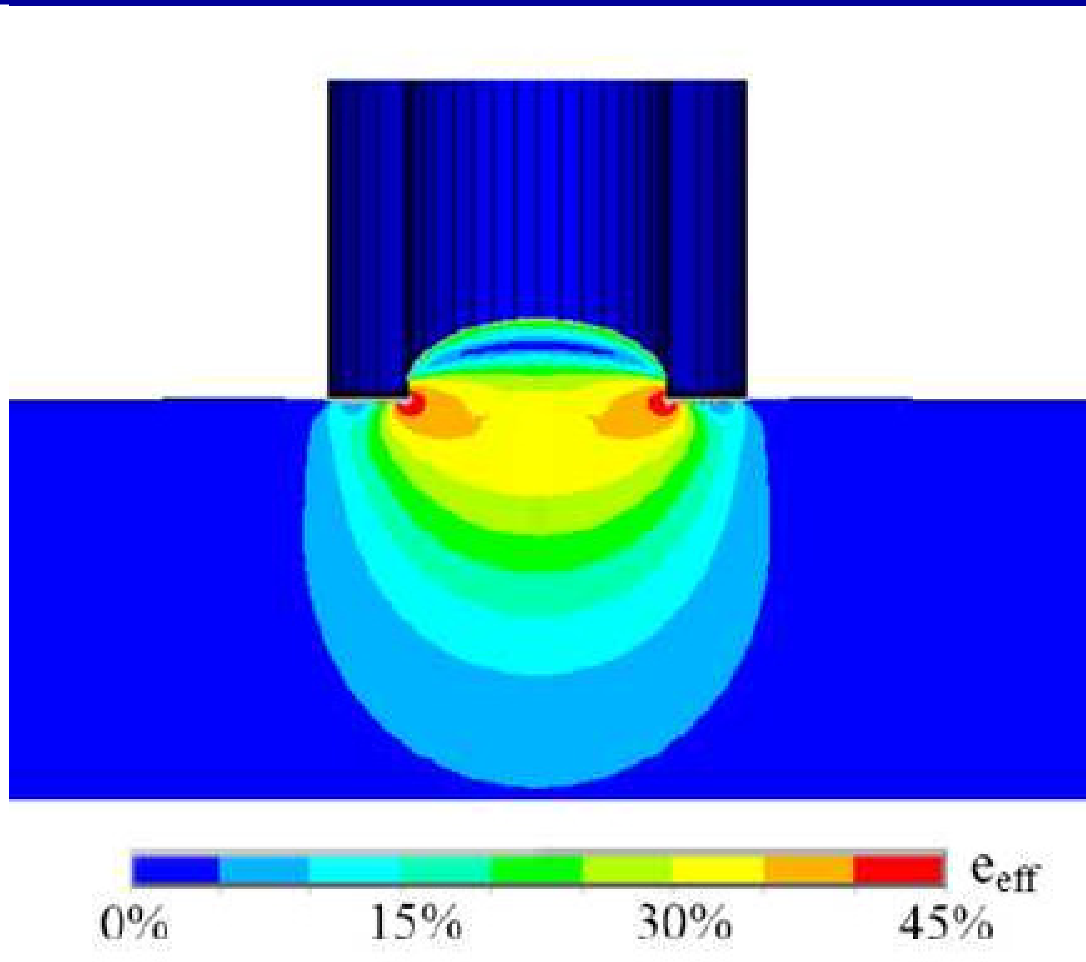
a Light Aspiration device for in vivo
Soft TIssue Characterization

TIMC-IMAG Laboratory
France

Light Aspiration Device: estimation of the constitutive law

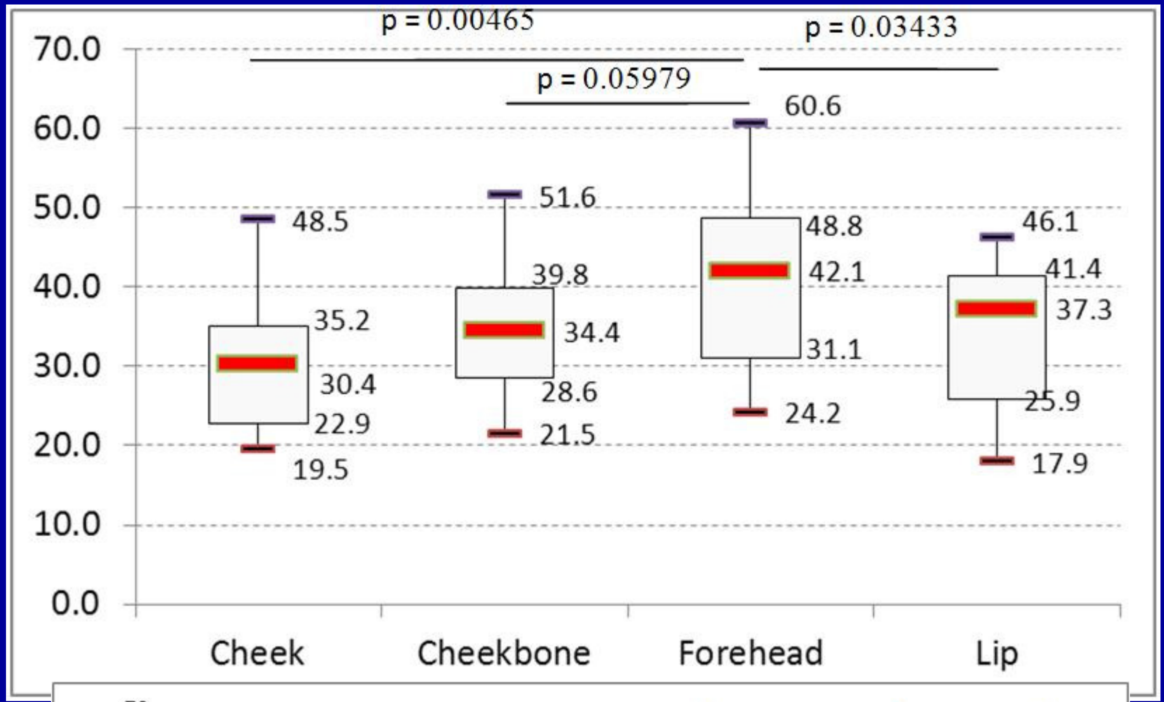
- Finite Element Analysis + Optimisation (Schiavone et al., 2010)

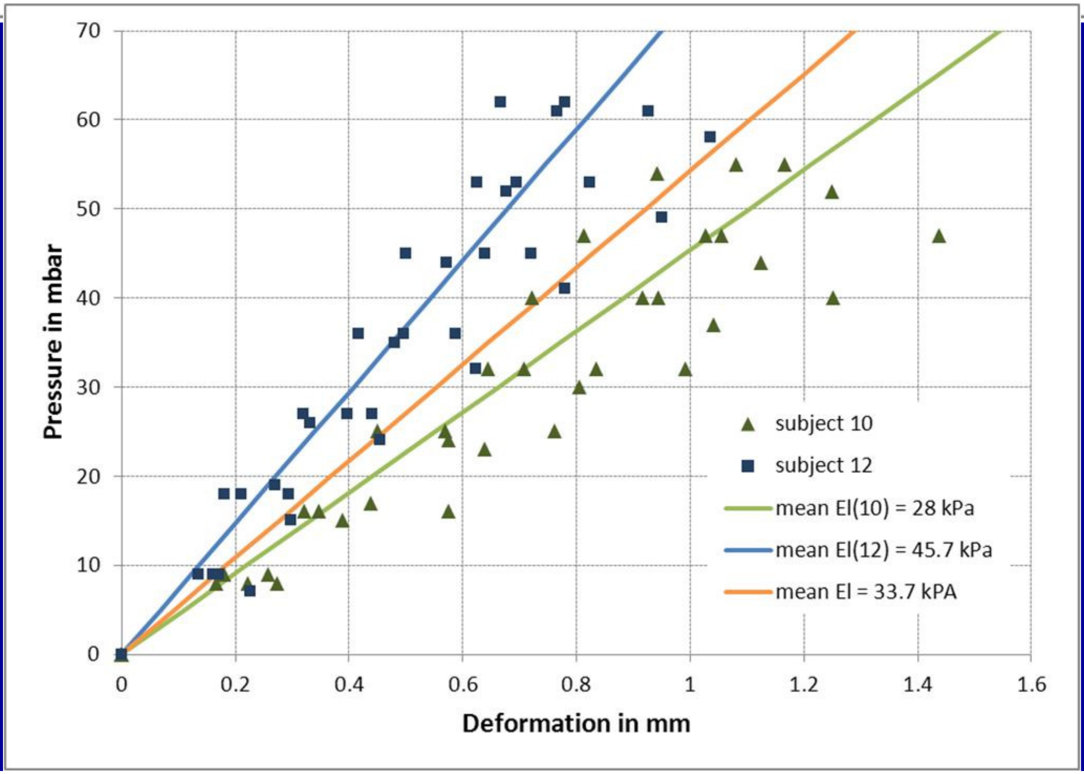




Estimation of the constitutive law

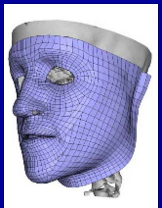
Estimation of the constitutive law



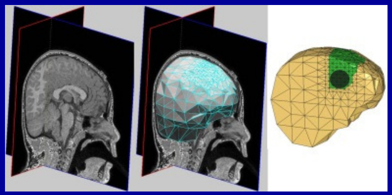


Outline

- Introduction
- Pre-operative Computer Aided Device: maxillo-facial surgery



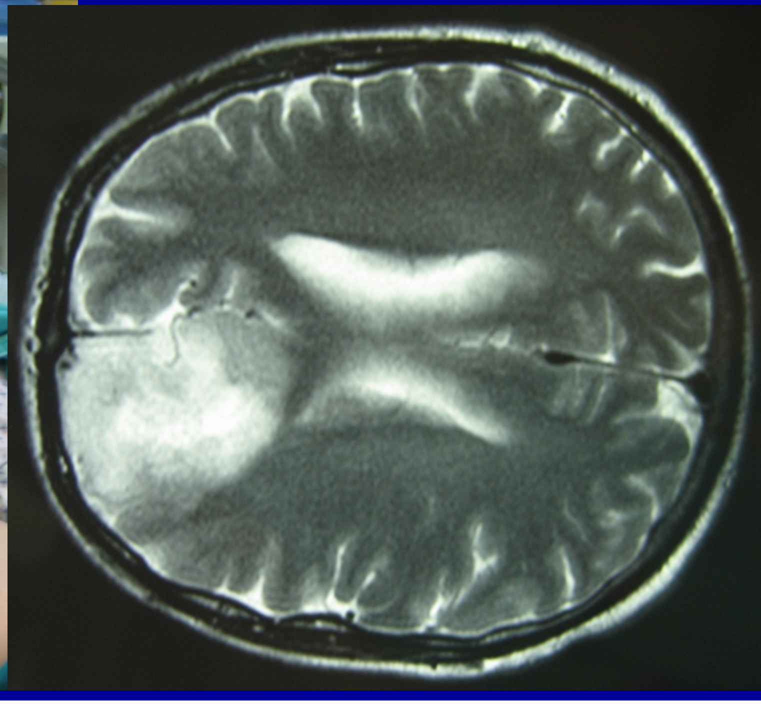
- Intra-operative Computer Aided Device: *Neurosurgery*



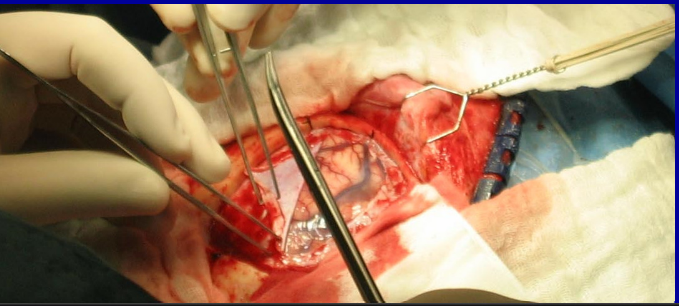
- Discussion

Intra-operative Computer Aided Device: *Neurosurgery*

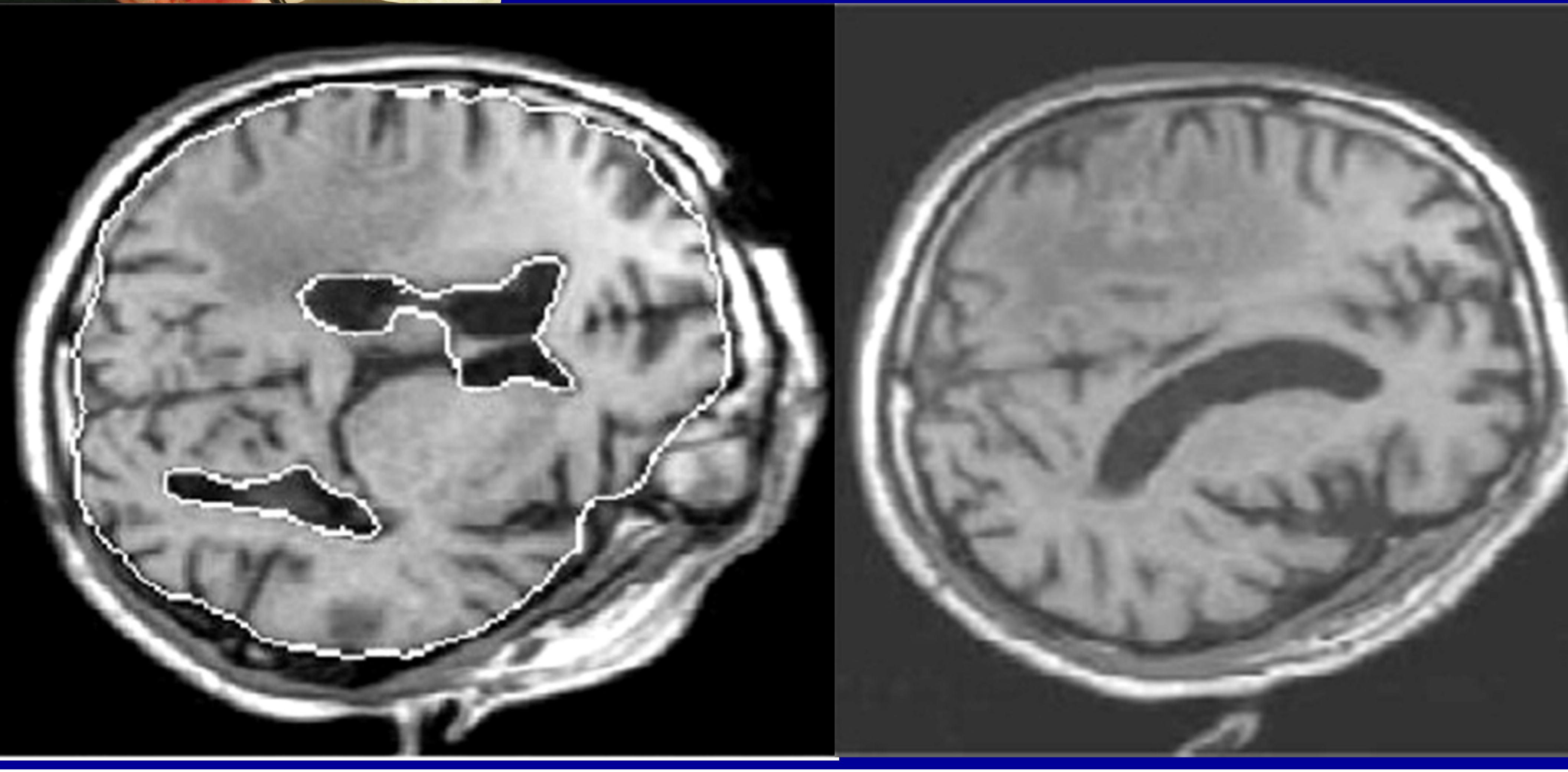
The “Brain-Shift” problem



Intra-operative Computer Aided Device: *Neurosurgery*



The "Brain-Shift" problem



The "Brain-Shift" problem

Two solutions to solve this problem:

1. The « expensive » solution: intraoperative MRI

Brain Suite, BrainLab™

The "Brain-Shift" problem

Two solutions to solve this problem:

1. The « expensive » solution: intraoperative MRI

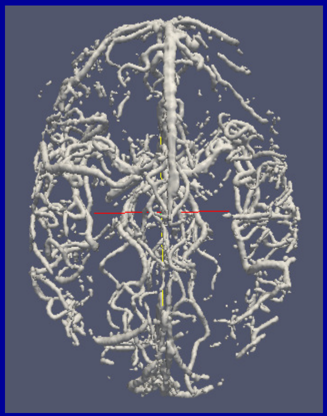
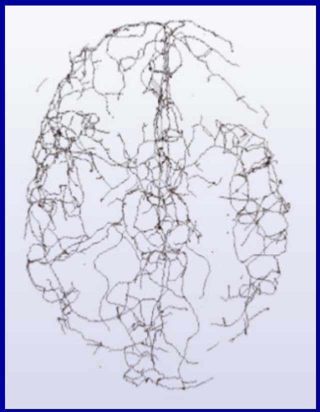
2. A « low cost » solution:

   - tracking the intraoperative displacements of the vascular tree thanks to 2.5 localized Doppler US images

   - computing a sparse 3D elastic transform that is going to match the actual vascular tree configuration with the preoperative one, measured on an angiographic MR exam

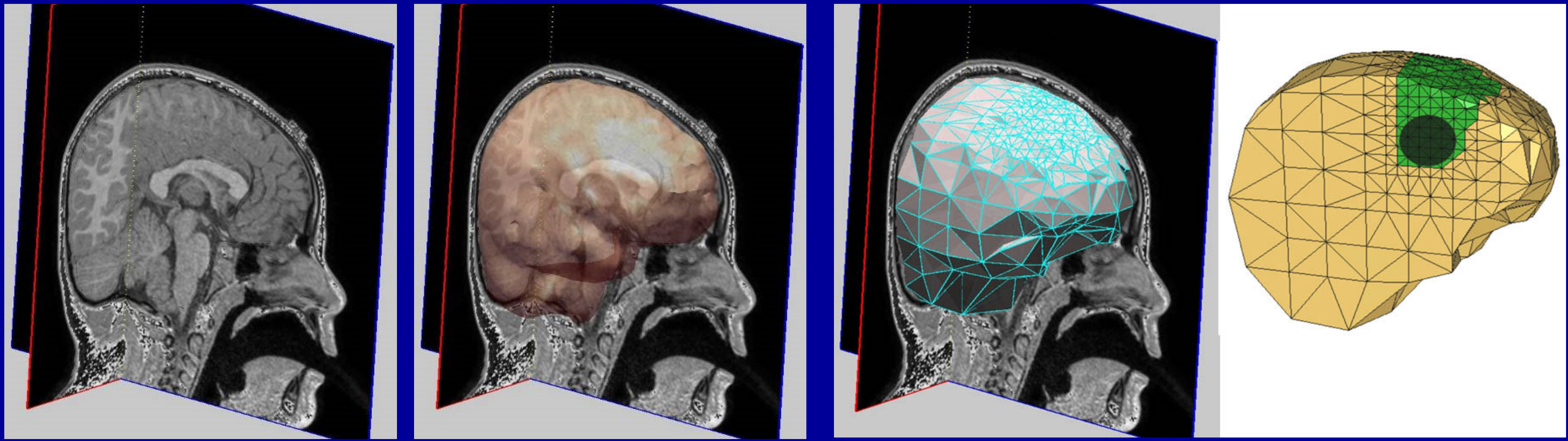
   - applying this 3D transform as boundary conditions to a real-time 3D biomechanical model of the patient brain.

Intra-operative Computer Aided Device: *Neurosurgery*

Before surgery

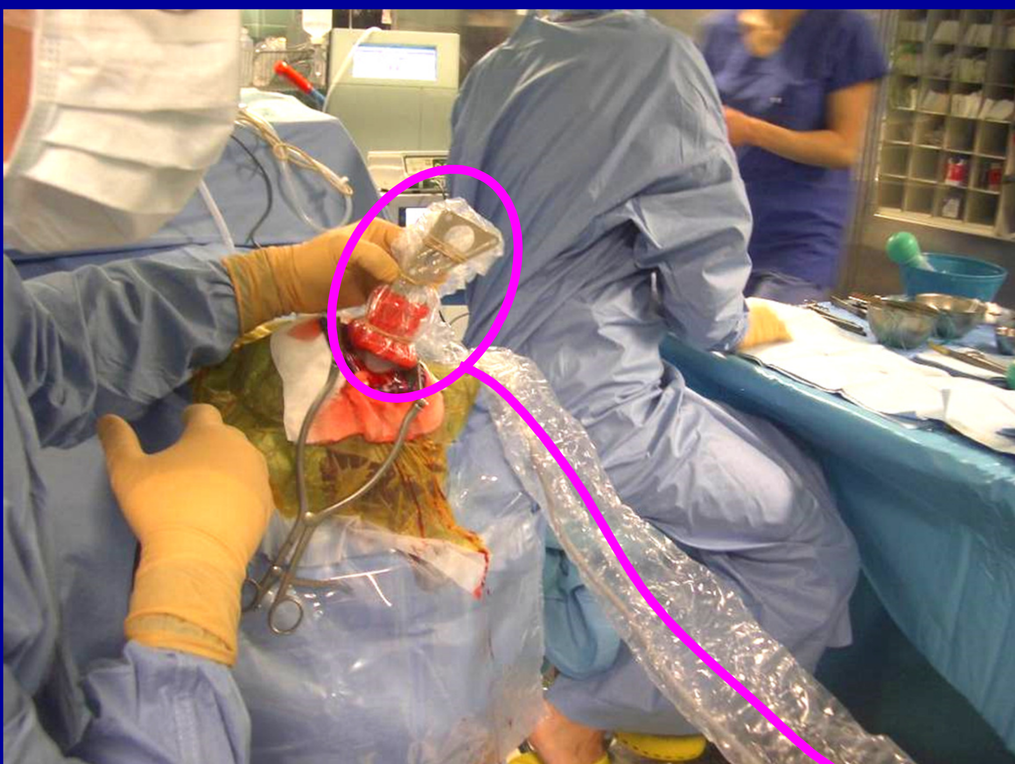
Angio-MRI

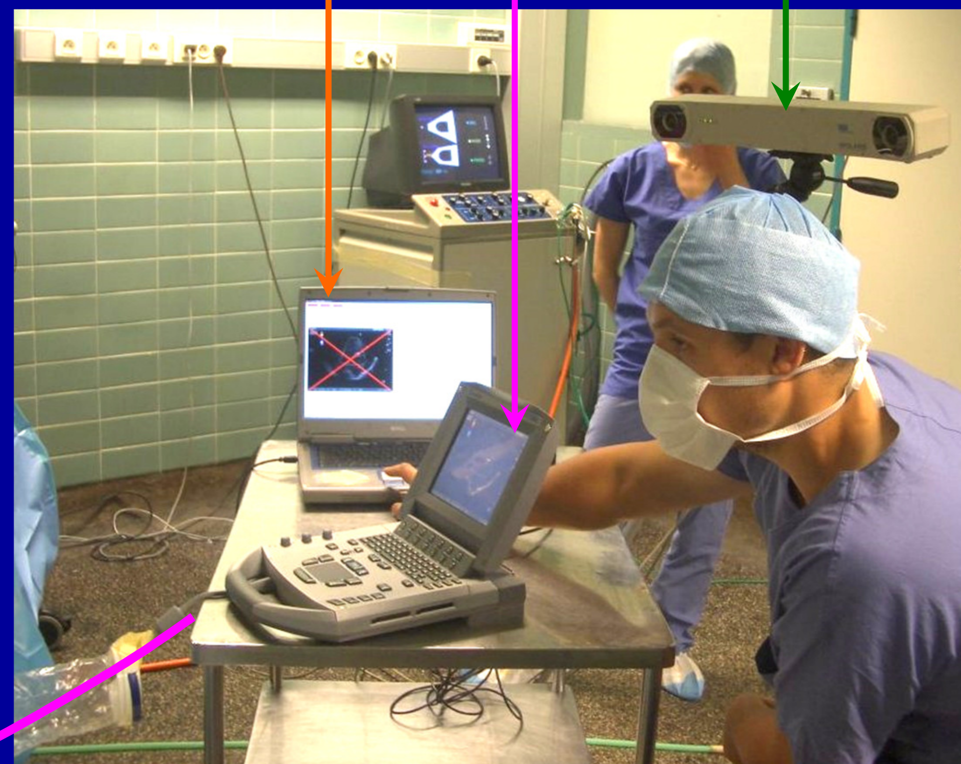


Patient-specific Finite Element model

Intra-operative Computer Aided Device: *Neurosurgery*

During surgery

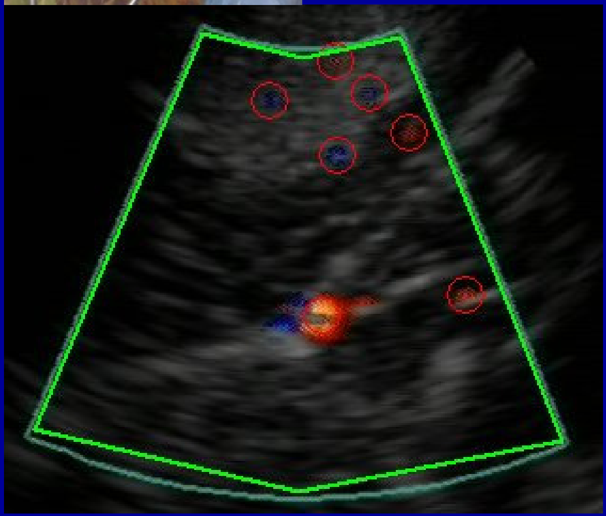


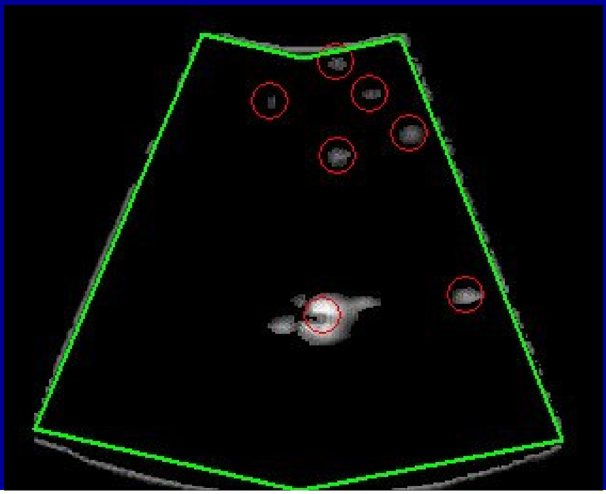


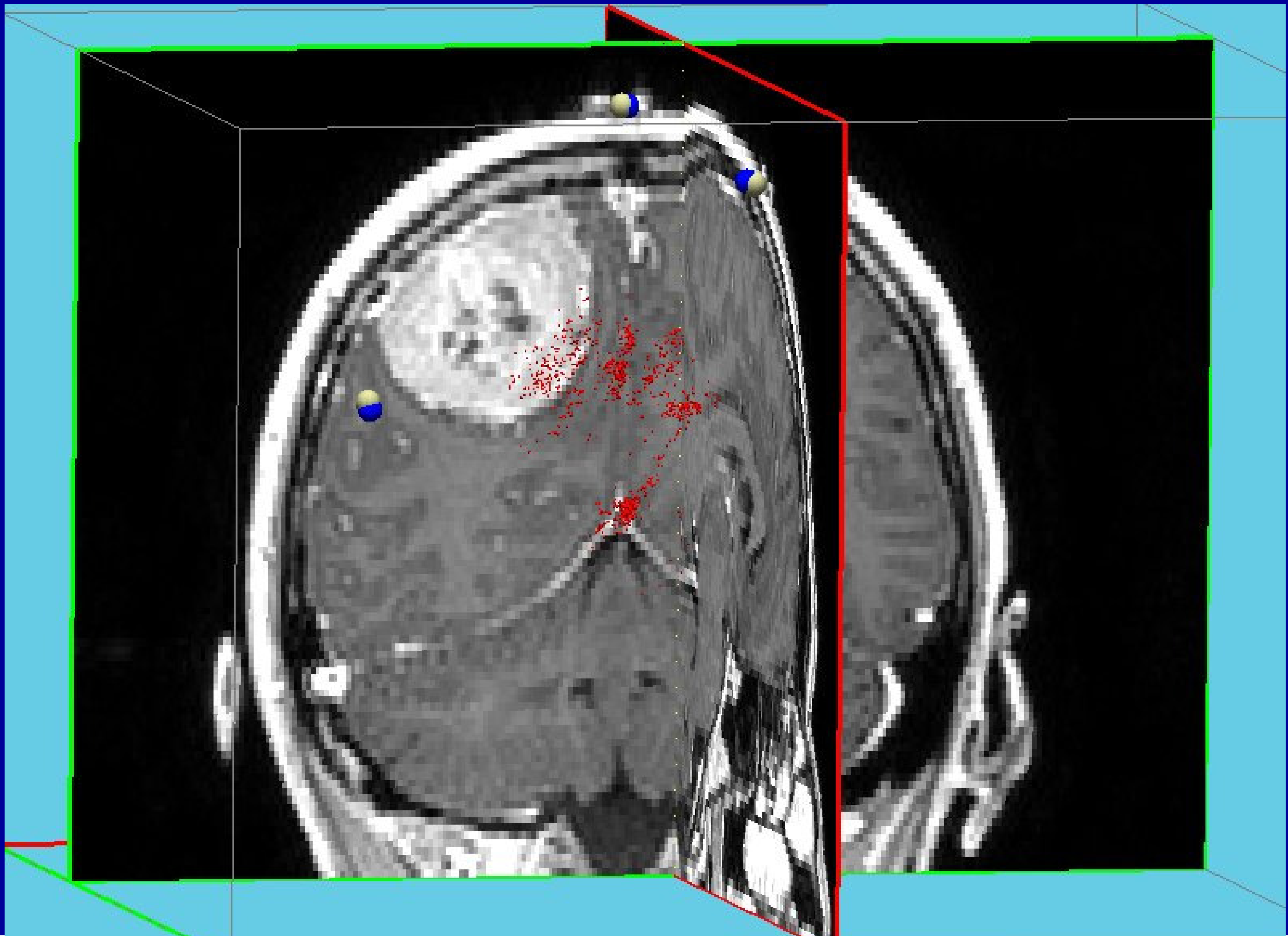
Intra-operative 2D Doppler US localized in 3D

Intra-operative Computer Aided Device: *Neurosurgery*

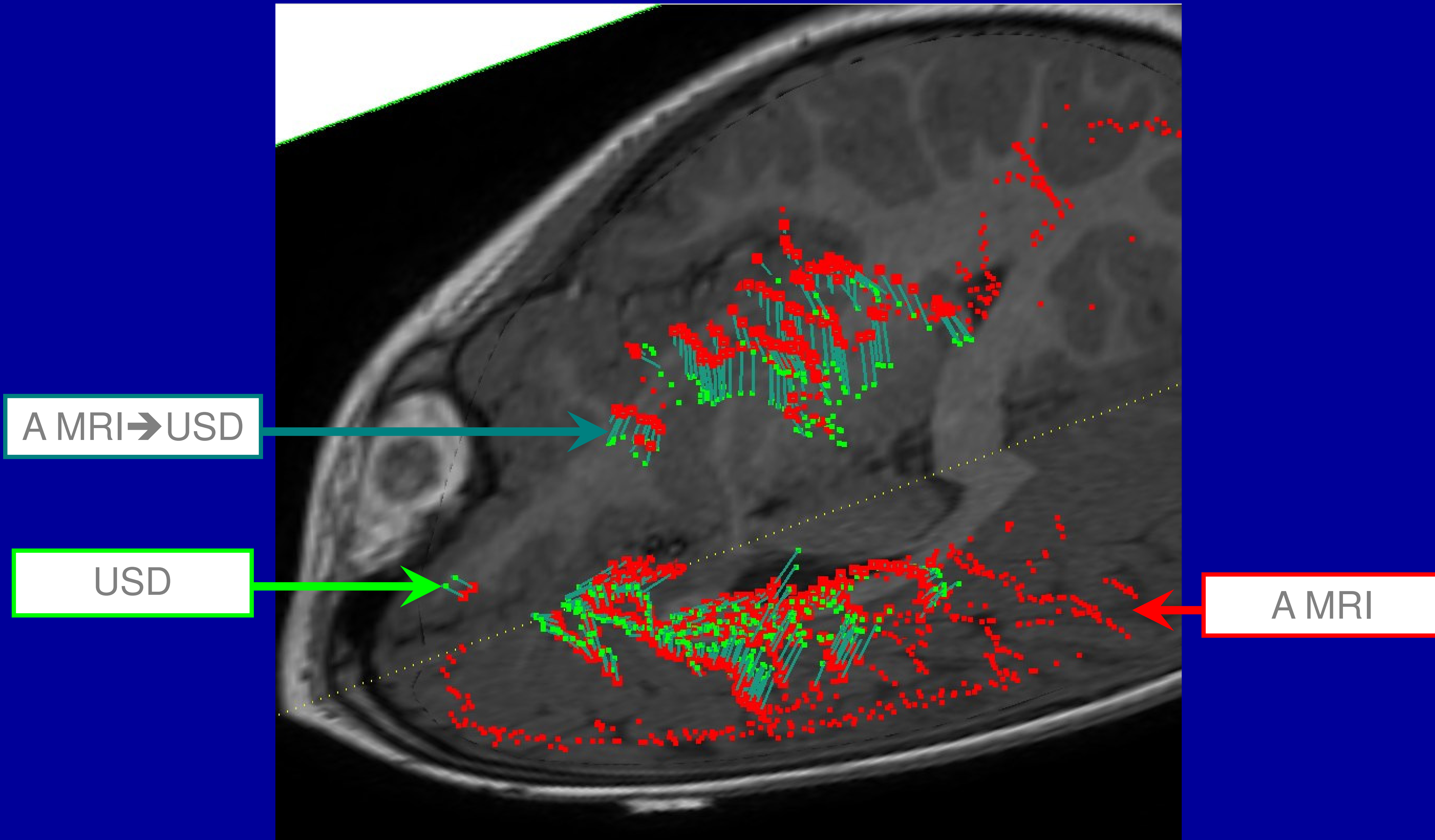
Echographie Doppler 2D ou 3D



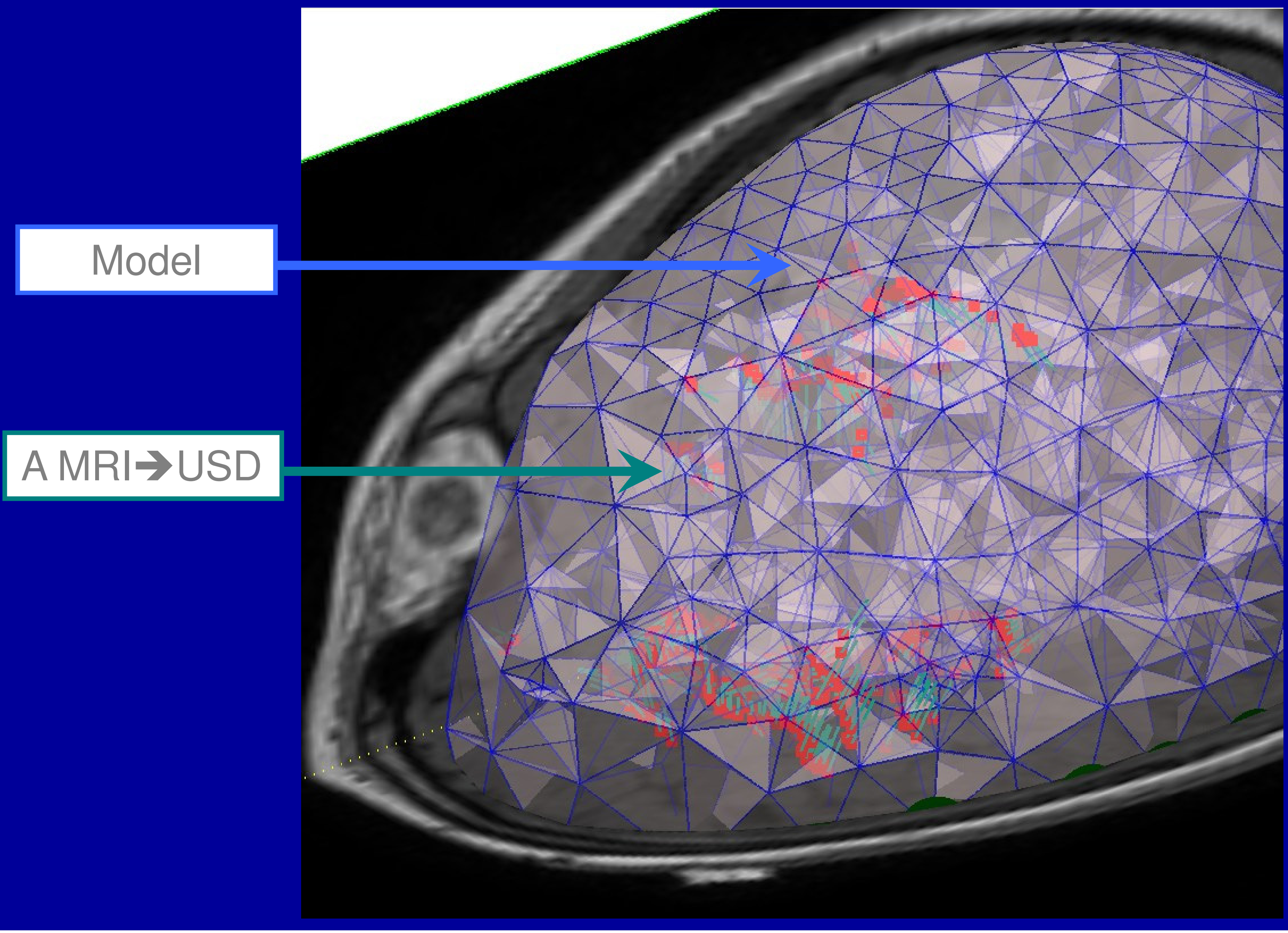




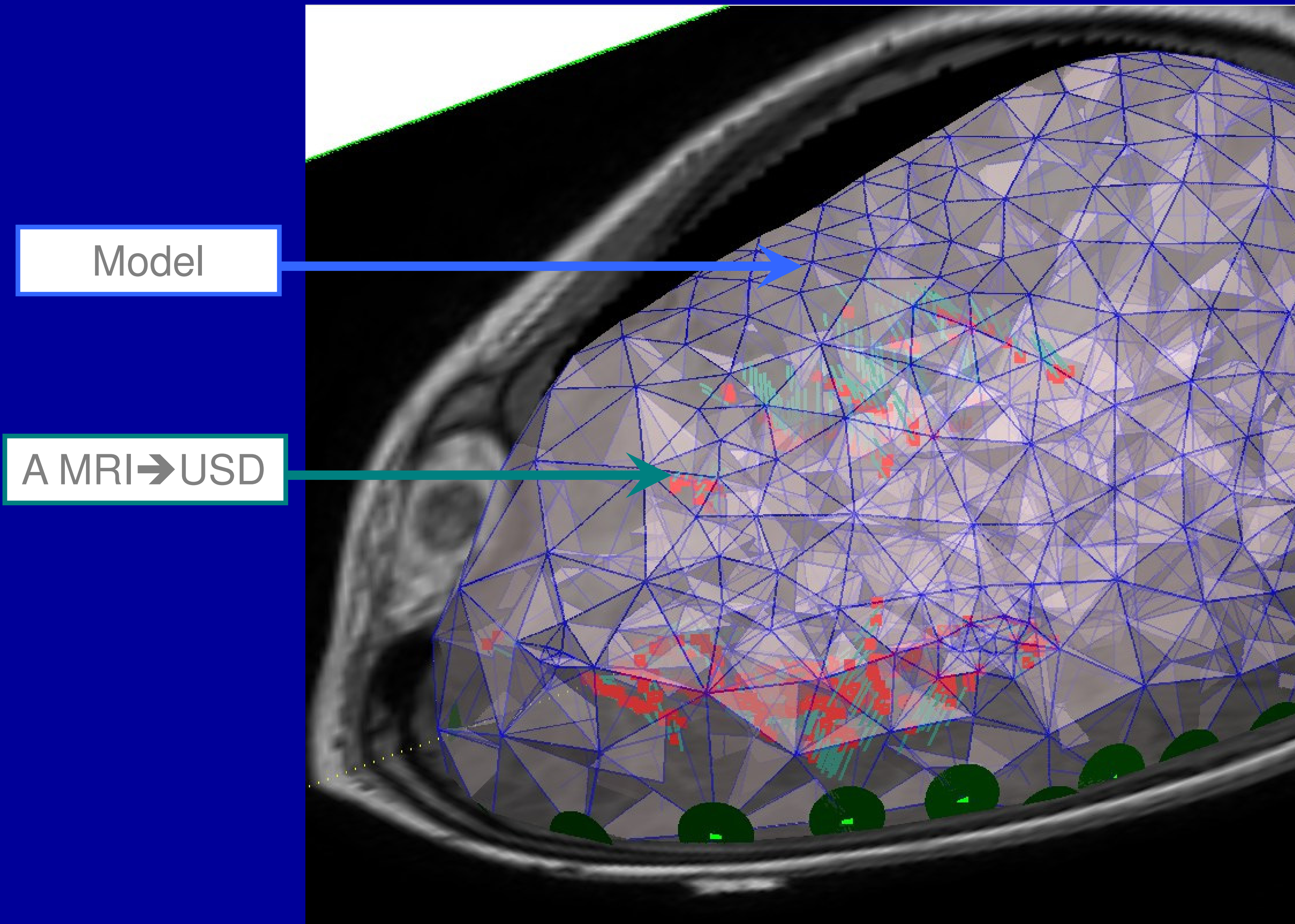
Intra-operative Computer Aided Device: *Neurosurgery*



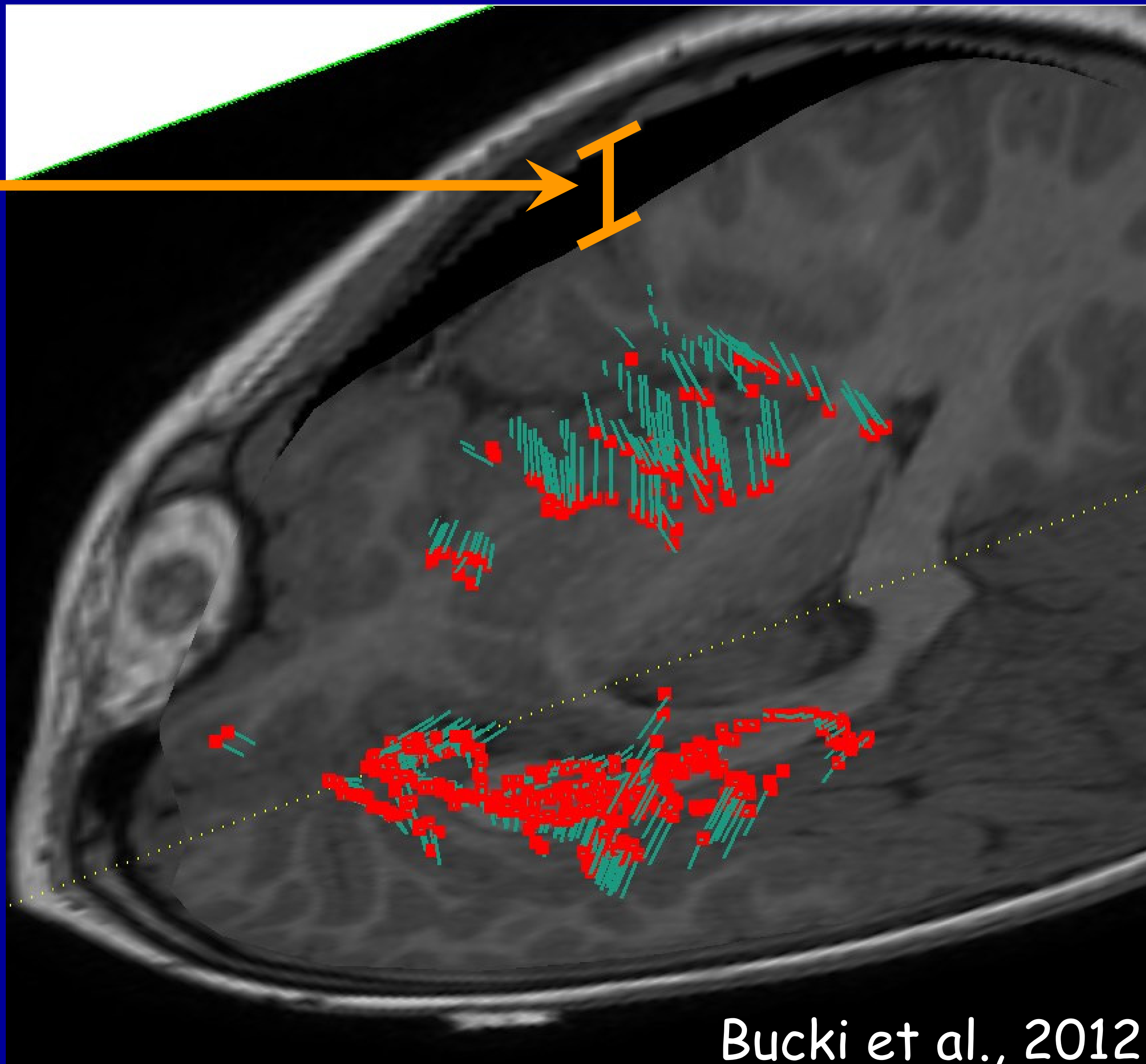
Intra-operative Computer Aided Device: *Neurosurgery*



Intra-operative Computer Aided Device: *Neurosurgery*



Intra-operative Computer Aided Device: *Neurosurgery*



Brain Shift

Computer Aided Medical Intervention

	Intra-operative computer Aided System
• A "fast" generation of the patient-specific biomechanical model of the organ	+++
• The possibility to estimate the patient-specific constitutive behavior of the organ	+++
• An almost real-time computation of the deformations simulated by the model	+++

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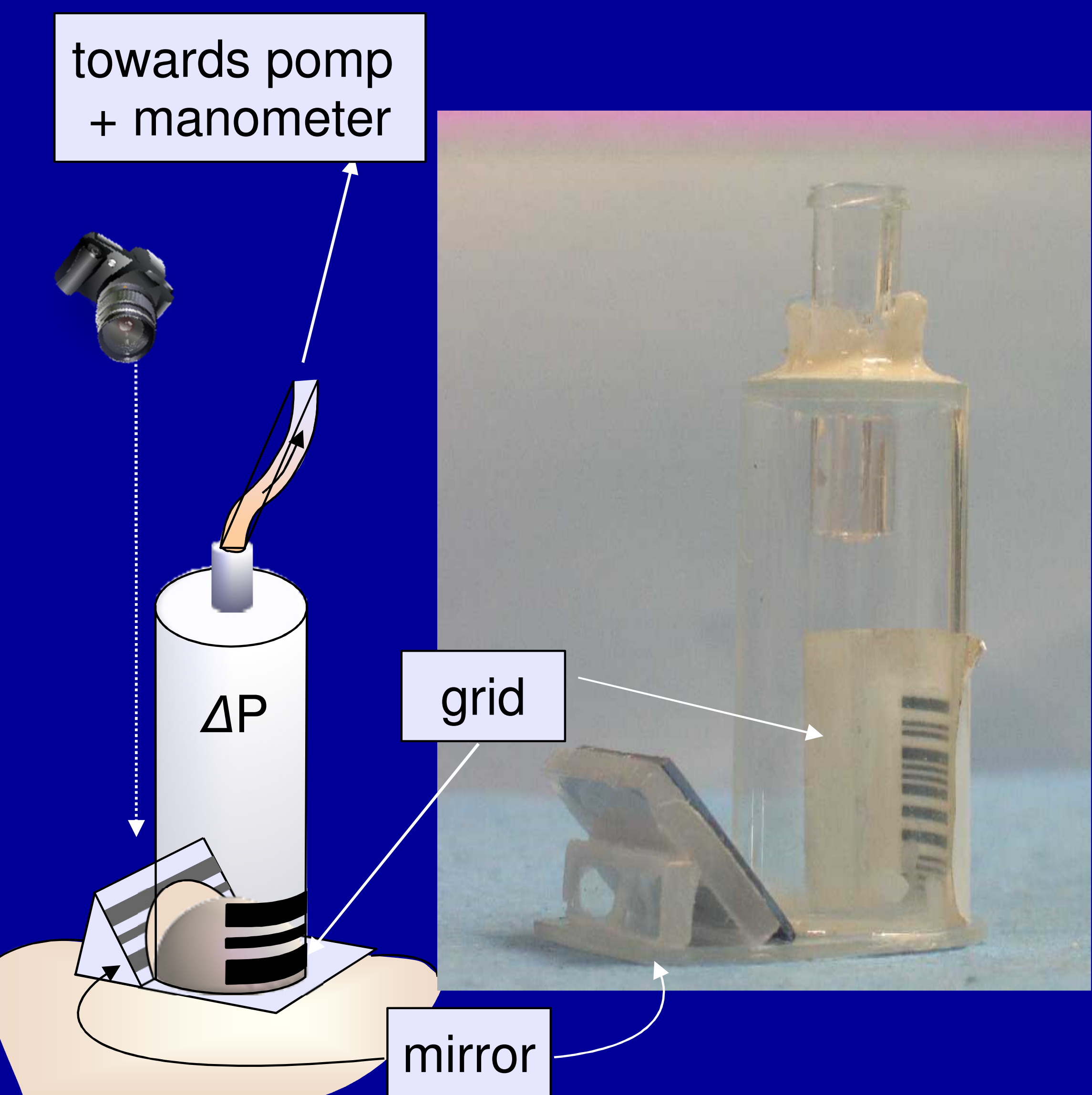
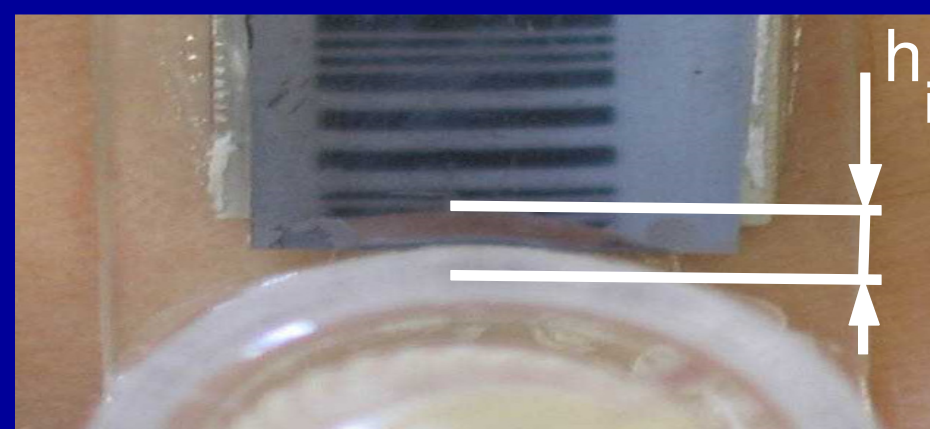
Light Aspiration Device: LASTIC V1

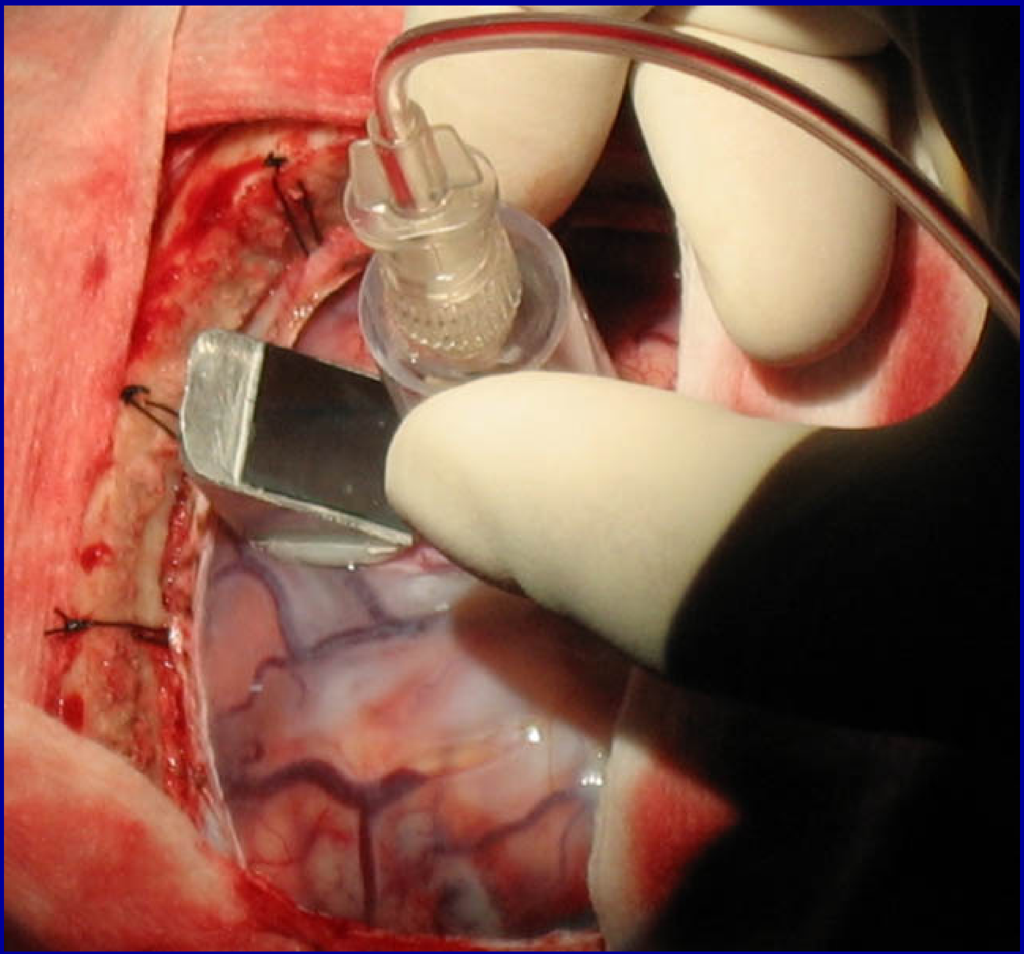


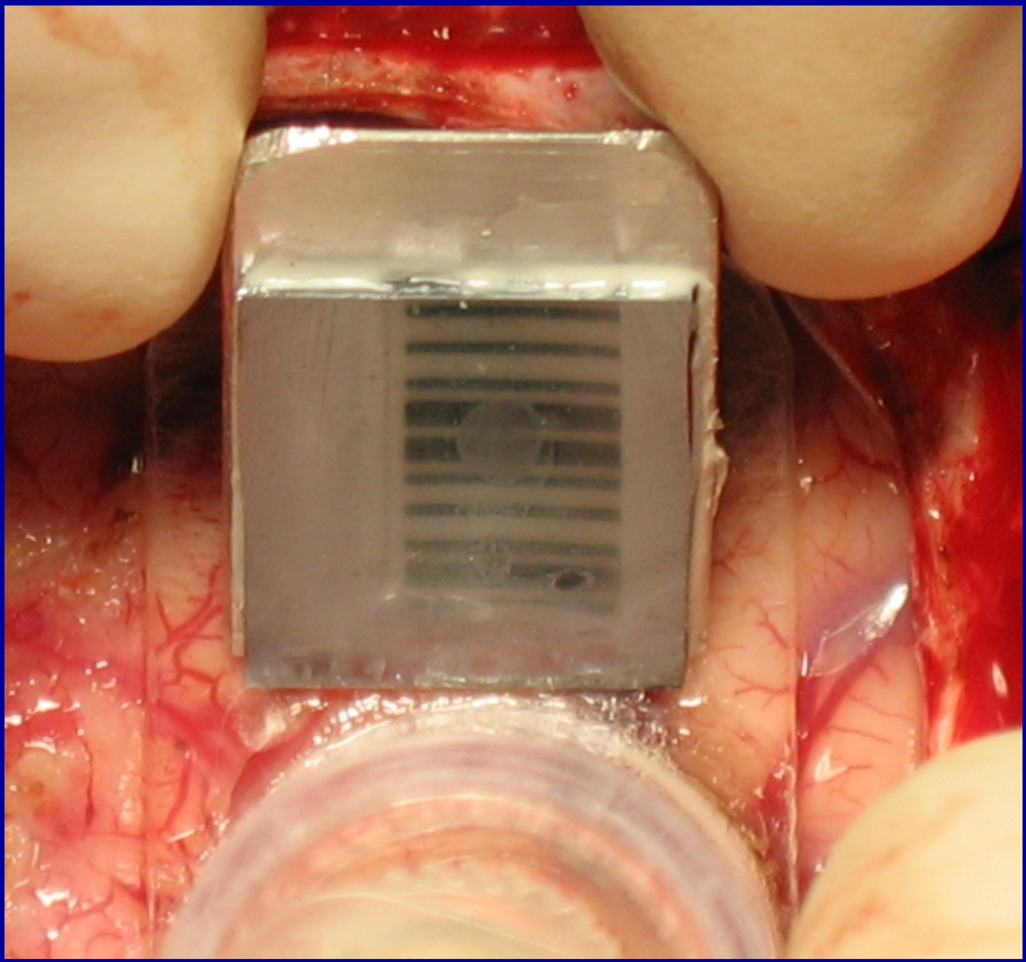
View from the camera



Schiavone et al., 2008

Light Aspiration Device: LASTIC





Aspiration: in vivo measurement of patient brain elasticity

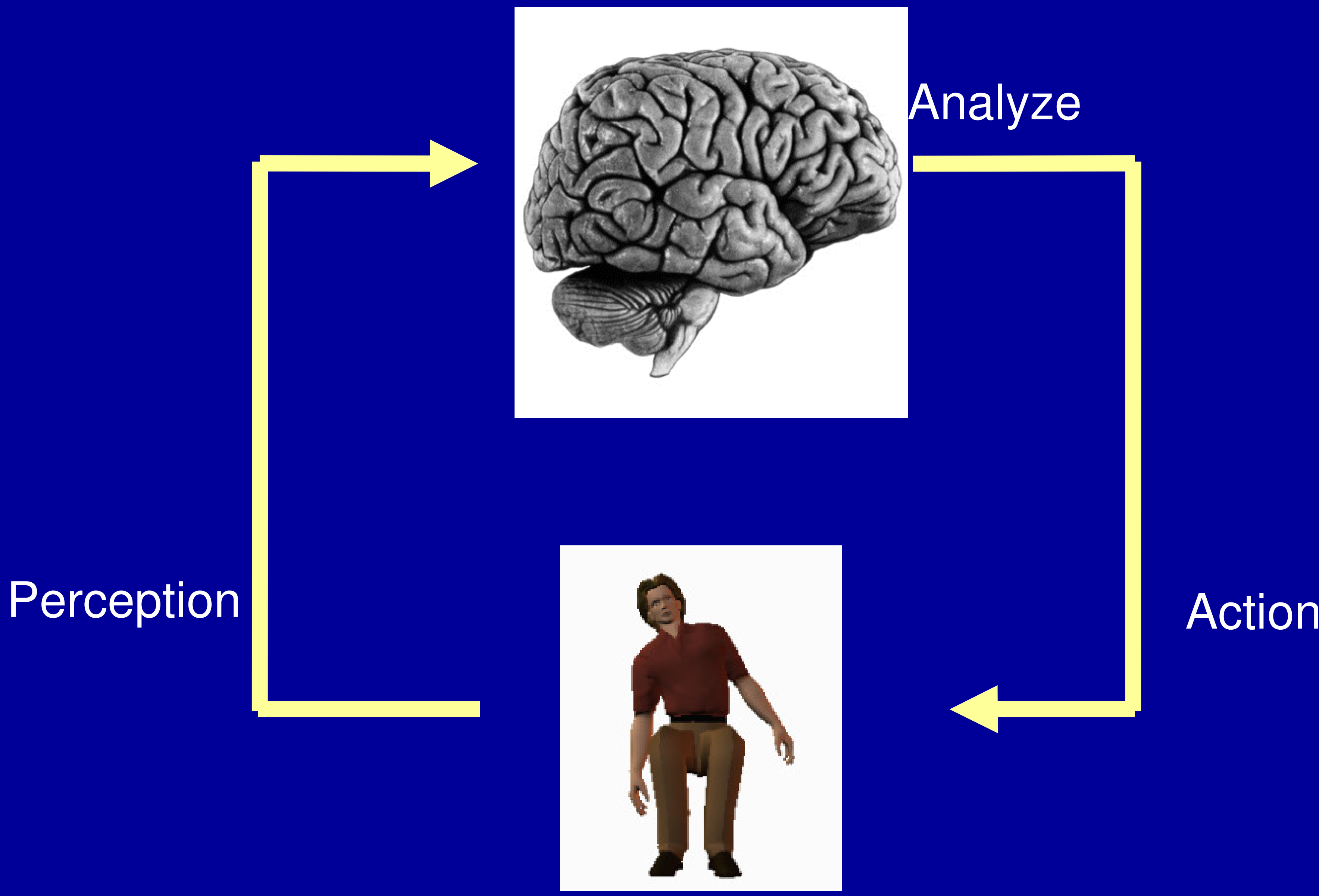
Schiavone et al., 2009

Pressure ulcers prevention

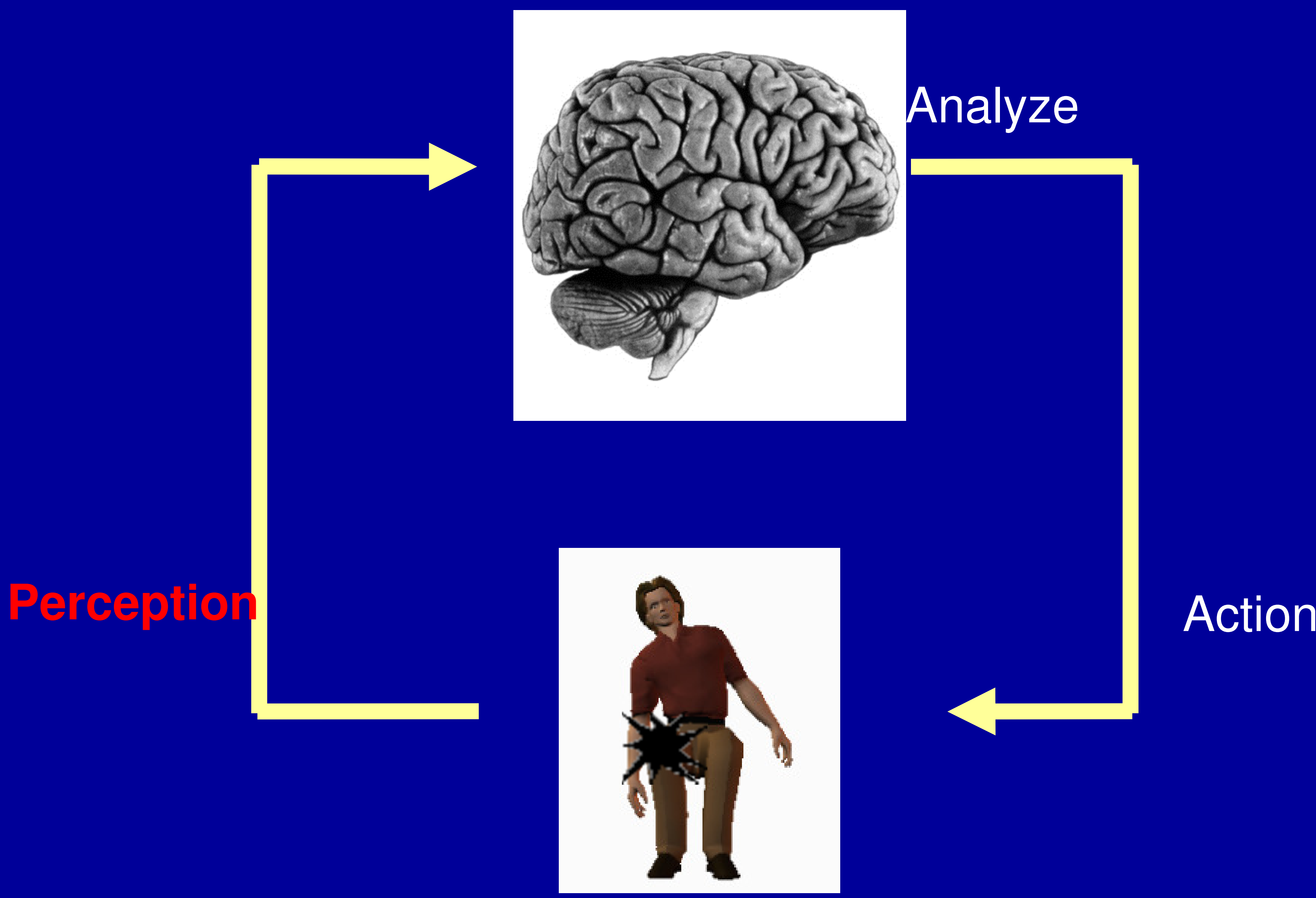


Pressure ulcers prevention for paraplegic persons

Over-pressures : healthy person



Over-pressures : healthy person



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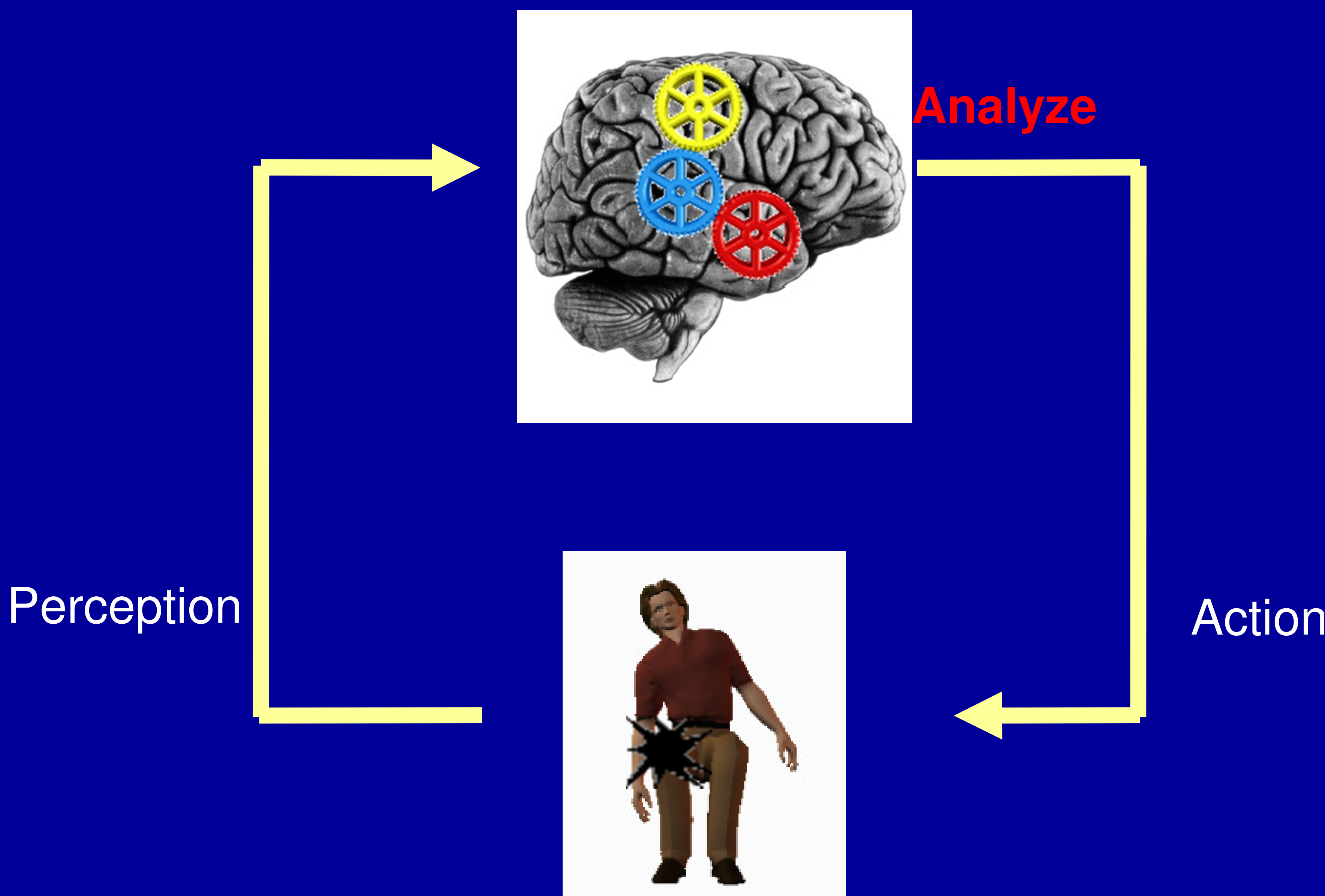
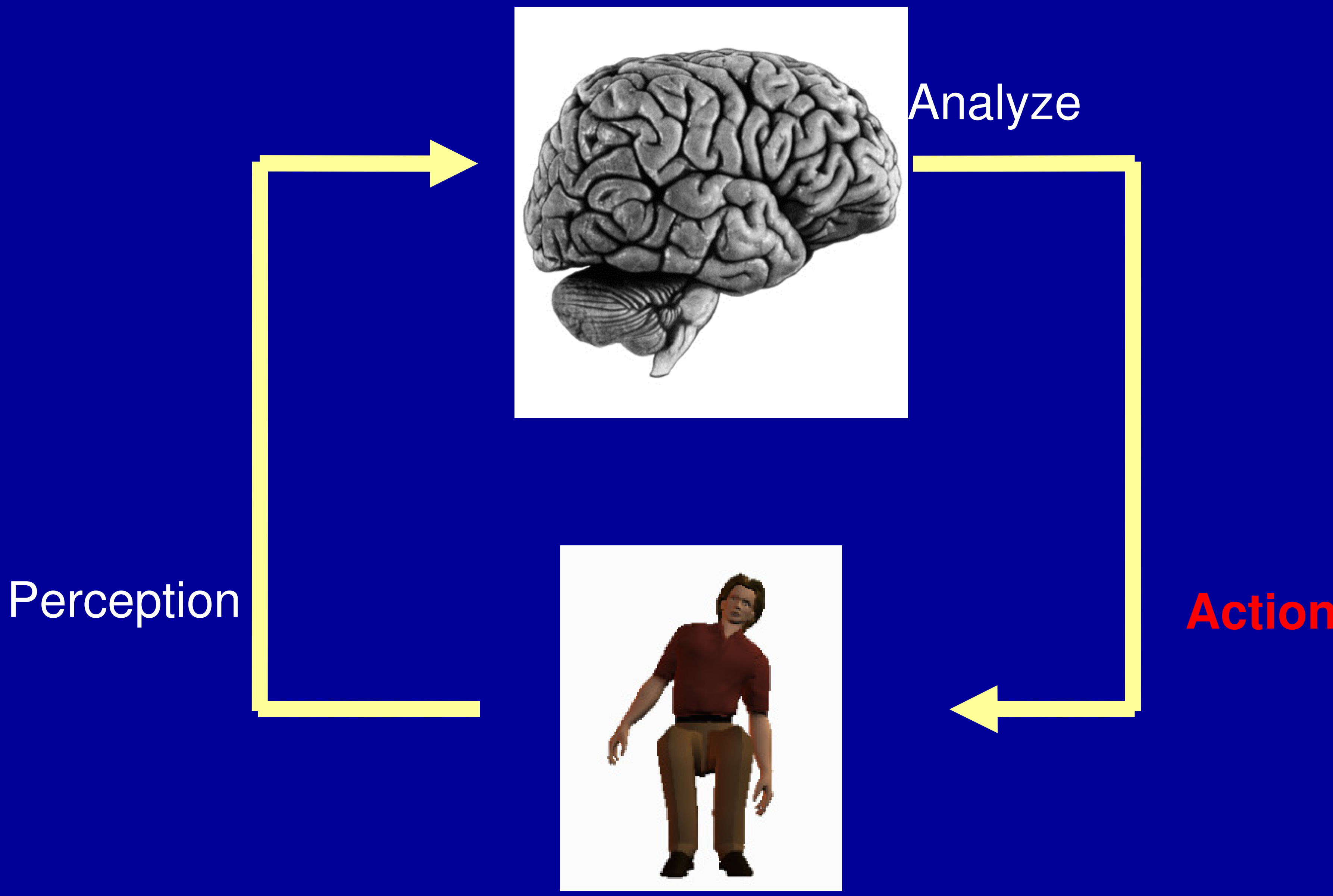
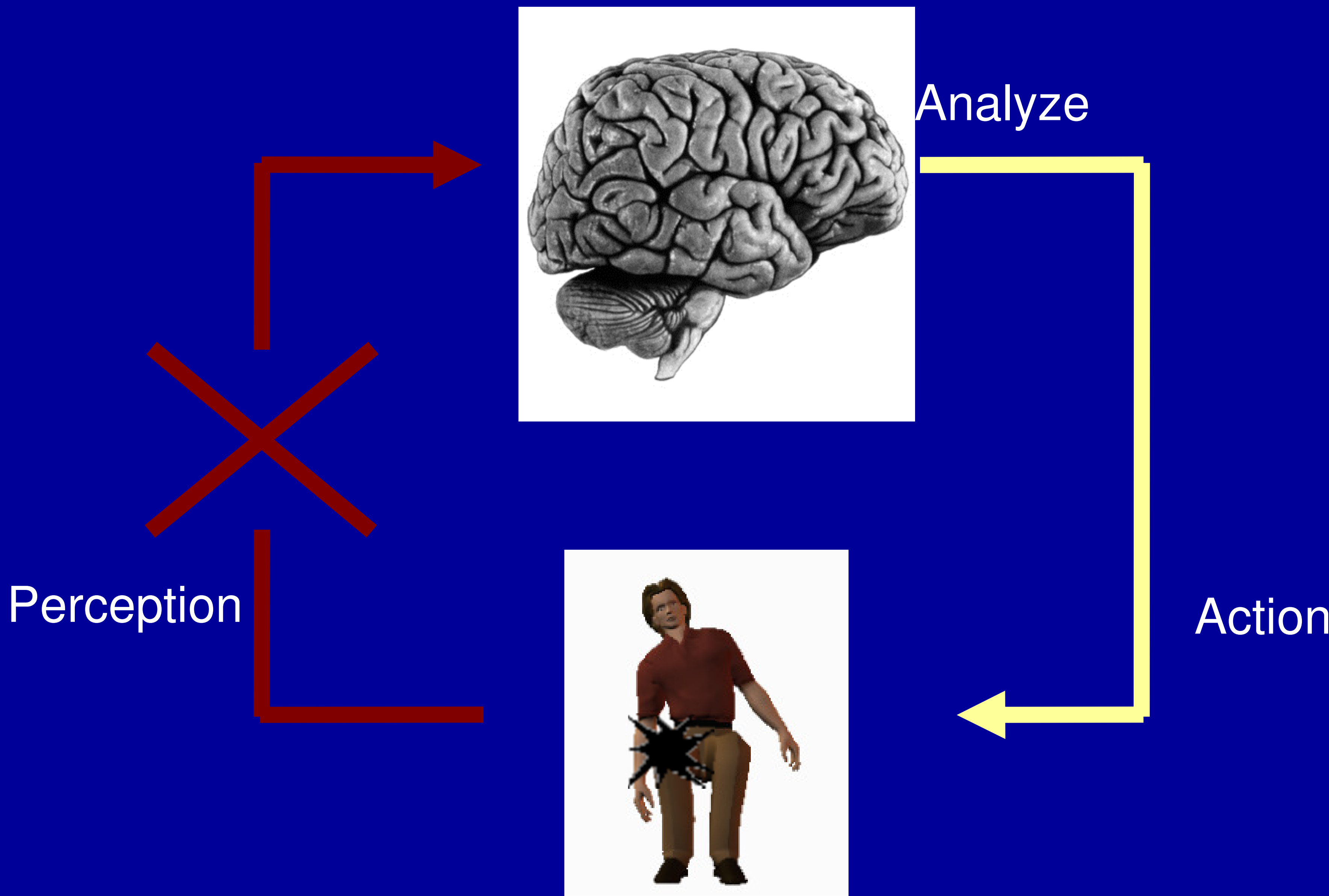


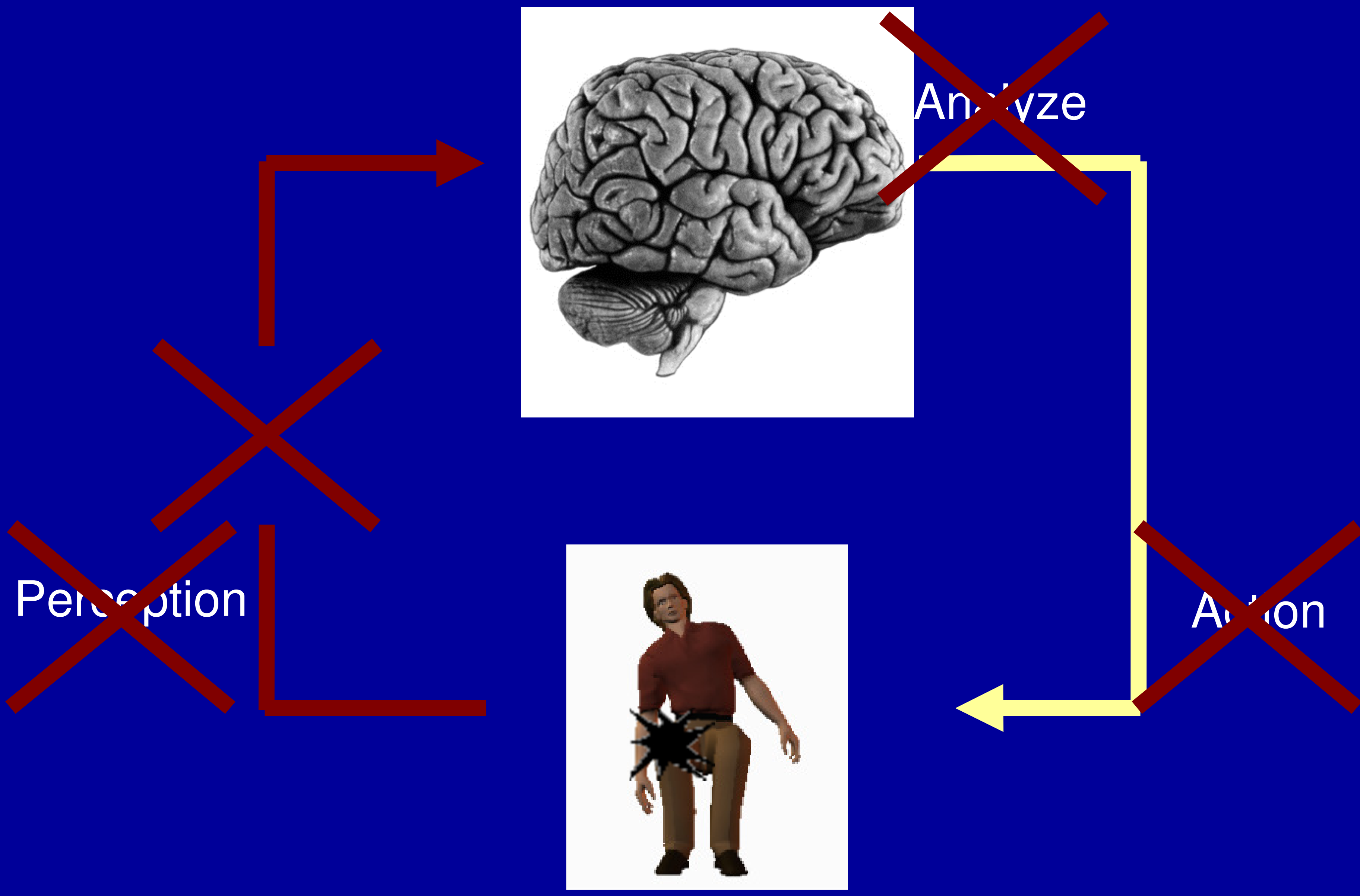
Over-pressures : healthy person

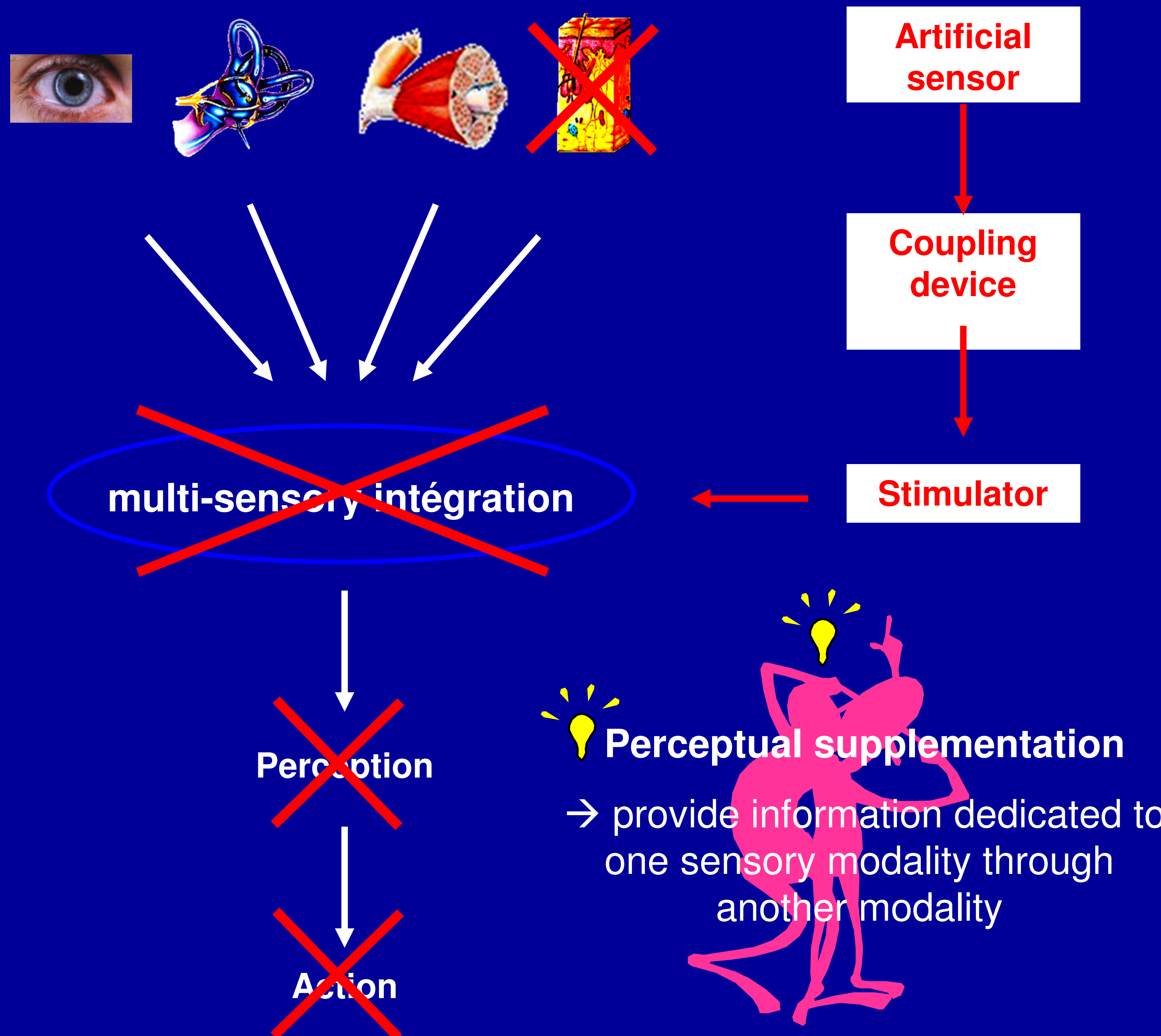


Over-pressures : paraplegics



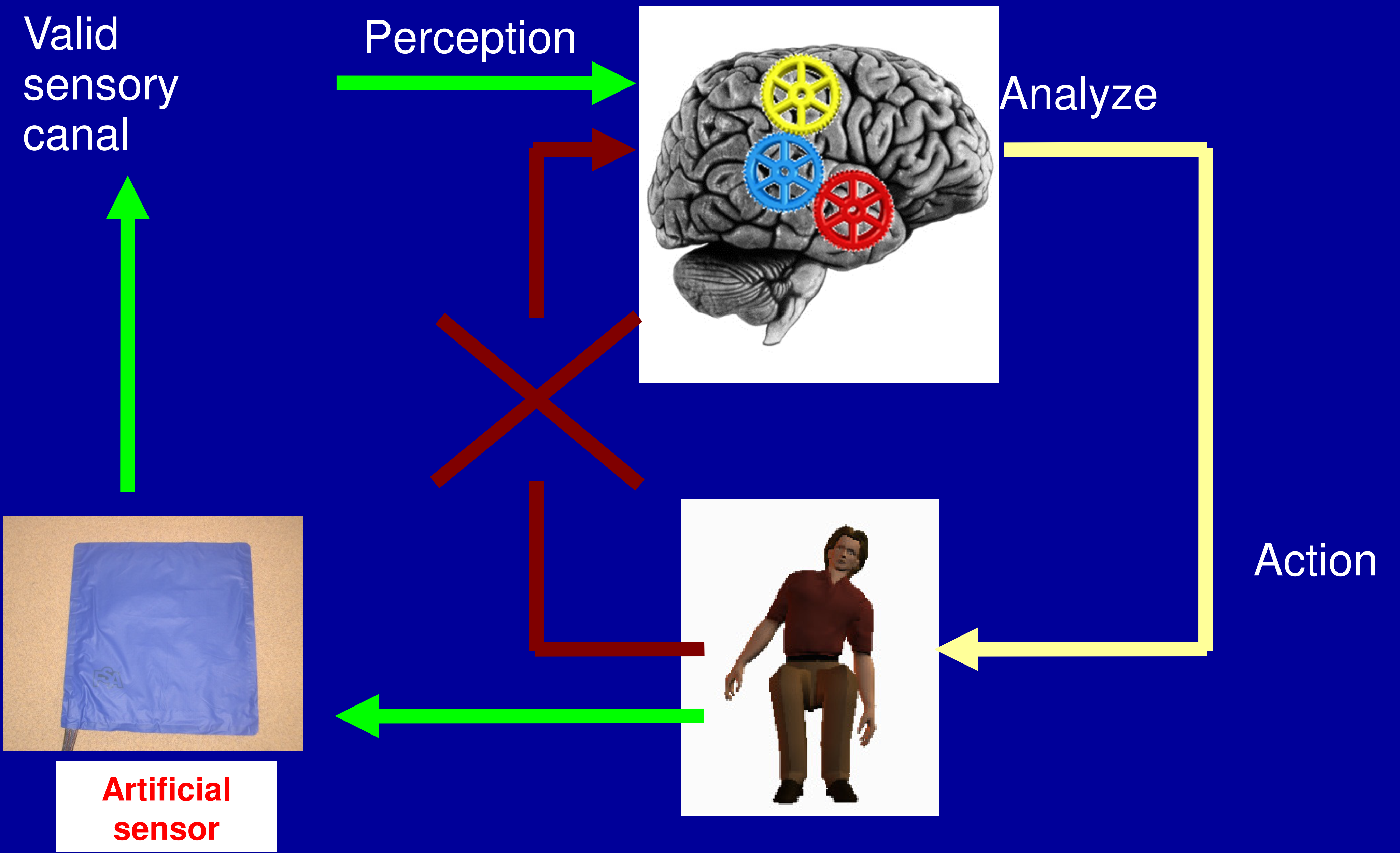
Over-pressures : paraplegics





Artificial sensor
Coupling device
Stimulator
multi-sensory intégration
Perception
Action
Perceptual supplementation
→ provide information dedicated to one sensory modality through another modality

Over-pressures : paraplegics



Pressure ulcer prevention

- Three questions :

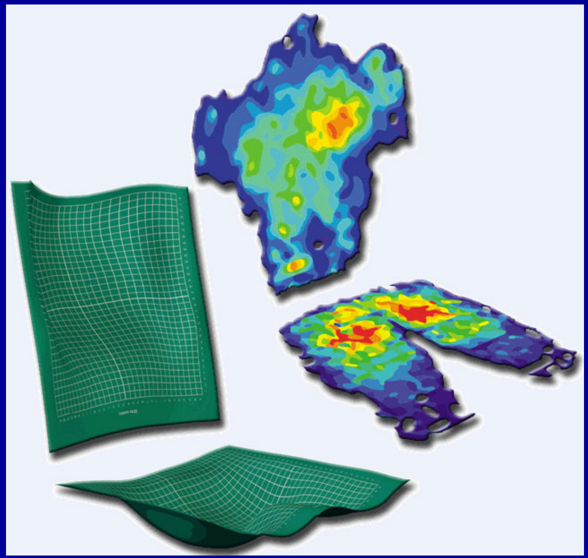
  - What kind of artificial sensor for the measurement of the pressure at the buttocks / seat interface?

  - When deciding that there is a risk for pressure ulcer?

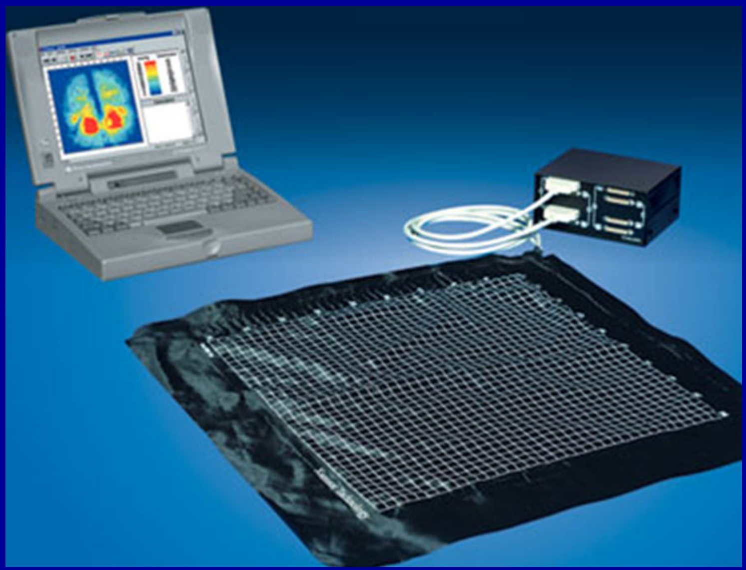
  - How to alert the person in case of a risk?

→ An Utility / Utilisability / Acceptability Study

What kind of artificial sensor ?



Tekscan Inc.



Xsensor Inc.

Vista Medical Inc.

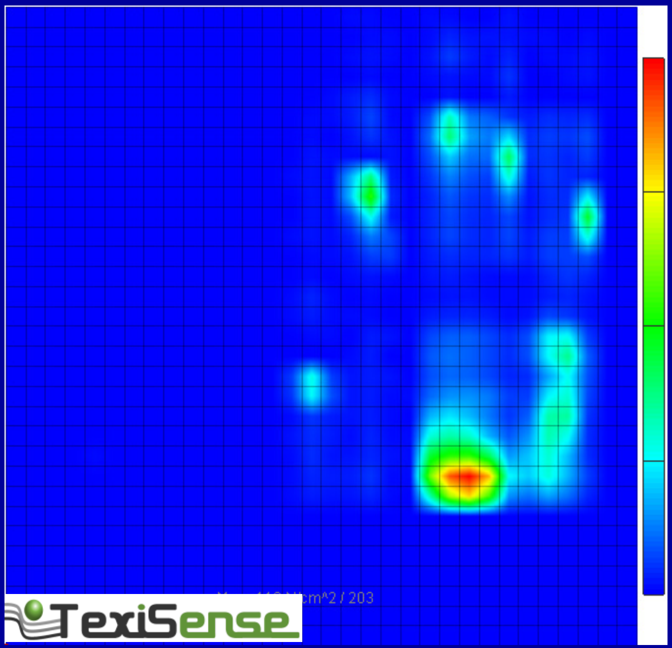
What kind of artificial sensor ?

- 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

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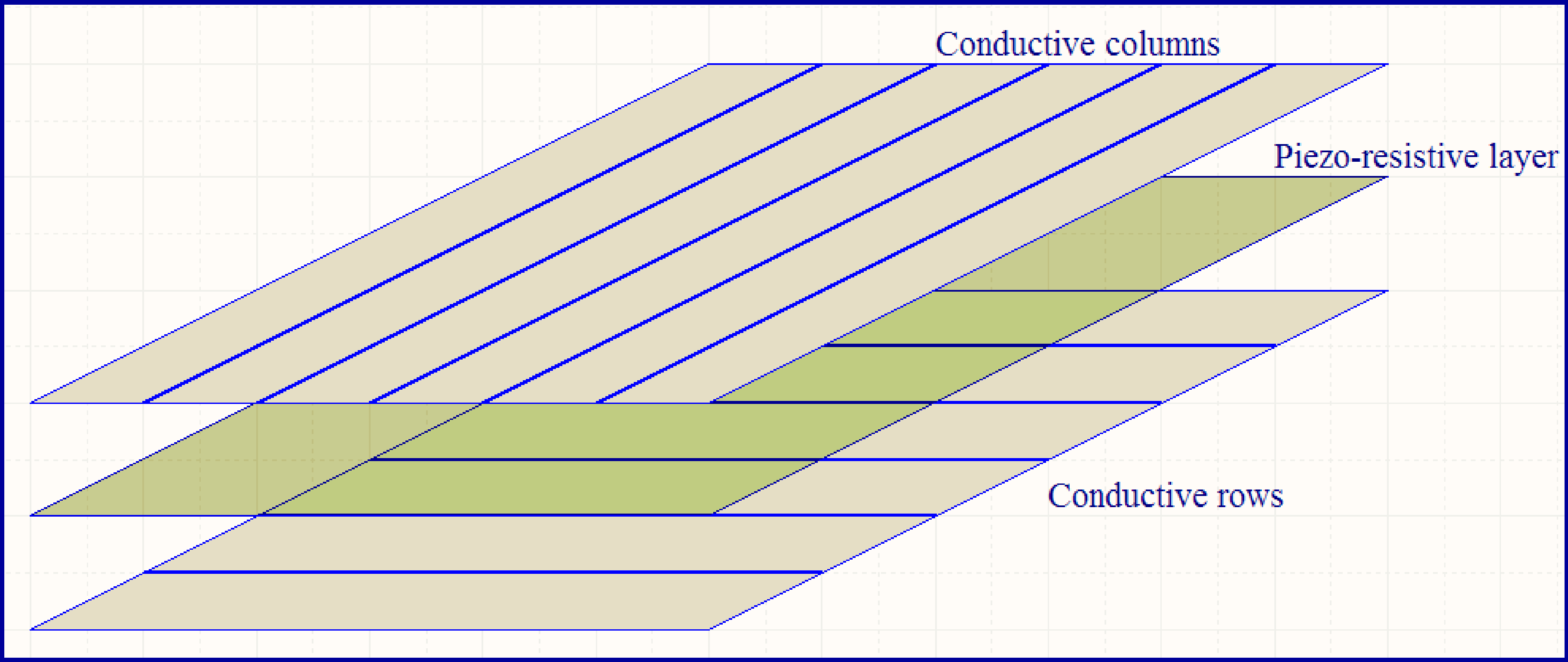


- Two outer layers form a matrix that defines the spatial resolution of the sensor: the nylon fibers coated with silver conduct current
- Any normal forces exerted onto the middle layer change the electrical resistance of the material : fibers are coated with polymers

Pressure ulcer prevention

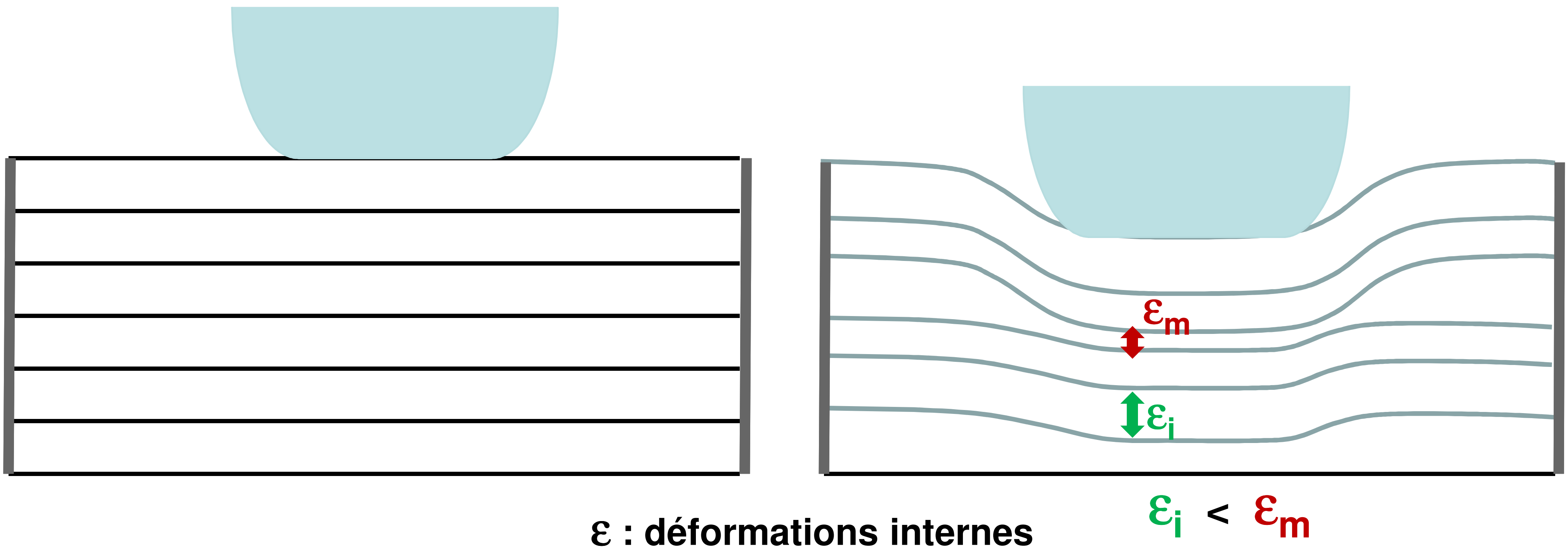
- Three questions :

  - 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 ?



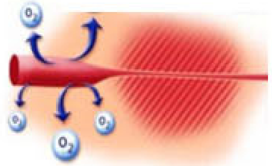
ε : déformations internes

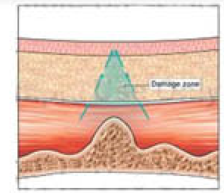
Pressions d'interface

déformations internes < ε_i

ε_i < déformations internes < ε_m

déformations internes > ε_m





Conséquences de l'ischémie

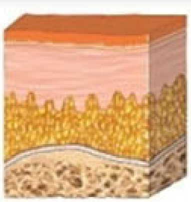
- défaut d'oxygénation
- accumulation de toxines
- diminution du pH

Conséquences des déformations

- rupture de la membrane
- perméabilité
- dégradation du cytosquelette

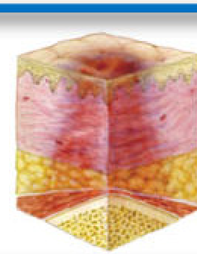
si durée > 2h

si durée > 10 mn



Tissus sains

Escarre



ε_i : seuil de déformations « ischémiques » (env. 20%)

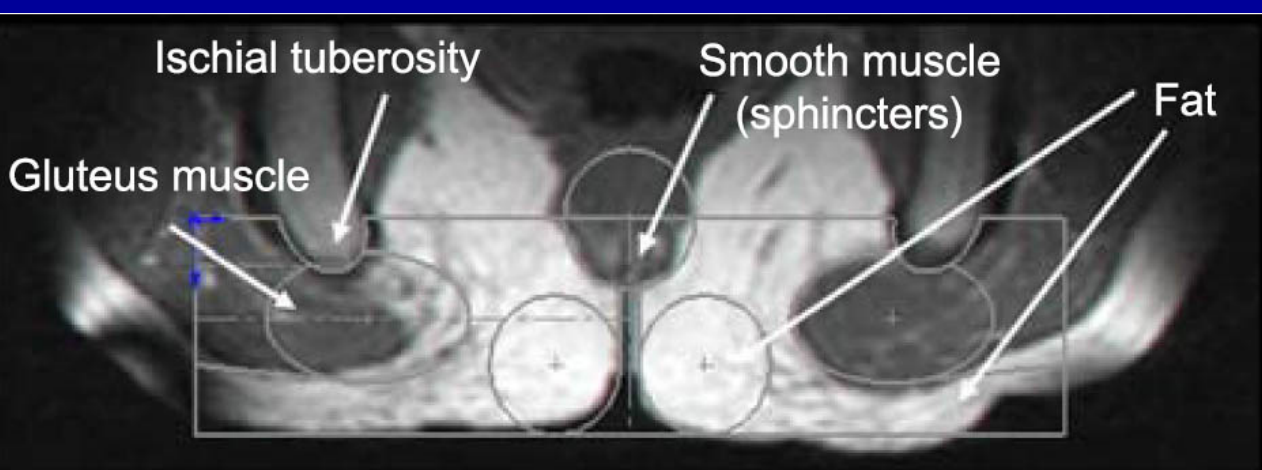
ε_m : seuil de déformations « mécaniques » (env. 50%)

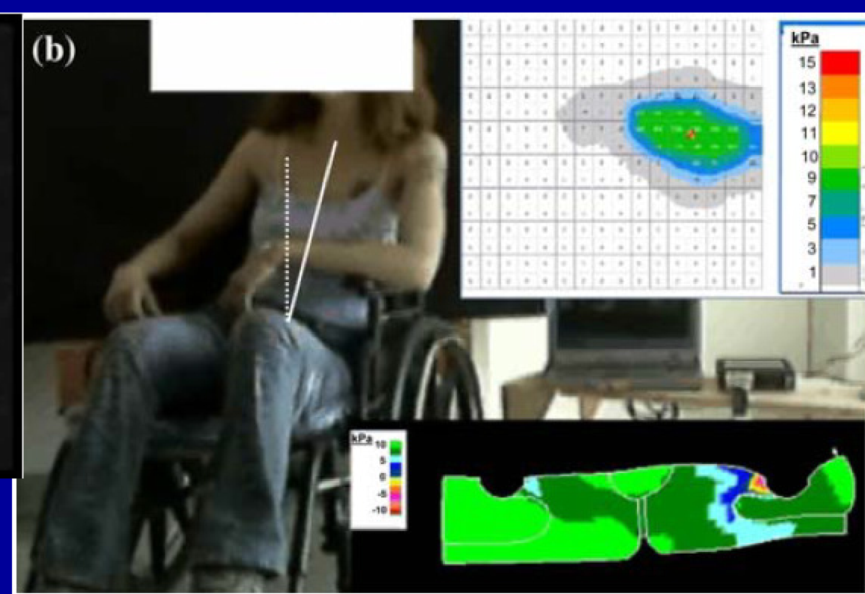
D'après Loerakker, 2011

When deciding that there is a risk for DPU ?

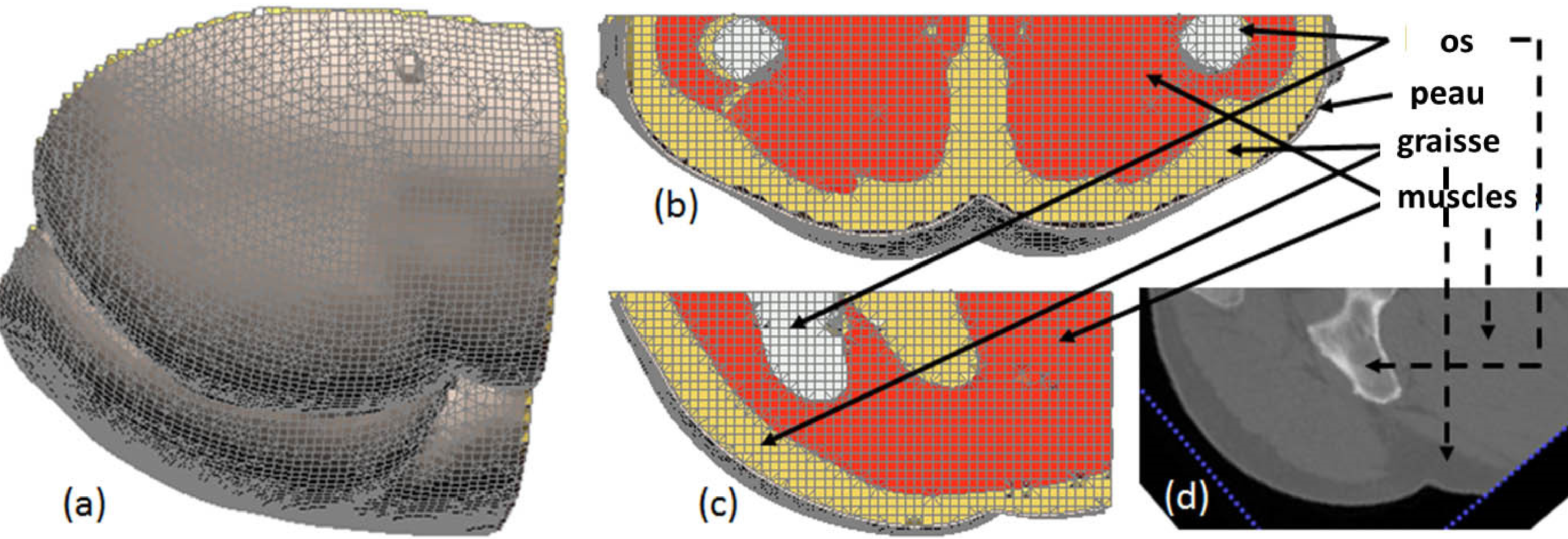
- How to estimate the deformations thresholds ε_i and ε_m from the measured pressures at the buttocks / cushion interface ?

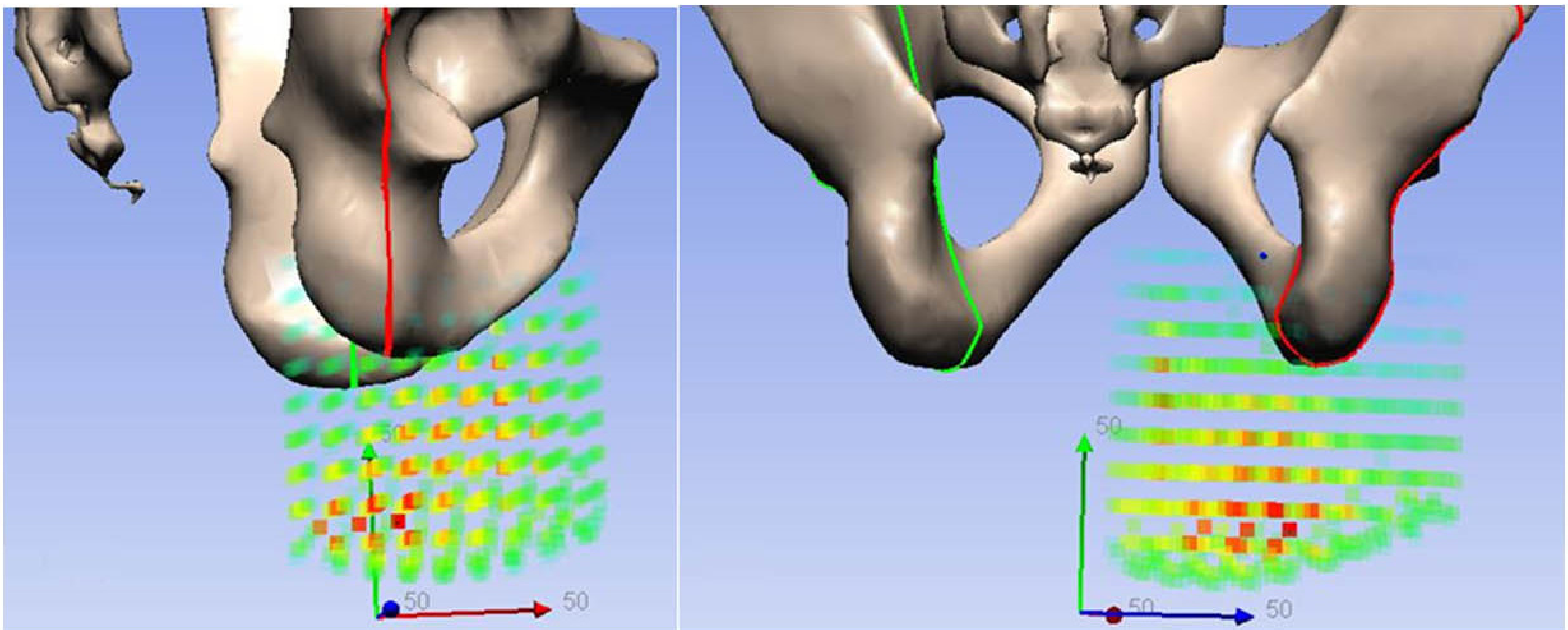
➡ The use of a patient-specific biomechanical model of the buttocks bone / soft tissues





Linder-Ganz *et al.*, 2009


(a)
(b)
(c)
(d)
os
peau
graisse
muscles


50
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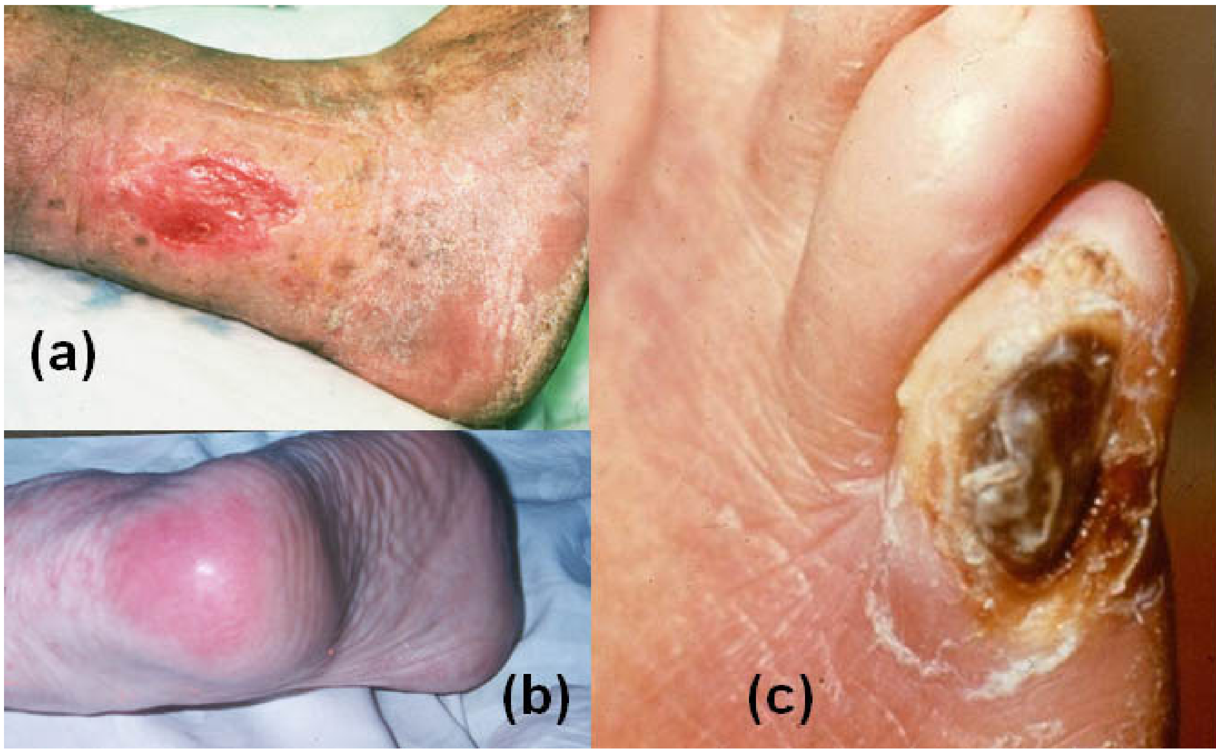
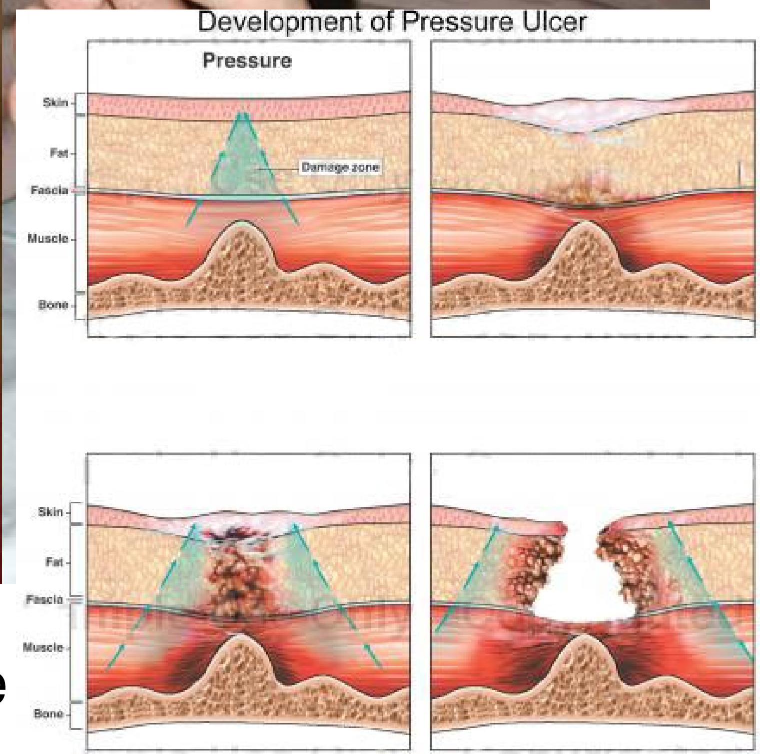
Contexte

Problématique du pied diabétique
(ulcère plantaire, mal perforant plantaire)





Origines : Diabète → angiopathie et neuropathie

Causes : marche et interaction pied/chaussure → micro-traumatismes répétés

Contexte

Chiffres :

- 250 millions de diabétiques dans le monde
- 15% des personnes diabétiques vont faire au moins un ulcère plantaire au cours de leur vie
- 15% de ces ulcères vont conduire à une amputation

⇒ Un pied amputé toutes les 30s à cause du diabète

Des coûts exhorbitants pour les systèmes de Santé
48 millards $ / an aux USA ; 3 millards £ / an en UK

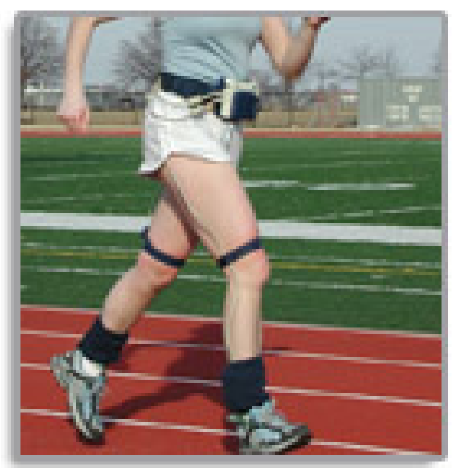
1. *The costs of diabetic foot: the economic case for the limb salvage team. Driver VR, Fabbi M, Lavery LA, Gibbons G. J Am Podiatr Med Assoc. 2010 Sep-Oct; 100(5):335-41.*
2. *The health care costs of diabetic peripheral. Gordois A, Scuffham P, Shearer A, Oglesby A, Tobian JA. neuropathy in the US. Diabetes Care 2003; 26: 1790-5.*

Contexte

Prévention :

- surveillance quotidienne du pied
- si besoin, prescription de chaussures orthopédiques
- si rougeur observée : repos du pied

Mesure :



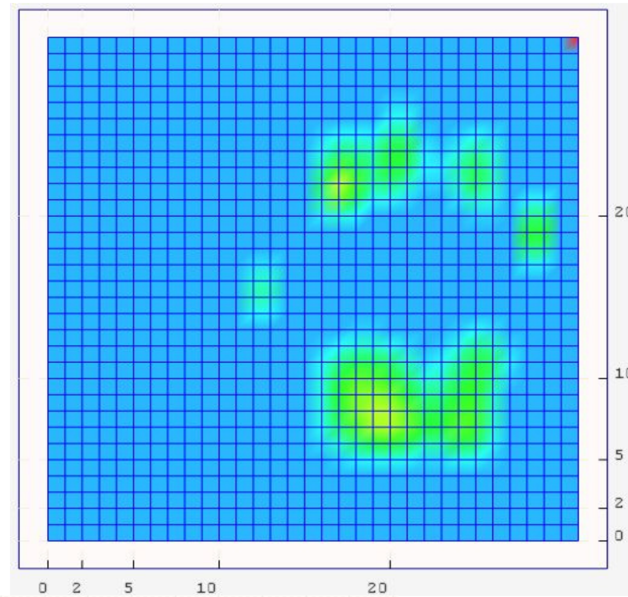
BioFoot® insoles

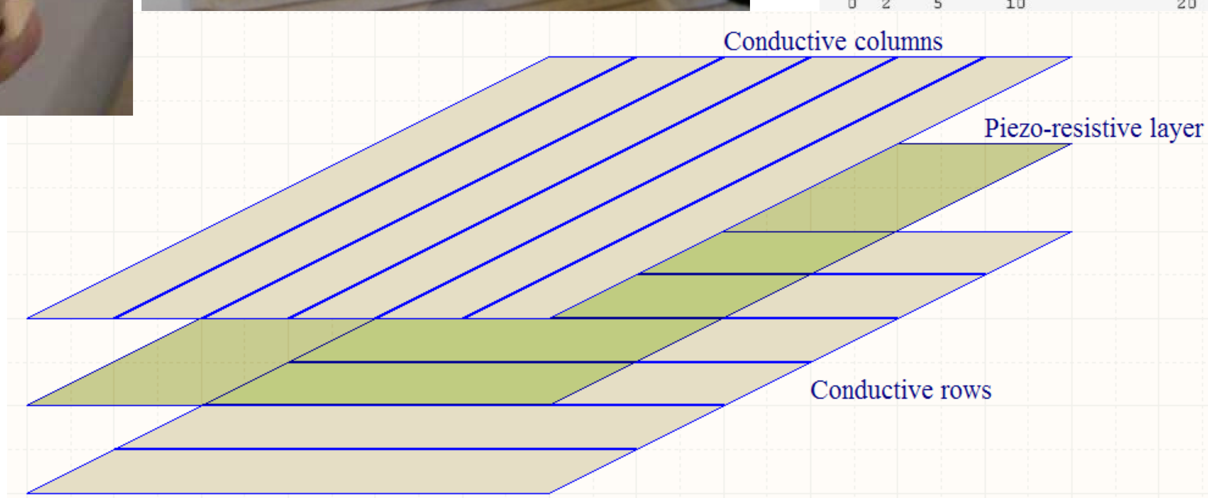
F-Scan®, Tekscan

Pedar shoes LilaBox

Contexte

- Antécédents : nappe de pression pour la prévention des escarres du paraplégique (UJF / IDS / Texisense)





Résultats du projet

- Tricotage d'une chaussette monocouche sur Métier Chaussant.



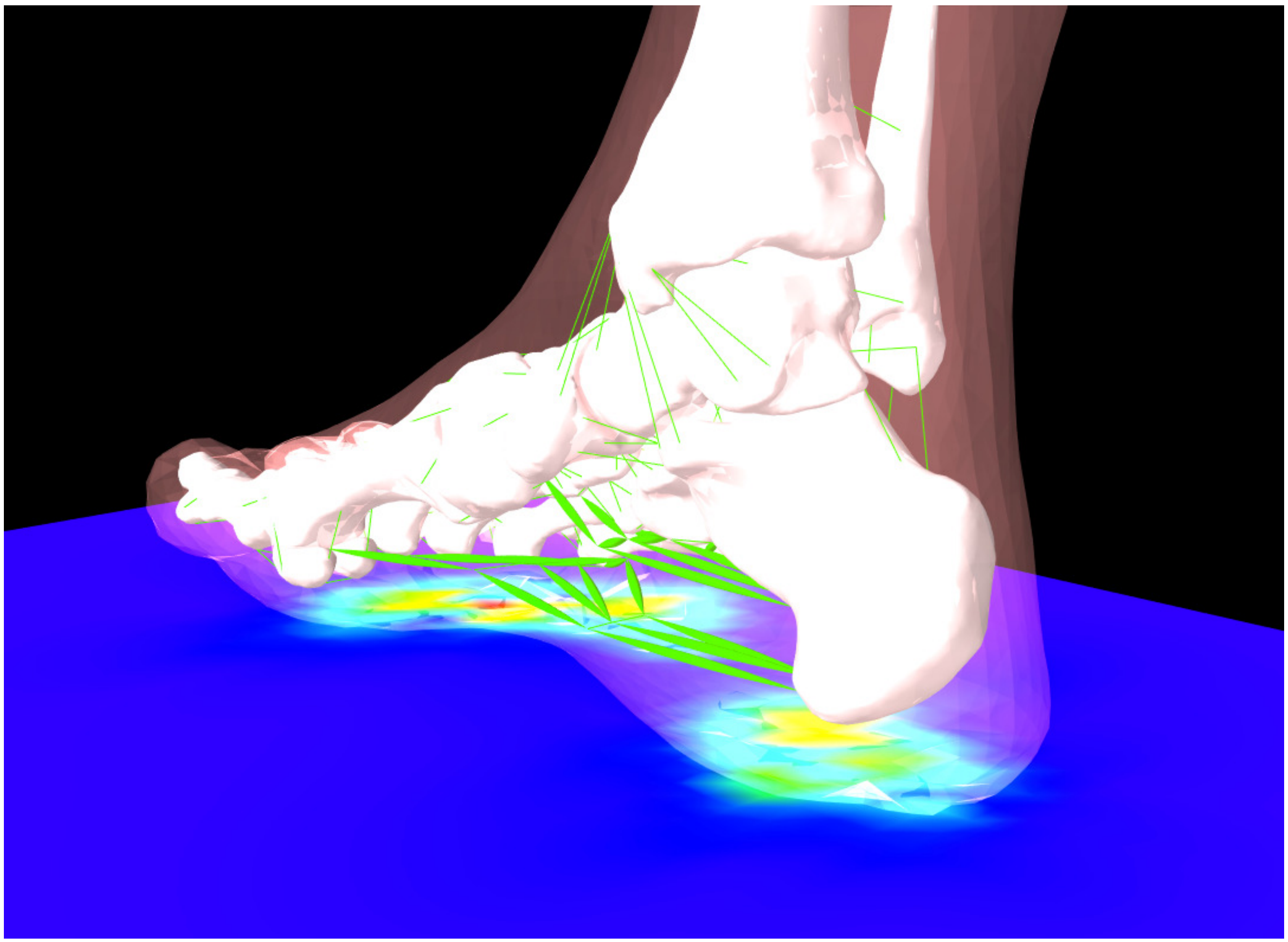
- Base mi-chaussette type ville / rapidité d'exécution et confort
- Insertion par tricotage de fils techniques piézo et conducteurs
- Liberté de forme et de positionnement des capteurs

Résultats du projet

- Unité Centrale miniaturisée et liaison radio.

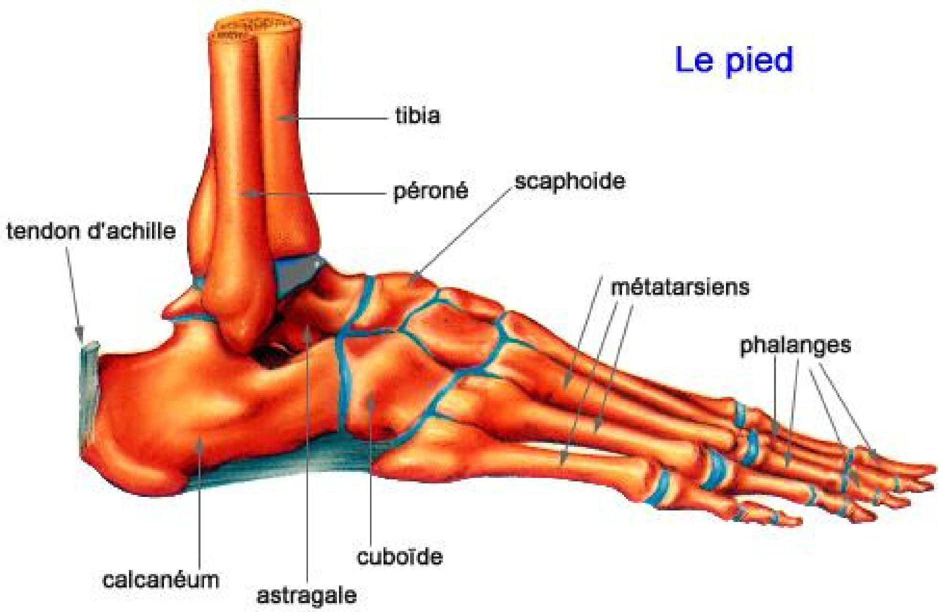
Résultats du projet

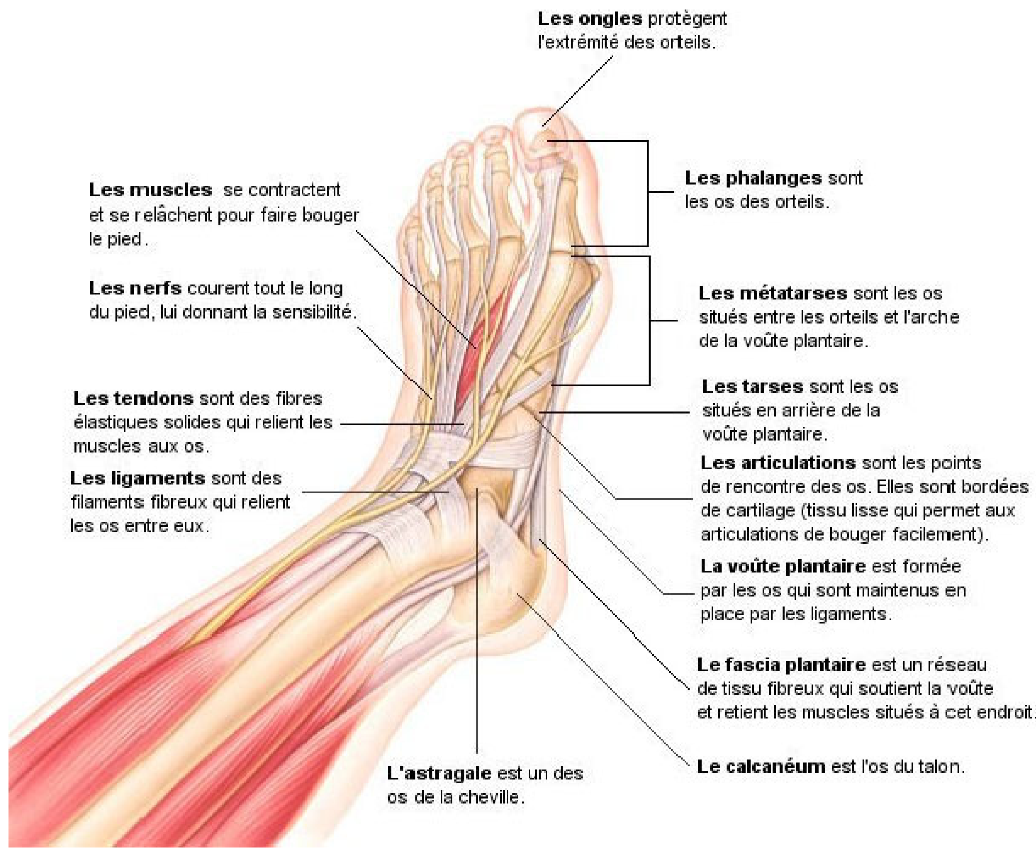
- Modèle biomécanique patient-spécifique du pied.

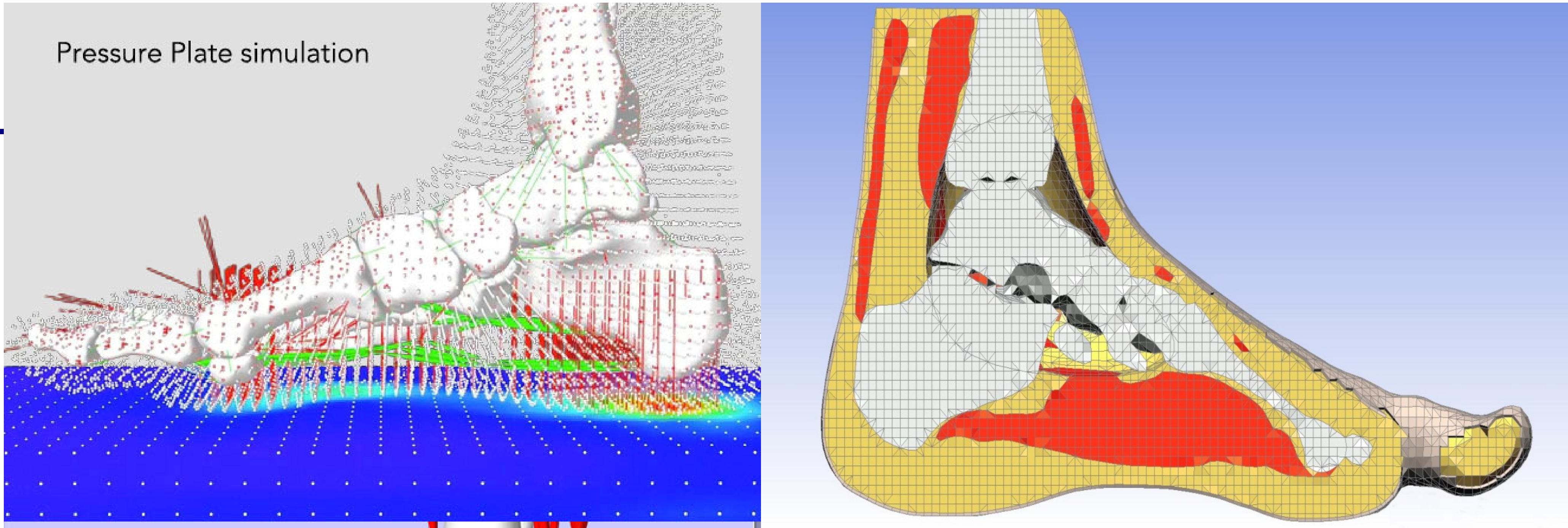


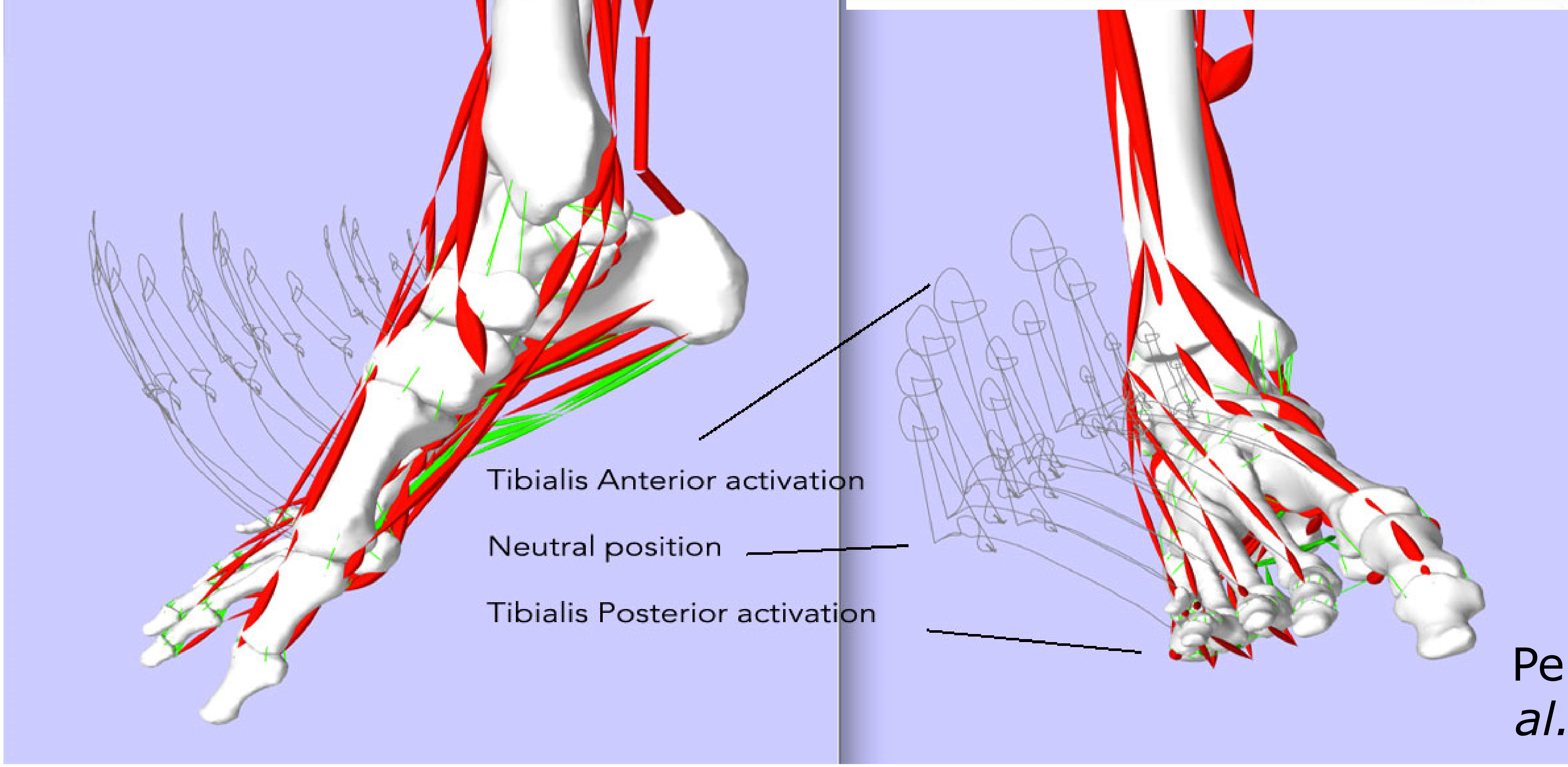
Résultats du projet

- Anatomie du pied : 26 os, 33 articulations et plus de 100 muscles, tendons et ligaments, ainsi qu'un réseau de vaisseaux sanguins, nerfs, peau et tissus mous.





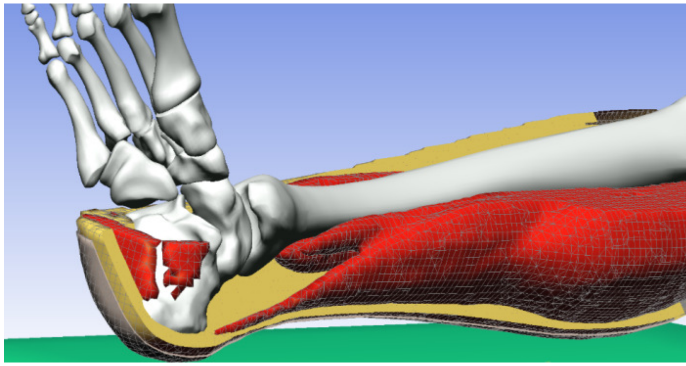


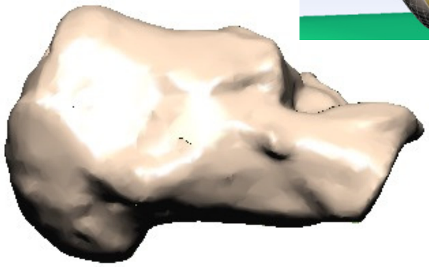


Perrier *et al.*, 2014

Résultats du projet

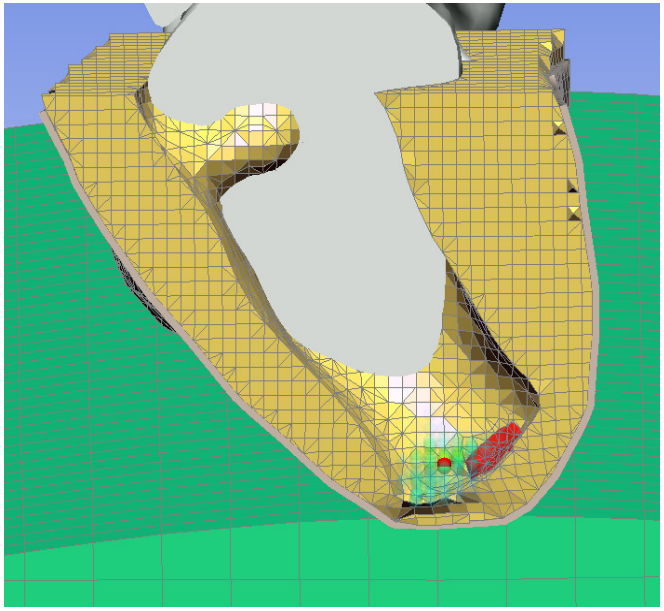
- Modèle biomécanique « patient-spécifique » du pied.

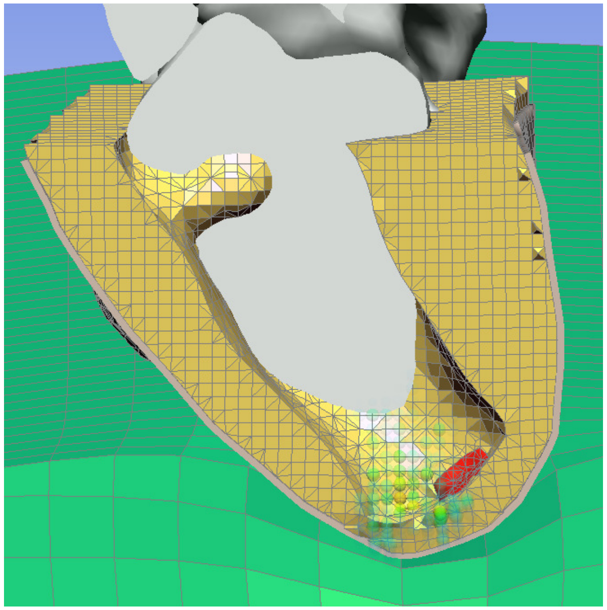




Calcanéum Patient 1

Calcanéum Patient 2

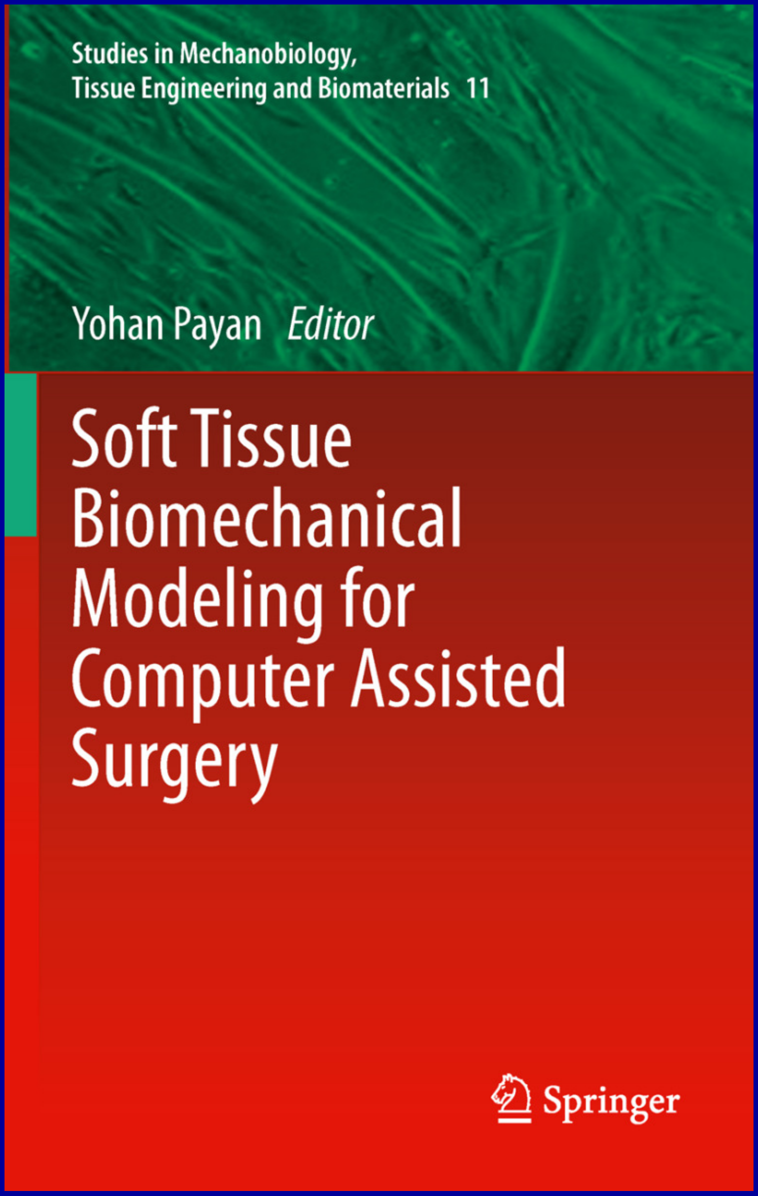




Outline

- Introduction
- Pre-operative Computer Aided Device: maxillo-facial surgery
- Intra-operative Computer Aided Device: *Neurosurgery*
- Discussion

Why most of the intra-operative medical robotic devices do not use biomechanical models?



TIMC

Computer-Assisted
Medical Intervention
Team

A3 Surgical

BlueOrtho
AUGMENTED ORTHOPAEDICS

praxim

IMACTIS

OrTHOTaXY

Surgivisio
Surgical Vision reloaded

TexiSense

KOELIS

M3
MinMaxMedical

endo
control

UroMems

SURGIQUAL
INSTITUTE

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Antherieu G., Barbier G., Bijar A., Berar M., Bluteau J., Buchaillard S., Bucki M., Chabanas M., Chekhchoukh A., Chenu O., Chouly F., Deram A., Galdames F., Gérard J.M., Jeannin C., Leroy A., Lobos C., Luboz V., Marécaux C., Mozer P., Nazari M., Nesme M., Perrier A., Pinsault N., Robineau F., Tissot F., Tong C., Vazquez J.

- Clinicians:

Becquet G., Bettega G., Boutault F., Brix M., Chartier-Kastler E., Colin D., Dubois M.D., Foong K, Grosgogeat B., Jeannin C., Letoublon C., Levy P., Marécaux C., Mozer P., Ong S.H., Palombi O., Paoli J.R., Pauget P., Prince A., Raphaël B., Richard F., Valdivia F., Voirin D.

- Co-authors:

Alonso T., Ambard D., André P.F., Bailly G., Barthod C., Boy F., Cannard F., Chagnon G., Connesson N., Coquillart S., Couteau B., Danilov Y., Demongeot J., Desbat L., Desvignes M., Diot B., Dittmar A., Elisei F., Faure F., Favier D., Fels S., Fleury A., Franco C., Gefen A., Géhin C., Gentaz E., Guenther F., Heller L., Hitschfeld N., Hlavackova P., Laboissière R., Lagrée P.Y., Lavallée S., Leloup T., Lloyd J., Loevenbruck H., Ma L., Marchal M., Marret R., Moreau-Gaudry A., Noury N., Odisio M., Ohayon J., Orliaguet J.P., Pedrono A., Pelorson X., Perkell J., Perrier P., Portnoy S., Promayon E., Rey T., Rochette M., Sanguineti V., Segaud B., Sittner P., Stavness I., Schiavone P., Swider P., Troccaz J., Van Hirtum A., Vilain C., Vogt F., Vuillerme N., Wilhelms-Tricarico R., Zandipour M.