Christian Duriez, head of DEFROST team
Research director at INRIA, FRANCE

MASTER IVI

INTERACTIVE SIMULATION

PLEASE CONNECT YOURSELF !

Modifier le Kahoot pour laisser + de temps aux étudiants !!

BACKGROUND & MOTIVATION

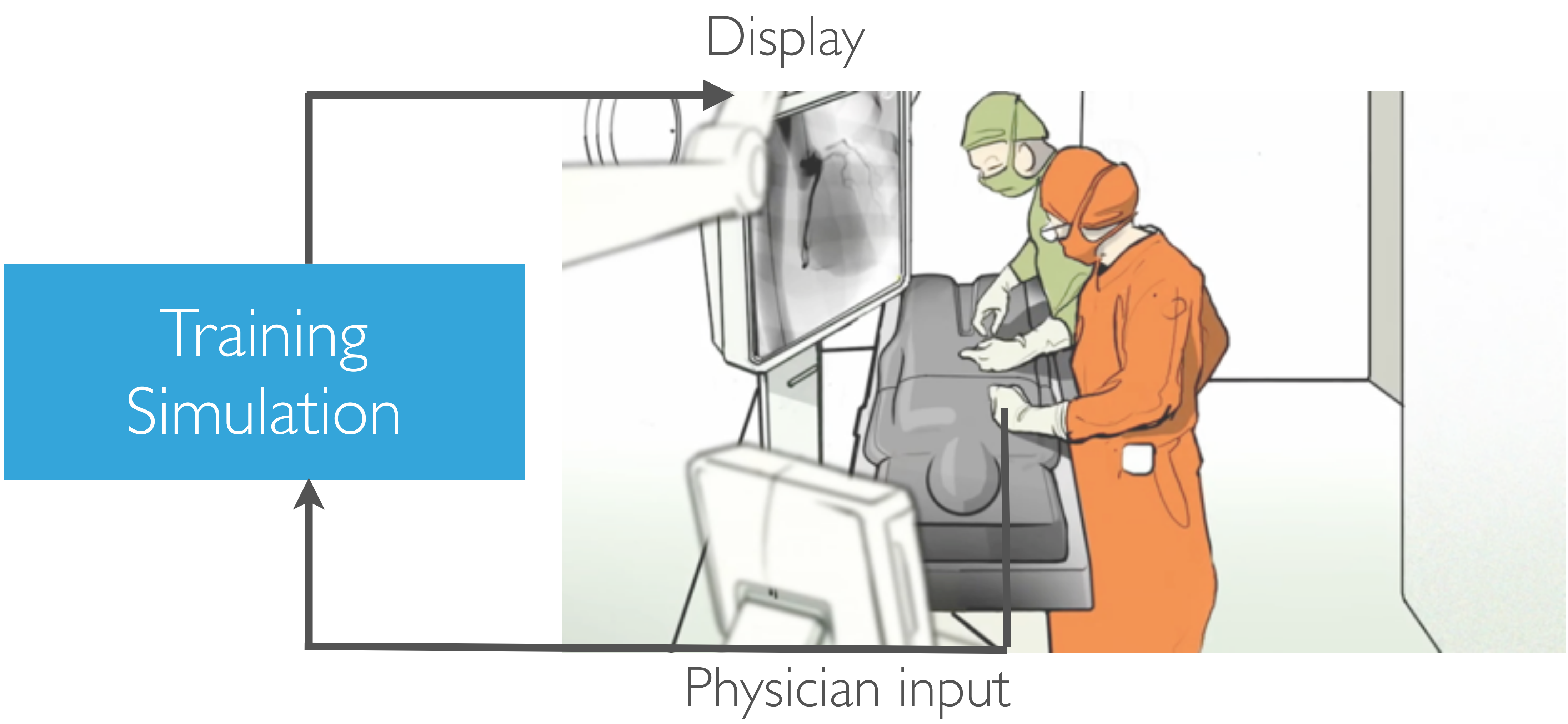
- Medical procedures: the revolution of images

- … and the coming role of simulation

Training Rehearsal & planning Per-operative guidance & Robotics

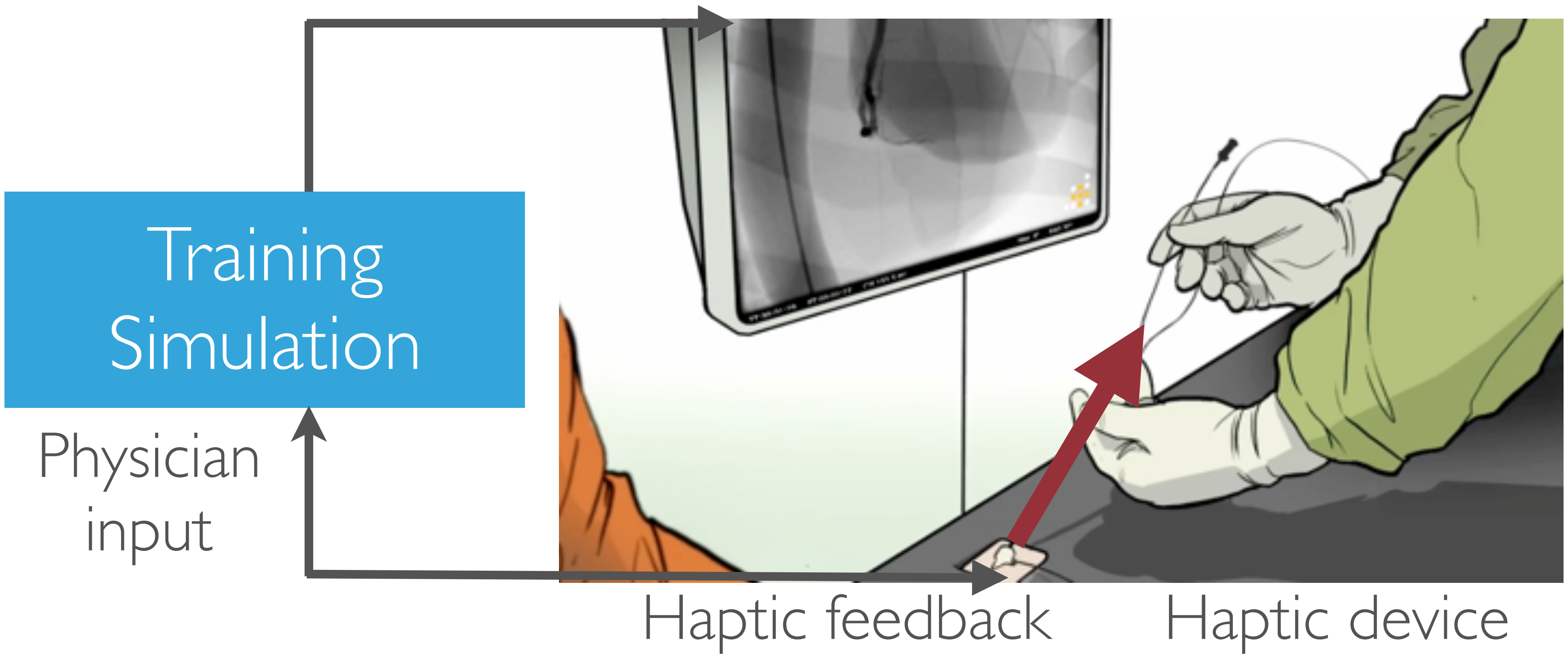
BACKGROUND & MOTIVATION

- Training



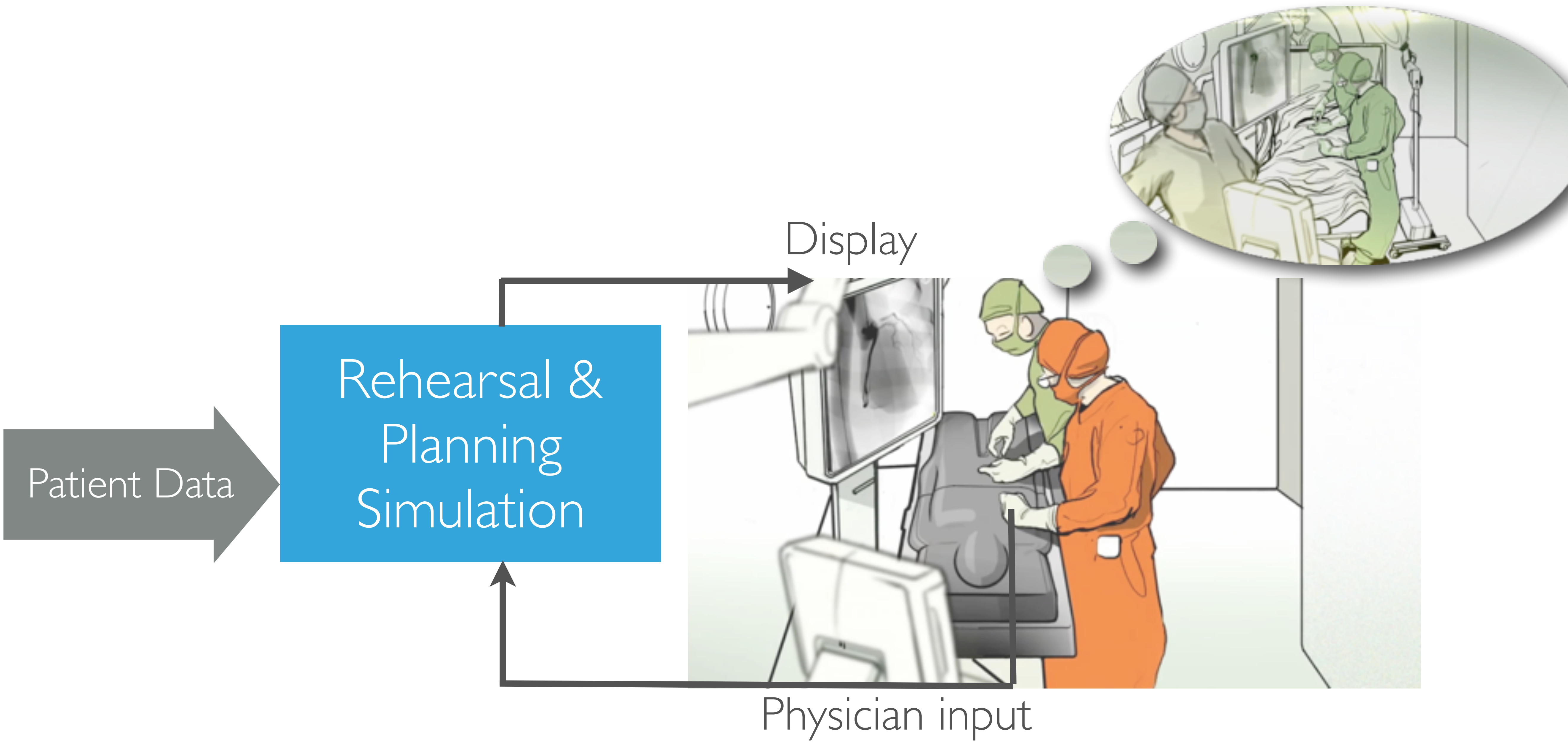
BACKGROUND & MOTIVATION

- Training



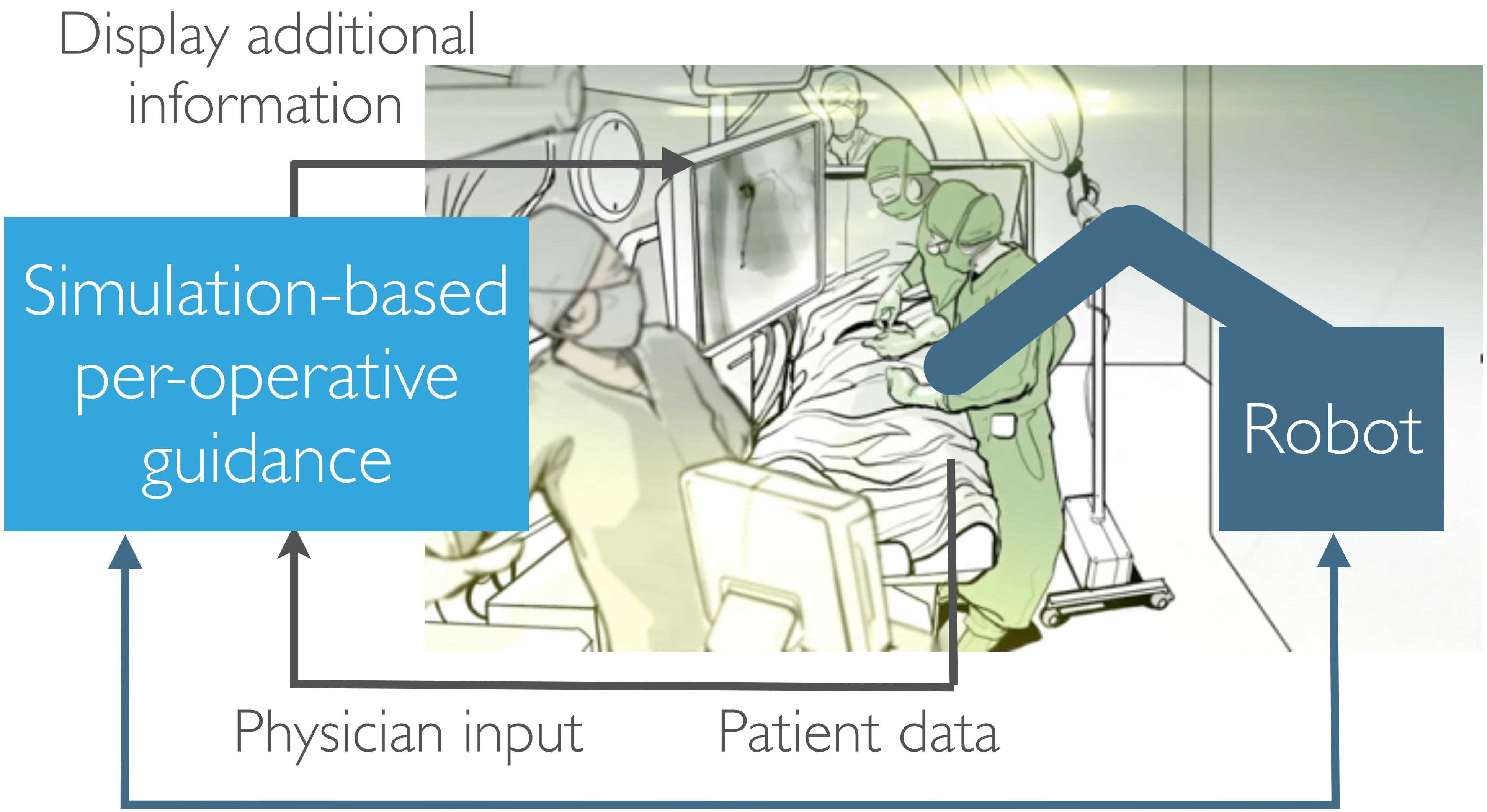
BACKGROUND & MOTIVATION

- Rehearsal & Planning simulation



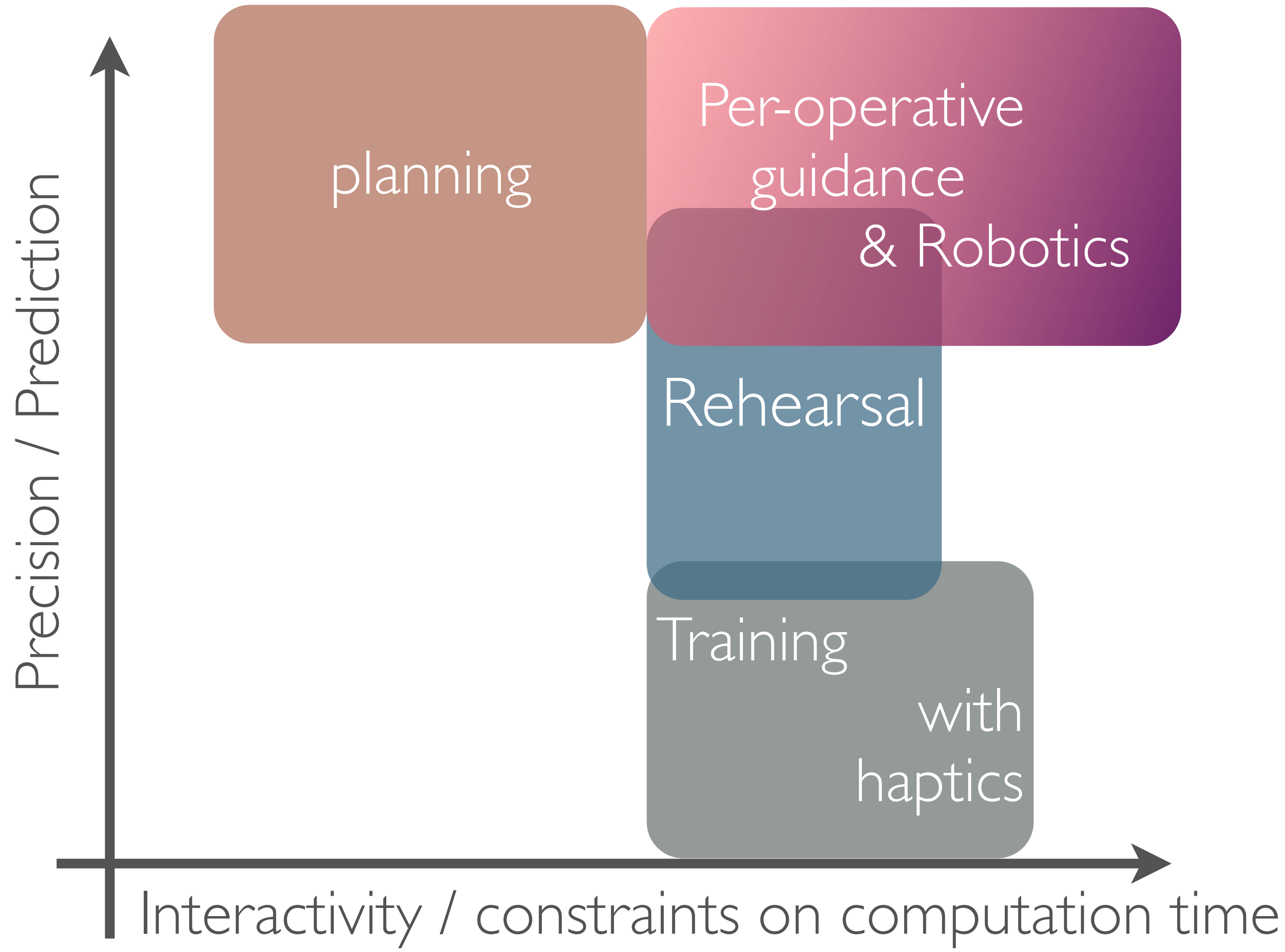
BACKGROUND & MOTIVATION

- Per-operative guidance & Robotics



ROLE OF SIMULATION

- Two humans in the loop (the physician and the patient)
- Simulations (often) need to be interactive
- Physics needs to be accurate (and even predictive)



LEADING CAUSE OF DEATH (UNITED STATES – 2010 CDC DATA)

1. Heart diseases 597,689

2. Cancer 574,743

4. Respiratory diseases 138,080

5. Cerebrovascular 129,476

6. Accidents 120,859

WHAT IS THE 3D LEADING CAUSE OF DEATH IN USA ?

What a funny QUIZ !

please connect you to https://kahoot.it

LEADING CAUSE OF DEATH (UNITED STATES – 2010 CDC DATA)

1. Heart diseases 597,689

2. Cancer 574,743

Medical errors 200,000 - 400,000

5. Cerebrovascular 129,476

6. Accidents 120,859

SURGERY SAFETY

“up to 98,000 people a year die because of hospital mistakes”
Institute of Medicine 1999
“To Err is Human: Building A Safer Health System”

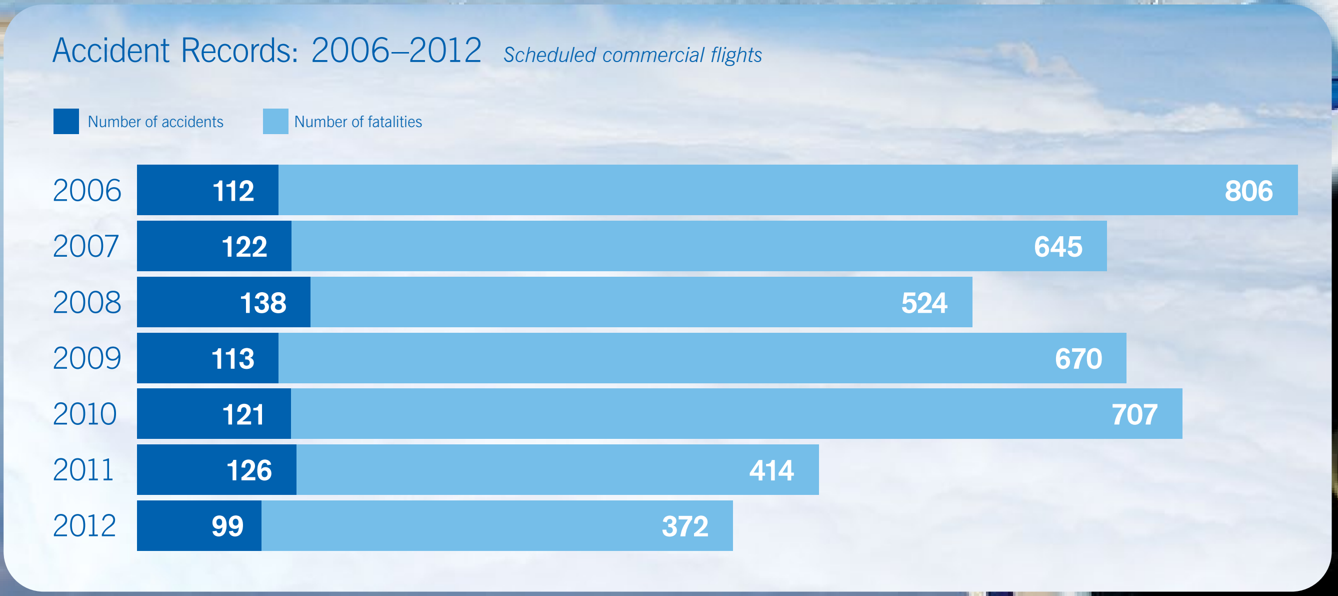
Rates of **death** following major surgery are reported to be between **0.4%** and **10%**
In the developed world, nearly **half of all harmful events** affecting patients in hospitals are related to **surgical care** and services.
The evidence suggests that at least **half of these events are preventable**
World Health Organization (WHO) 2008
"10 facts on safe surgery"

Medical errors kill enough people to fill four jumbo jets a week
The Wall Street Journal, September 2010
"How to Stop Hospitals From Killing Us"

210,000-440,000 deaths per year due to preventable harm in U.S. hospitals
Journal of Patient Safety September 2013
“A New, Evidence-based Estimate of Patient Harms Associated with Hospital Care”

2013 Safety Report

2.9 billion passengers in 2012
3.2 accidents per million departures
372 fatalities
=> Rates of **death** = **0.000013%**



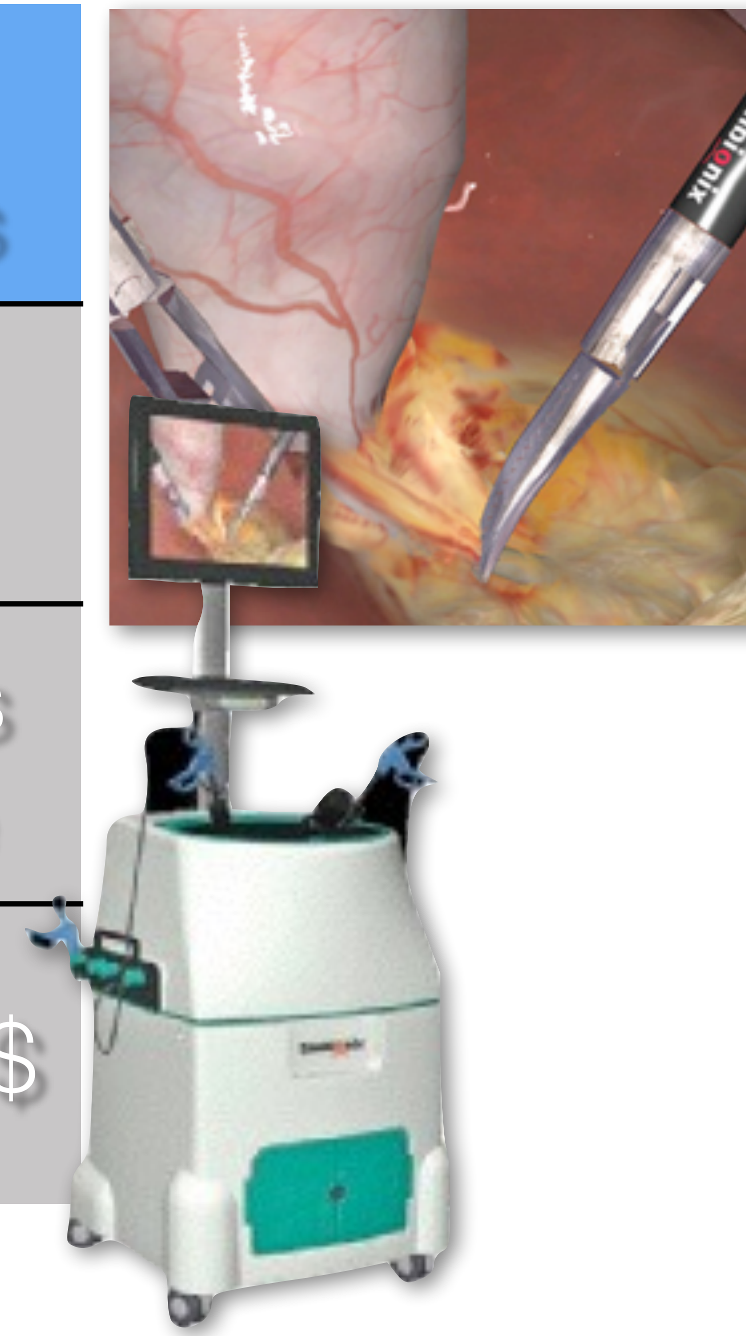
TRAINING METHODOLOGY

Pilots :
"In the **simulator**, you'll experience just about **every emergency and anomaly imaginable**. All maneuvers are practiced until they are satisfactorily completed"

Surgeons :
"**apprenticeship** with progressive transfer of patient care responsibilities and graded autonomy in the OR"

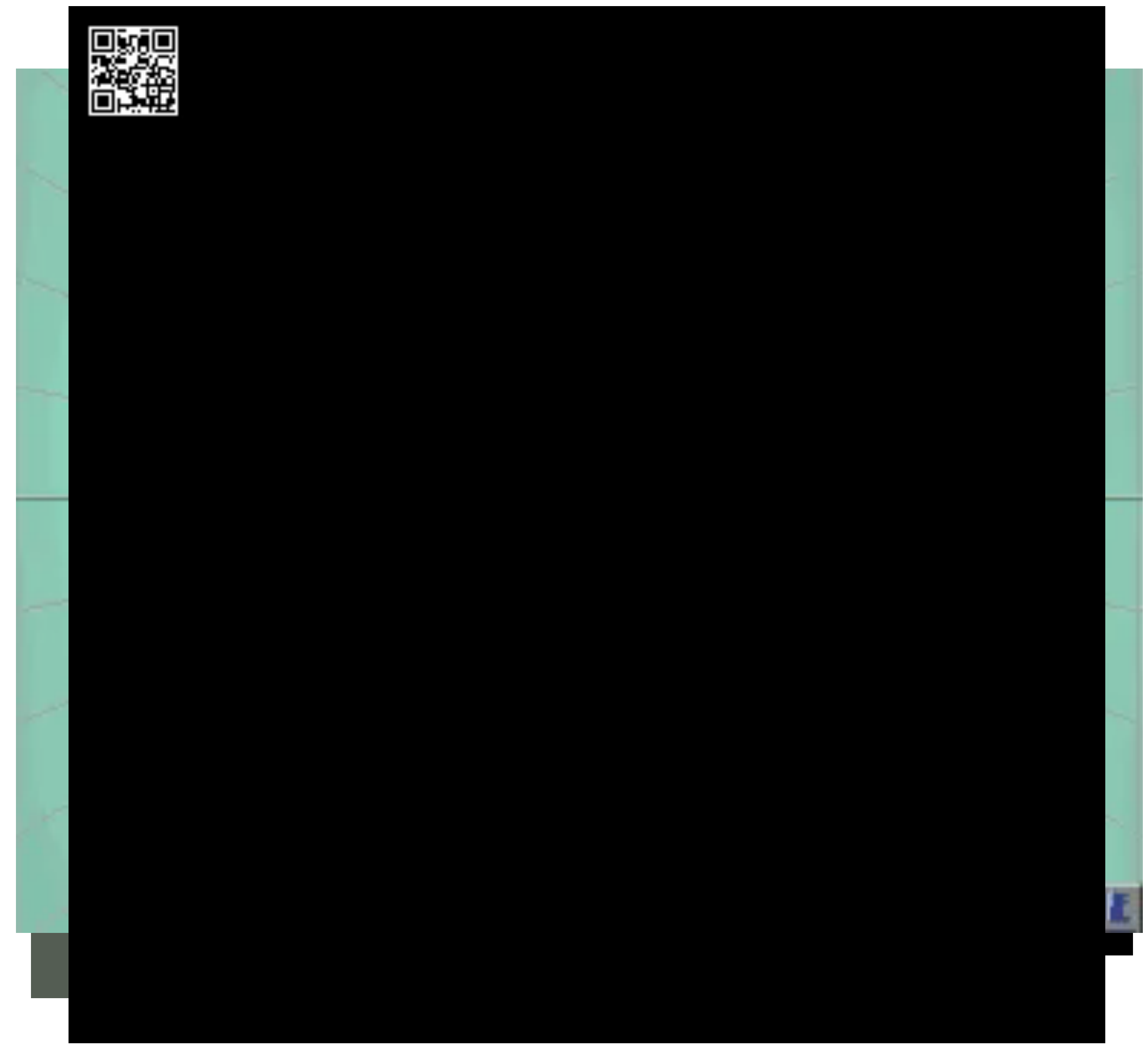
SIMULATORS

Flight Simulators	Surgery Simulators
Immersive	Limited Realism
Exhaustive emergencies	Basic skills Ideal case
20 M$	0.1 - 0.2 M$



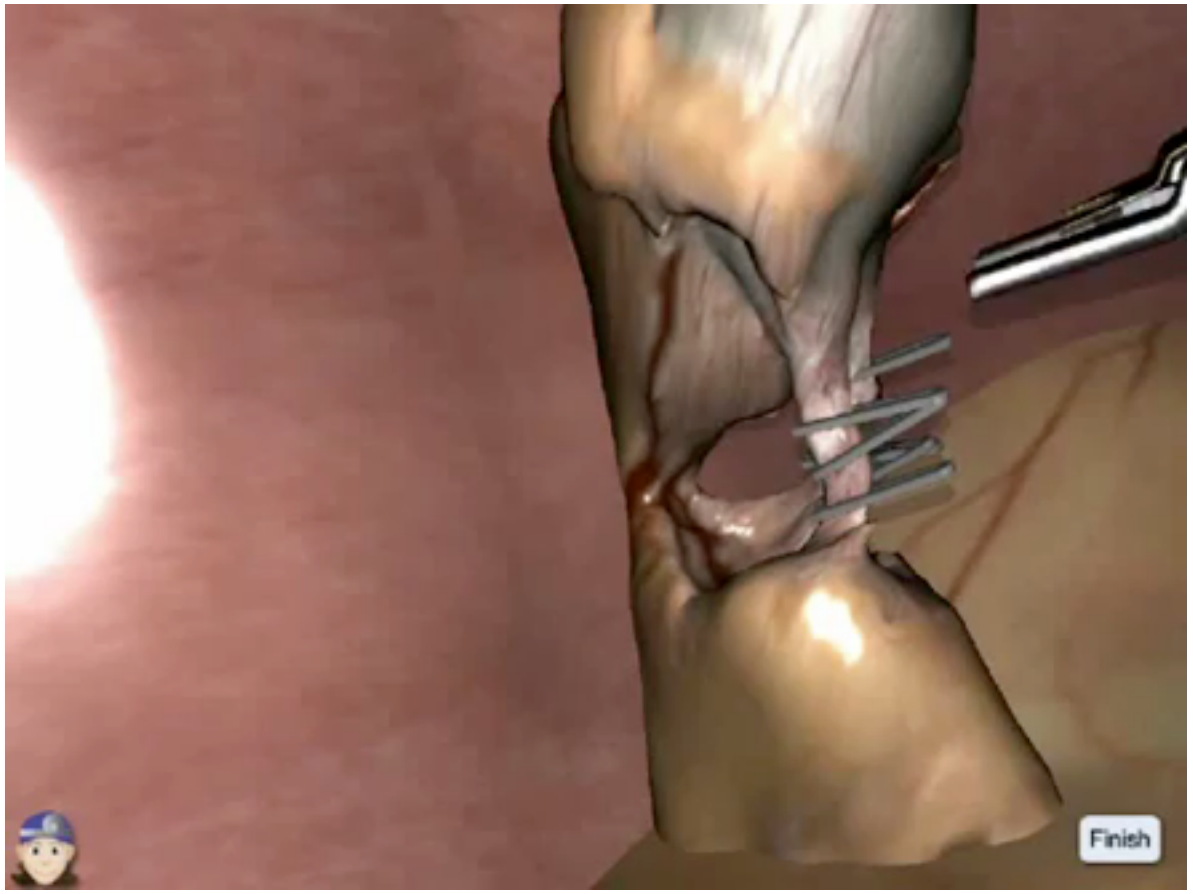
EXAMPLES OF COMMERCIAL SIMULATORS

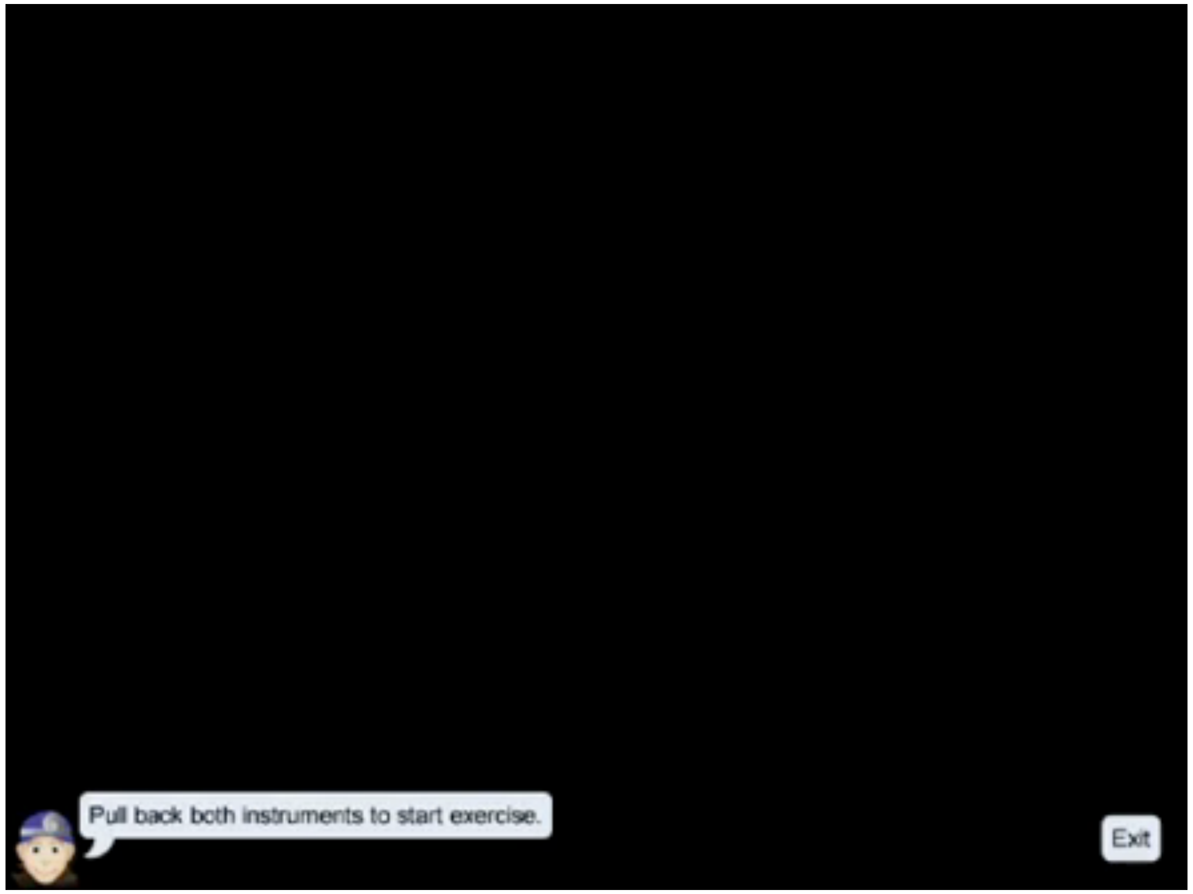
- Computer-based training
- MIST-VR: generic skills training system
- Mentice: neurovascular simulation
- Virtamed: gynecology simulation
- Virtual Magic: eye surgery simulation



- More companies: CEA healthcare, Moog, Surgical Science, Touch of Life…
- All these companies are focussing on simulation for training

DESIGNED LIKE GAMES (LEVEL 1 / LEVEL 2, ETC…)





source: *Cholecystectomy procedure* Surgical Science

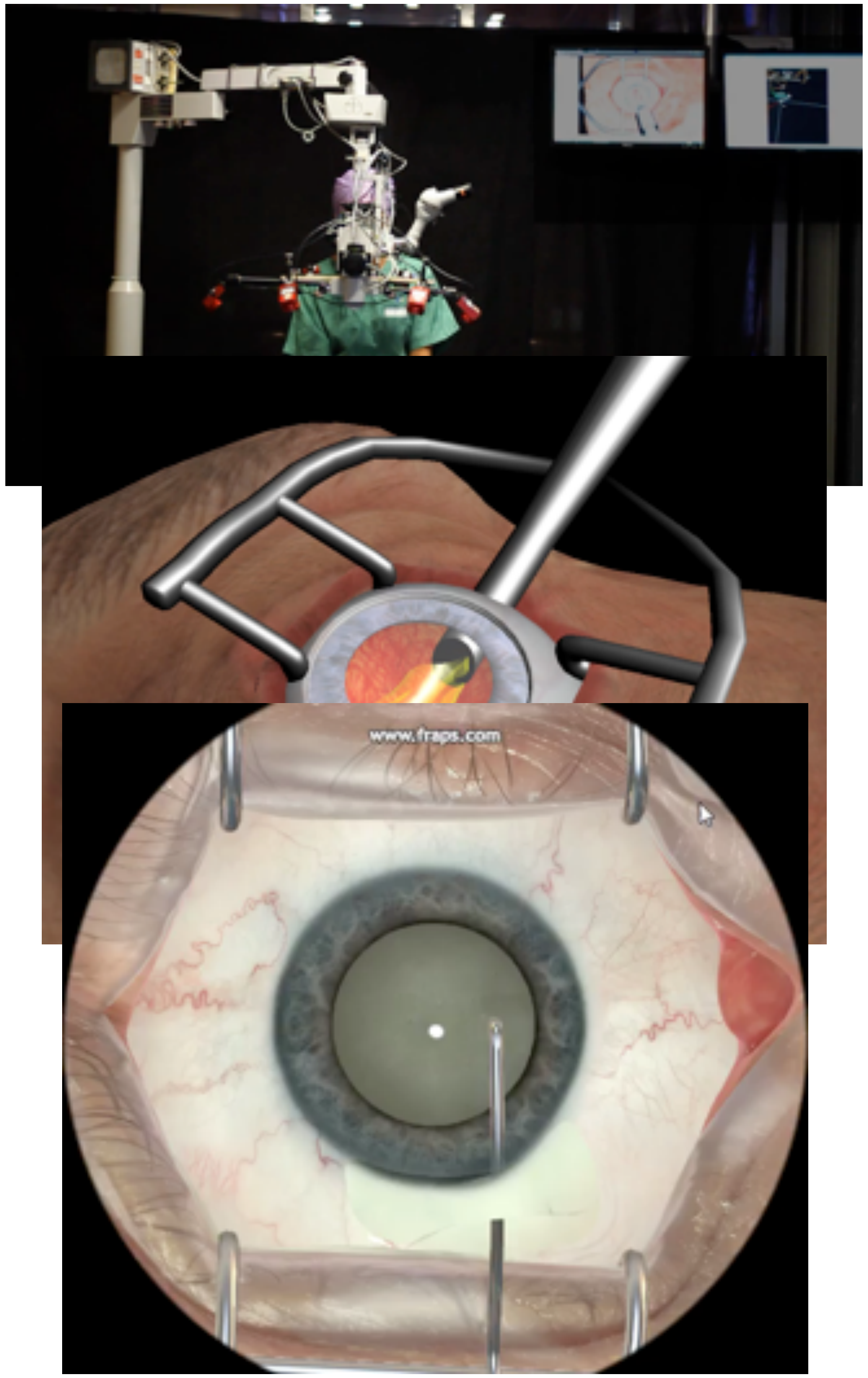
IMPORTANCE OF REALISM

- **Ideal surgical simulator ≠ scripted game**
  - Limited possible precomputation
  - Should allow for mistakes…
- **Modeling the behaviors**
  - For both tools and soft tissues
  - Interactions between anatomical structures
- **Tool-tissue interaction realism**
  - Post interaction deformation
  - Behavior of the instruments
  - Haptic rendering

- **… NEED OF PHYSICS & REAL-TIME !**

CATARACT SIMULATION EXAMPLE

- Phacoemulsification technique
  - Only one commercial simulator available (EyeSi)
  - Importance of the hardware
  - Simulation of lens implant injection
- MSISC (HelpMeSee project)
  - Very realistic simulator: aims at replacing a good part of the conventional learning.
  - Project moving from Inria to inSimo (start-up focus on medical simulation)

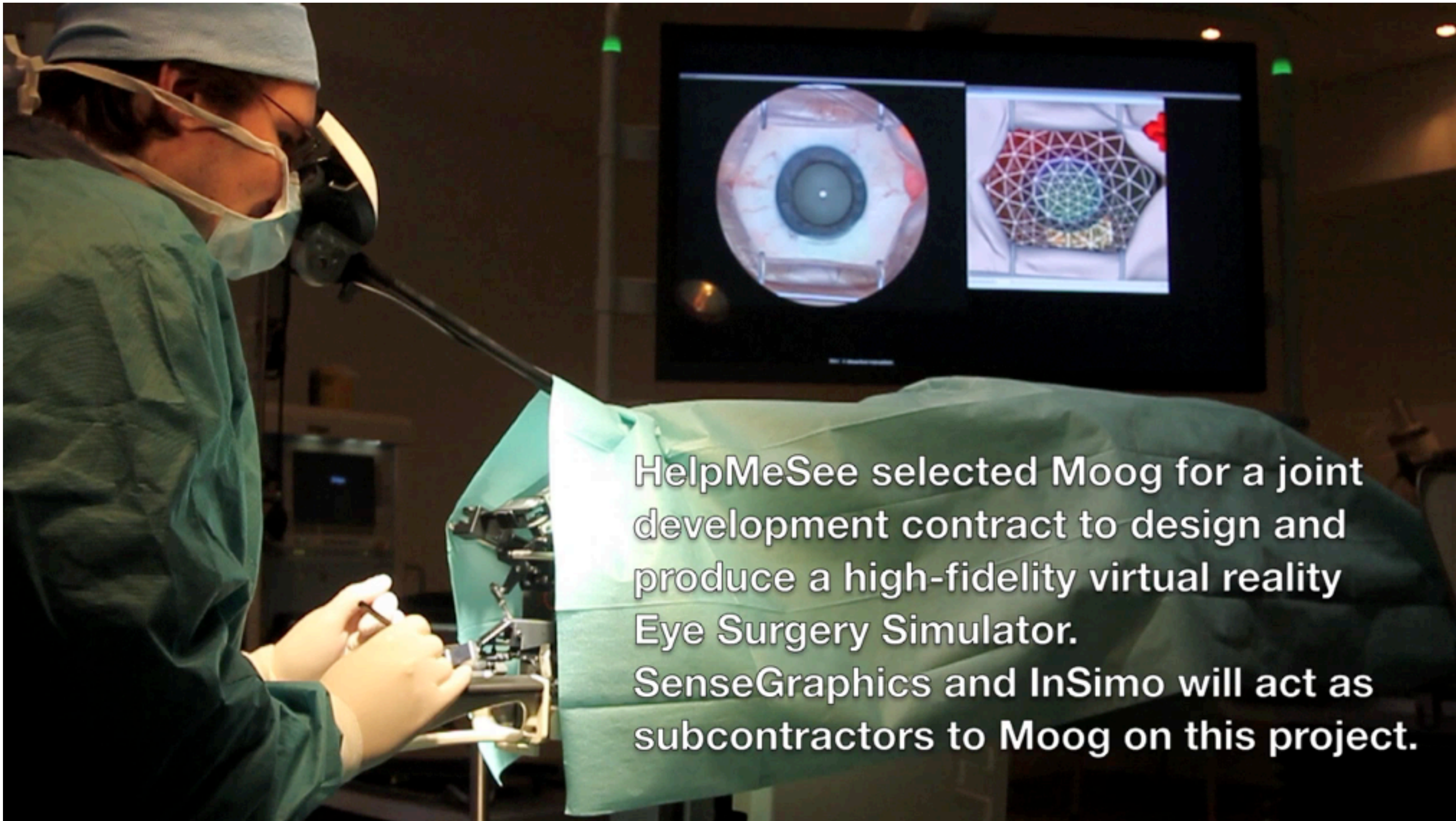


CATARACT SIMULATION EXAMPLE

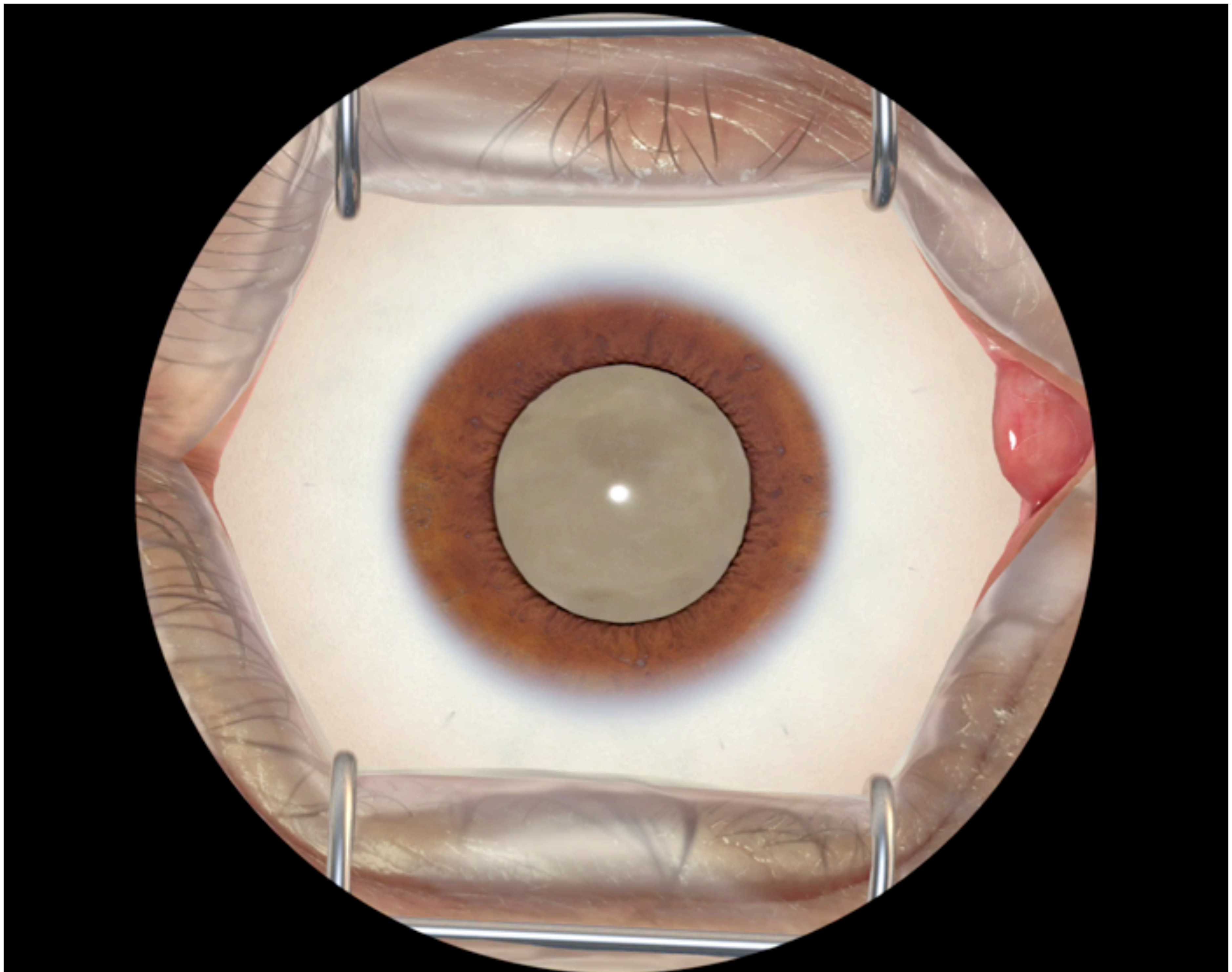
http://helpmesee.org

CATARACT SIMULATION EXAMPLE

http://youtu.be/kE33G0awe_0



CATARACT SIMULATION EXAMPLE



MAIN TOPICS ON INTERACTIVE & PHYSICS BASED SIMULATION

- Mechanical models for real-time computation
- Constraint-based modeling of mechanical interactions
- Haptic rendering & control
- Applications (games, medecine, robotics…)

Jonathan Pepe

MECHANICAL MODELS FOR REAL-TIME COMPUTATION

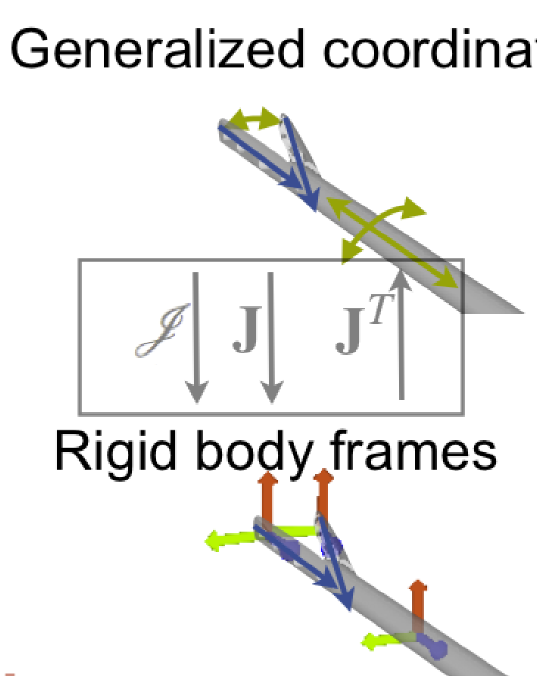
RIGID VS. DEFORMABLE MECHANICS

QUIZ !

How many degrees of freedom for the following objects ?

RIGID VS. DEFORMABLE MECHANICS

- Articulated Rigid Models
  - Geometry based model
  - Kinematics (Jacobian)



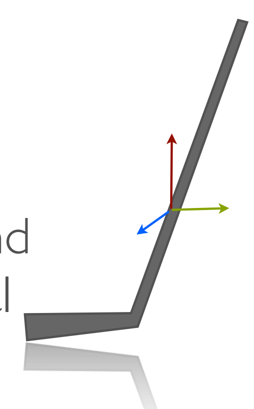
  - Dynamics

$$\mathbb{M}(\mathbf{q})\dot{\mathbf{v}} = \mathbb{P}(t) - \mathbb{F}\left(\boxed{\mathbf{q}}, \mathbf{v}\right)$$

Mass, Inertia

Gravity

Coriolis and centrifugal Forces



- Deformable models

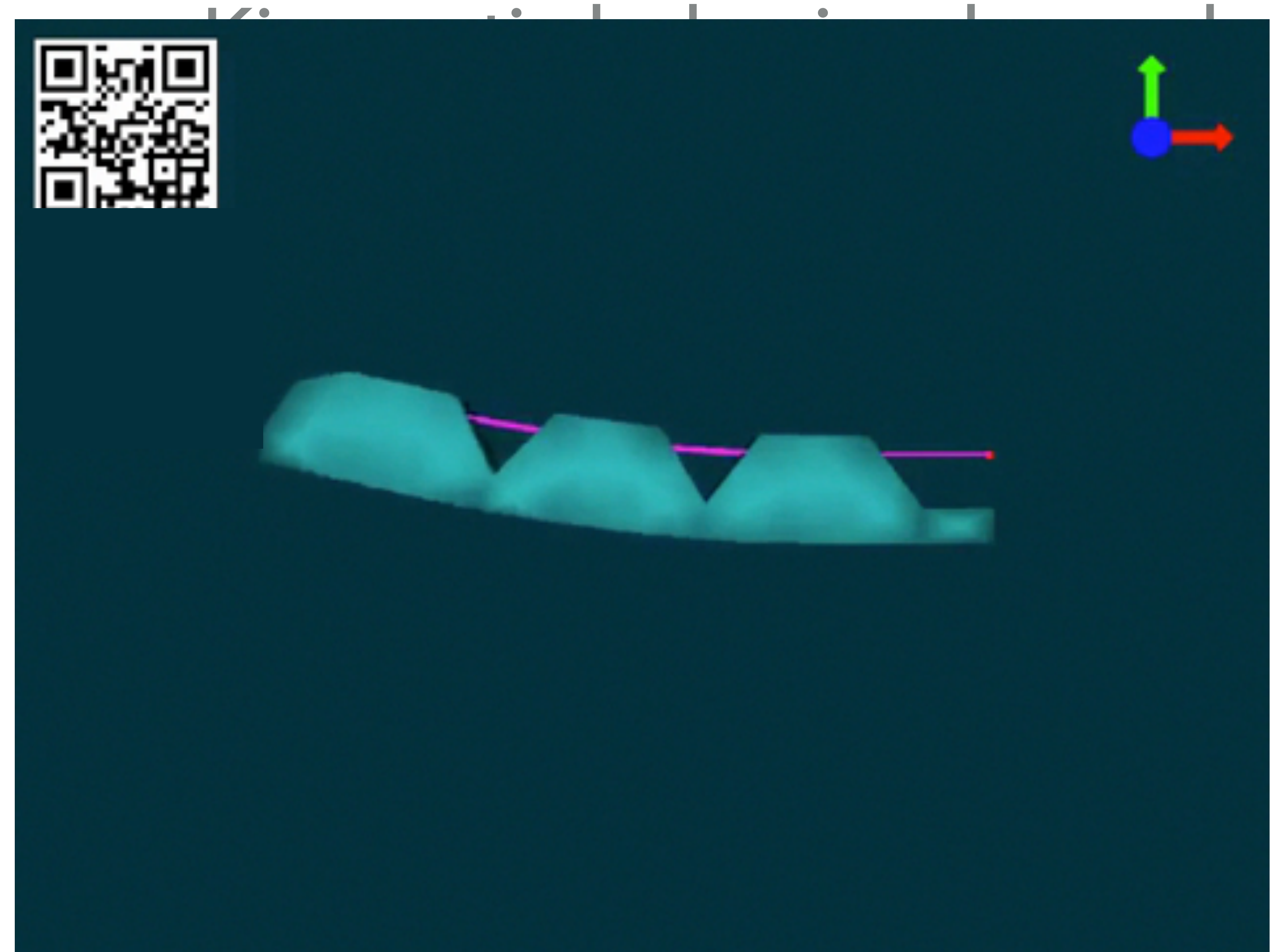
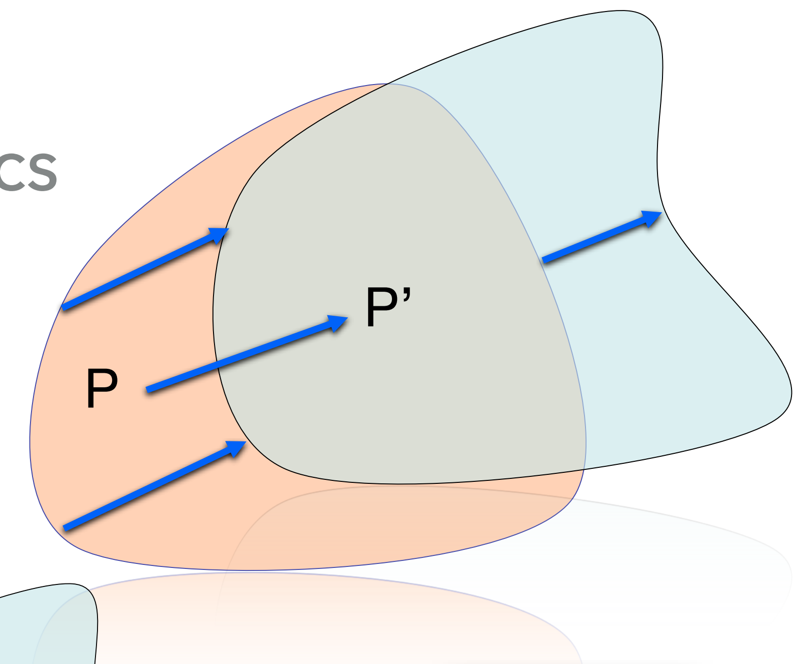
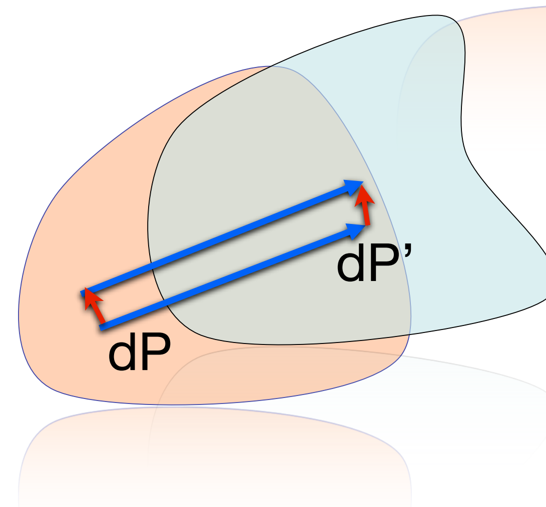


Figure 4. *Kinematic behavior depends on material properties.*

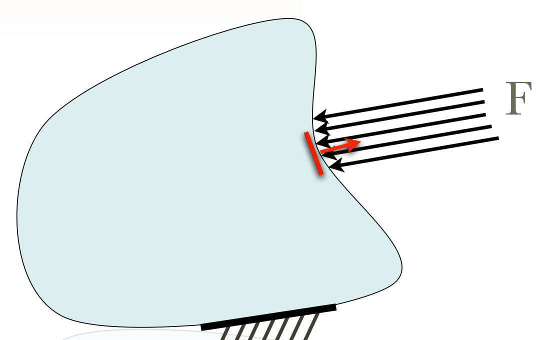
CONTINUUM MECHANICS

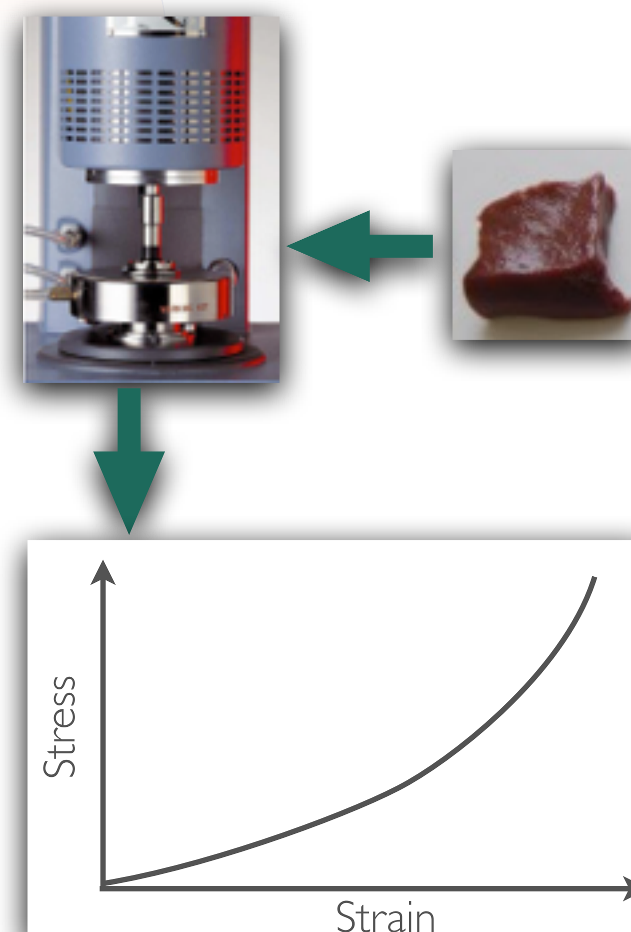
- Hypothesis: « Total Lagrangian » mechanics
  - « Continuity » of the material
  - Infinite number of points
  - A reference domain





  - Use of partial derivatives
  - Strain tensor
    - ~ Geometrical or Kinematic Model



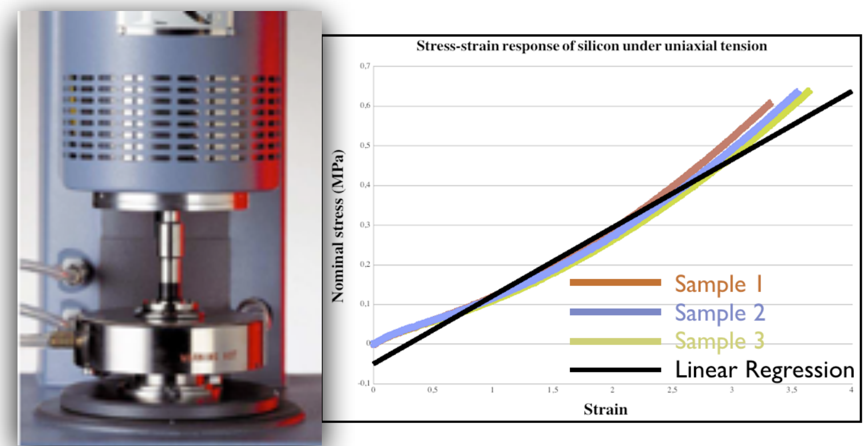


  - Use measurements (Physics)
  - Stress tensor
    - ~ Provide a notion of internal pressure due to deformation
    - Need to be in equilibrium with external forces

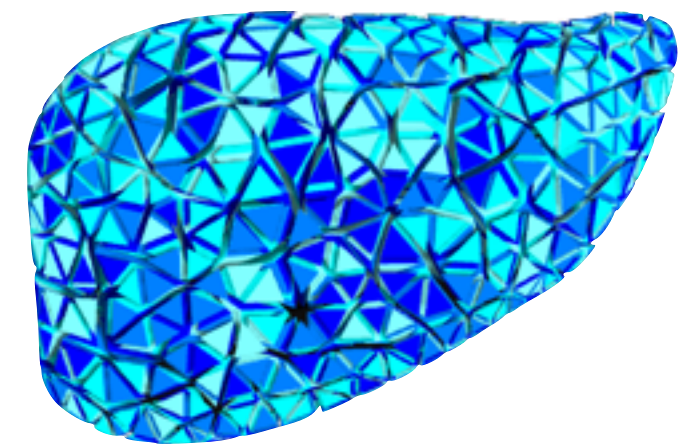
NUMERICAL METHOD

- FEM model

Soft tissue



Constitutive law



FEM mesh

- Newton's second law

$$\mathbb{M}(\mathbf{q})\boxed{\dot{\mathbf{v}}} = \mathbb{P}(\boxed{t}) - \mathbb{F}\,(\mathbf{q},\boxed{\mathbf{v}}) + \boxed{\mathbf{H}^T\lambda}$$

$\mathbf{q} \in \mathbb{R}^n$ Vector of generalized degrees of freedom (nodes of a deformable model)

$\mathbf{v} \in \mathbb{R}^n$ Vector of velocities

$\mathbb{M}(\mathbf{q}) : \mathbb{R}^n \mapsto \mathcal{M}^{n\times n}$ Inertia Matrix

$\mathbb{F}\,(\mathbf{q},\mathbf{v})$ Internal forces (non-linear model)

$\mathbb{P}(t)$ External forces

$\mathbf{H}^T\lambda \in \mathbb{R}^n$ Constraint force contribution

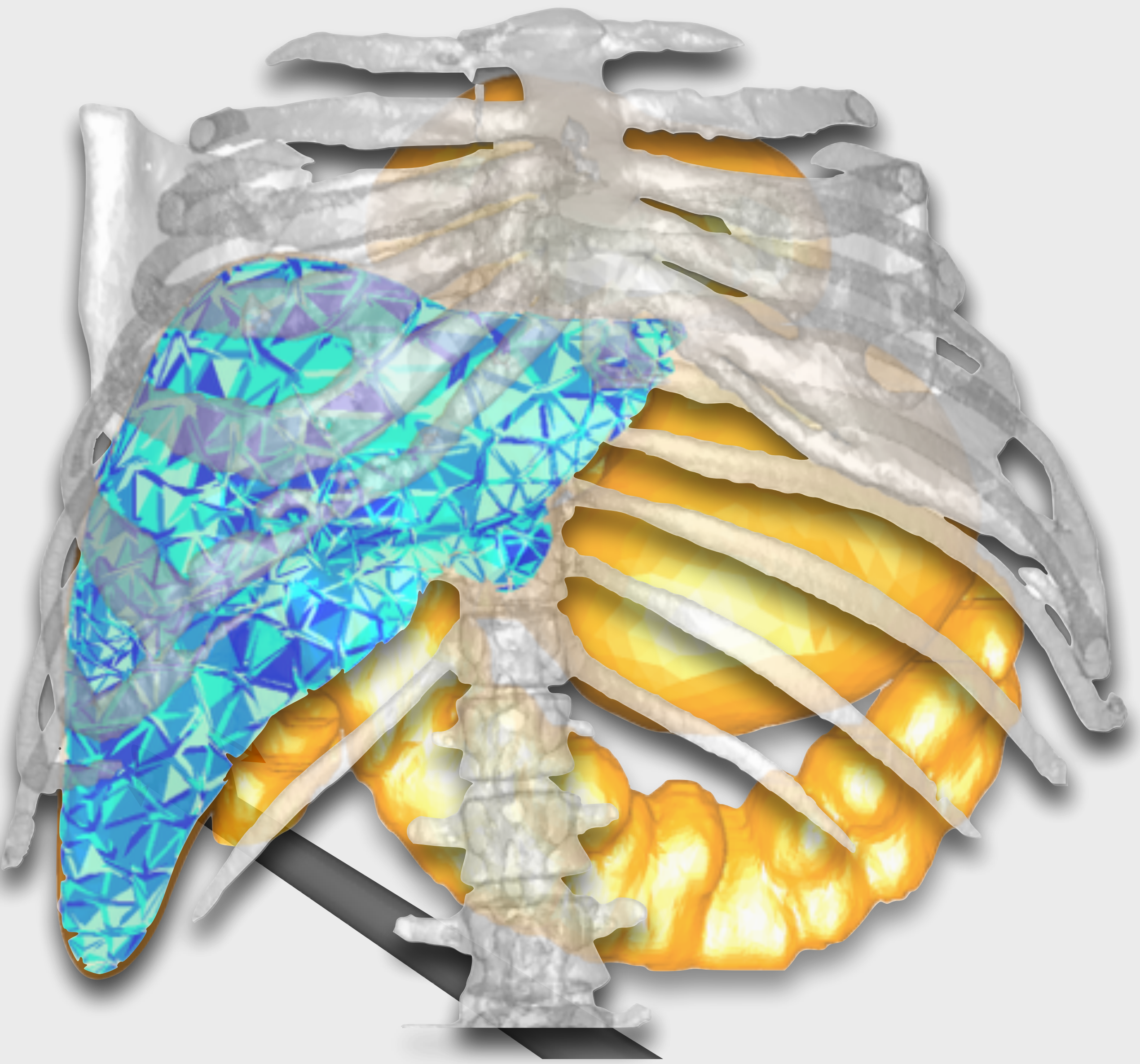
REAL-TIME INTEGRATION

- Interactive Simulation = the physician can modify the course of the simulation
- Time derivatives in model equation = integration scheme (notion of time step…)
- Between these two steps, the user do a certain motion in a REAL interval of time
- The time elapsed in the simulation must be EQUAL to the REAL interval of time

$h = dt$

$t + h$

$t + dt$



CONSTRAINT-BASED MODELING OF MECHANICAL INTERACTIONS

COLLISION RESPONSE

QUIZ !

What will happen in a few ms ?

COLLISION RESPONSE

A non-smooth event !

V- <0 before impact and V+ >0 after impact.. between them, an infinite small time step

COLLISION RESPONSE

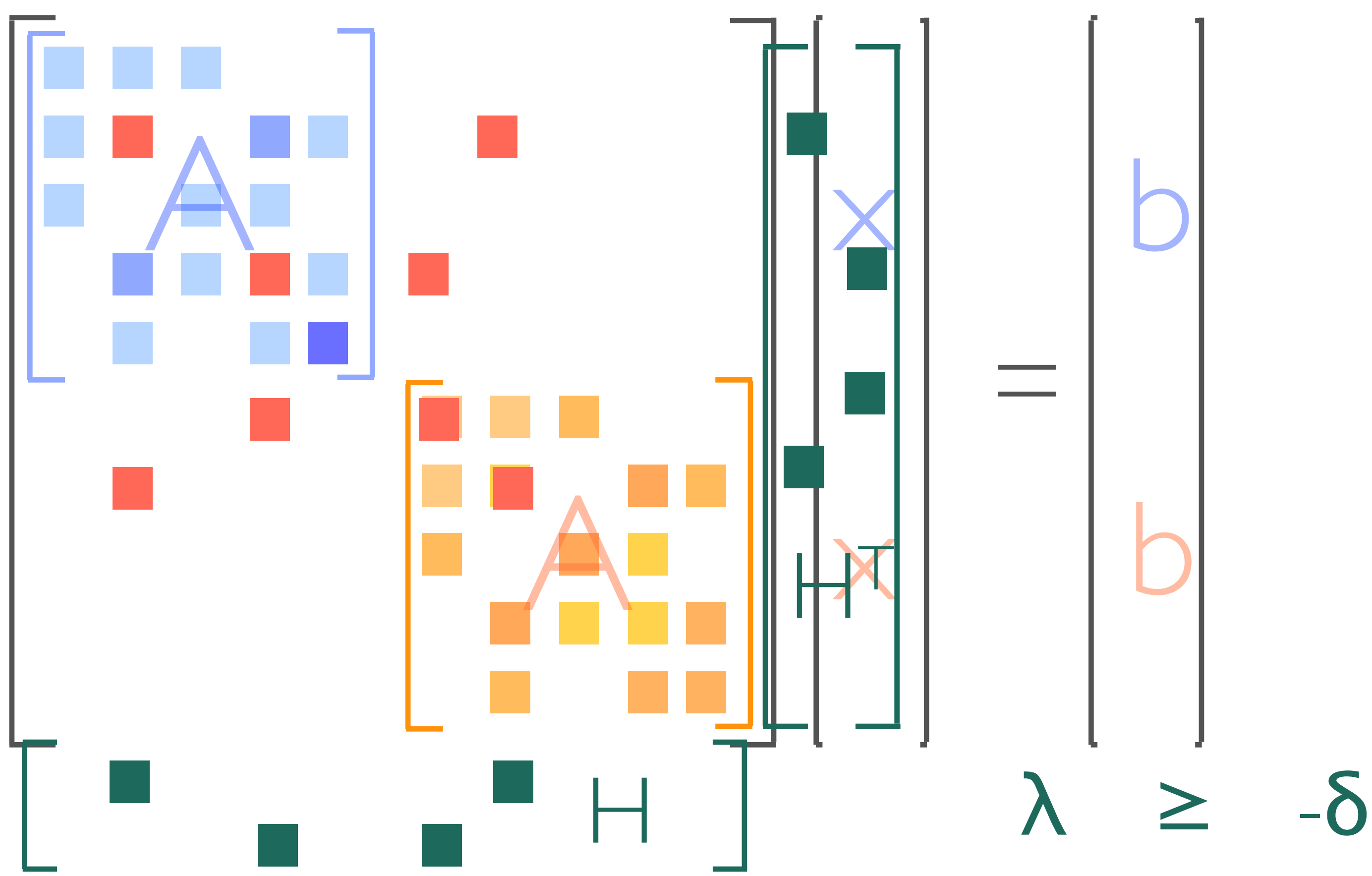
- Why important ?
  - Boundary conditions between anatomical structures
  - Device-tissues interactions
- Why difficult ?
  - Non-smooth events
    - Time-stepping : impulse formulation

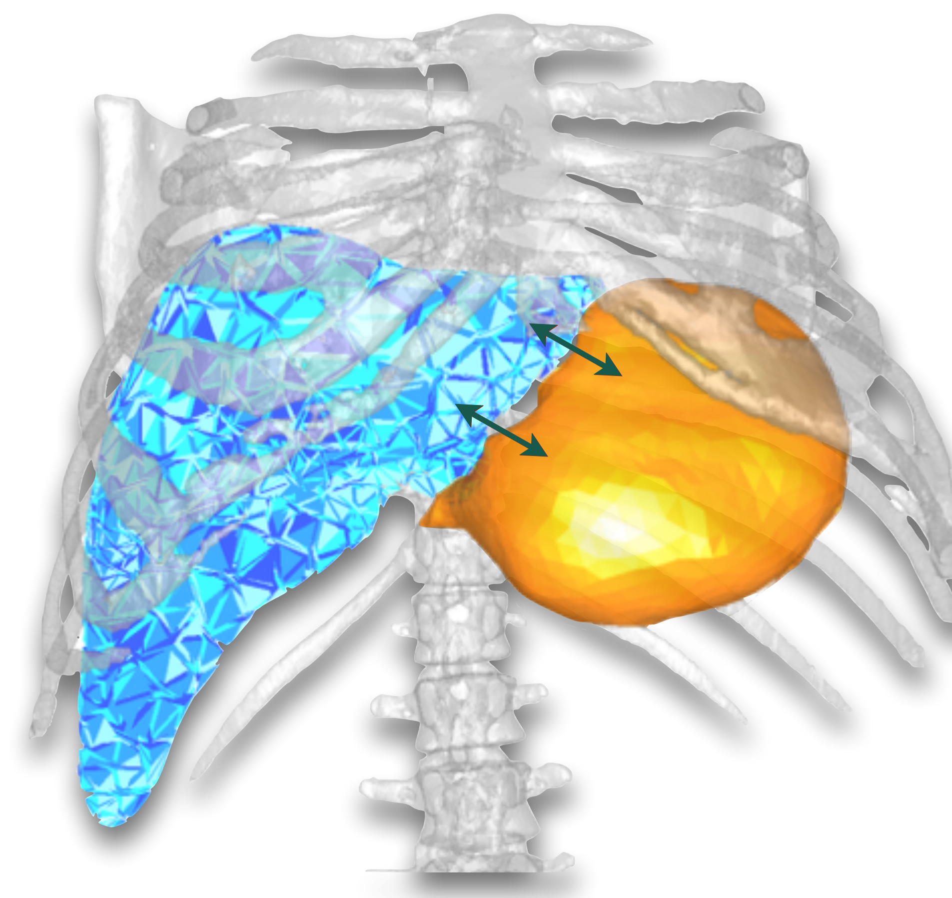
$$\begin{aligned} \mathbf{M}(\mathbf{v}_f - \mathbf{v}_i) &= h\left(\mathbb{P}(t_f) - \mathbb{F}(\mathbf{q}_f, \mathbf{v}_f)\right) \boxed{+\; h\mathbf{H}^T \lambda_f} \\ \mathbf{q}_f &= \mathbf{q}_i + h\mathbf{v}_f \end{aligned}$$

    - Event driven: stop the simulation at each new collision
  - Multi-Contact / Multi-Constraint response
    - Contact: Signorini's law (linear inequalities)
    - Friction: Coulomb's law (non-linear inequalities)
    - Many other interactions… (Complex anatomical and mechanical links between organs, Specific interactions for some devices)

INTERACTION BETWEEN TWO DEFORMABLE MODELS

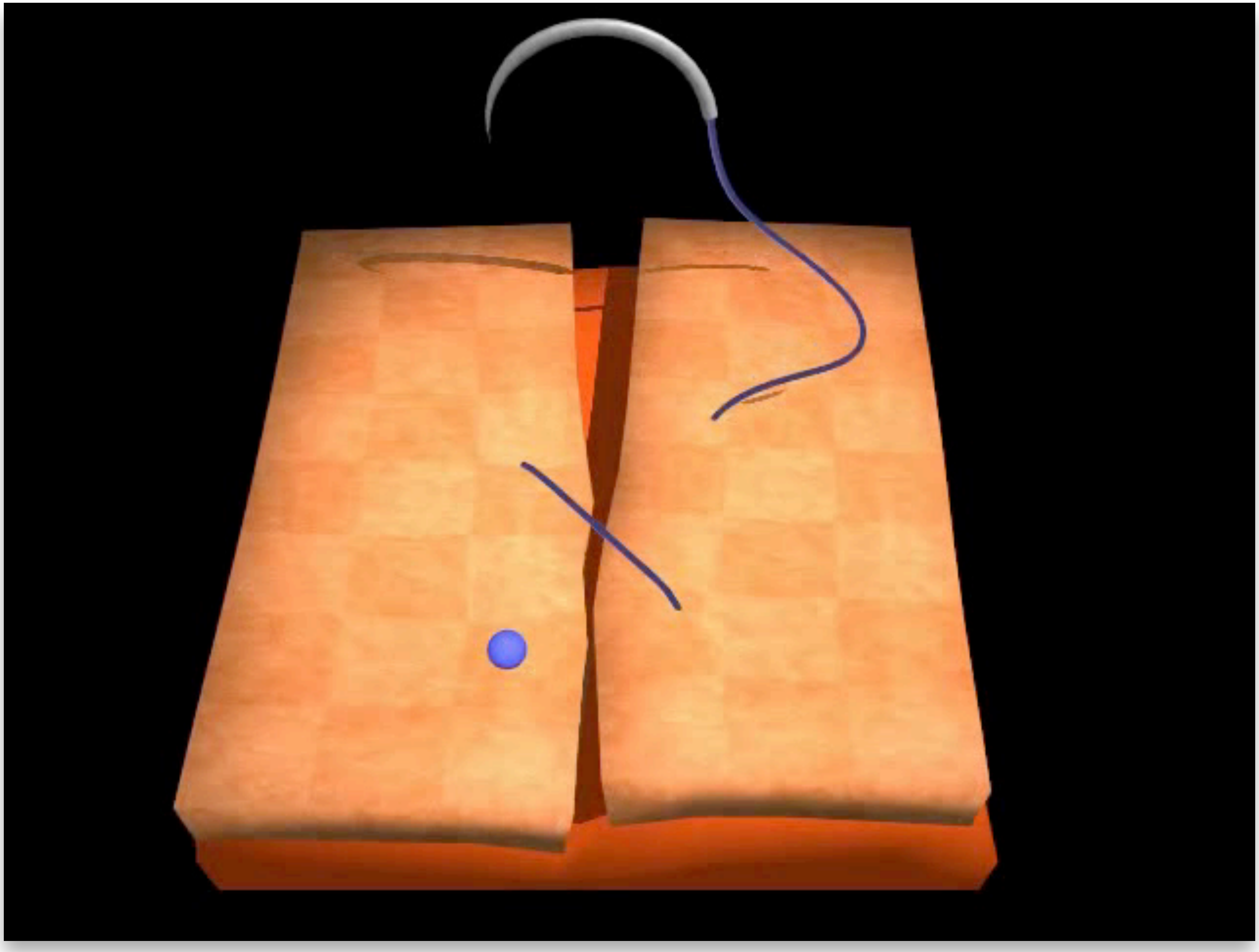
- 2 system of equations A x = b for each object
- Modeling interaction
  - Modeling the link between the models
  - Increases the size of the problem





Direct approach

EXAMPLE OF INTERACTION: SUTURE SIMULATION



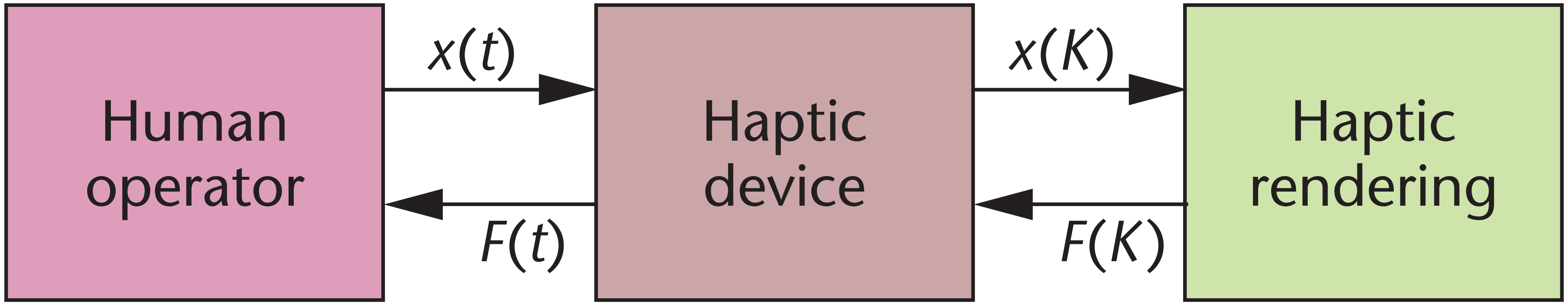
HAPTIC RENDERING

IMPORTANCE & PARTICULARITY OF HAPTIC FEEDBACK

- Visual & Audio channels = unidirectional information
- Haptic modality = bidirectional
  - Information exchange
  - Energy exchange

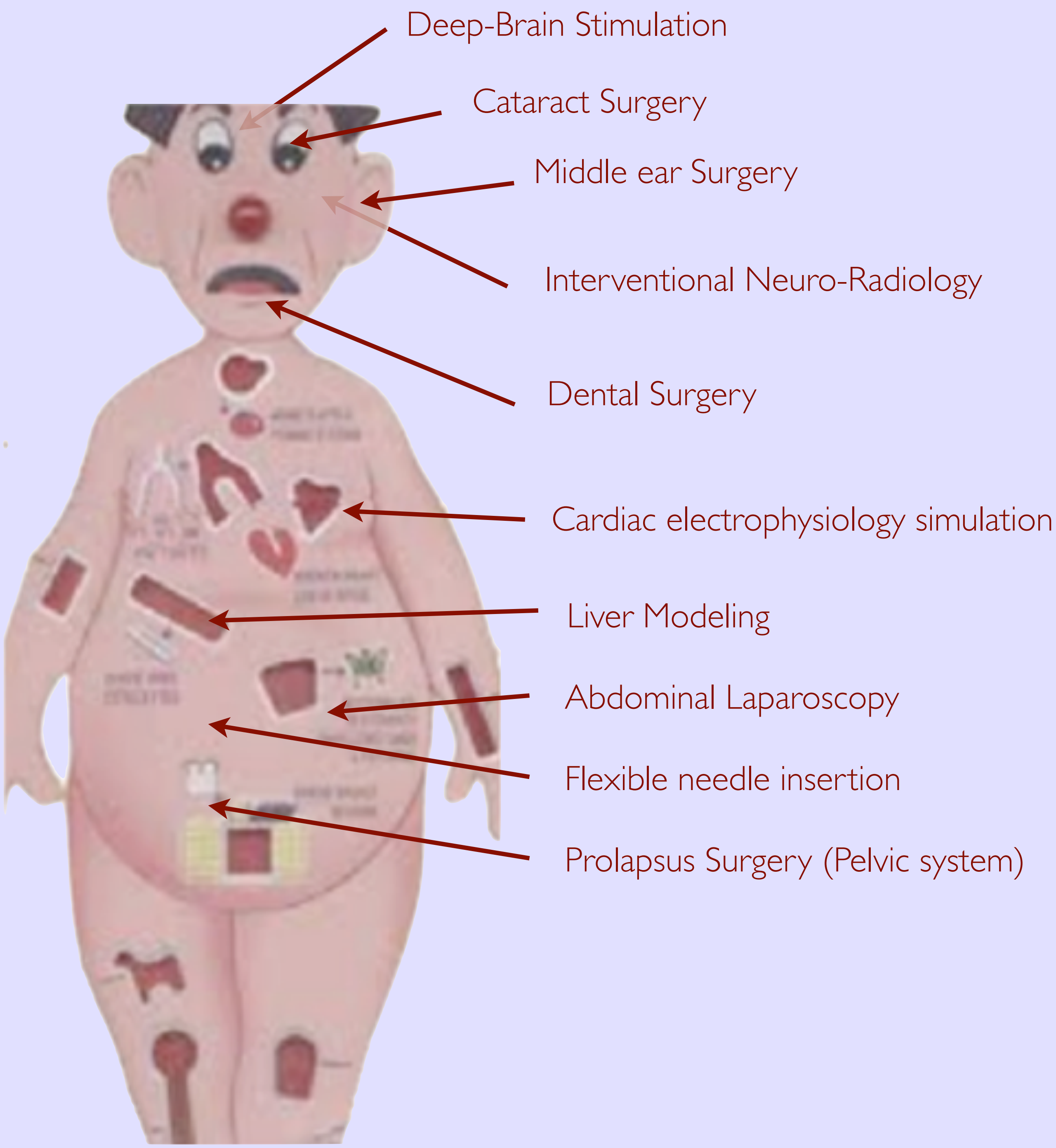
Incredulity of Saint Thomas, Le Caravage

THE USER IS IN THE LOOP !!!



HAPTIC RENDERING ISSUES

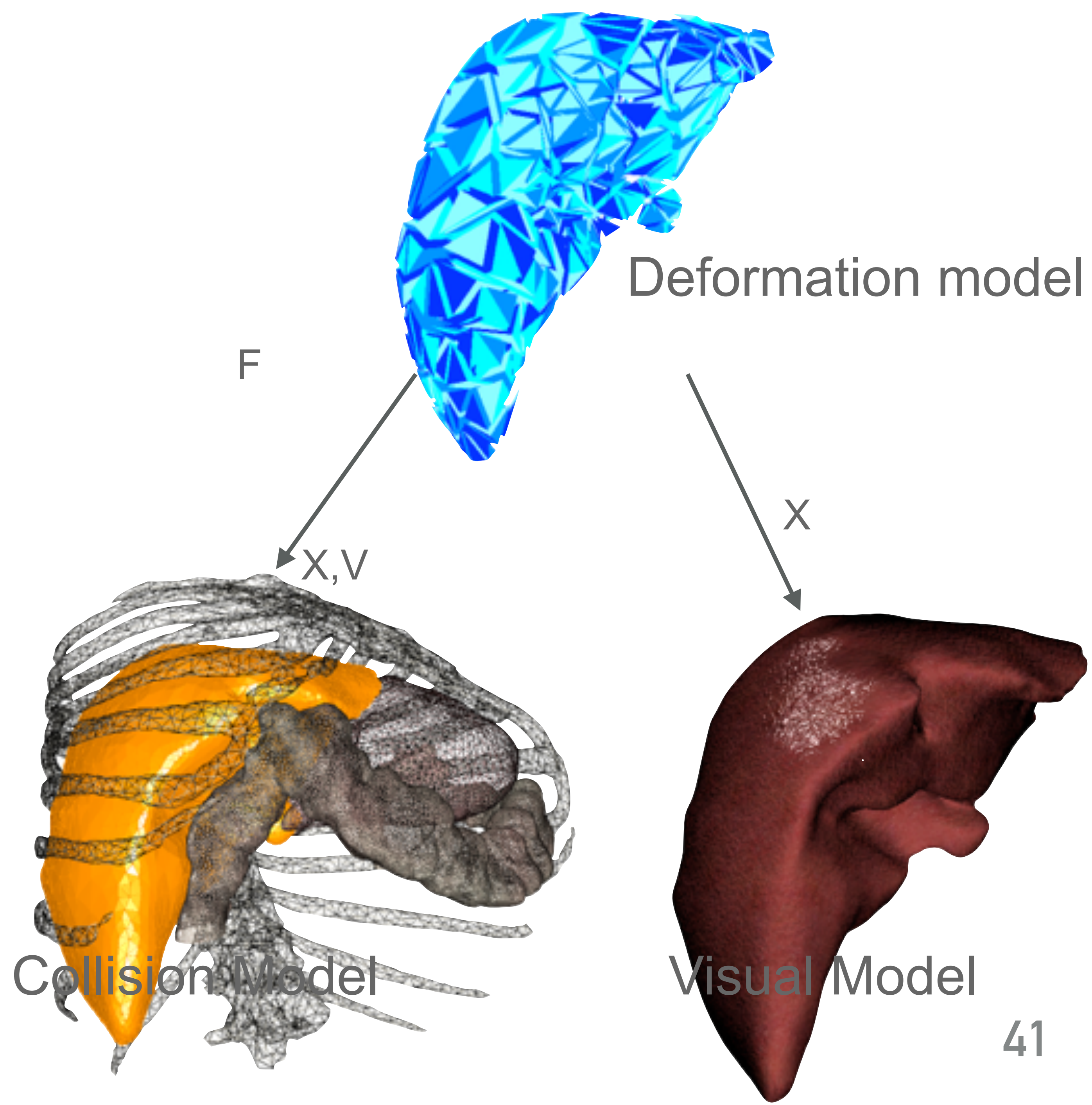
- **Stability**: Haptic device is a robotic arm !! The control must be stable
  - When coupling, both simulation and control must be stable !
- **Transparency**: the force that is transmitted to the user is supposed to be the actual force, computed in the simulation
  - Computation of forces in the simulation must be correct + the control should not perturb the rendering



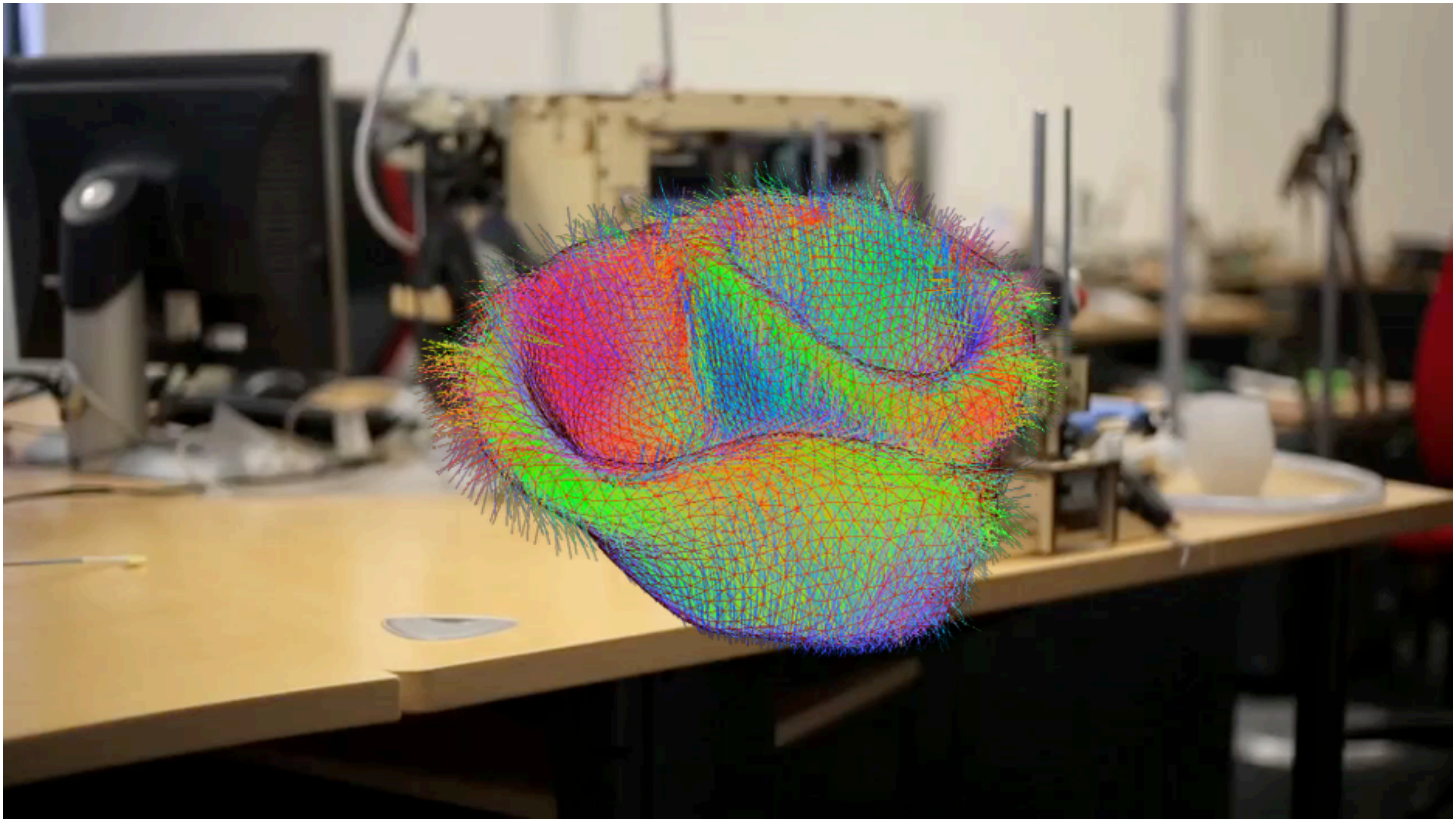
SOME APPLICATIONS

SOFA-FRAMEWORK

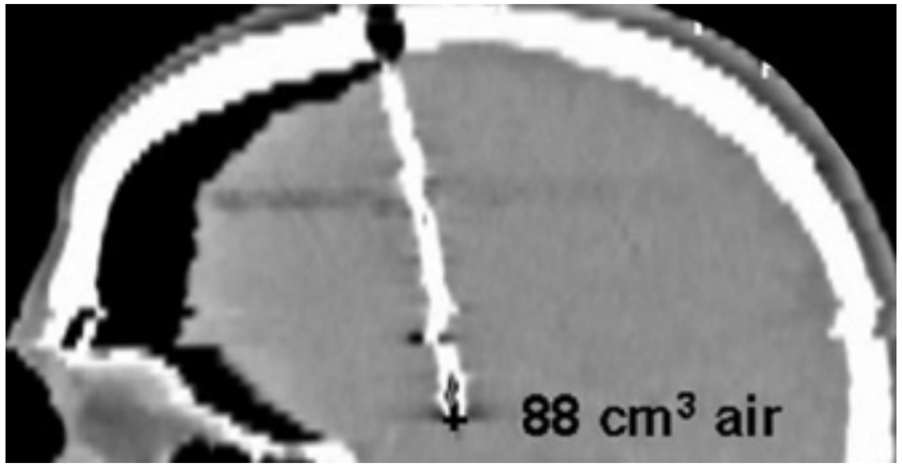
- SOFA is a framework for interactive medical simulation
  - Open source (LGPL Licence)
  - Separate components to allows for adding new algorithms more easily
- SOFA-community and network
  - SOFA was downloaded more than 139000 times.
  - 75 contributors (with 40 active in 2013)
  - Many research team are using SOFA: TIMC (France), IRCAD (France), CSIRO (Australie), ICL (UK), Kitware (USA), Bandung Institute of Technology (Indonesia), KIST & KAIST (Korea) TU-Berlin (Germany), Technicka univerzita vo Zvolene (Slovakia), Universidad de las Ciencias Informaticas (Spain), University of Twente (Netherland), University of North Carolina (USA), Thomas Jefferson University (USA), Bradley University (USA), Siemens (USA and Germany)...
  - 3 european start-up: InSimo, Anatoscope, TruPhysics

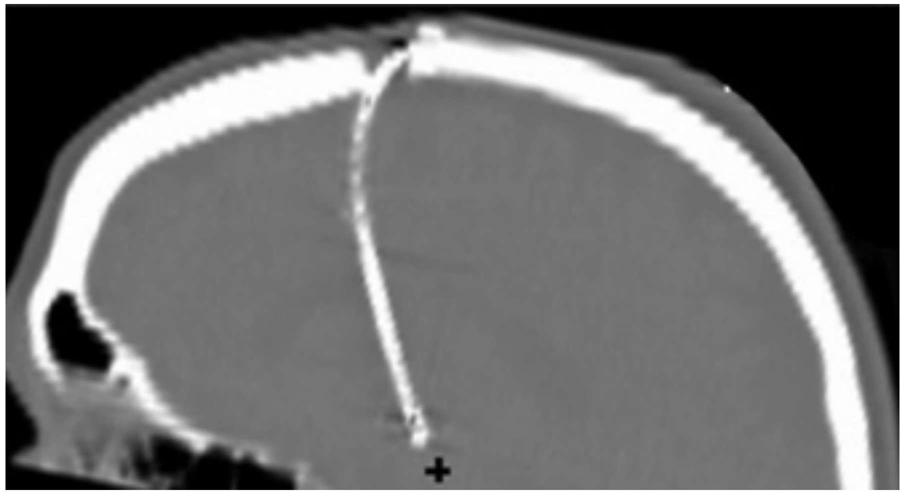


CARDIAC ENDOVASCULAR PROCEDURES

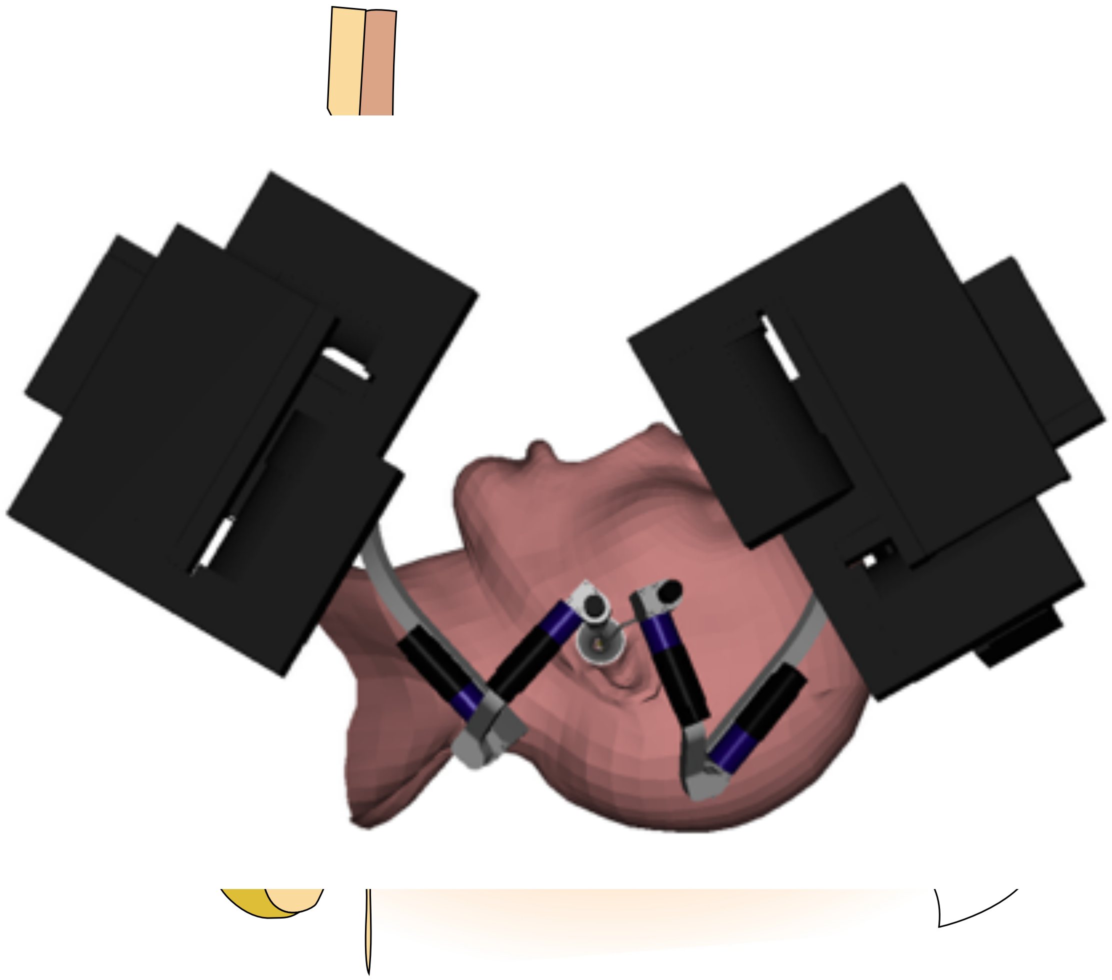


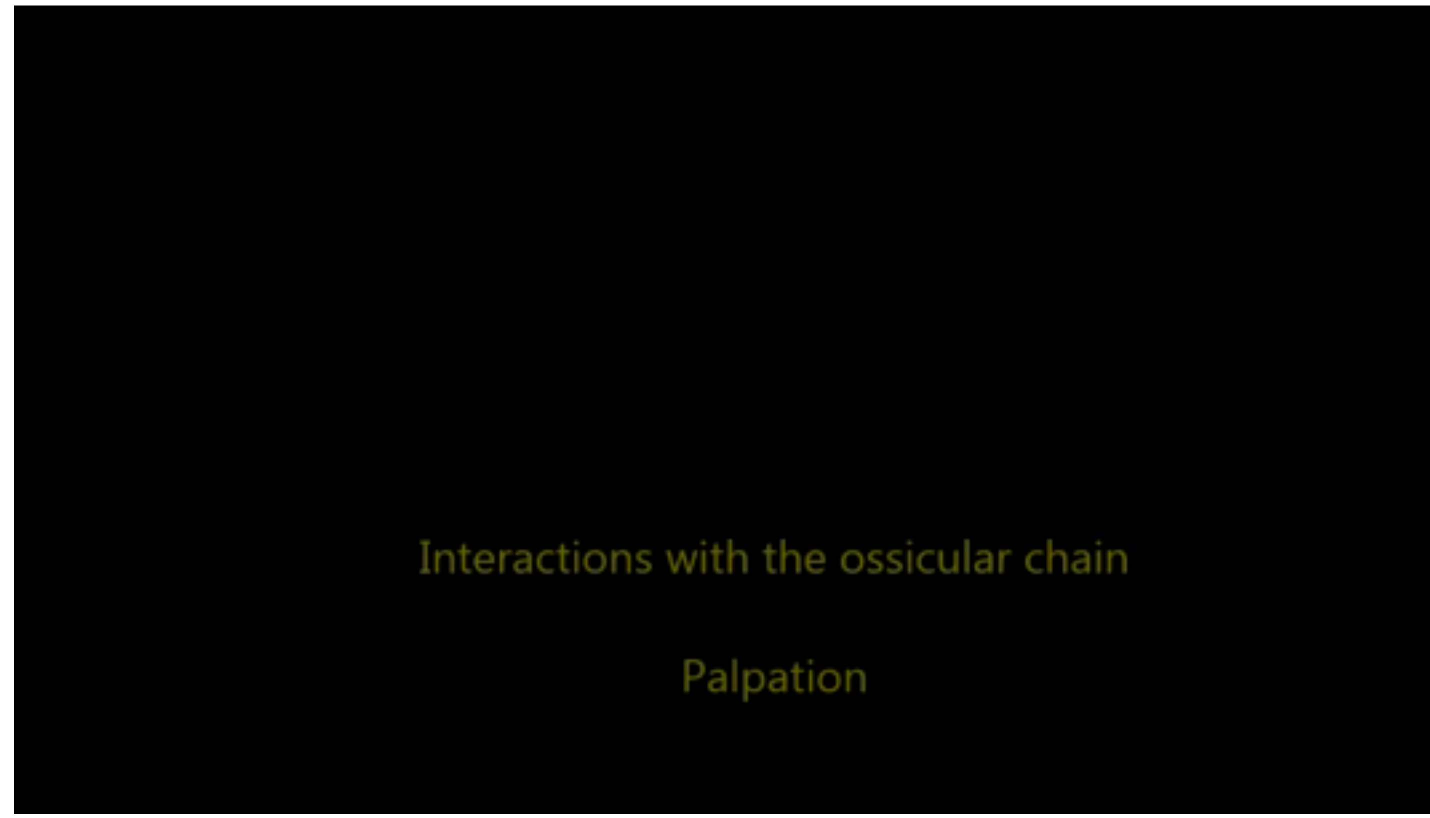
DEEP BRAIN STIMULATION

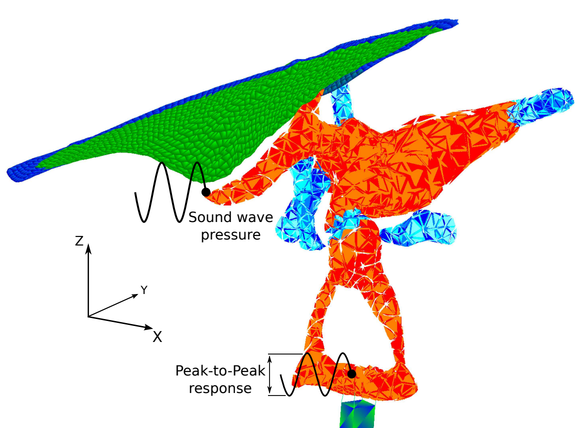




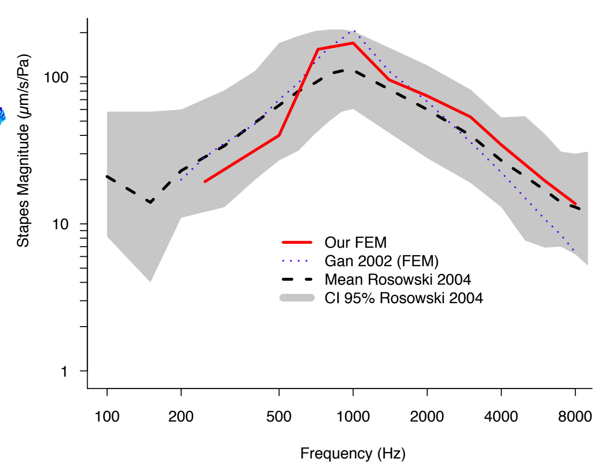
MIDDLE EAR SURGERY



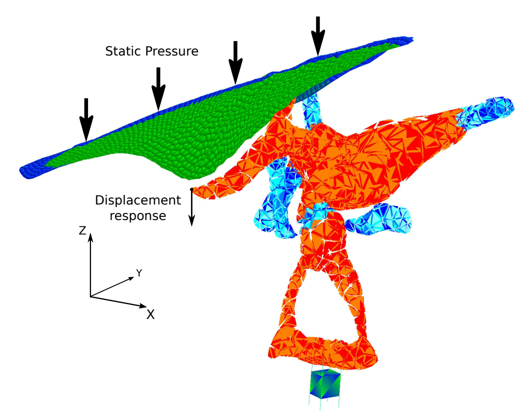




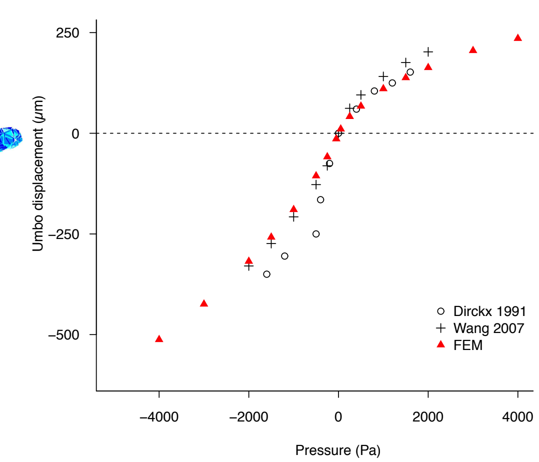
(a) Transfer function method.



(b) Transfer function results.



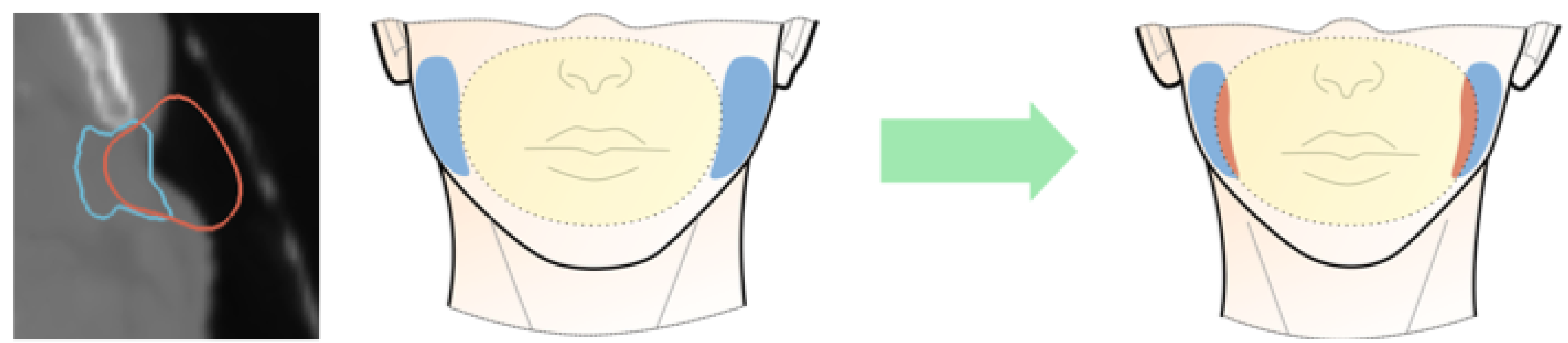
(a) Static pressure method.

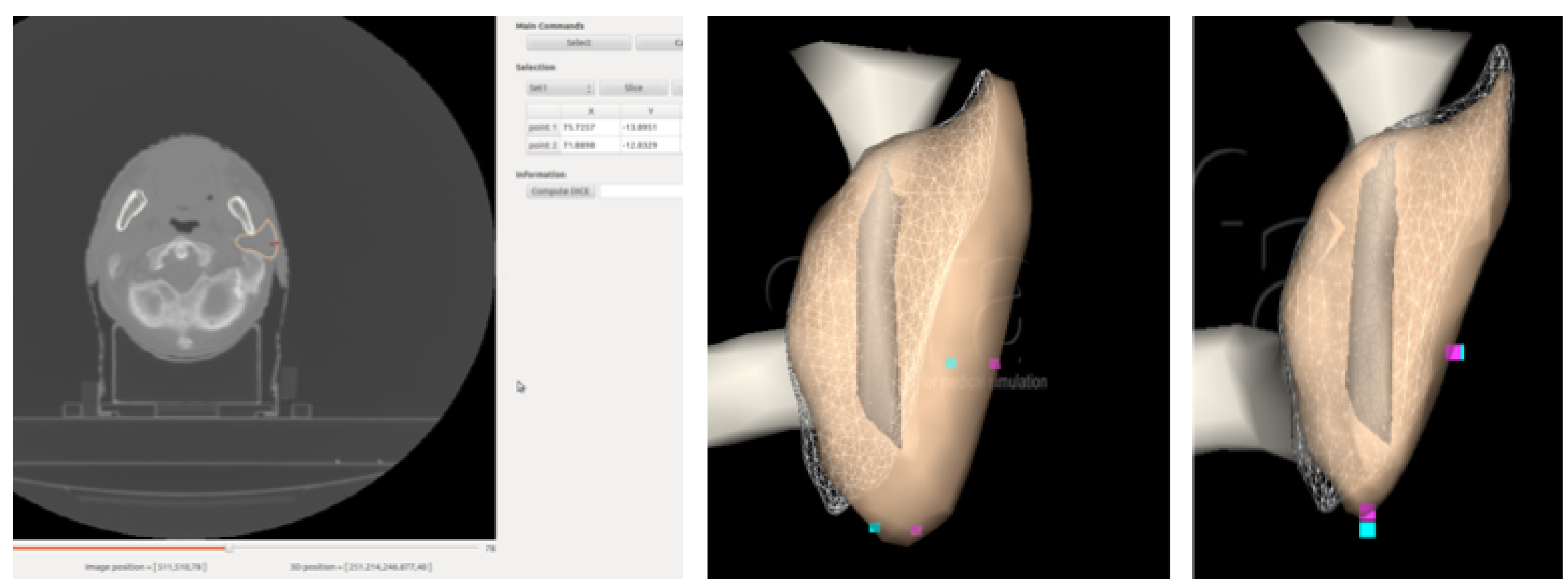


(b) Static pressure results.

REAL-TIME INVERSE SIMULATIONS

- Adaptive radiotherapy
  - Motion of the parotid glands
  - Bad quatlity of images
  - Semi-automatic method
- Input
  - Initial 3D image
  - Motion of 2 or 3 control points
- Output
  - Volume loss
  - New geometry of the parotid
  - Real-time possible ajustement of the control points

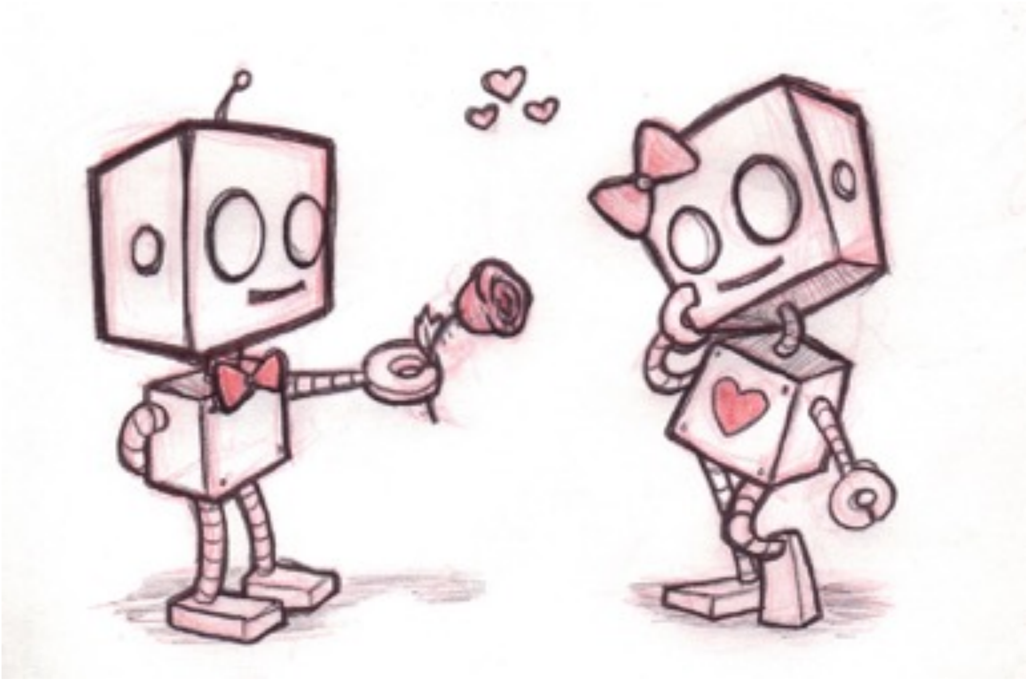




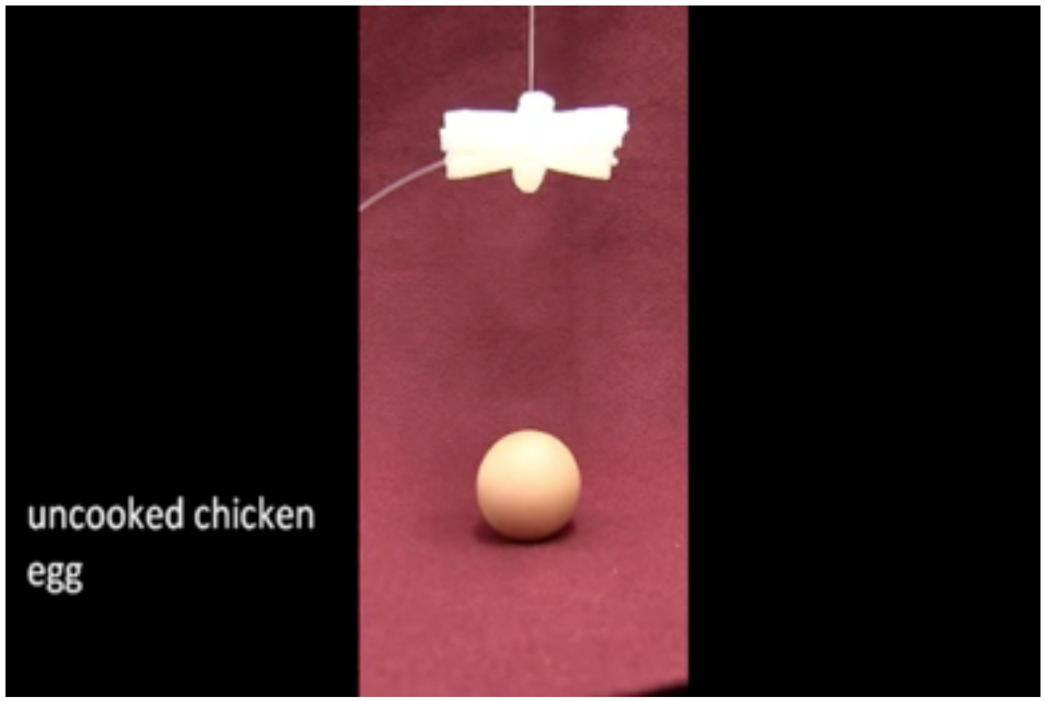
CONTROL METHODS FOR SOFT ROBOTS

WHAT ARE THE SOFT ROBOTS ?

QUIZ !



SOFT-ROBOTS



Safety and interaction with fragile parts of an environment

Ilievski, F. et al Harvard University
Angewandte Chemie 2011

But also hostile environments…

Seok et al. MIT
IEEE/ASME Transactions on mechatronics 2013

MOTIVATION: SOFT SURGICAL ROBOTS

Surgical robotics

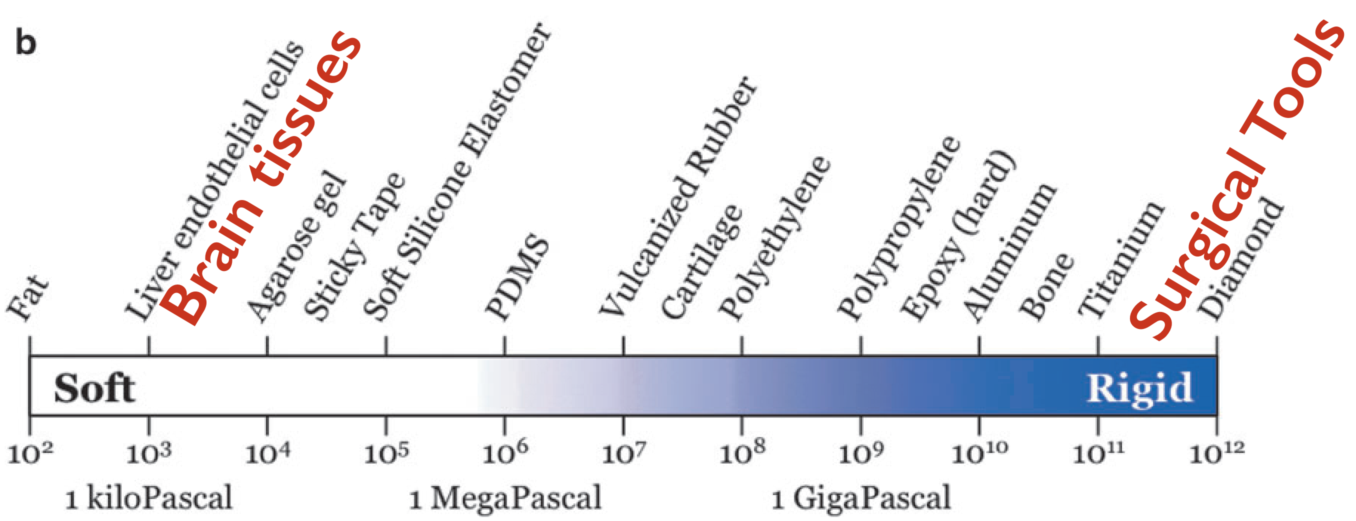
\+

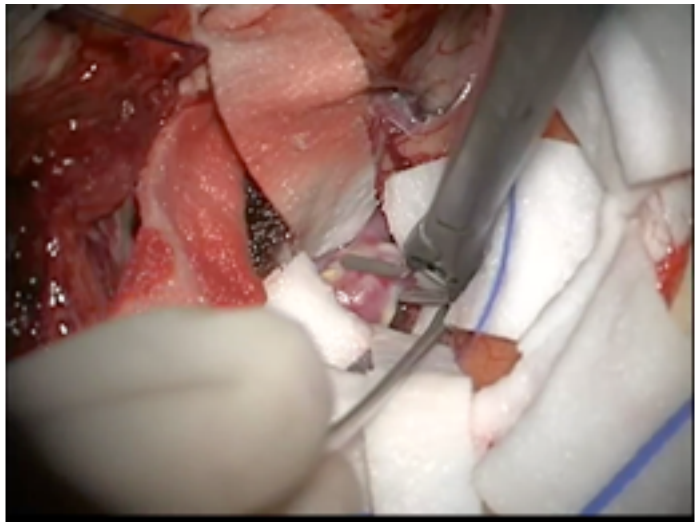
Soft robotics

=

Capacity of **access with security**
- Less pressure
- Reduced damage

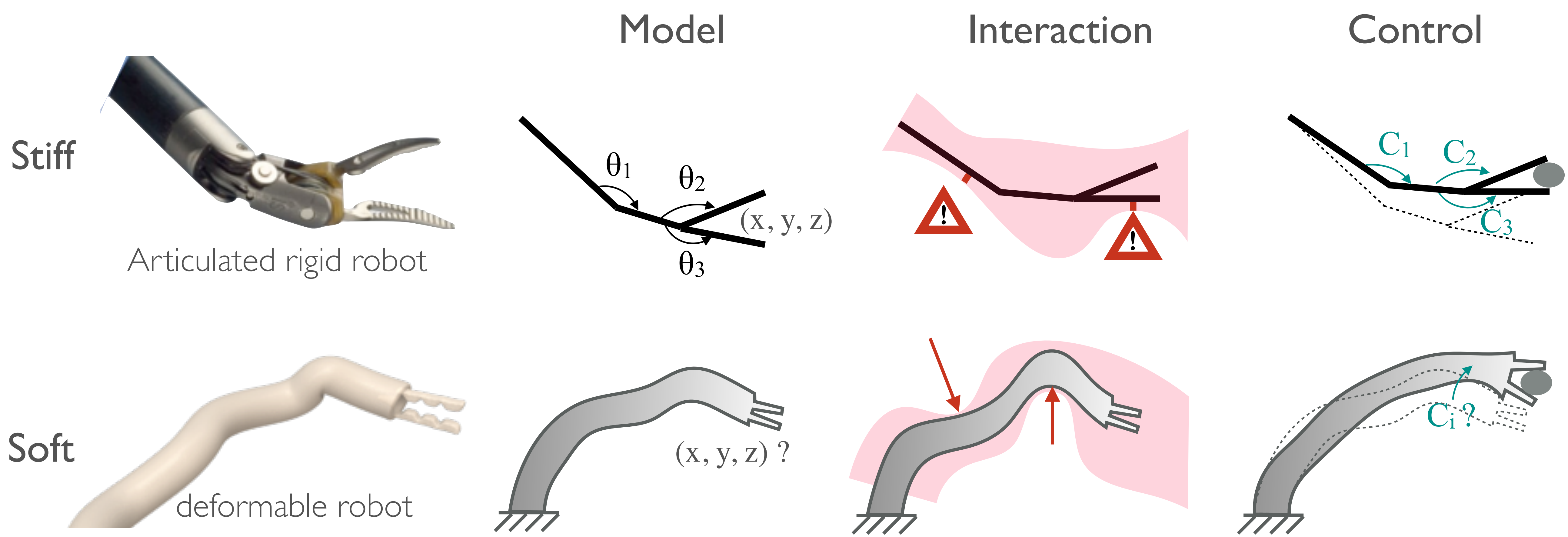
Easier **maneuvering**
- Augmented skills for the surgeon
- New minimally invasive approaches





Incompatibility of stiffness between surgical tools and living tissues

MODELING AND CONTROL ARE AN OPEN PROBLEM



CONCLUSION

- Interactive simulation
  - Multidisciplinary field: geometry, mechanics, control, medecine…
  - Many possible applications: games, surgical training, robotics…
- This course
  - Main basis of simulation

END…

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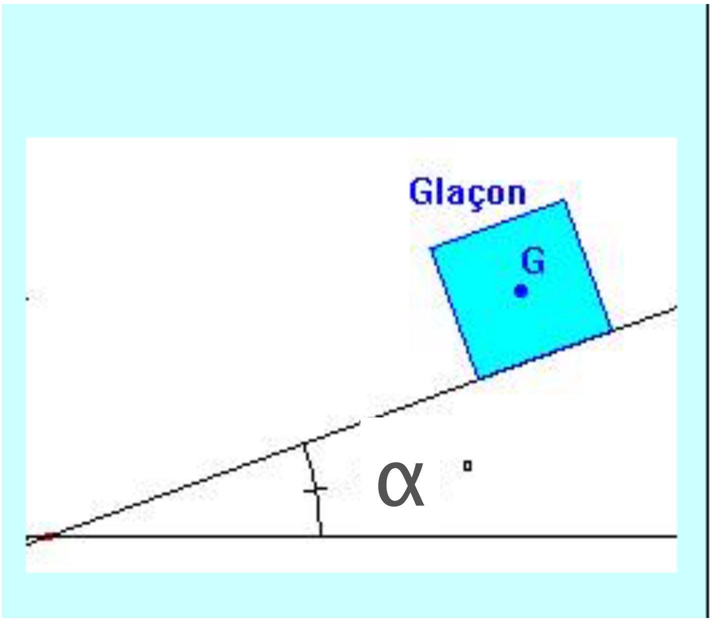
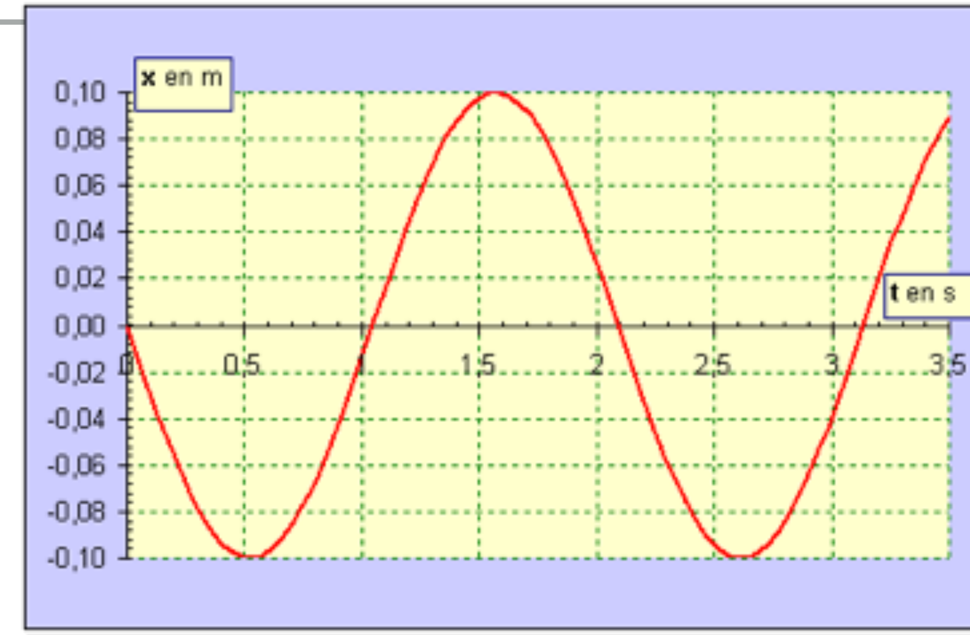
EQUATION DE LA DYNAMIQUE

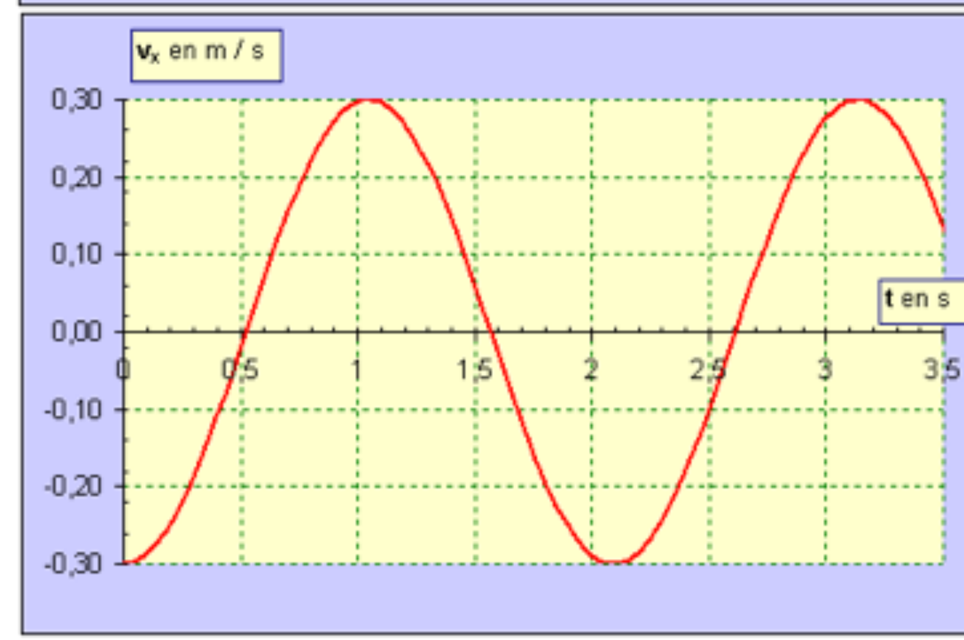
- Plan incliné avec un glaçon de masse m. (On néglige les frottements)
  - Déterminer les forces qui s'exerces sur le glaçon
  - Quelle est la valeur de l'accélération du glaçon ?

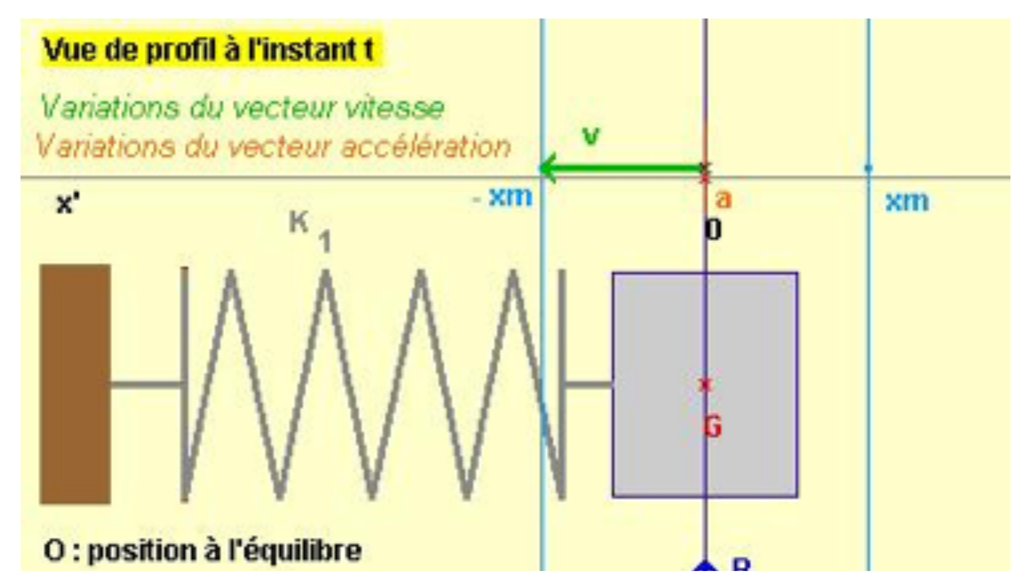


EQUATION DE LA DYNAMIQUE

- Masse attachée à un ressort parfait
  - Quelle est la position initiale du centre d'inertie G du solide ? Quel est le sens de la vitesse communiquée au solide par l'opérateur ?
  - Quelle est l'amplitude du mouvement de G ?
  - Déterminer la valeur maximale de la vitesse de G.
  - Calculer la valeur de l'accélération de G :
    - À l'instant t = 0 s ;
    - Quand l'abscisse x est maximale ;
    - Quand l'abscisse x est minimale.
  - Quelle est la valeur de la constante de raideur k du ressort ?







LES MATRICES

- Qu'est-ce qu'une matrice ?

LES MATRICES & SYSTÈMES LINÉAIRES

- Somme de matrices
- Produit (par un scalaire, par une matrice)
- Transposée
- Déterminant (matrice 3x3)
- Inverse
- Méthodes de résolution de système directe

RÉSOLUTION D'UN PROBLÈME NON-LINÉAIRE

- Méthode de Newton