From CAMI
(Computer Assisted Medical Interventions)

…

to QIS
(Quality Inspired Surgery)

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Quality Inspired Surgery (QIS)

- Multiple Challenges
- Initial Vision : CAMI
- Achievements of CAMI
- Present Vision of QIS
- Preliminary Research on “μ-QIS”

Medical Challenges:
Enhanced and Quantified Quality

- Perform classical interventions with enhanced:
  - Safety
  - Efficiency
  - Efficacy
  - Reproducibility
- Enable performance of new interventions, especially minimally invasive procedures, by surpassing human limitations

Information Technology Challenges

Introduce IT in the Operating Room

- cross-fertilisation of multi-modal information
- quantified surgical planning
- enhanced performance of the action

Industrial Challenges

Create a new industrial domain

Heard in 1987 from a leading medical imaging company:

"**it is so difficult and dangerous to contribute to diagnosis: nobody shall ever dare contributing to surgical intervention performing**"

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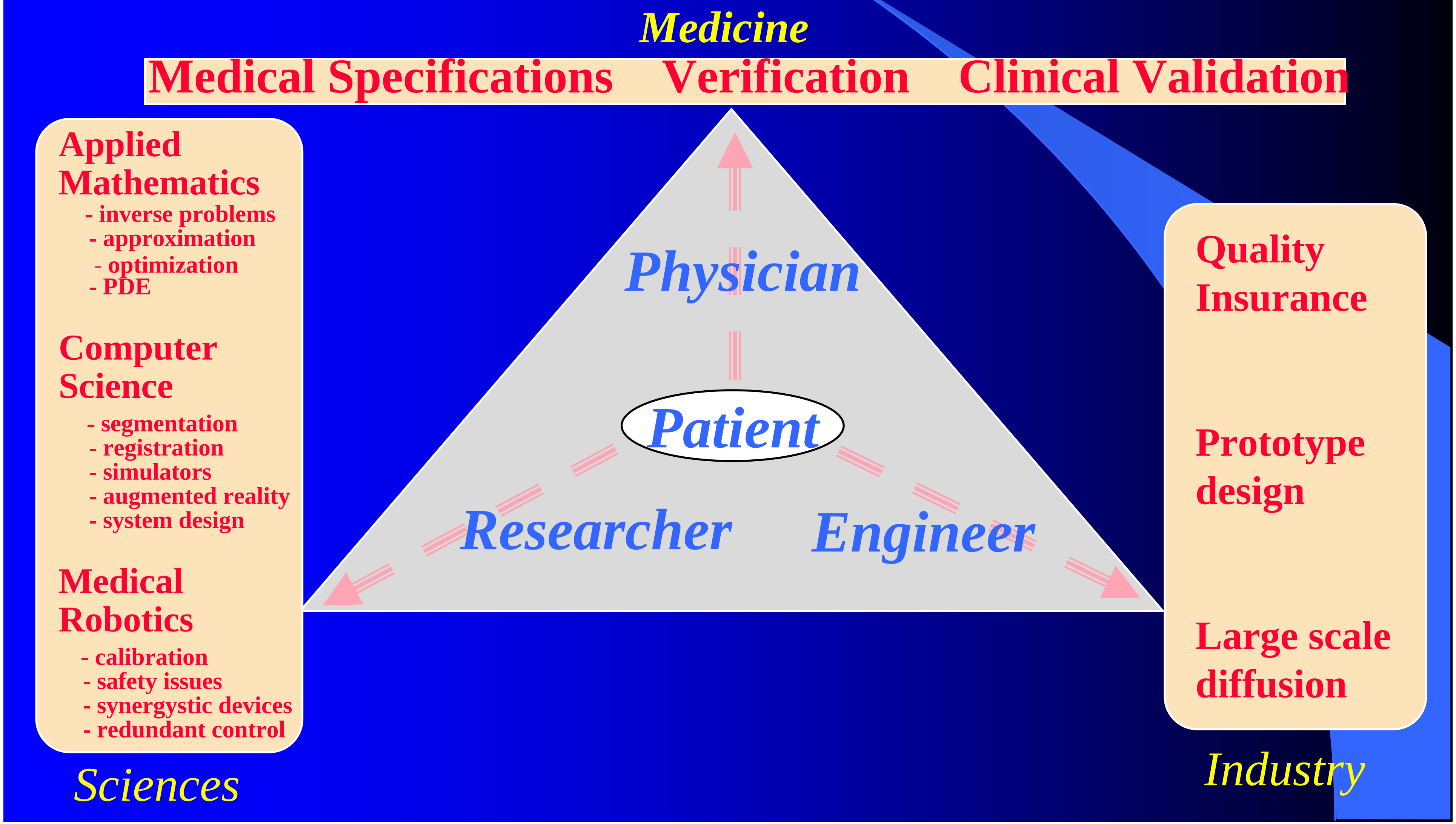
CAMI (Computer Assisted Medical Interventions)

a multi-disciplinary challenge

Sciences, Medicine and Industry cooperation for mutual benefit



CAMI: organizational vision

multidisciplinary team and efforts,

framework for mutual respect and benefit

- Grenoble University Hospital: 12 departments, 25 Hospital Practitionners
- CAMI-TIMC-IMAG (UJF&CNRS): 35 researchers
- PRAXIM SA: 50 employees
- International cooperation (4th FP CAMI, 5th FP IGOS 1&2, VOEU, MI3)

CAMI: Medical Vision

Medical objectives driven project

- deep understanding of surgical requirements
- importance of clinical validation:
  - multi-centric validation
  - participation of independent international experts
- IT education of surgeons and physicians

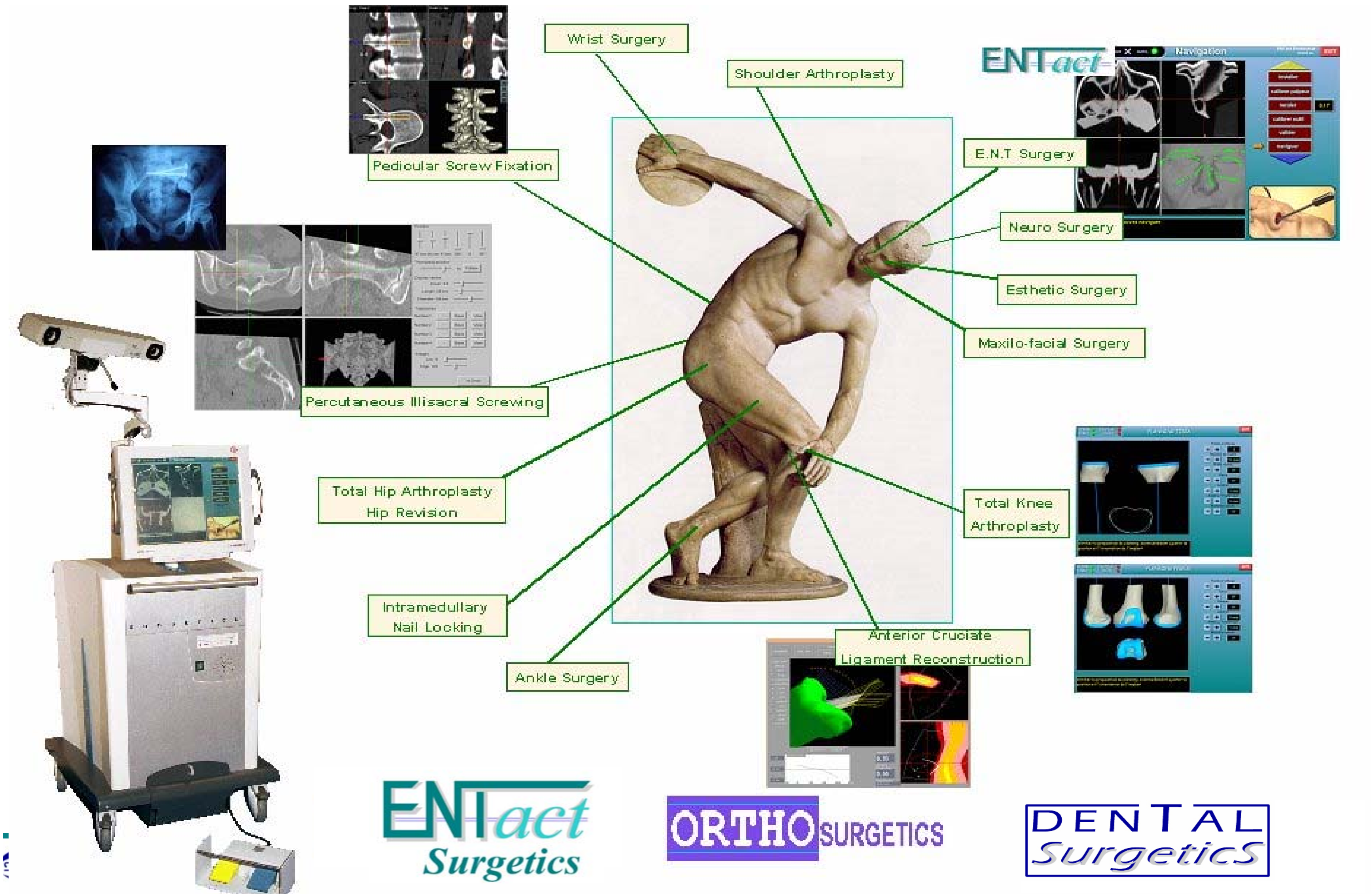
CAMI: IT Vision

- Medical immersion of engineers
- Favour the “lightest” solutions:
  - Simple intra-operative information acquisition,
  - Surgical navigation,
  - Light and synergistic robotics;
- Favour generic solutions
- Patent and publish

CAMI: Industrial Vision

- Partnerships with companies:
  - Philips, Siemens, GE, Medtronic, Aesculap, France-Telecom, …
- Creation of PRAXIM in 1995:
  - > 100 SURGETICS®, >300 surgeons, > 2000 patients

PRODUCT : Multi-application Surgetics Station



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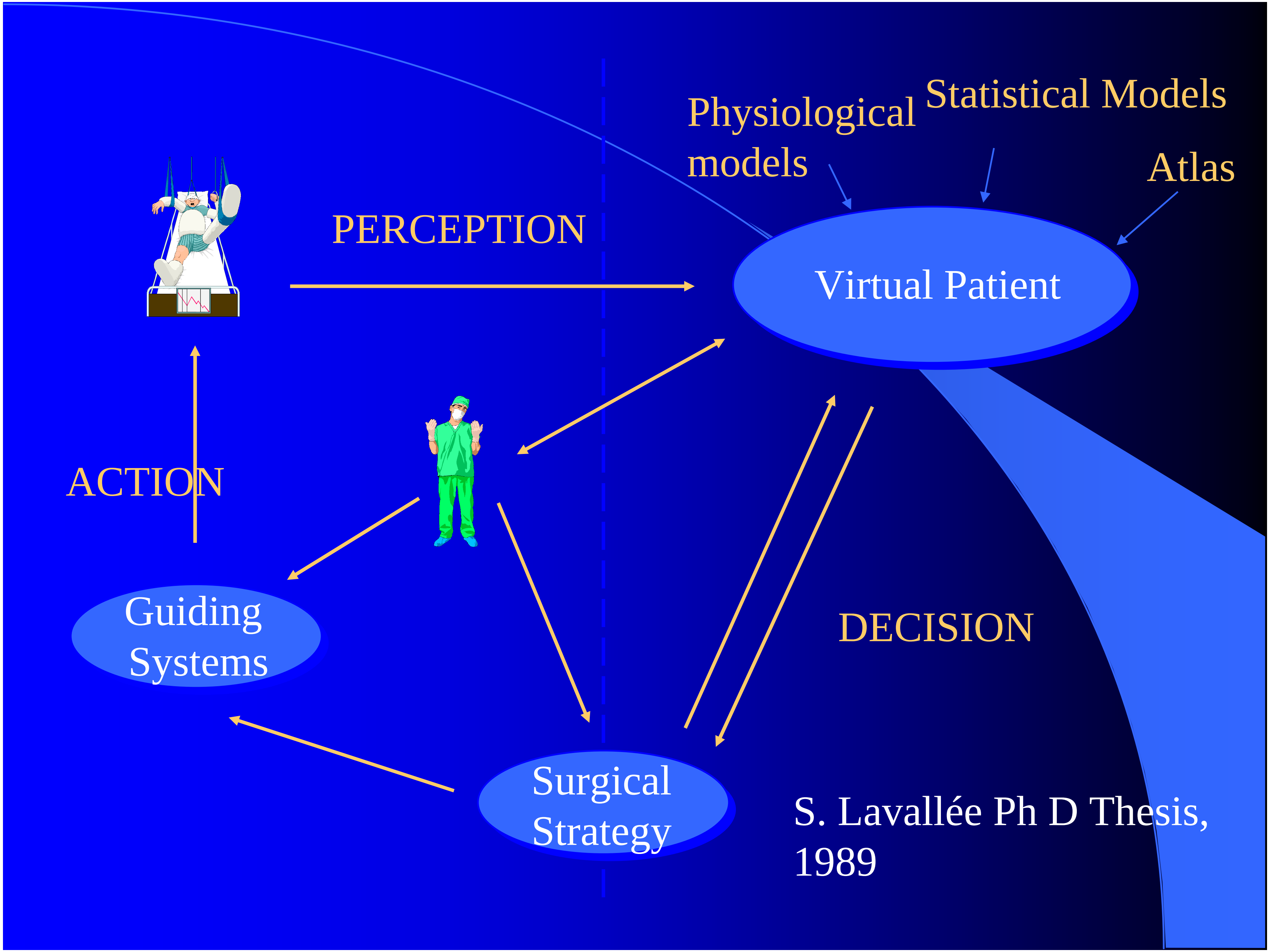


Physiological
models
Statistical Models
Atlas
PERCEPTION
Virtual Patient
ACTION
Guiding
Systems
DECISION
Surgical
Strategy
S. Lavallée Ph D Thesis,
1989

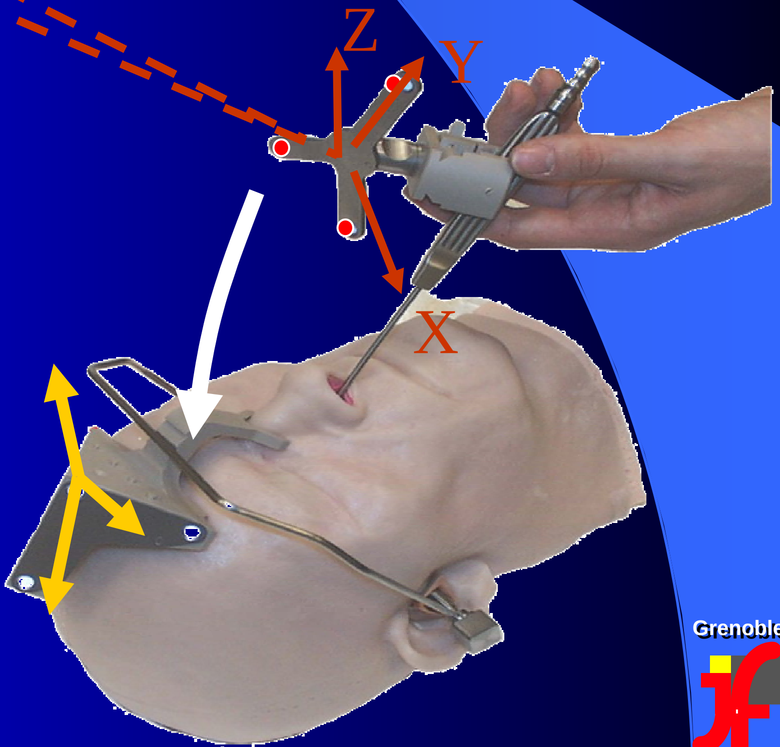
Specificities of the *Perception - Decision - Action loop* in CAMI Applications

- TWO categories of human beings:
  - The patient
  - The surgical team
- Perception level:
  - The most relevant information is often purely virtual!
  - Highly multi-modal
- Decision level:
  - Distributed over time, space, and medical specialists
- Action level:
  - Man-Machine Co-operation

A Highly Multi-Modal Perception

- Position (3D), Orientation (3D)
- Shape (nD)
- Cinematics:
  - Rigid movements (6D + time)
  - Deformations (nD)
- Dynamics (6D + 3D forces +3D torques)
- Organs characteristics (X-ray, Ultrasound, Color, …)
- Physiological signals (EMG, ECG, EEG, …)
- …

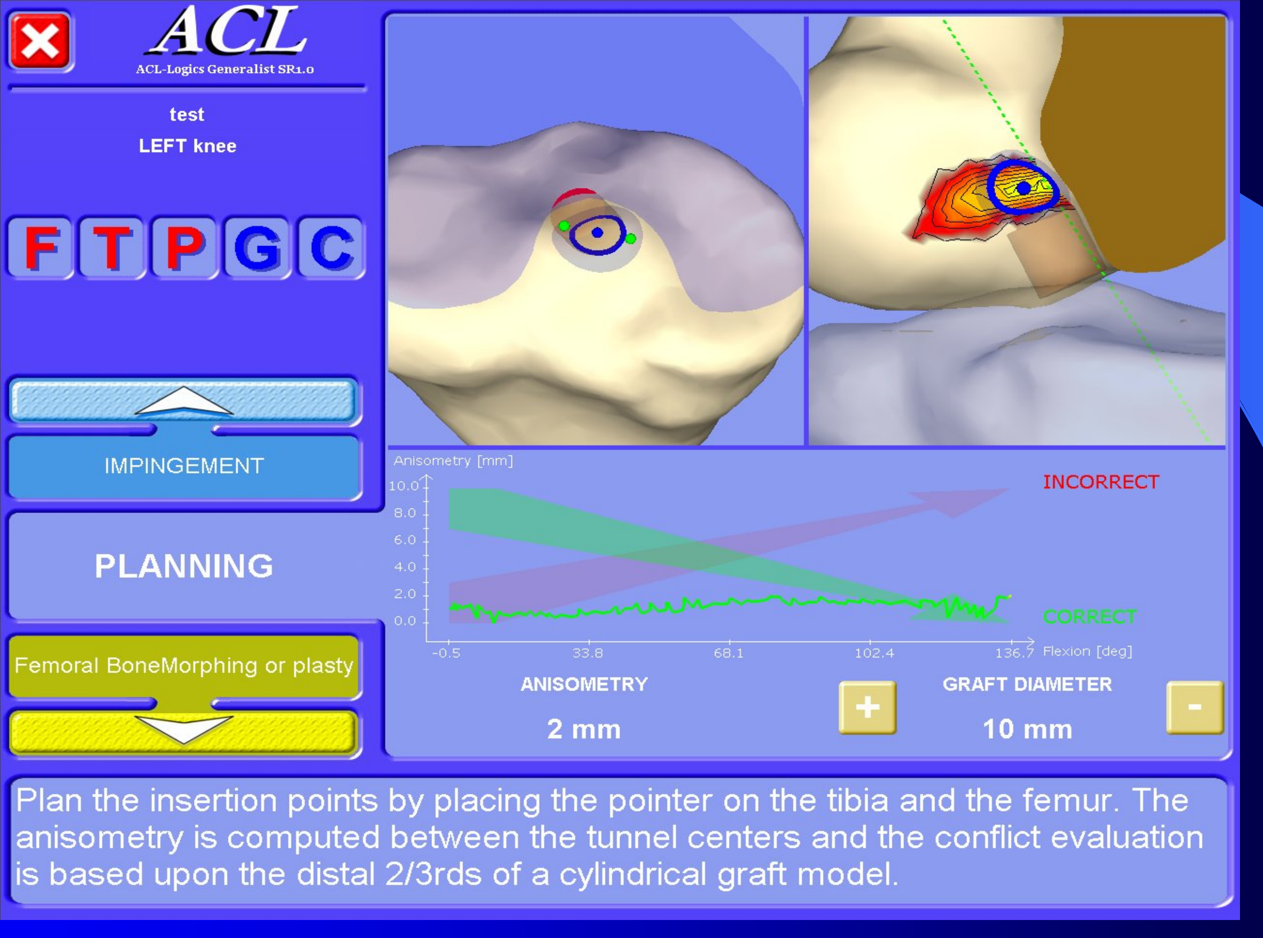
A typical Perception system for "Navigational Surgery": *"GPS" for Surgery*



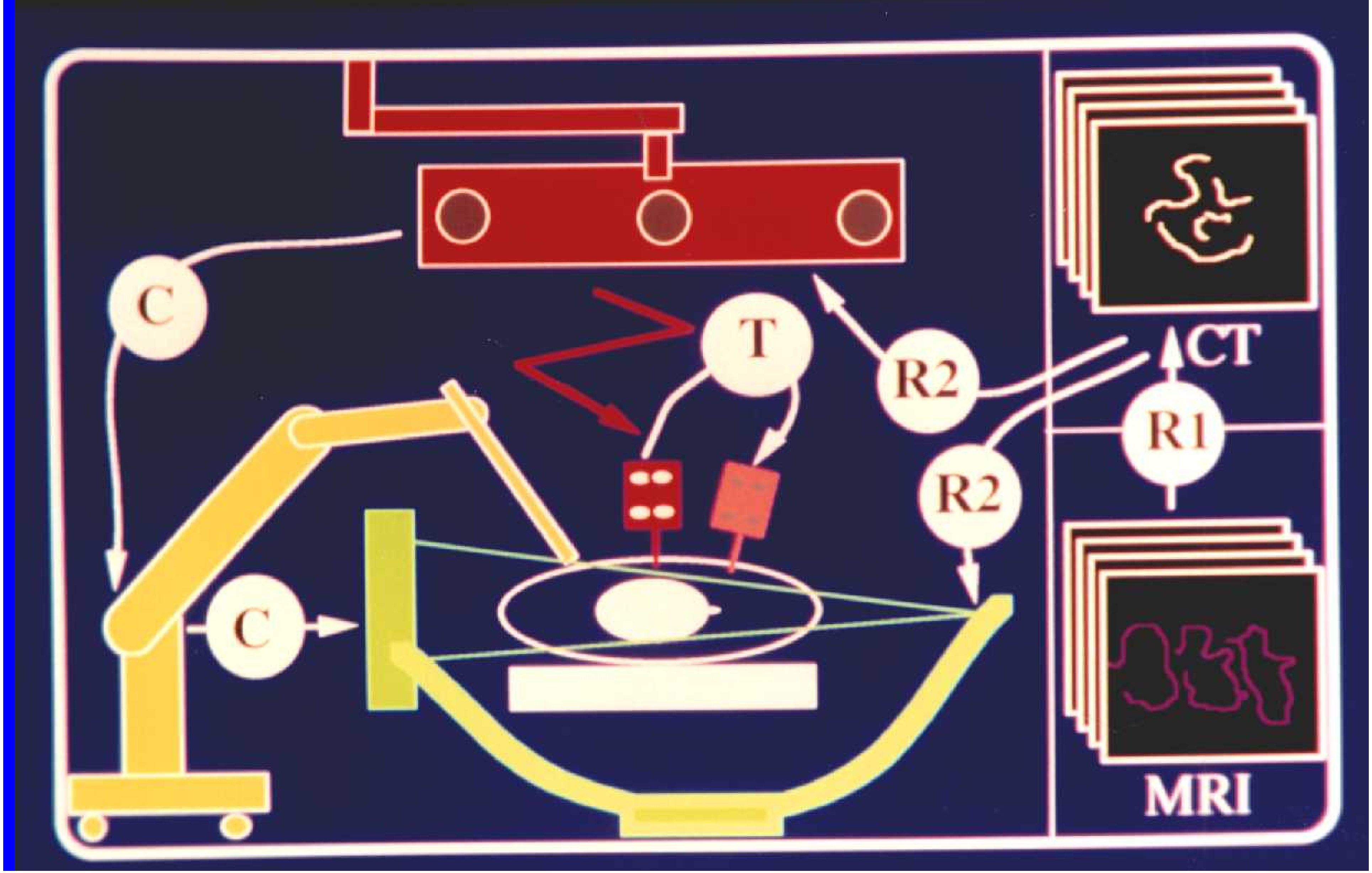
Acquisition of position, shape and cinematics with a 3D digitizer: the instance of Anterior Cruciate Ligament Replacement

QuickTime™ et un
décompresseur 3ivx D4 4.0PR2
sont requis pour visionner cette image.

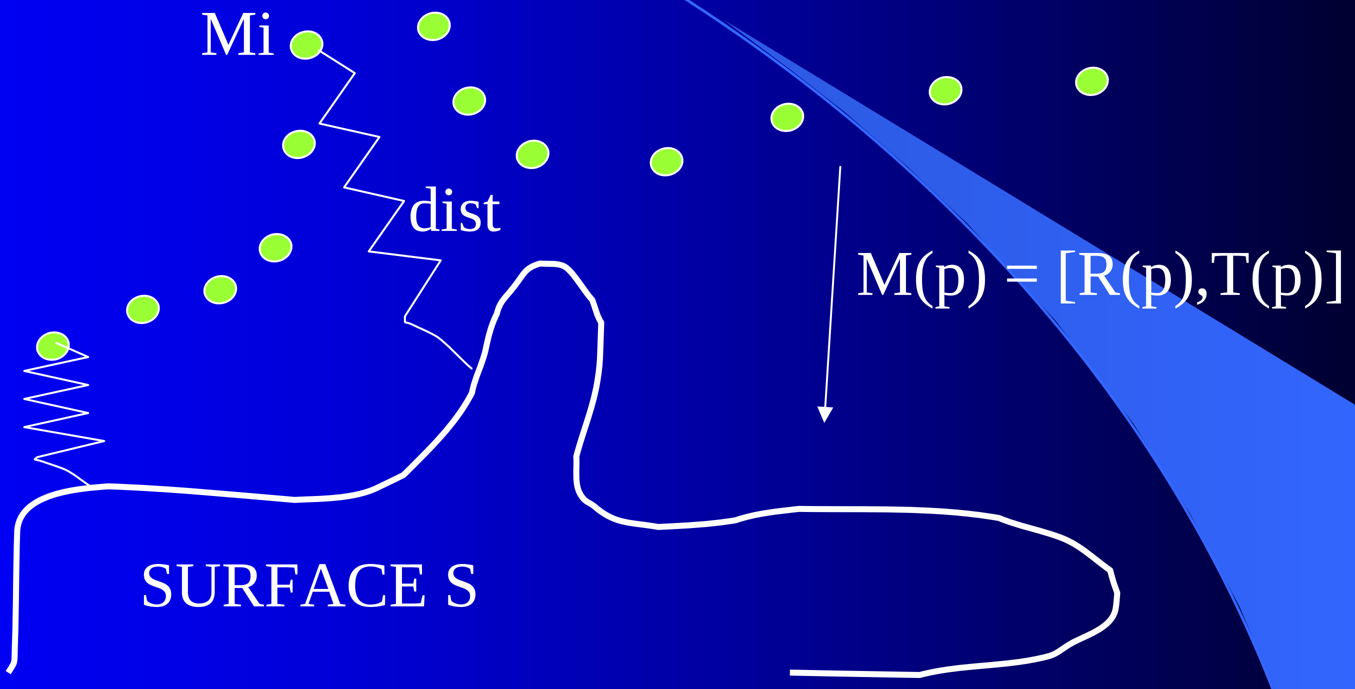
Interfaces for Decision: the instance of Per-operative planning



MULTIMODAL INFORMATION REGISTRATION



RIGID 3D/3D



$$E(p) = \sum_{i=1}^{n} \frac{1}{\sigma_i^2} dist^2\big(S, R(p)M_i + T(p)\big)$$

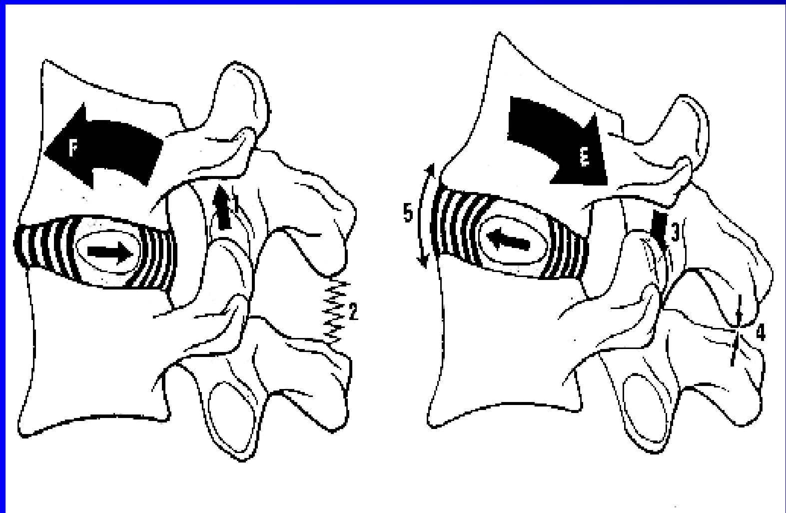
$$with : p = \big(t_x, t_y, t_z, \varphi, \theta, \psi\big)$$

3D Kinematic Study of the Spine

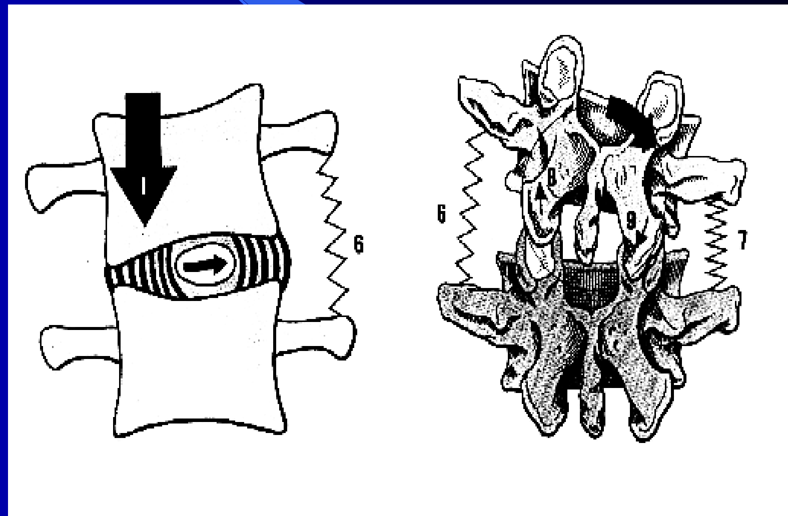
(A. Hamadeh)

- **Aim :**
  - Detect spinal instability by 3D measurement of the motion of vertebrae.
- **Data :**
  - Functional Radiographies: different positions of the spine (flexion - extension, lateral inflexion ...)
- **Methods:**
  - Qualitative interpretation : easy, subjective, not accurate..
  - The spinal motion is ***three-dimensional***:
    - ☞ 3D techniques: accurate, simultaneous estimation of the 6 parameters of motion (3 rotations, 3 translations)

3D Motions of the Lumbar Spine

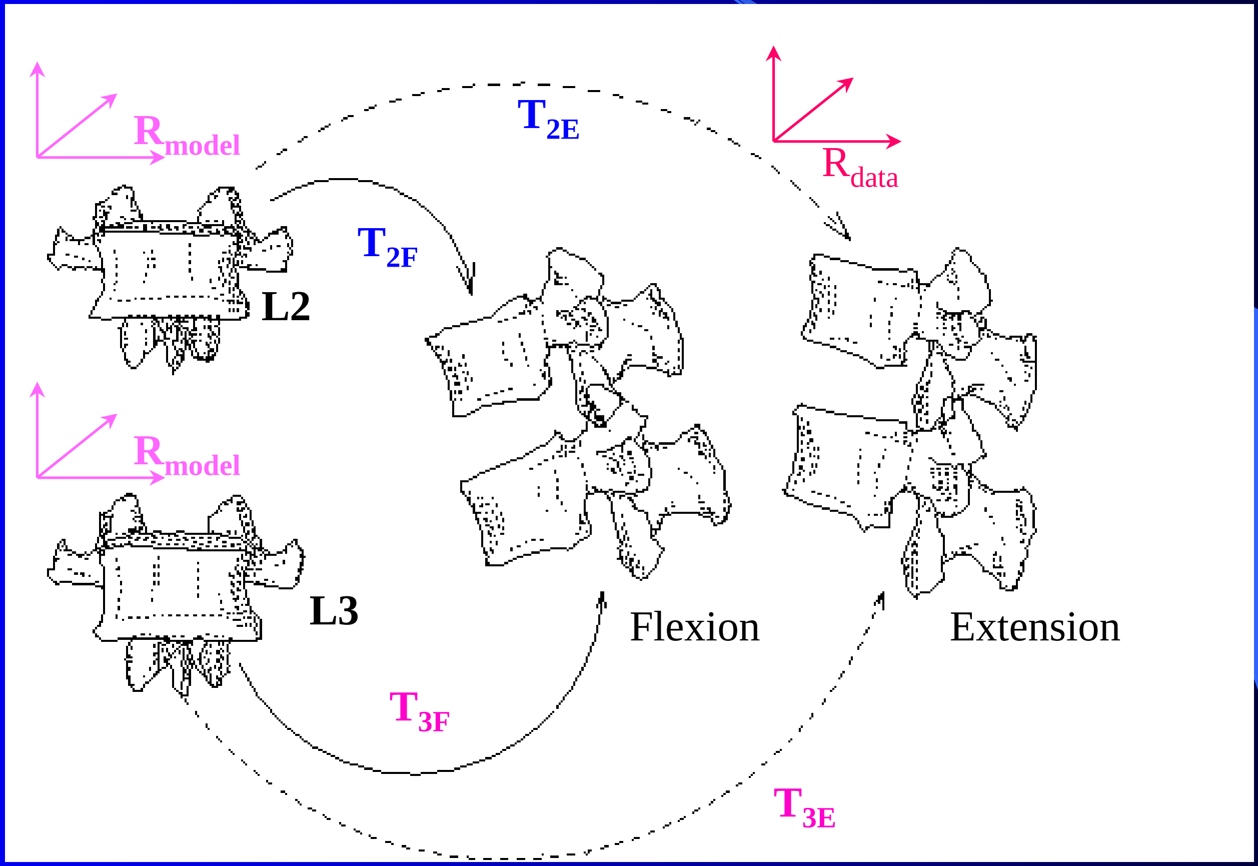


Flexion - Extension of the lumbar spine.
(source: Kapanji)

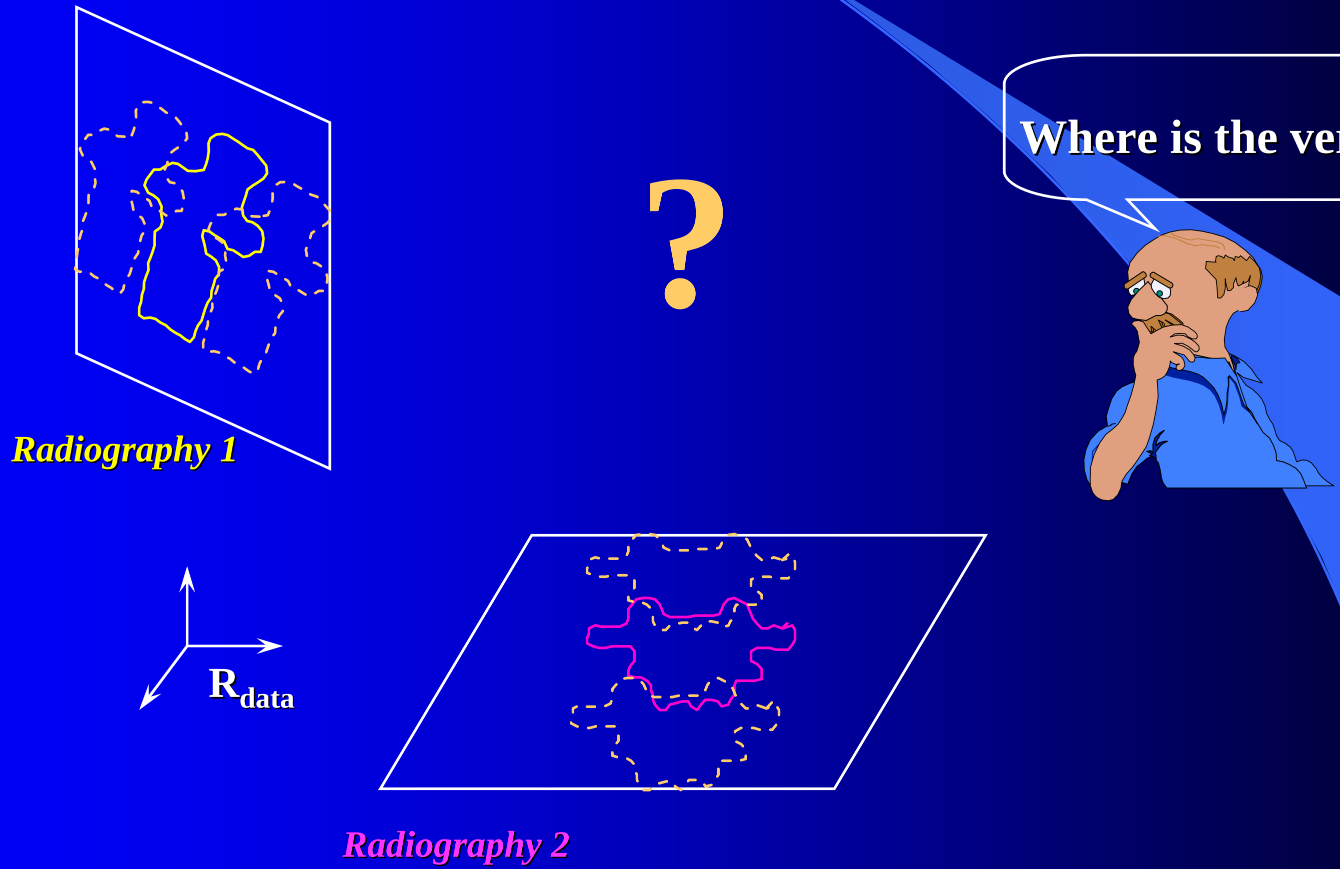


Lateral Inflexion of the lumbar spine
(source: Kapanji)

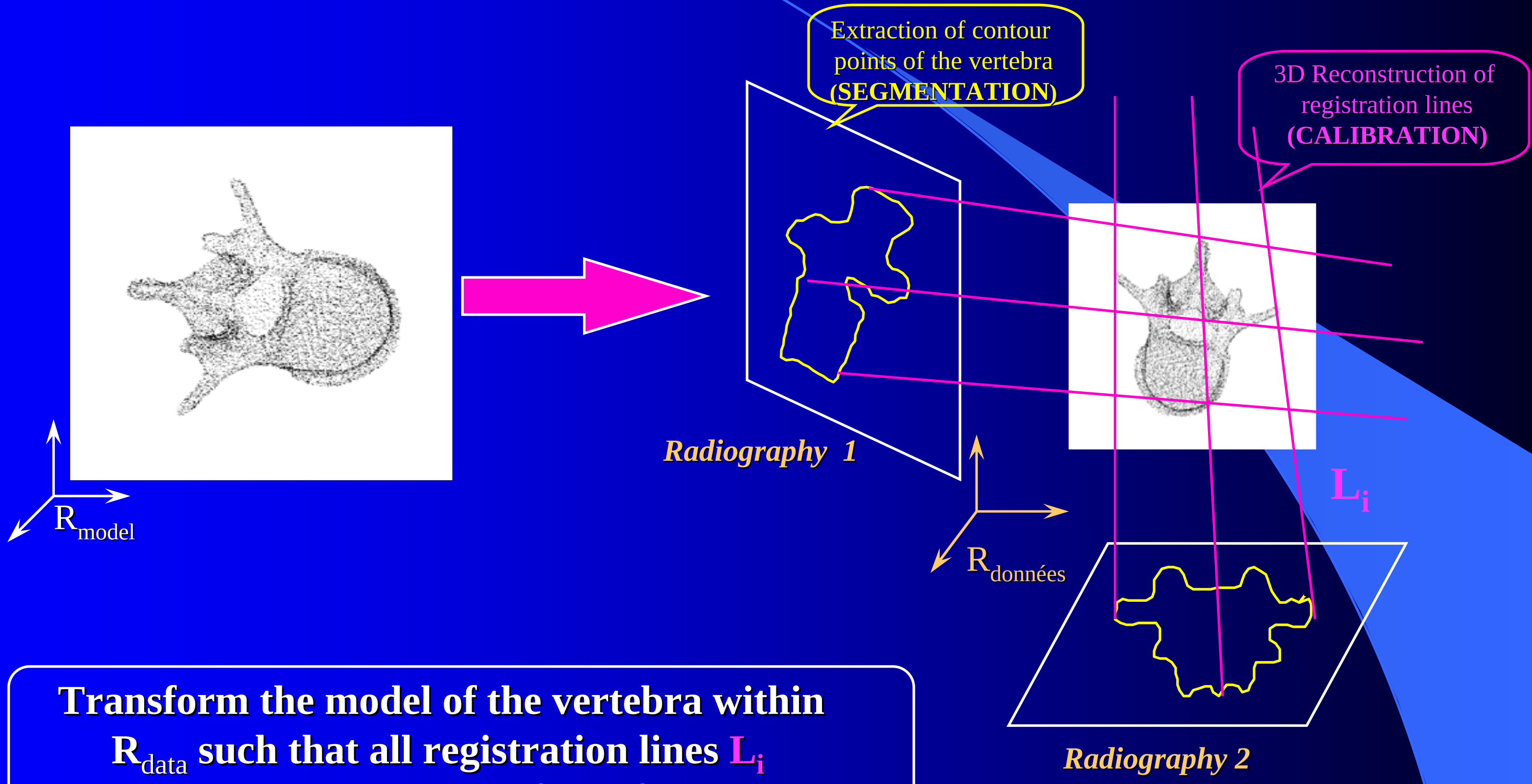
Principle of the method



3D/2D Registration
The problem !



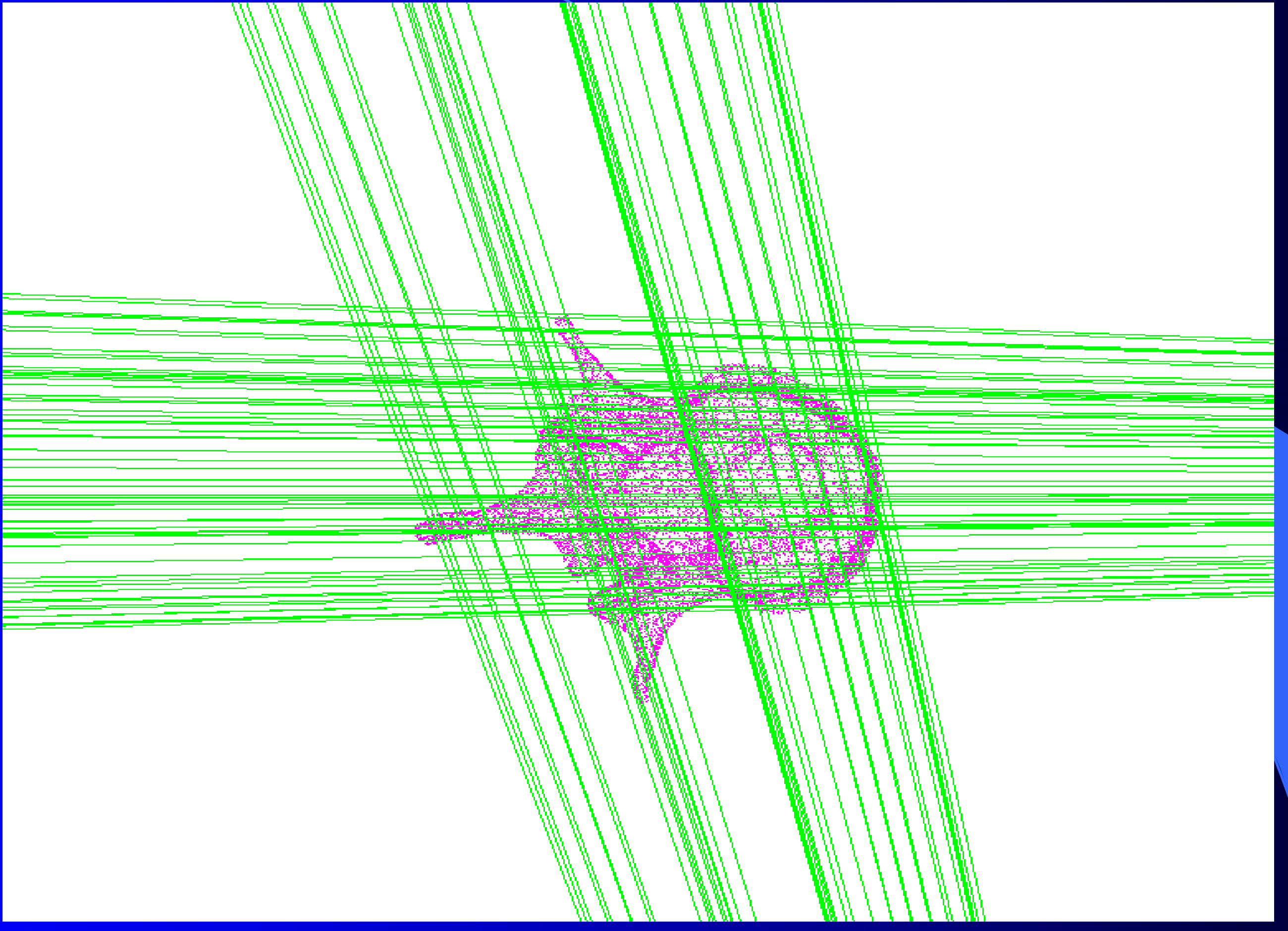
3D/2D Registration methodology



Transform the model of the vertebra within R_{data} such that all registration lines L_i become *tangent* to the 3D surface of the vertebra

Dynamic Pose of the vertebra / R_{data}

3D/2D Registration Results

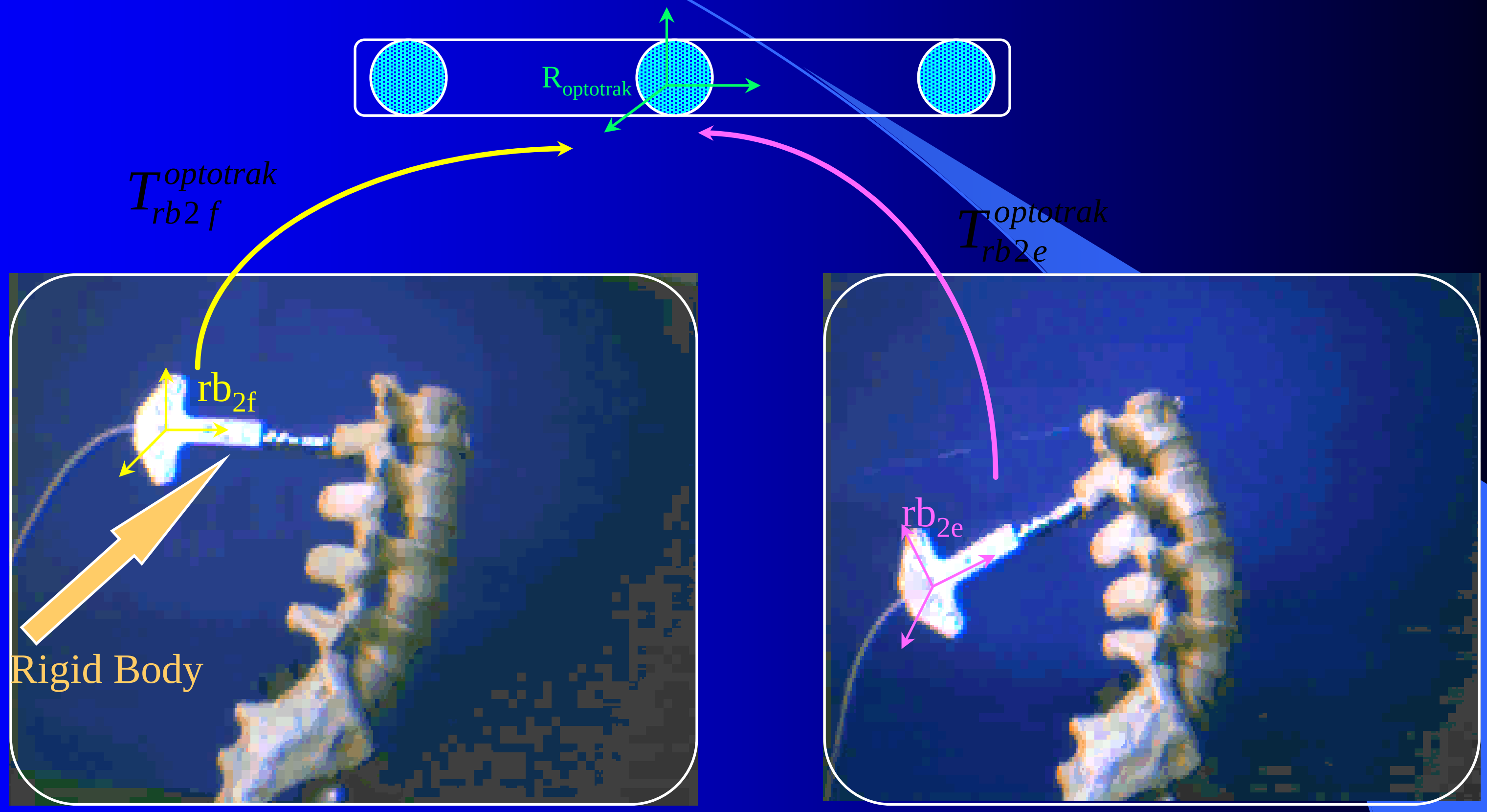


3D/2D registration between 3D pre-operative model of the vertebra and intra-operative registration lines

Experimental Setup

- Plastic phantom:
  - Rigid body fixed on L2: Tracking by the 3D localizer
  - Flexion - Extension positions.
  - Two functional radiographies / position
- Measurements of the 3D motion:
  - Optotrak: $M2_{opto} = T_{rb2f}^{rb2e} = T_{optotrak}^{rb2e} . T_{rb2f}^{optotrak}$
  - Registration: $M2_{reg} = T_{2F}^{2E} = T_{data}^{2E} . T_{2F}^{data}$
- Validation:
  - Compare M_{2reg} and M_{2opto}

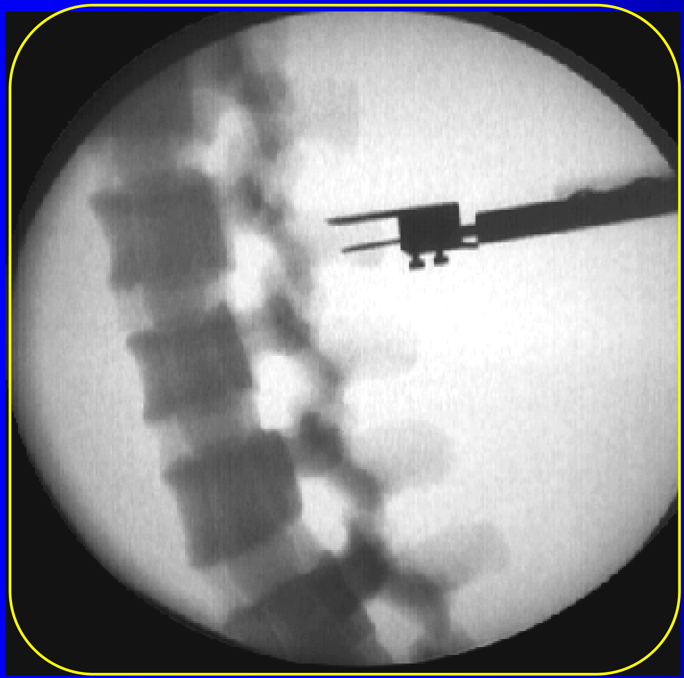
Experimental Setup



Lumbar spine phantom in flexion

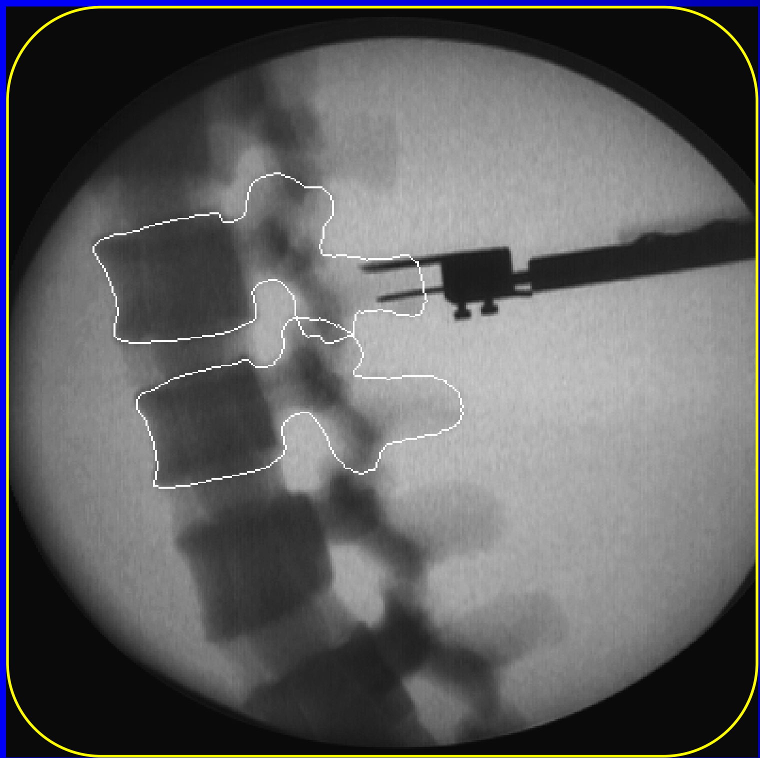
Lumbar spine phantom in extension

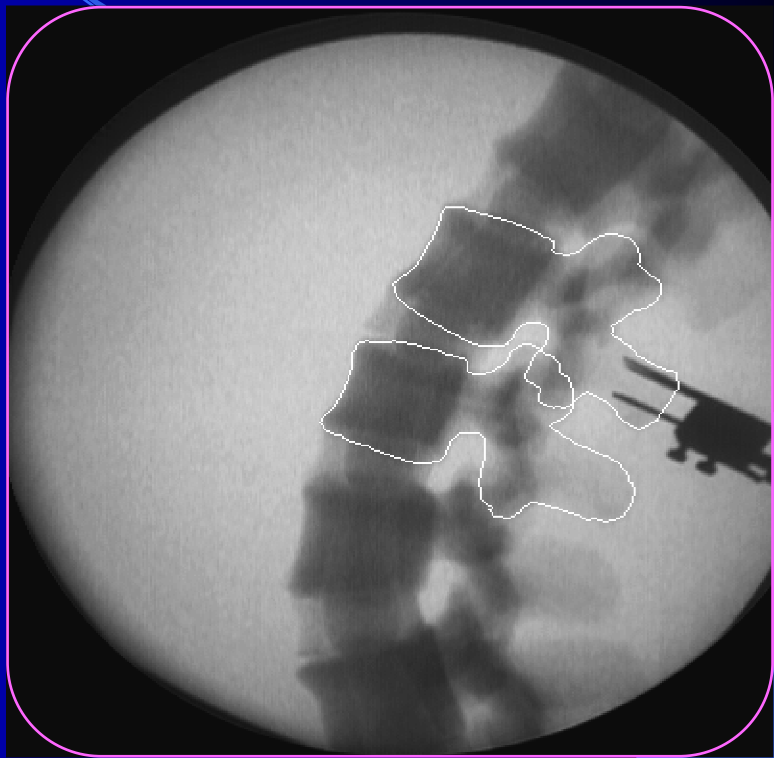
Functional Radiographies



Functional radiographies of the phantom of a lumbar spine in flexion (left) and extension (right) positions

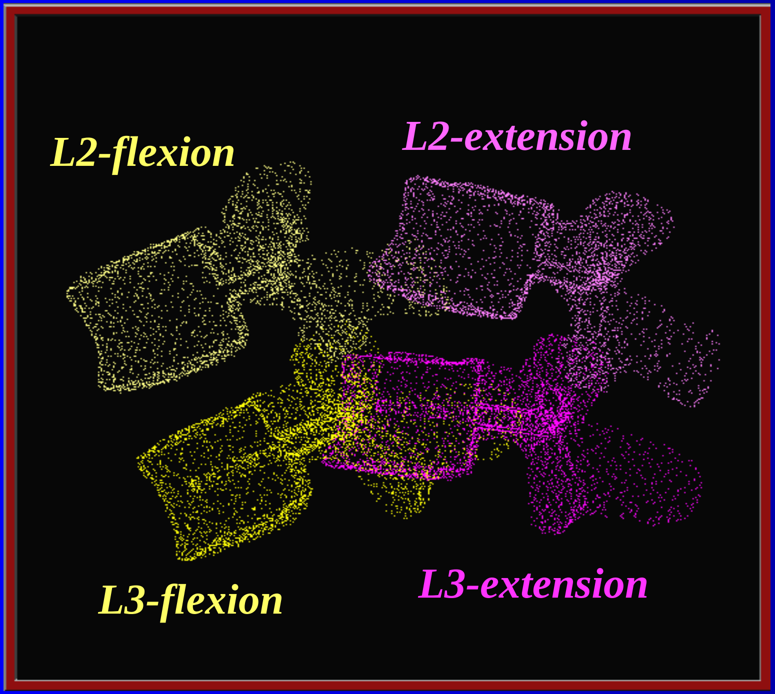
Results (2D)



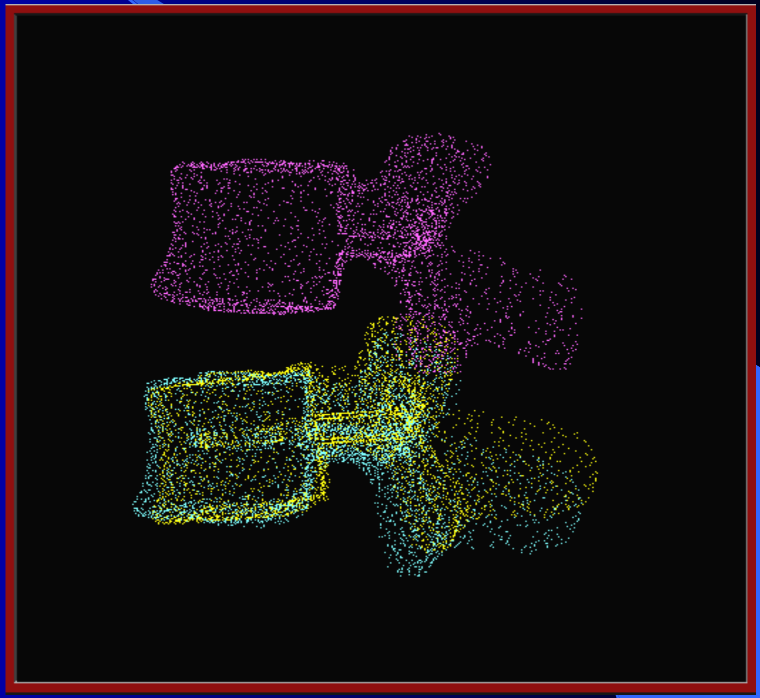


Superimposition of projective contours of the vertebrae L2 and L3 on the functional radiographies in flexion *(left)* and extension *(right)* positions

Results (3D)



3D representation of the lumbar vertebrae L2 and L3 in flexion and extension positions



Relative 3D motion of the vertebrae L2 and L3

Interfaces for Action

- Physician’s natural senses *versus* artificial sensors
- Physician’s intelligence *versus* artificial intelligence
- Physician’s dexterity *versus* guiding devices

Physician and Machine Co-operation

Humans

Strengths

- Superb eyesight
- Superb dexterity
- Hand-eye coordination
- Judgement
- Comprehension
- Instructable
- Adaptable

Weaknesses

- Cannot see thru tissues
- Tremor, imprecision
- Geometric inaccuracy
- Bulky
- Inattention, fatigue
- Susceptible to radiation
- Hard to keep sterile

Robots

Strengths

- Multiple sensors
- Direct connection to data
- Very precise
- Geometric accuracy
- Untiring, stable
- Work in hostile environments
- Sterilizable

Weaknesses

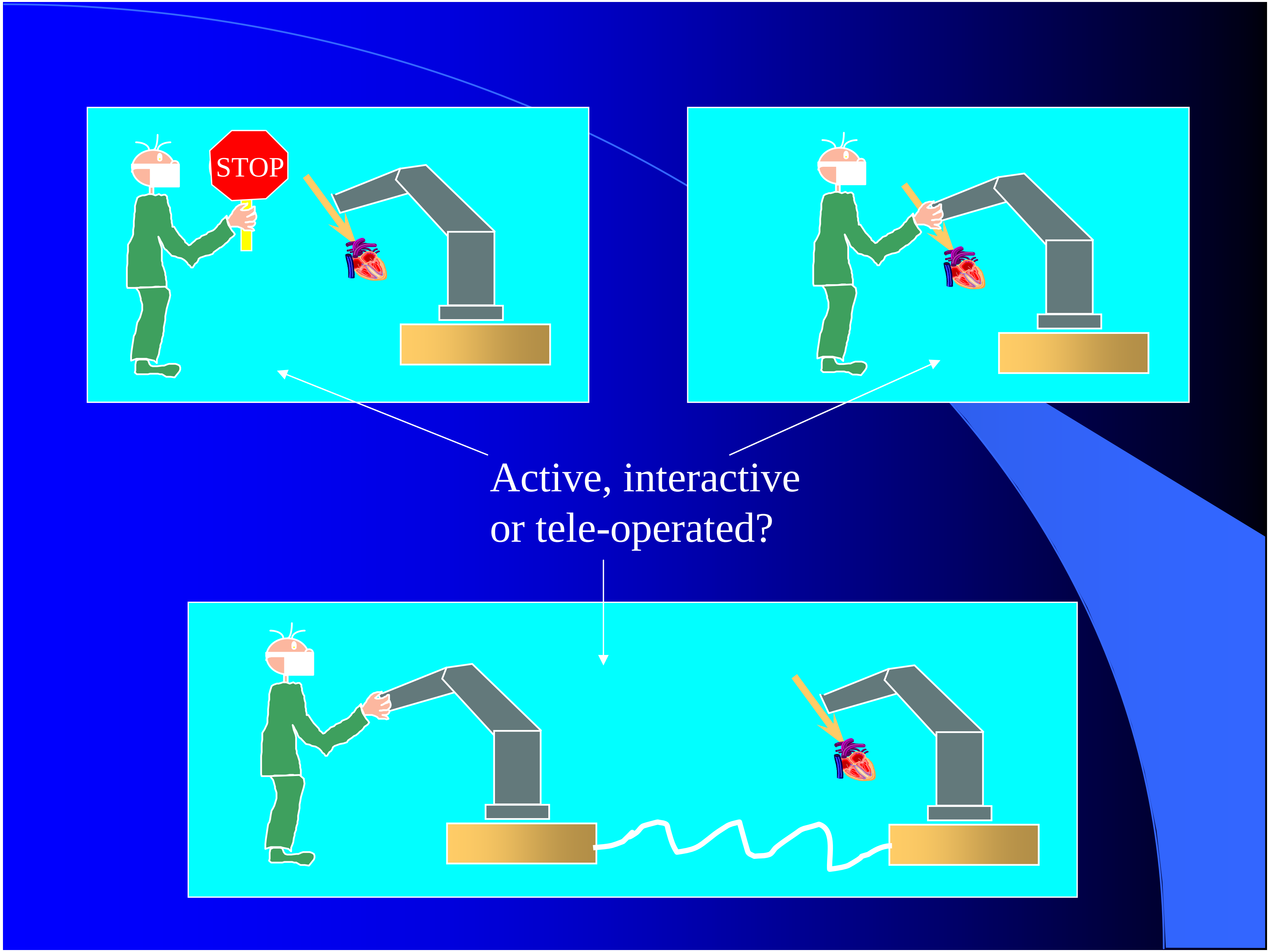
- Poor judgement
- Often expensive
- Hard to instruct
- Limited ability to do complex tasks or to react to unexpected events
- Poor hand-eye coordination

A robot: what for?

- Tasks with a complex geometry
- Third hand
- Intra-body tasks
- Tasks on moving targets
- Carry or hold heavy tools
- Force controlled actions
- Remote action
- Motion and force augmentation or scaling

Robots in the OR: a classification

- *Passive* systems
  - give information to the surgeon
- *Active* systems
  - realize the intervention with human supervision
- *Interactive* systems: mechanical guides
  - Semi-active devices
  - Synergistic devices
- *Teleoperated* devices


STOP
Active, interactive
or tele-operated?

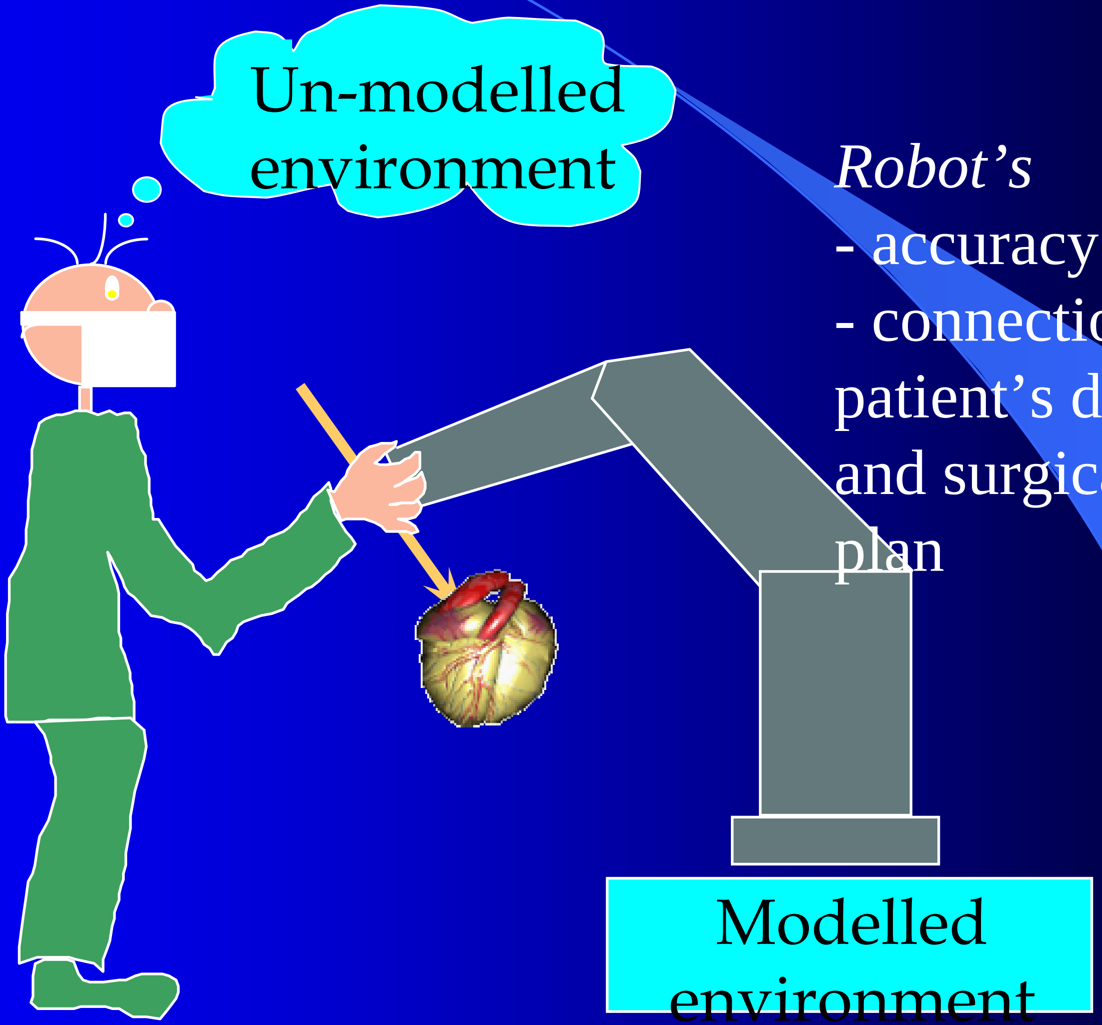
Surgical Navigation: an instance with visual feedback

Action: semi-active tools

Action: synergistic devices

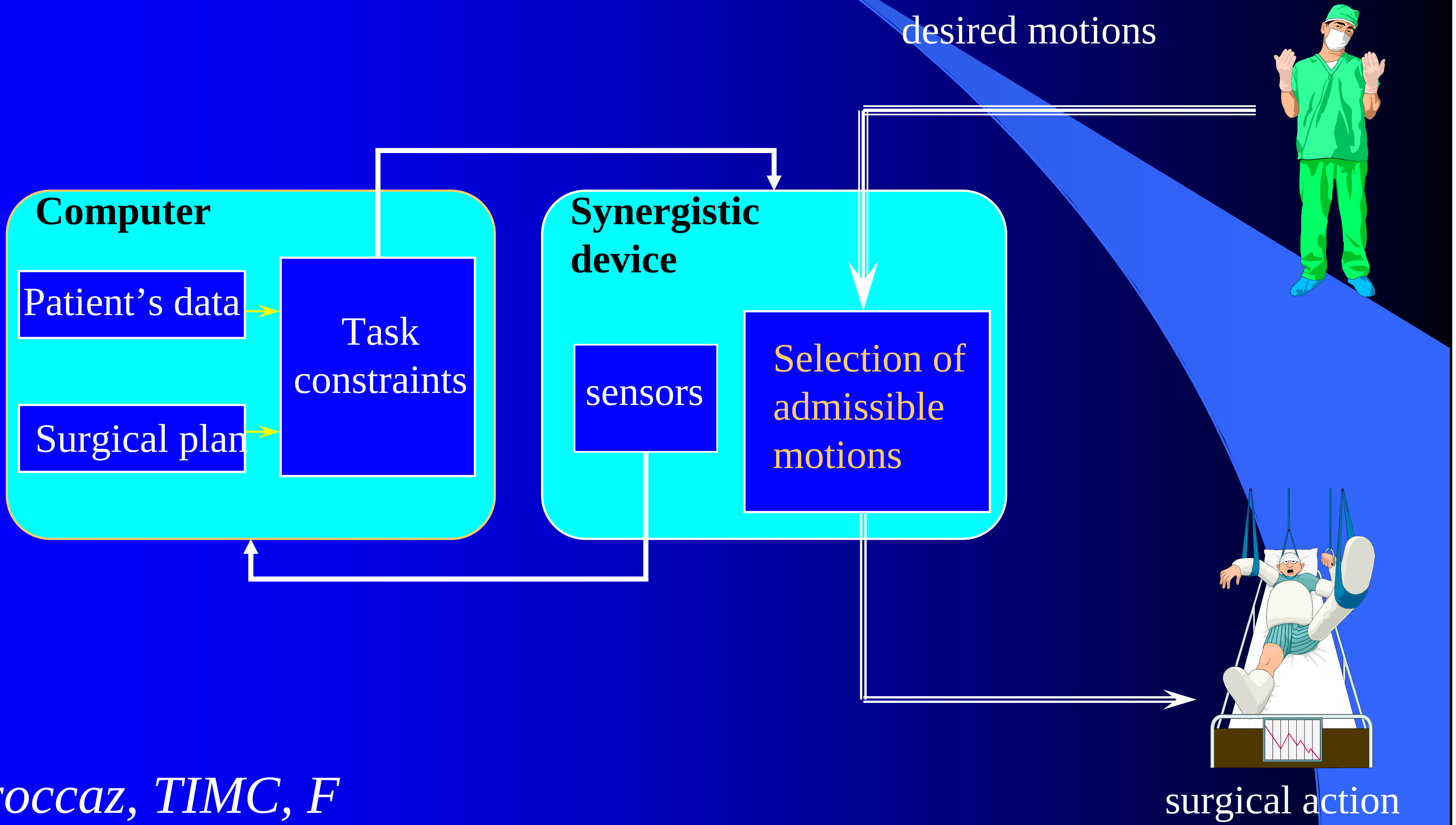
Benefit from:

Surgeon's
- sensing
- know-how
- ability to react to unexpected events



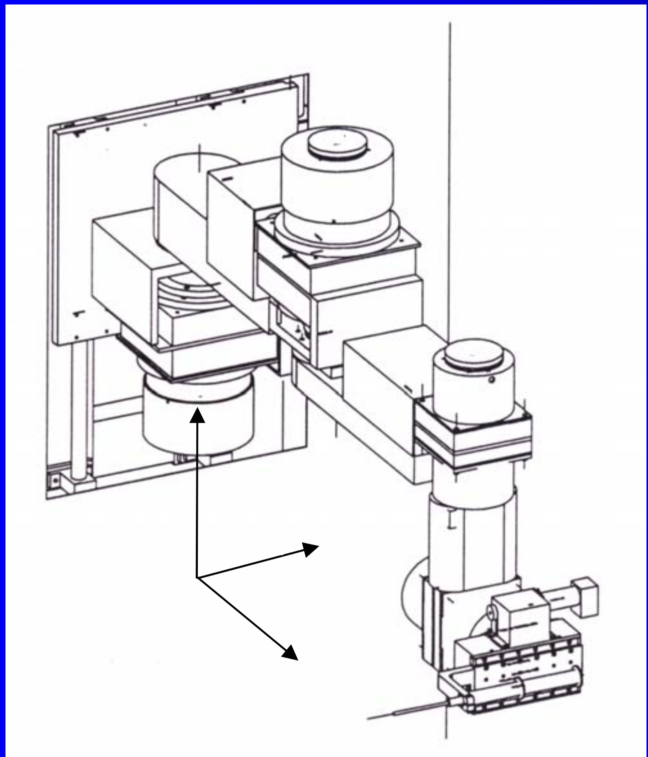
Robot's
- accuracy
- connection to patient's data and surgical plan

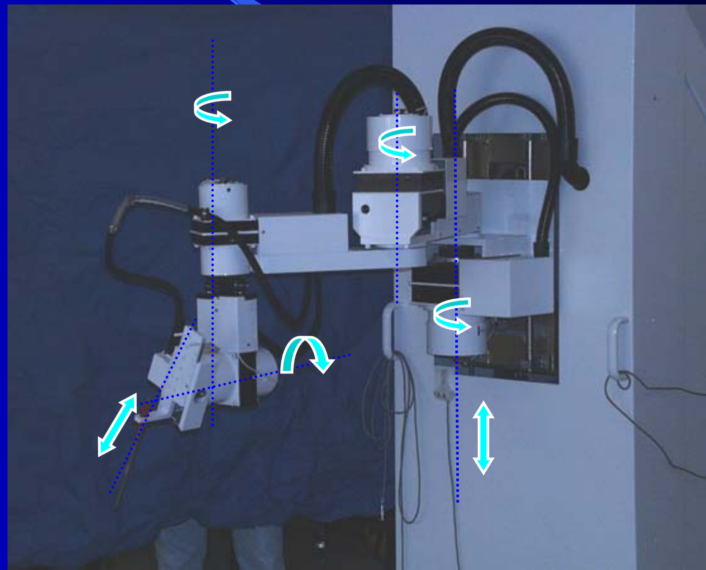
PADyC
(Passive Arm with Dynamic constraints)



J. Troccaz, TIMC, F

6 DOFs prototype

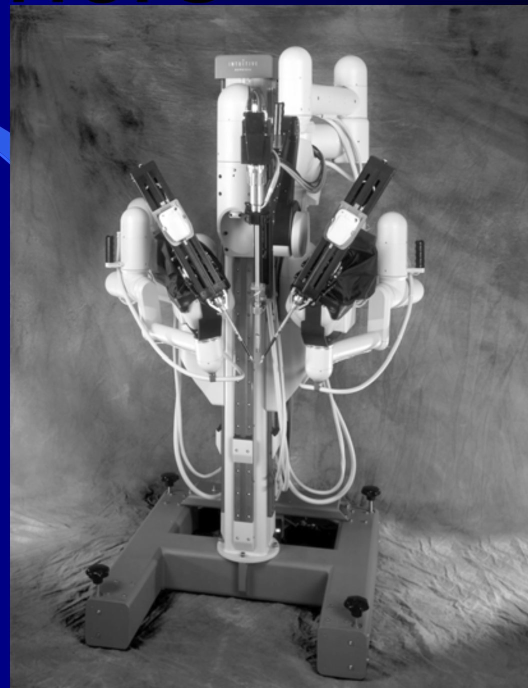


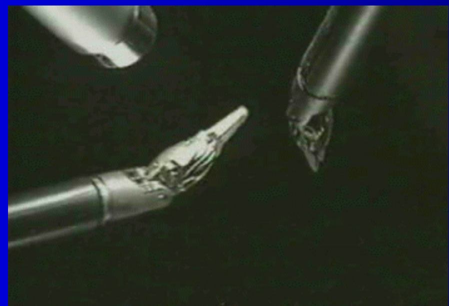


Tele-operated tools: the instance of Da Vinci®

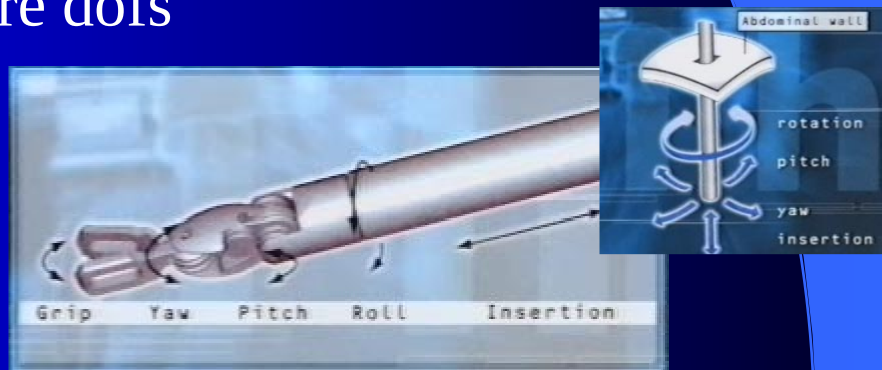
3D master console

3 robotic arms



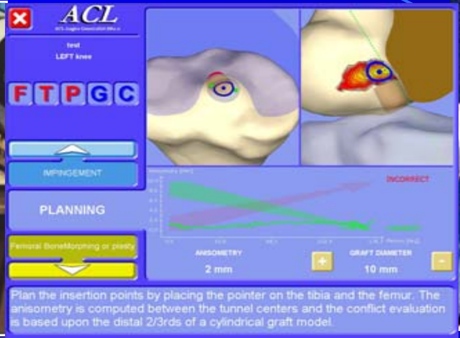


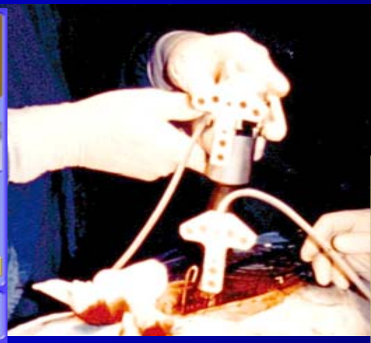
3 more dofs

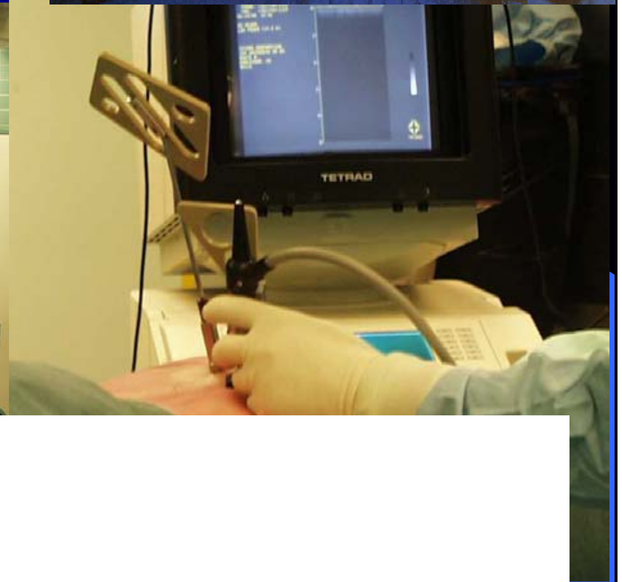


DaVinci in use

Computer Assisted Medical Interventions at Grenoble







Dental Implantology

QuickTime™ et un décompresseur TIFF (non compressé) sont requis pour visionner cette image.

Proven clinical benefits: *Enhanced Quality*

- Enhanced:
  - Precision and Reproducibility
  - Implant lifetime
- Reduction of:
  - failure or complications rates
  - “variance” around the objective
  - invasiveness
  - X-ray dose
  - Post-operative pain
  - Hospitalization length
- Quantified and accurate surgical reports

Potential economical benefits:

- Total Knee Arthroplasty (TKA): 10 years survival rate should raise from 90% to 97% [Computer Assisted Implantation of Total Knee Prostheses: A Case Control Comparative Study With Classical Instrumentation, Jenny J.Y., Computer Aided Surgery 6:217-220 (2001)]
  - 187 000 TKA/year in Europe
  - 10 000 € / TKA
  - Potential saving = 187000 x 10000 x 0.07 = **131 M€/year**
- Total Hip Arthroplasty (THA): 10 years survival rate should raise from 93% to 98% [Comparison of a Mechanical Acetabular Alignement Guide with Computer Placement of the Socket, A.M. DiGioia III, B. Jaramaz et al. The Journal of Arthroplasty, Vol. 17 N° 3 2002, pp 359- 364]
  - 450 000 THA/year in Europe
  - 11 000 € / THA
  - Potential saving = 450000 x 11000 x 0.05 = 245 M€/year

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Present Vision of **Quality Inspired Surgery**

- From ***Computer Assisted Medical Interventions*** (introduce IT in the OR) …
- to ***Quality Inspired Surgery*** (Model Driven Medical and Surgical Interventions),
- thanks to a ***Virtual SURGETICA University***

Quality Inspired Surgery

- **Consensually defining Quality in Surgery,**
- **Thanks to massive use of IT-based Models,**
- **Thus enabling development of completely innovative solutions to renew Surgical Practice.**

Virtual Orthopaedic European University

February 2000 - June2003

VOEU project overview

General Goal: compensate for the limits of the apprenticeship of specialist skills of Orthopaedics

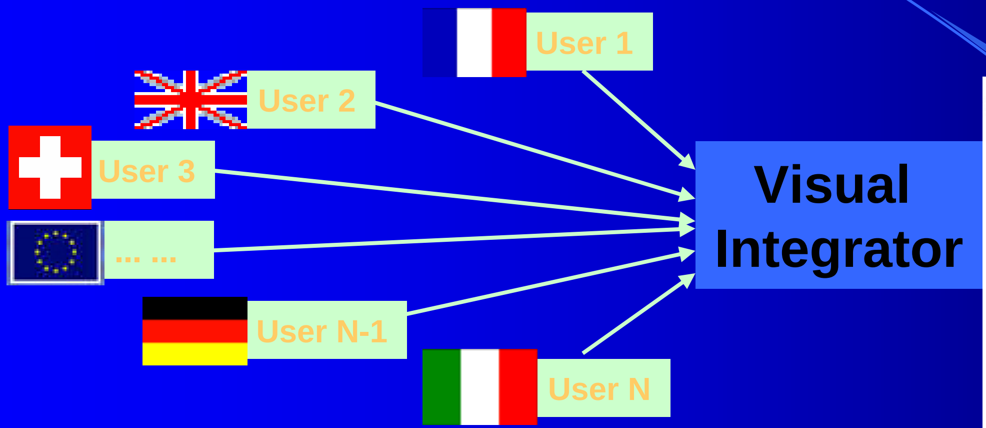
Great variation in Orthopaedic Practice Throughout Europe, due to the limits of the present learning process

Project Objective: enhanced student-teacher interaction in Orthopaedics

- *1) Enhanced learning material,*
- *2) Enhanced remote learning and interaction,*
- *3) Enhanced skill acquisition and evaluation.*

The VOEU "Visual Integrator"

http://www.voeu.rwth-aachen.de/default.htm

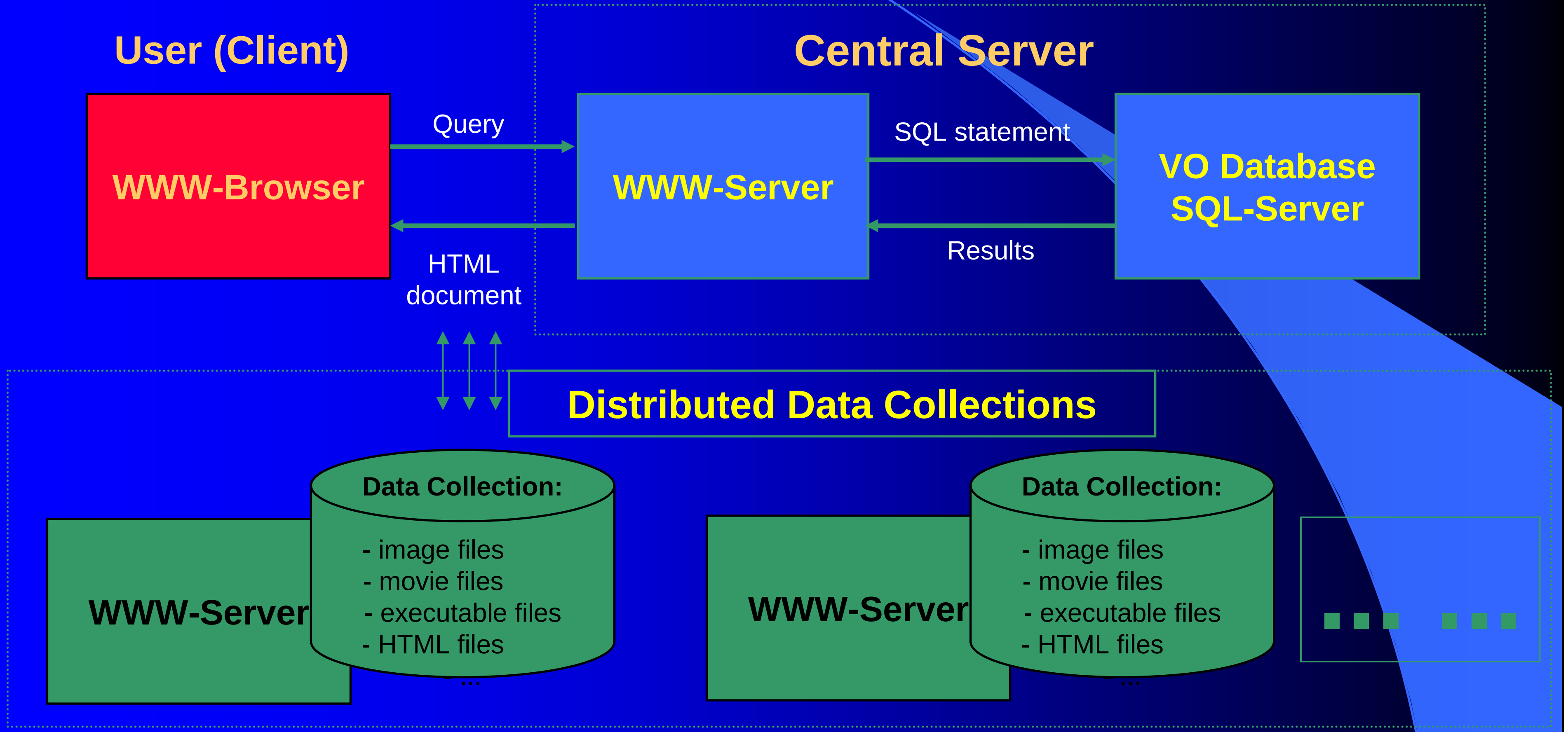


VOEU Information Server

Visual Integrator:

- An internet entry point for VOEU users from the geographically distributed sites
- A common platform with homogenous interface for users to utilize the VOEU service

WP03: Virtual Observatory System Architecture
- a WWW based Client/Server DB System -



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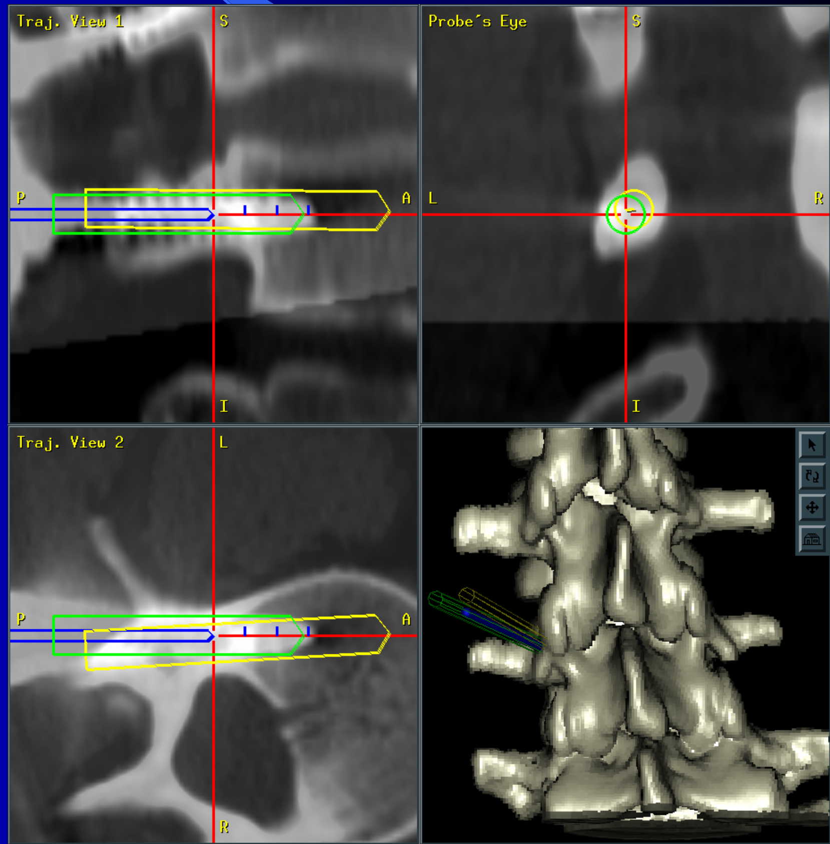
IT-based models for Quality Inspired Surgery

- **Modelling the surgical protocol**
- **Modelling the biomechanical behaviour of relevant organs**
- **…**

IT-based models of Surgical Procedures: *Taking ergonomics into account…*

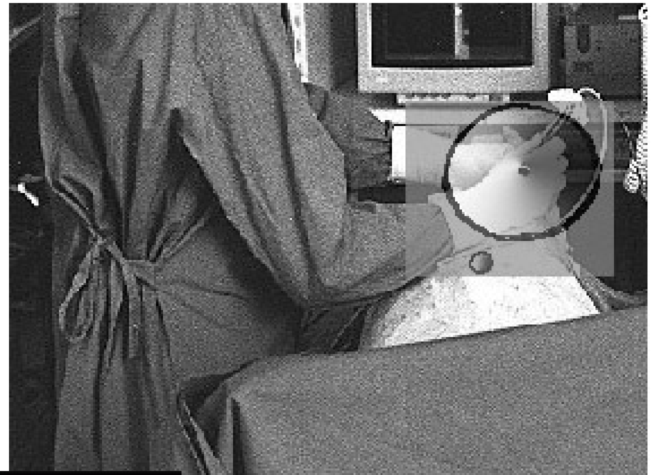


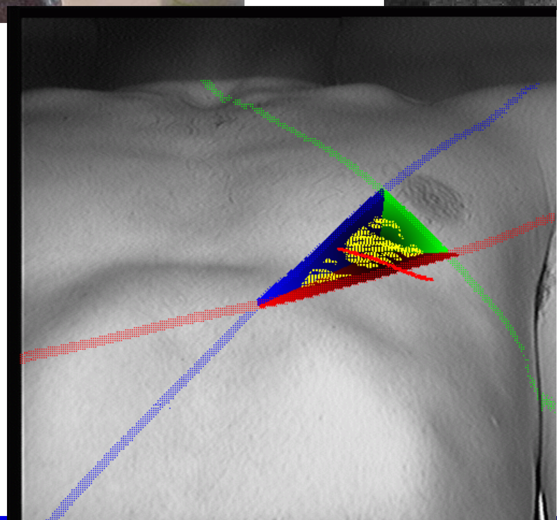
The instance of CASPER (Computer ASsisted PERicardial puncture)

O. Chavanon, D. Blin, J. Troccaz
Sce de Chirurgie Vasculaire, CHUG, TIMC-IMAG

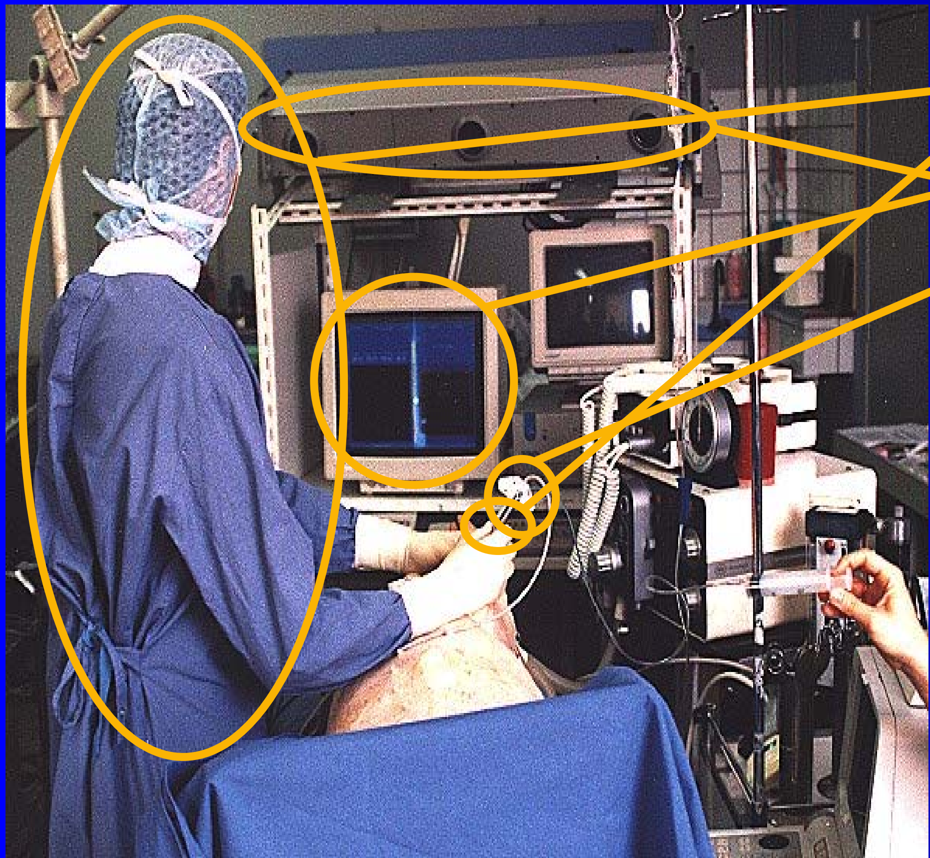
Ergonomics

- Visual continuity while performing the task





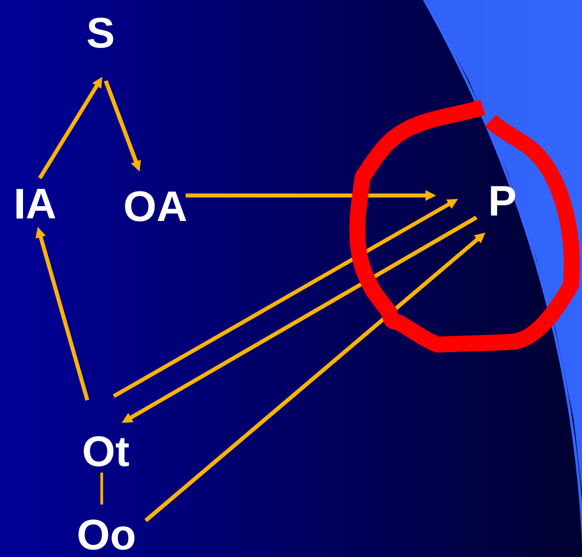
Ergonomics Modelling (E. Dubois, L. Nigay)



Components identification:

- Oo : Patient
- Ot : Puncture Needle
- P : Surgeon
- OA : Screen
- IA: 3-D localizer
- S : Computer

Relationships :

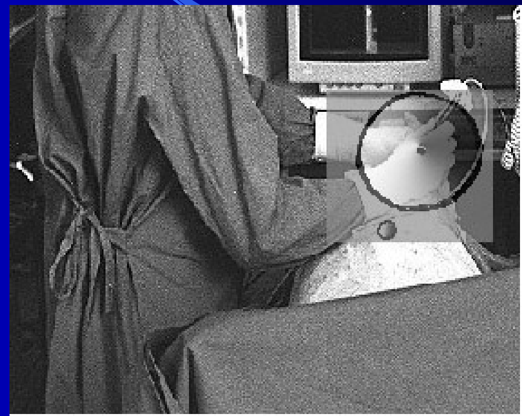


Ergonomics Modelling

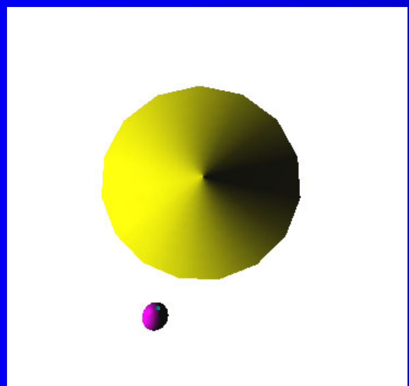
- **Physical level**
  - Perceptual environment
  - For instance in CASPER: the screen and the operating field
- **Cognitive level**
  - Distance between information pertinent for a single concept
  - For instance in CASPER : **2D representation of a 3D needle**

Ergonomics Modelling

- perceptual level: a new adaptor

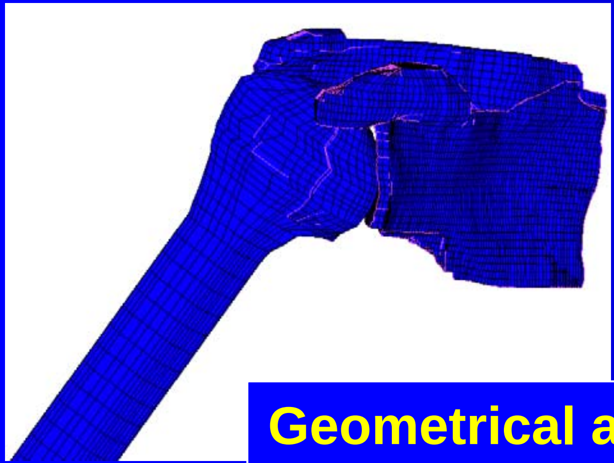


- Cognitive level: a 3-D stereoscopic representation



3-D cone = the trajectory
Simultaneous Representation of the real and planned trajectory

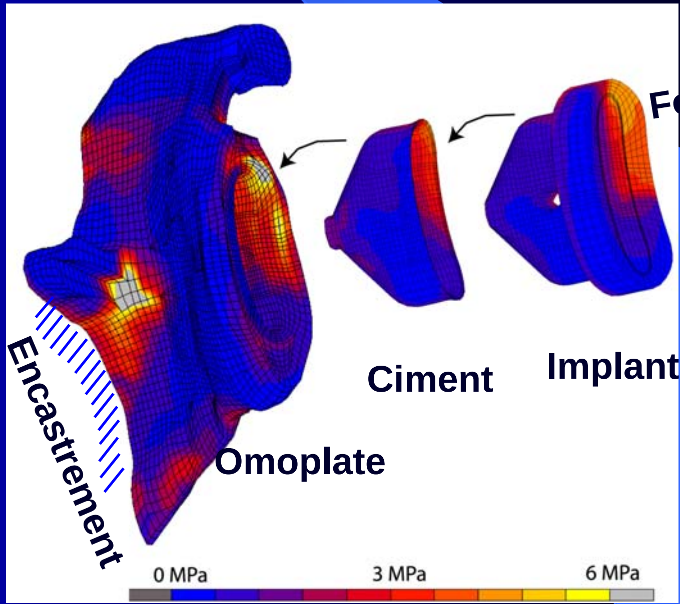
Shoulder Arhtroplasty



3-D Finite Element Model

Geometrical and mechanical criteria

Optimal Position (Geometric + mechanical + bone characteristics)



Implant Navigation

RNTS

Quality Inspired Surgery

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- **Thanks to massive use of IT-based Models,**
- **Thus enabling development of completely innovative solutions to renew Surgical Practice.**

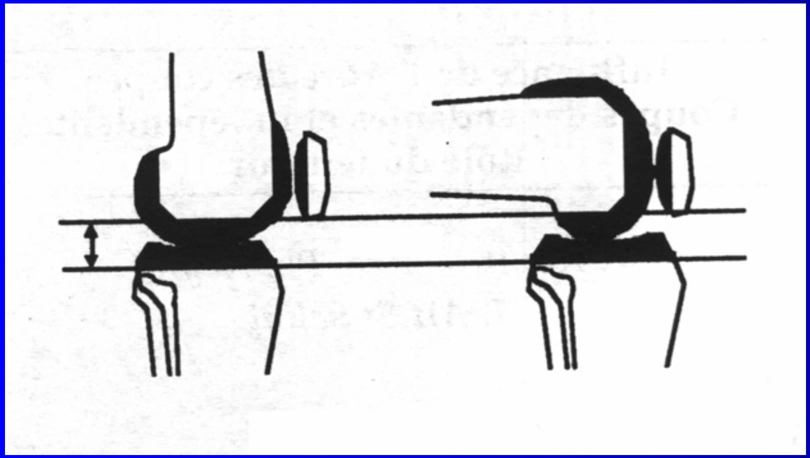
Innovative solutions for PERCEPTION

- Minimally Invasive Intra-operative Imaging (MI3)
- Articular Space Exploration

QuickTime™ et un
décompresseur 3ivx D4 4.0PR2
sont requis pour visionner cette image.

Model Driven Perception for Ligament Balance in Total Knee Arthroplasty

- **HKA alignment of 180 degrees**
- **Ligament balance = Equilibrium of Articular pressures**



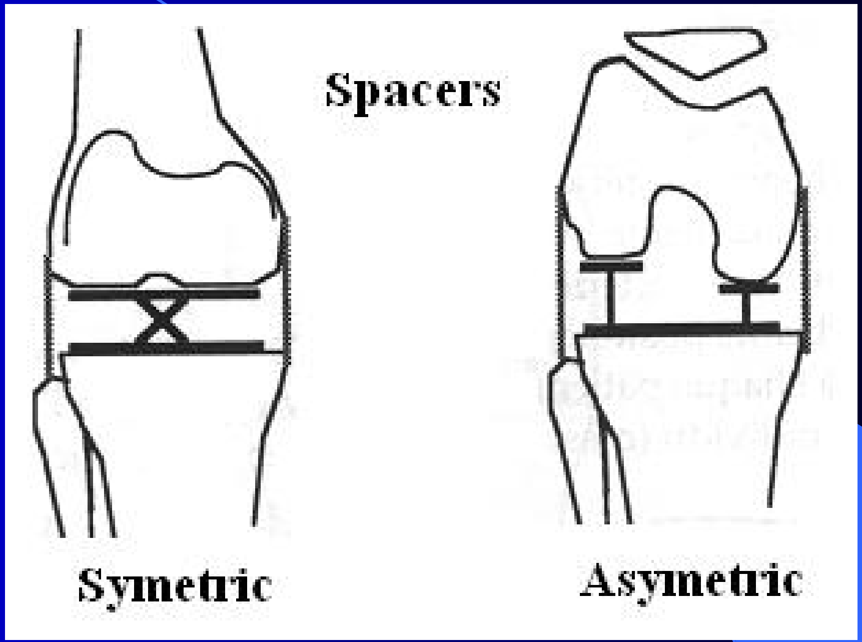
- **Extension**
- **Flexion**

➔ Bone cuts & Ligament releases

Model Driven Perception for Ligament Balance in Total Knee Arthroplasty

- Classical method

  ➔ Position information



- CASurgery

  Measures the laxities with a localizing system

Model Driven Perception for Ligament Balance in Total Knee Arthroplasty

Examples of spacers

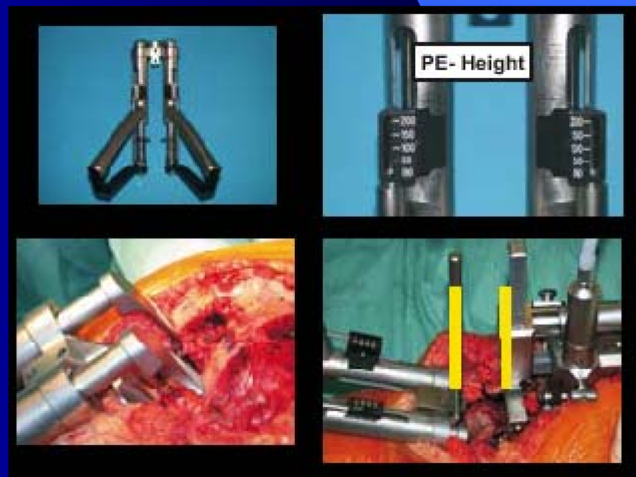
Balansys

Muratsu

Freeman

Cores

Insall

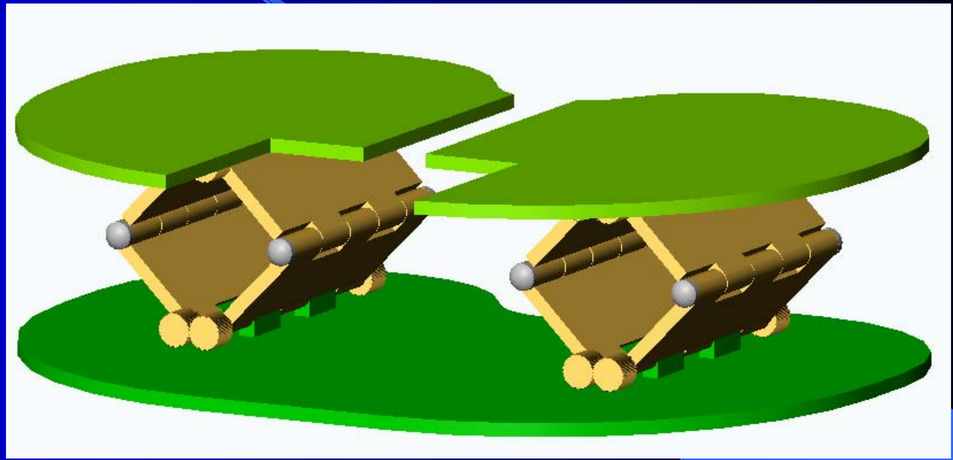


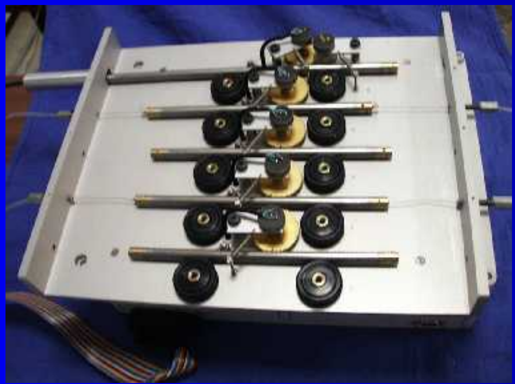
Ritschl Centerpulse

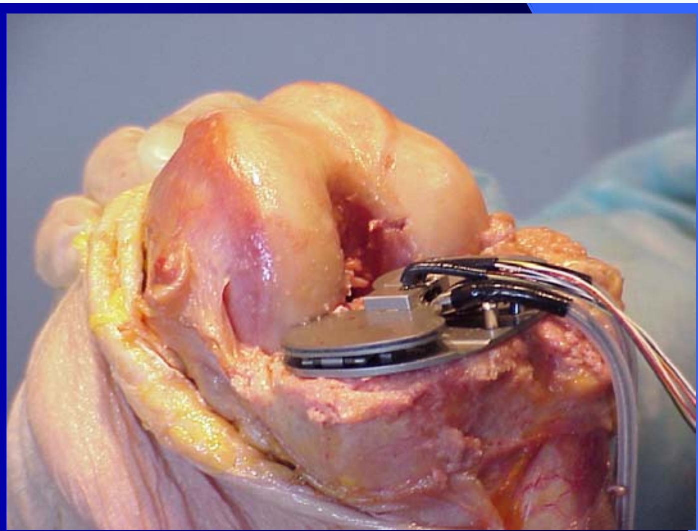
Model Driven Perception for Ligament Balance in Total Knee Arthroplasty

Robotized Spacer (C. Marmignon)

- ☺ « Closed » Envelope
- ☺ Real time measures
- ☺ Dynamic information
- ☺ Envelope modelling



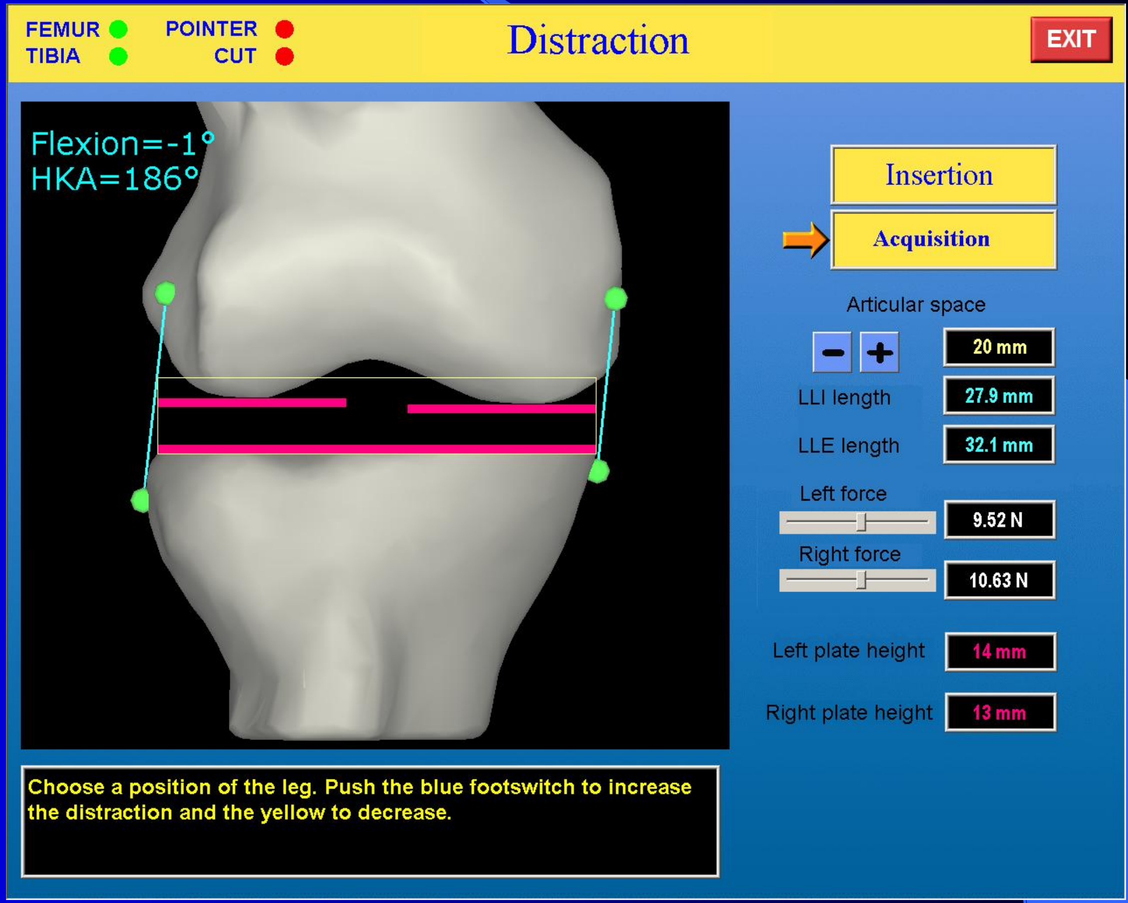




Model Driven Perception for Ligament Balance in Total Knee Arthroplasty

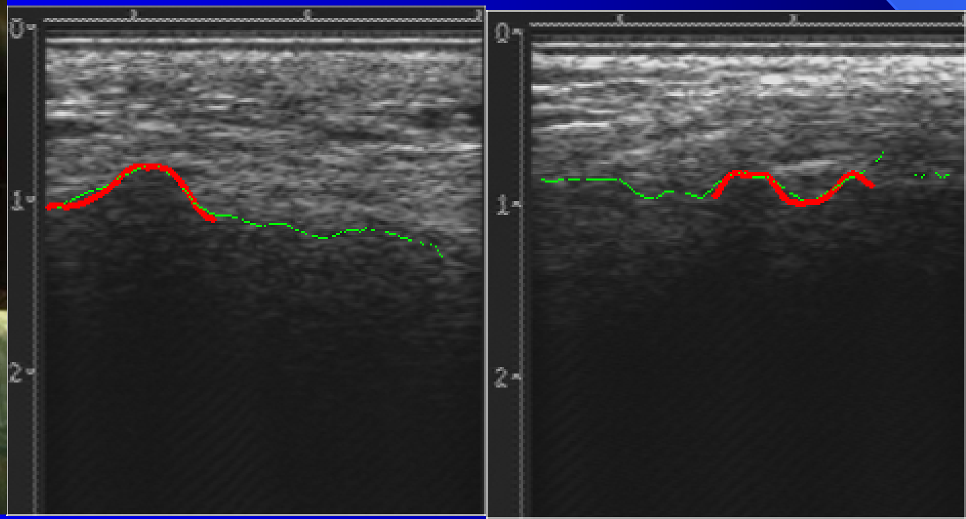
Results

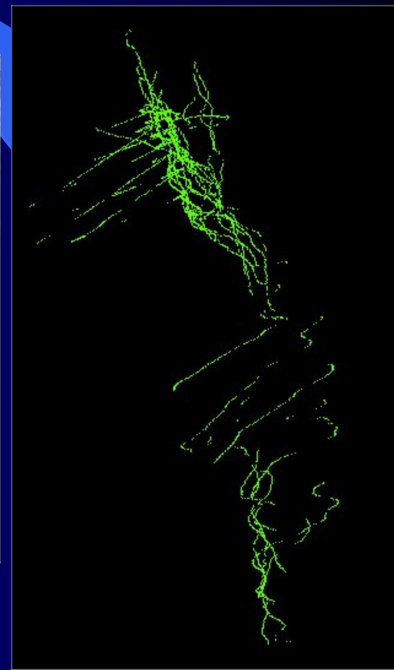
- ☺ Allows the distraction of the knee
- ☺ Measures the forces of distraction
- ☺ Measures their lengths at every time
- ☺ Helps to choose the bone cuts
- ☺ Helps to release



Innovative solutions for DECISION

The instance of CT-US automatic registration for sacro-iliac screw insertion





J. Tonnetti, P. Merloz, ***Automatic segmentation of bones from US***

CHU Grenoble

V. Daanen

3D set of US points for registration with CT data

Innovative solutions for ACTION

Tongue Display Unit (J. Vazquez, Y. Payan, J. Demongeot)

Tongue Display Unit

Innovative solutions for ACTION

Light Endoscopic Robot (P. Berkelman, E. Boidard, J.A. Long)

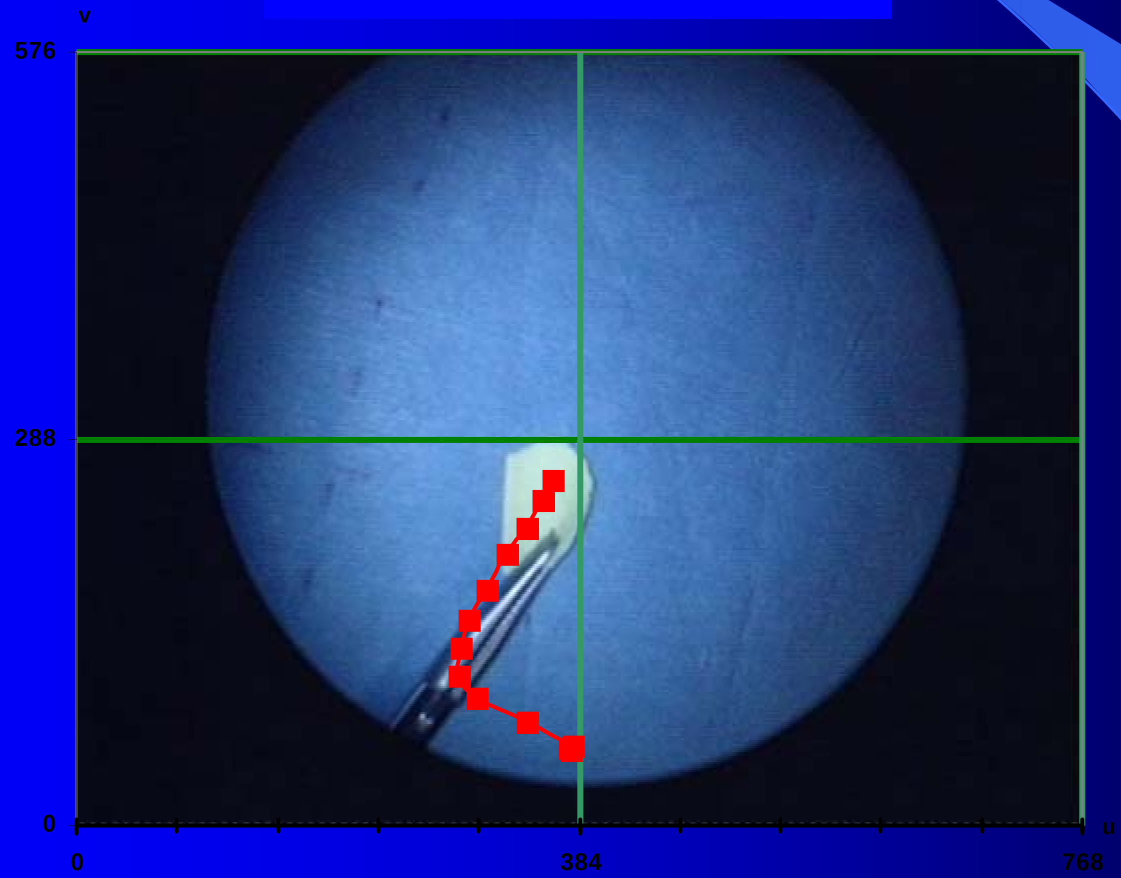
QuickTime™ et un décompresseur TIFF (non compressé) sont requis pour visionner cette image.

Lightweight Tele-Endoscopy

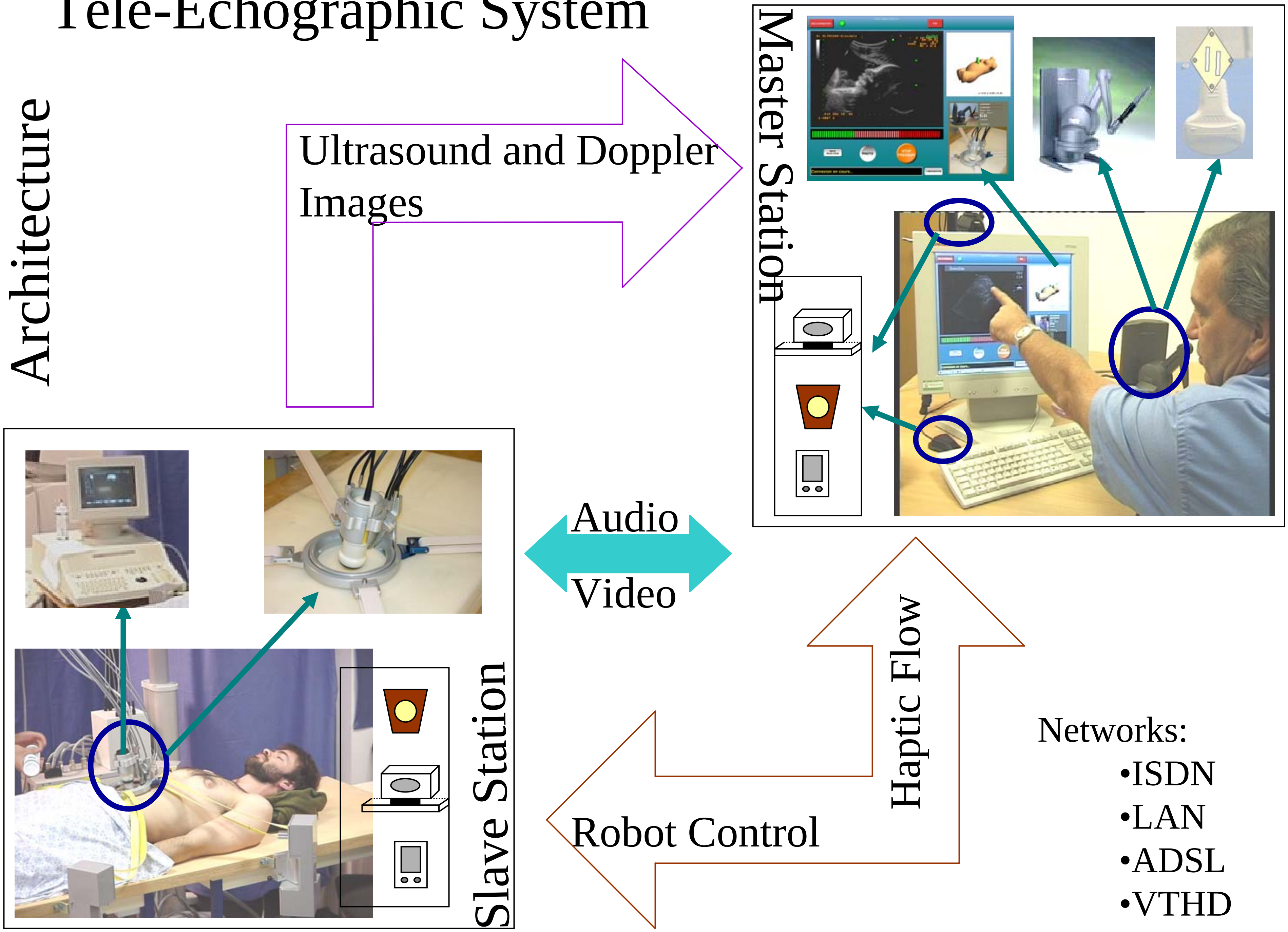
QuickTime™ et un
décompresseur 3ivx D4 4.0PR2
sont requis pour visionner cette image.

Combining ACTION and Perception

(S. Voros, E. Orvain)



Tele-Echographic System



Innovative solutions for ACTION

Light Robotized Tele-Echography

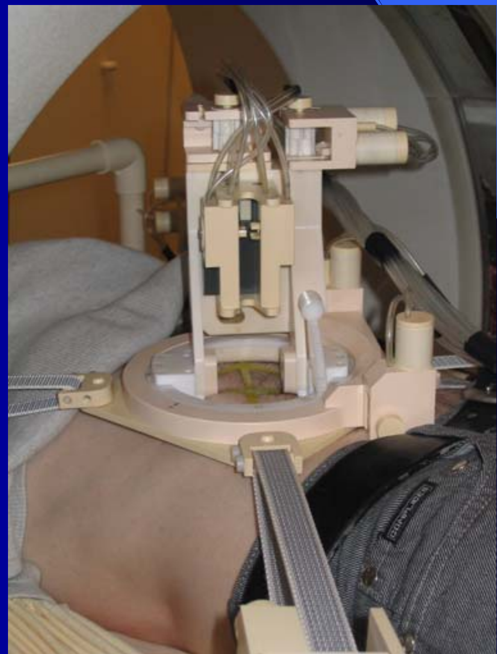
QuickTime™ et un
décompresseur codec YUV420
sont requis pour visionner cette image.

Innovative solutions for ACTION

Light Puncture Robot *(E. Taillant, C. Allegrini, D. Arnaud, I. Bricault)*

Robot Architecture

- *CT/MR compatible*
- *Interdependent of patient's body*
- *Sterilizable*

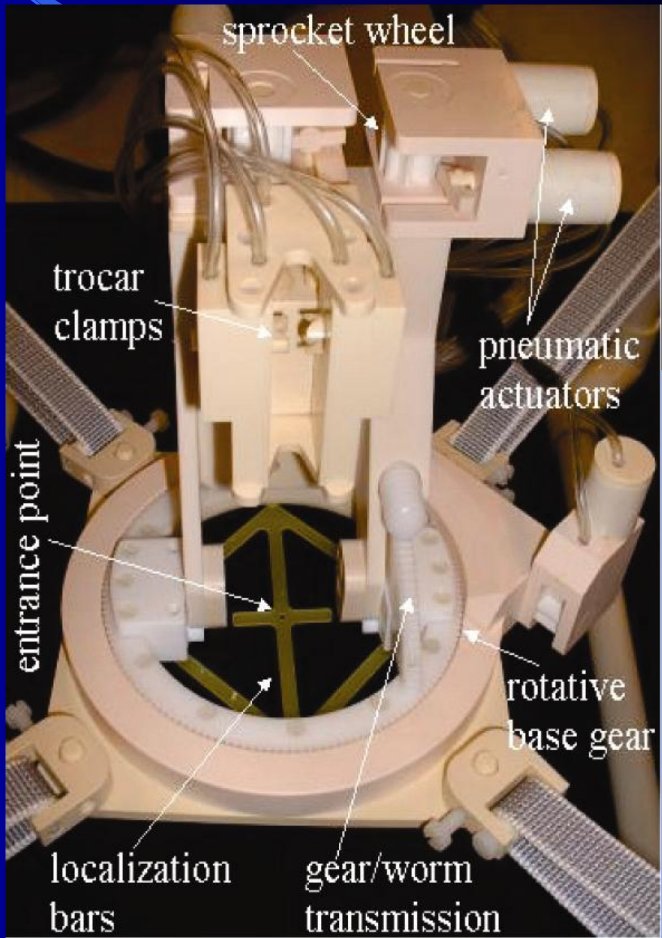


Robot Architecture

5 Degrees of Freedom

Compressed air powered

Embedded Localization Device



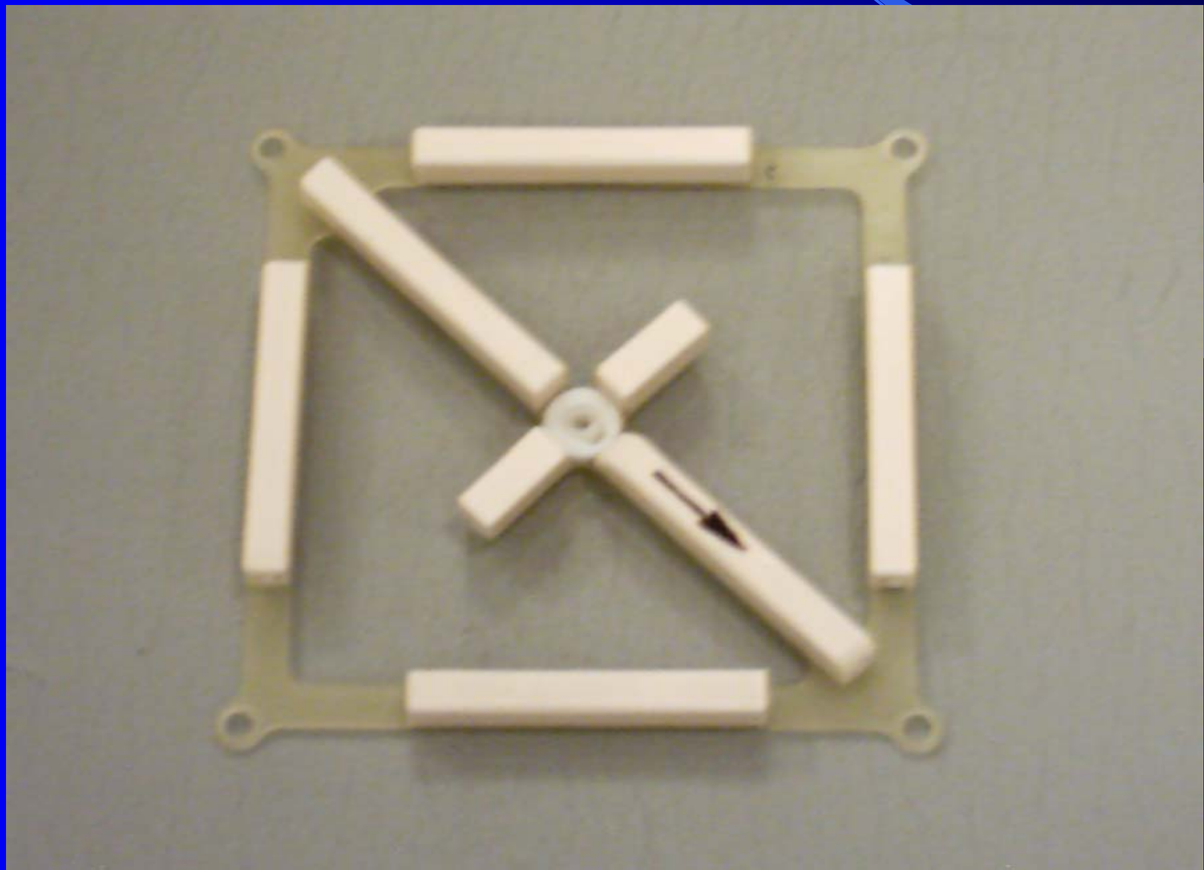
Localization

No active sensors (CT/MR compliance)

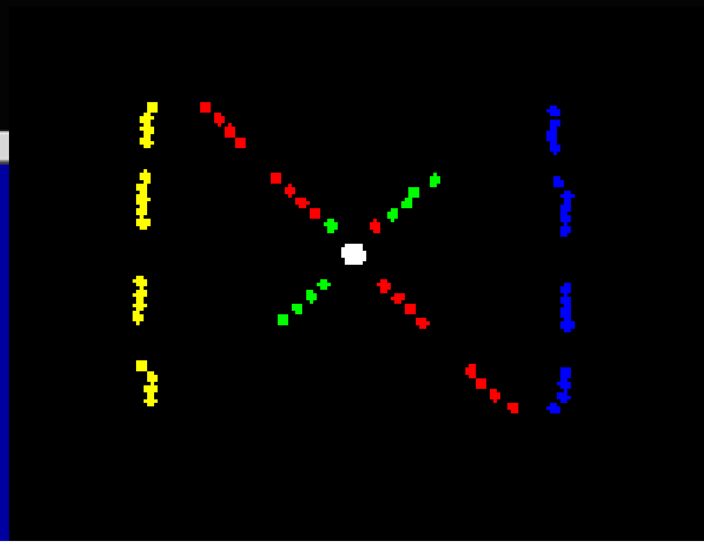
Passive localization devices using CT/MR image processing.

Fully determined attitude.

Localisation device for MR




Dicom View
R



Experiments & Results

Open Loop Performance

Translation Accuracy : 5% of distance

Rotation Accuracy : less than 1°

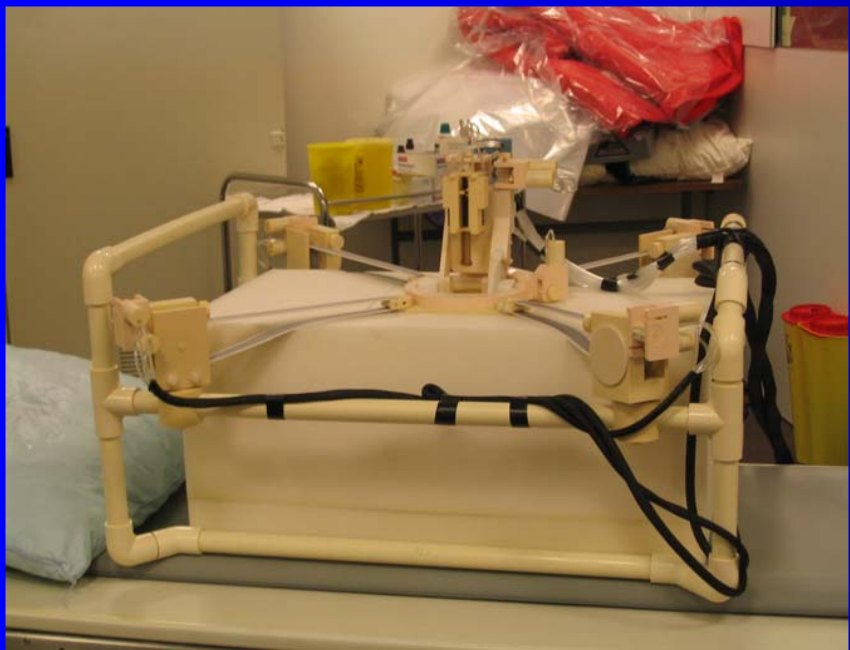
Image Processing Performance

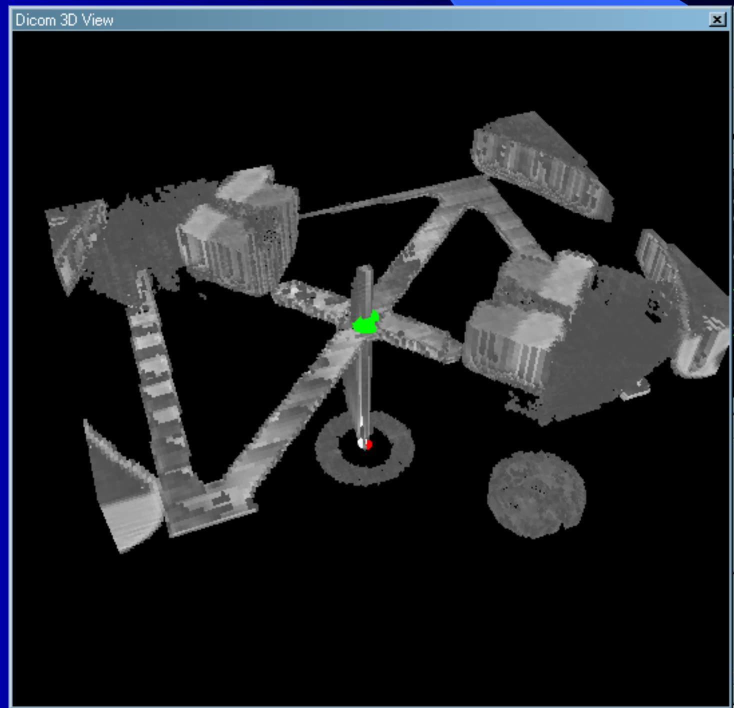
Entry Point Localization Accuracy : ~1mm

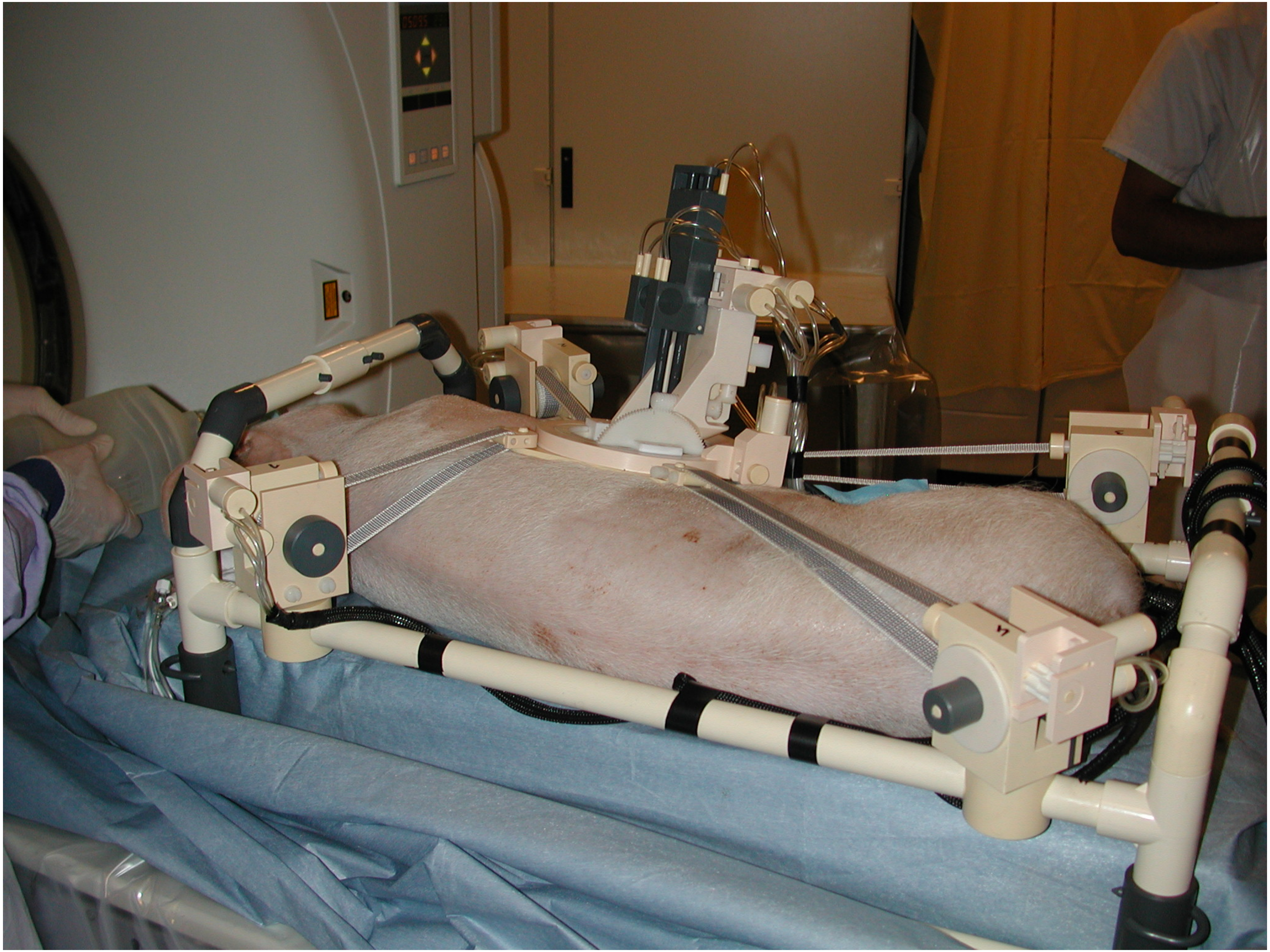
Angles Determination Accuracy : ~2°

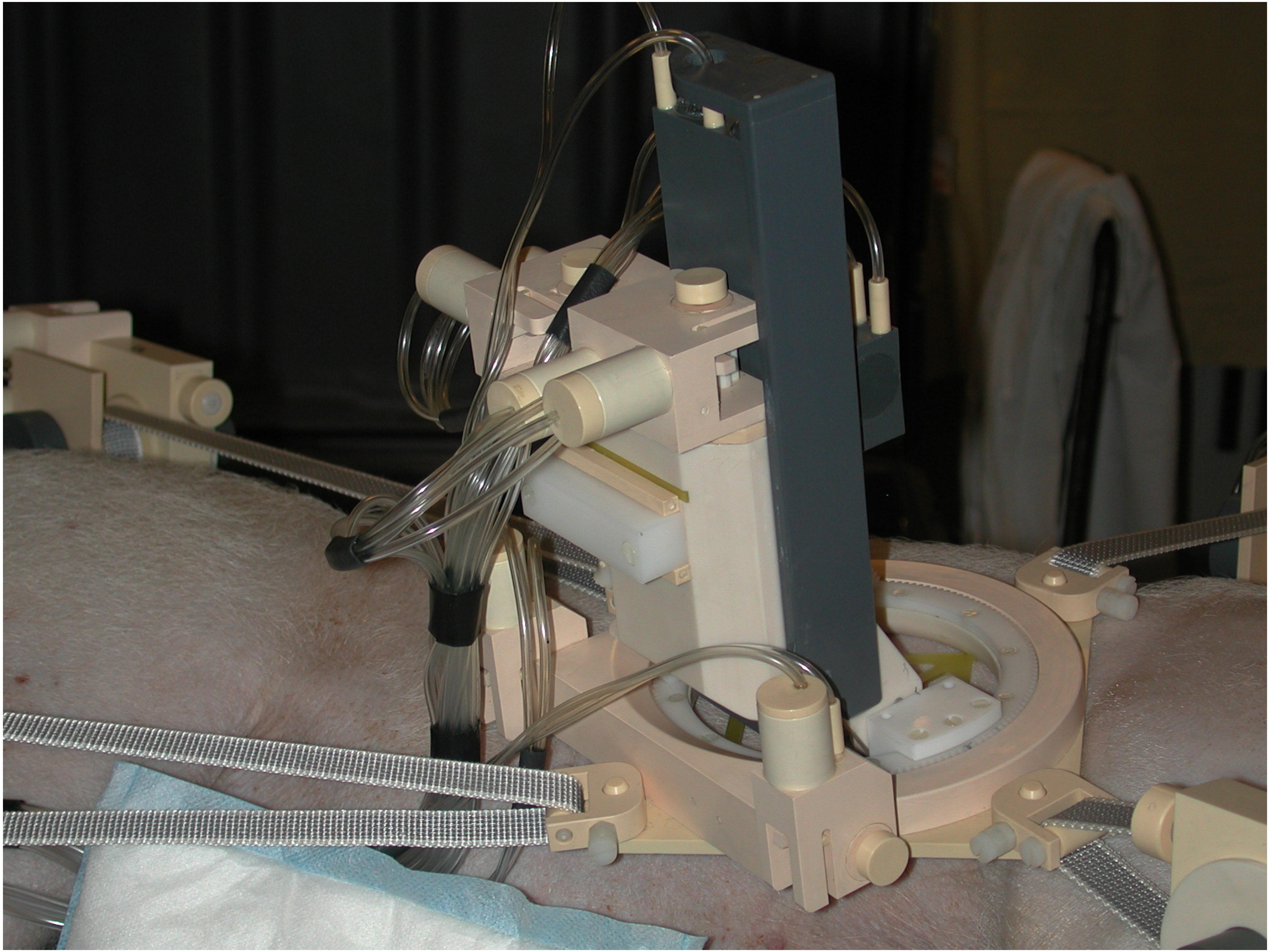
Experiments & Results

- *Phantom Experiments*
  - *2 attempts (1vertical,1 inclined)*
  - *Targeting Accuracy : less than 1.5mm*





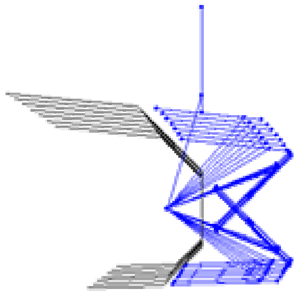


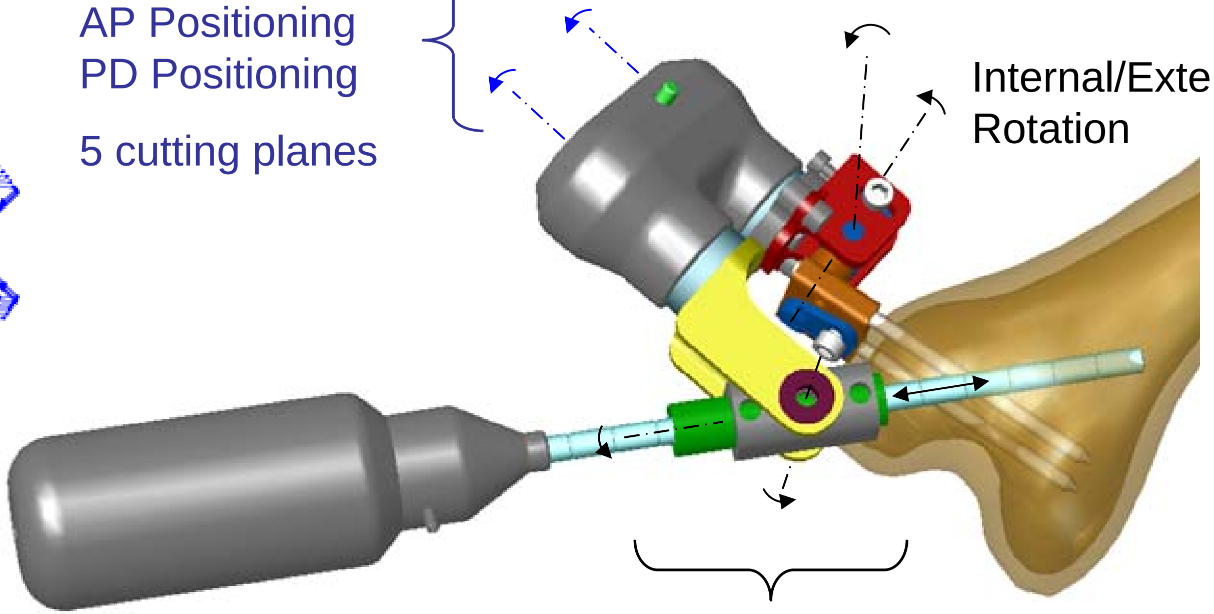


QuickTime™ et un
décompresseur DV - PAL
sont requis pour visionner cette image.

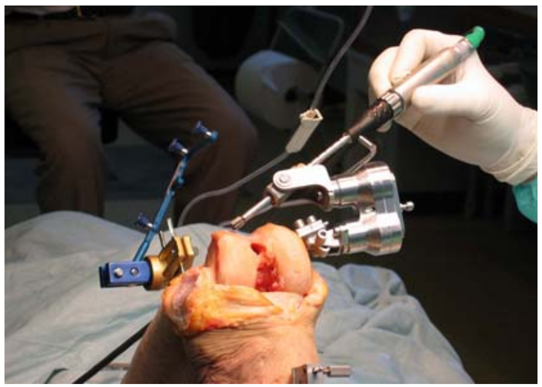
QuickTime™ et un
décompresseur DV - PAL
sont requis pour visionner cette image.

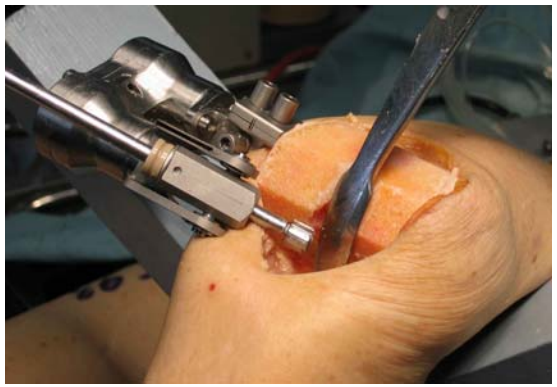
Praxiteles mini-robot (C. Plaskos)





Hybrid
Passive / Motorized
Architecture





Praxiteles (C. Plaskos)

- Multiple Challenges
- Initial Vision : CAMI
- Achievements of CAMI
- Present Vision of QIS
- Preliminary Research on “μ-QIS”

Quality Inspired Surgery (QIS)

- Multiple Challenges
- Initial Vision : CAMI
- Achievements of CAMI
- Present Vision of QIS
- Preliminary Research on “μ-QIS”

Sources of Energy for "μ-QIS" systems

- **Objective**: implantable micro-robots and micro-systems, capable of assisting weakening functions (cardio-vascular, kidney, breathing, bladder, …)
- **Common issue**: need for a renewable and controllable source of energy

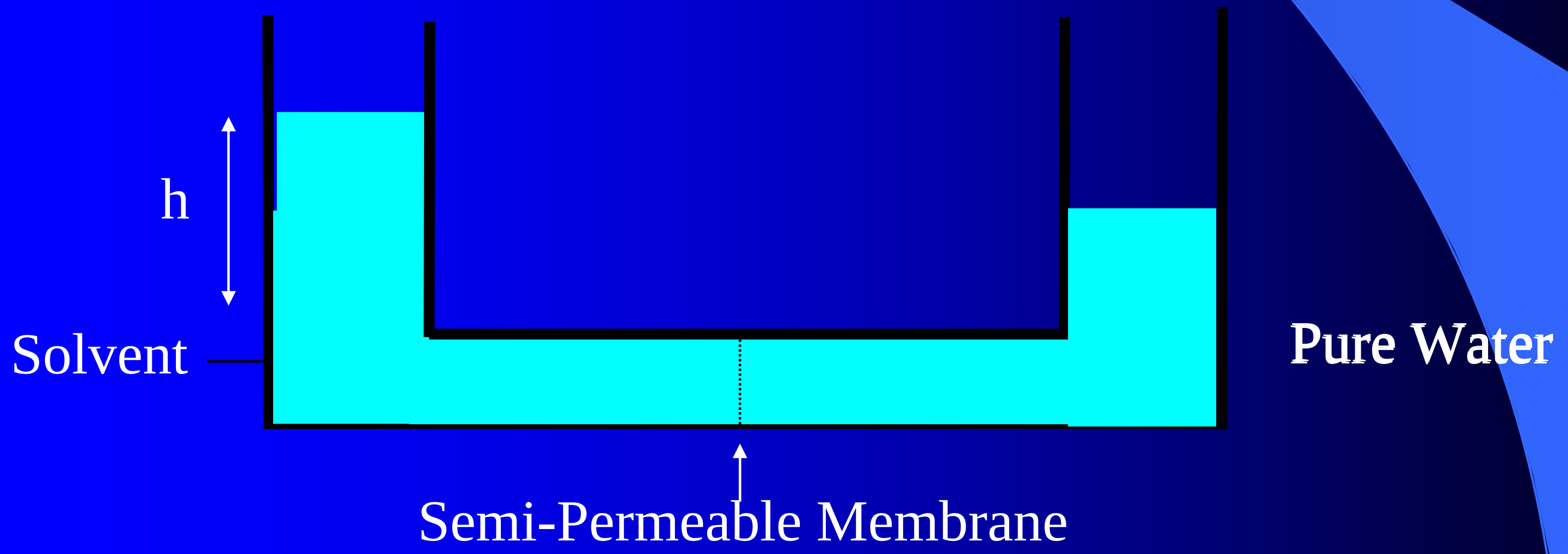
Osmotic "μ-muscle":

preventing revascularisation of grafts in endovascular surgery of Abdominal Aortic Aneurisms (AAA)

Osmotic "μ-muscle":

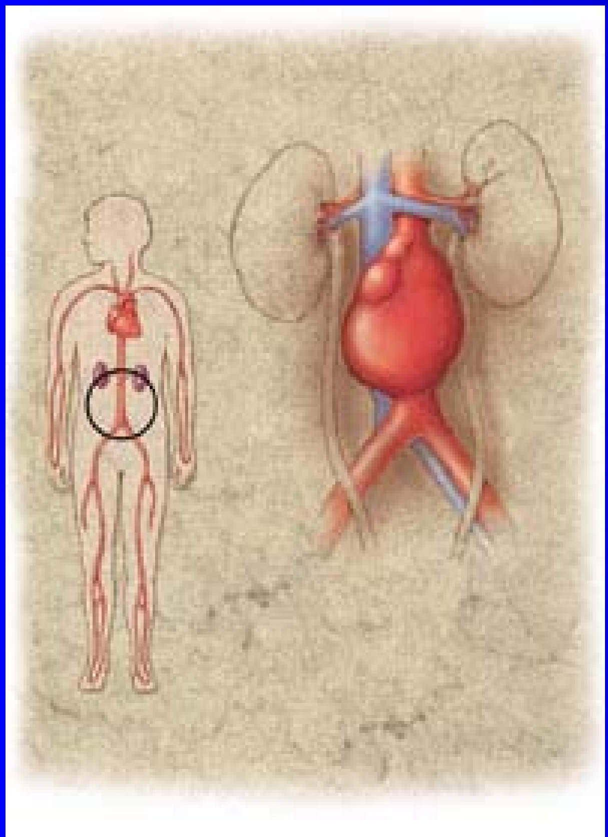
preventing revascularisation of grafts in endovascular surgery of Abdominal Aortic Aneurisms (AAA)

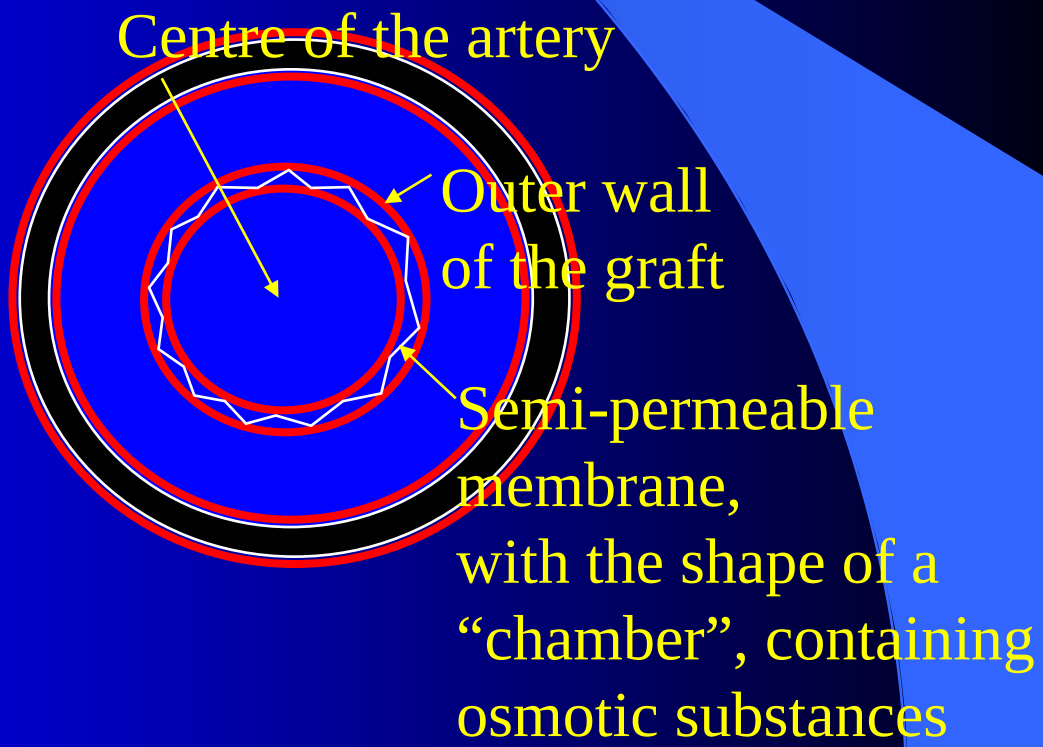
$$\Pi = \rho\, g\, h = \Delta W\, R\, T$$



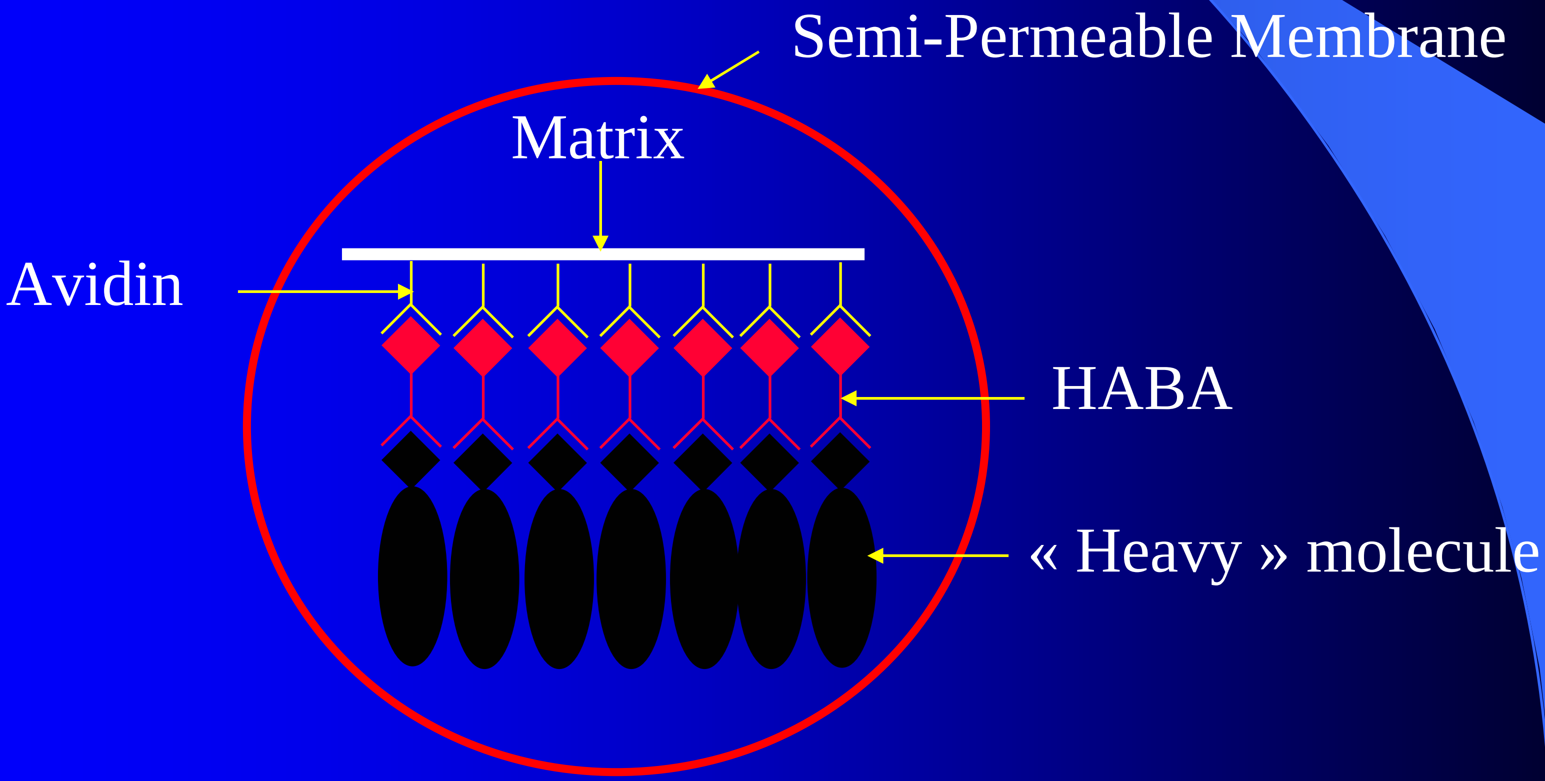
Osmotic “μ-muscle”:

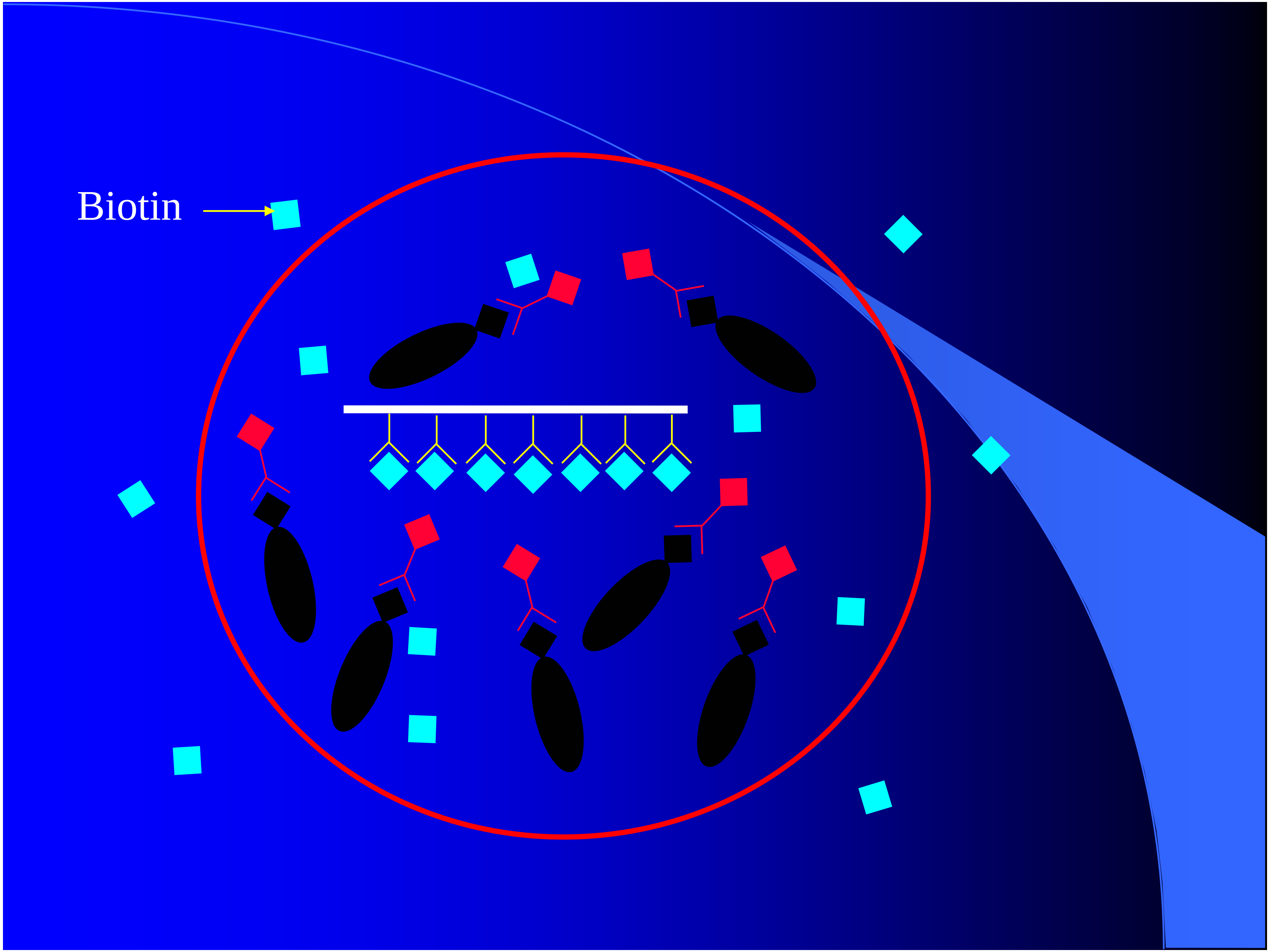
preventing revascularisation of grafts in endovascular surgery of Abdominal Aortic Aneurisms (AAA)



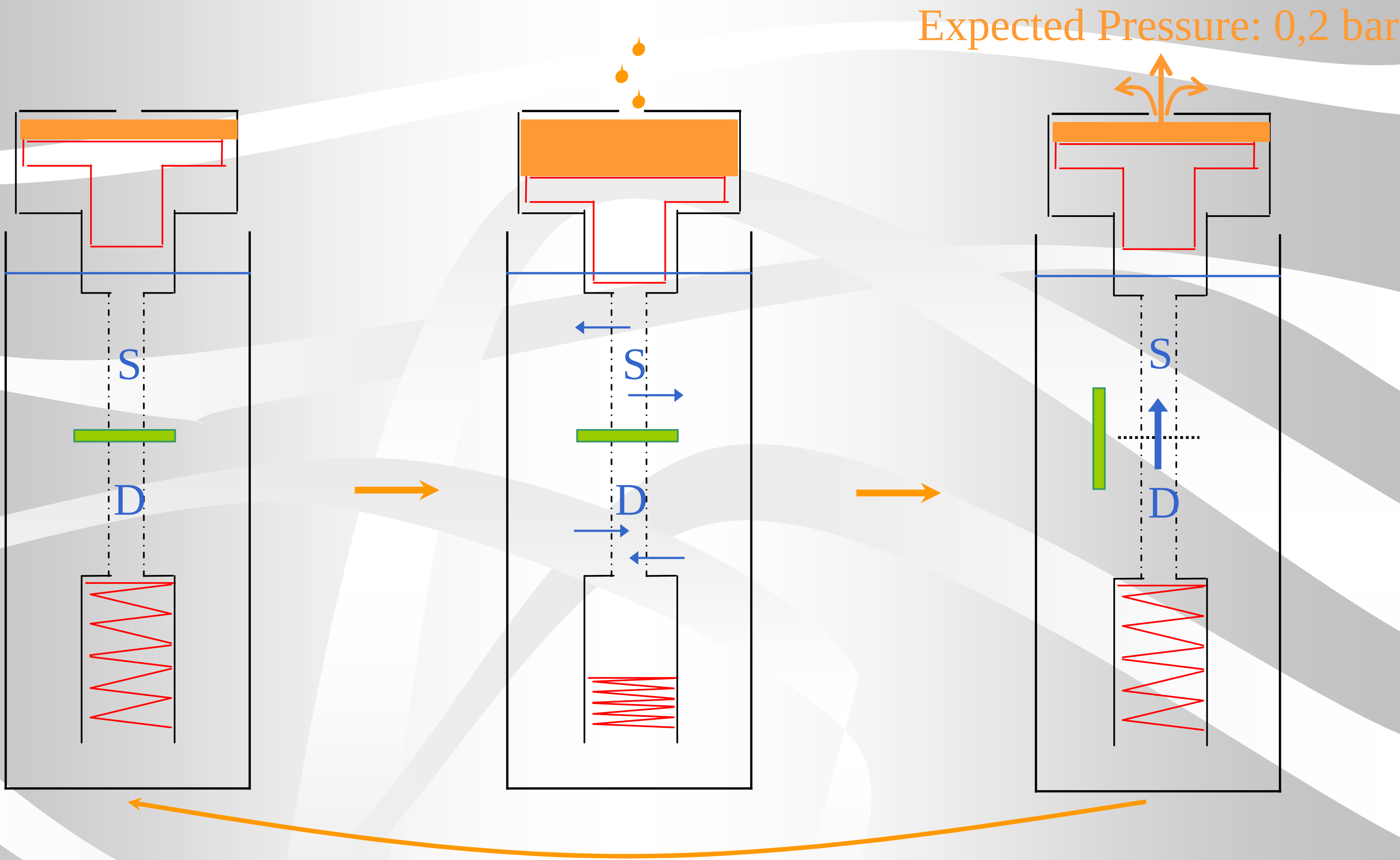


Biochemical control of osmotic pressure




Biotin

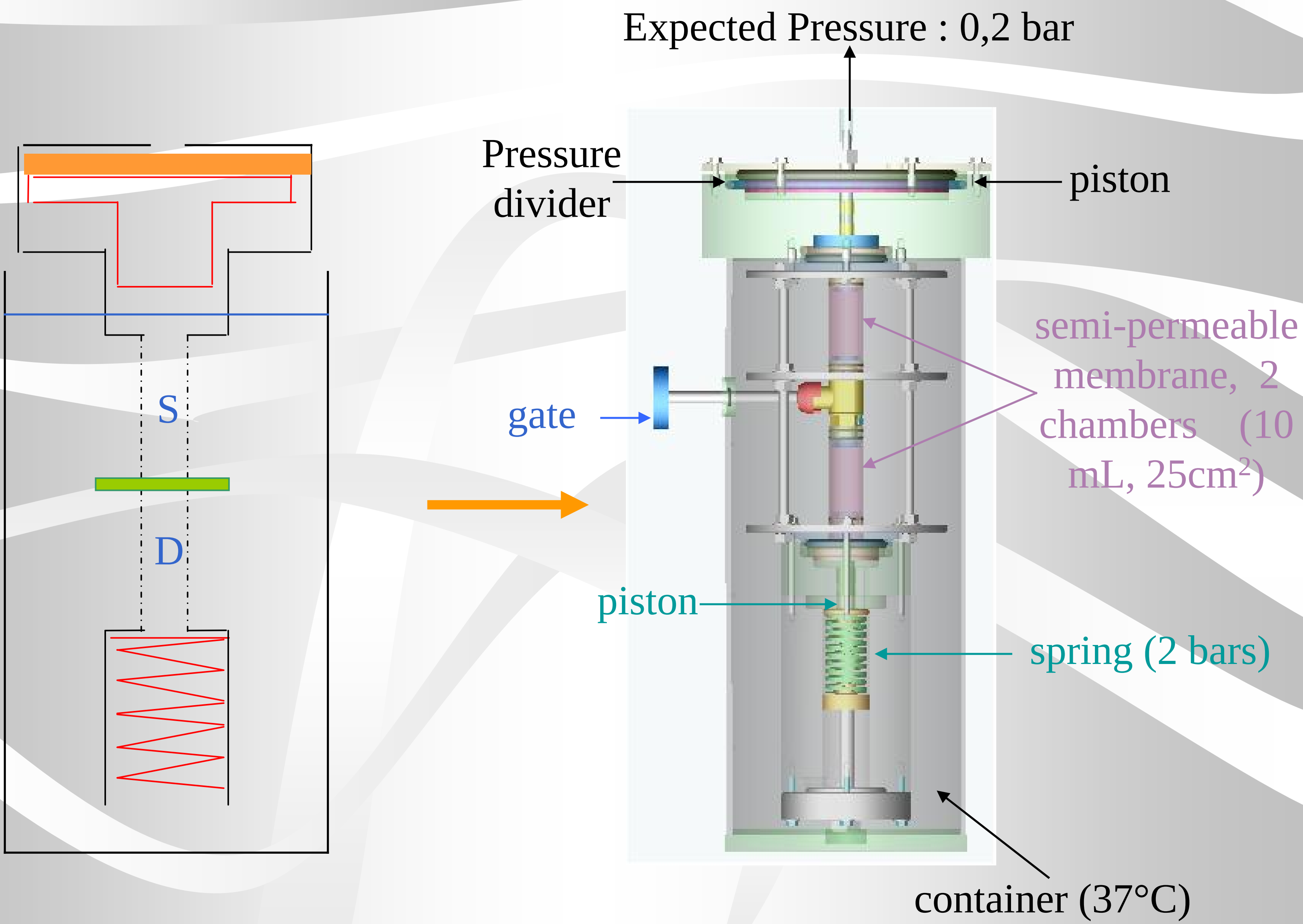
OSMOTOR: conversion of biochemichal energy into mechanical energy



Synthesis : Π int < Π ext ⟶ water flows out

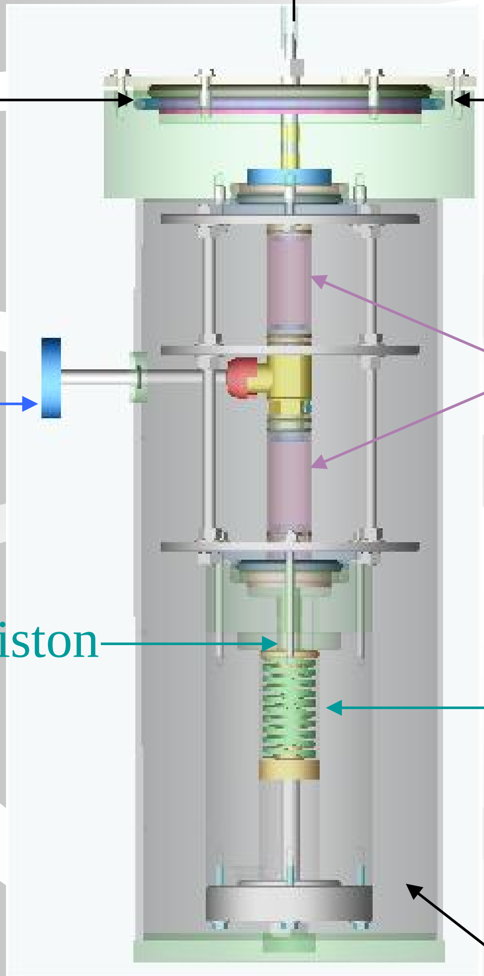
Dégradation : Π int > Π ext ⟶ water flows in

Osmotor demonstrator



Osmotor demonstrator

Expected Pressure : 0,2 bar



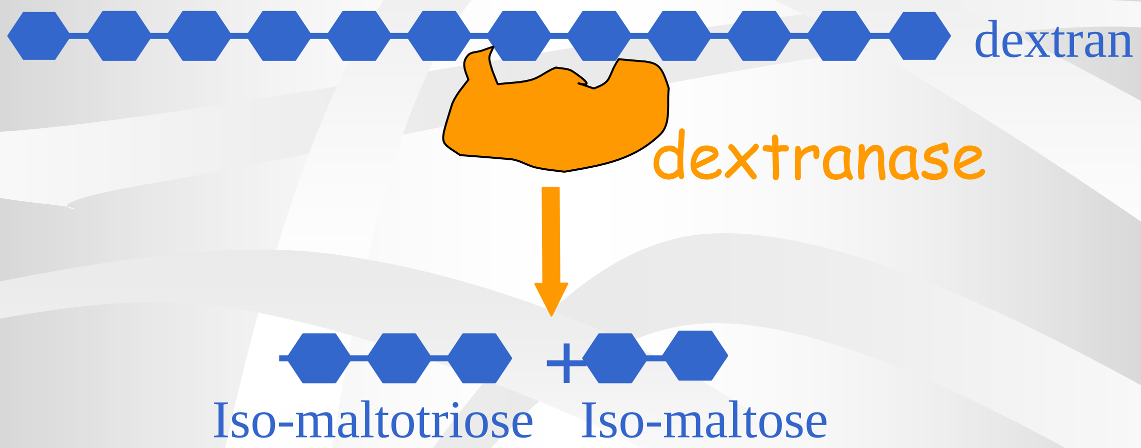
Creation of energy

Dextran

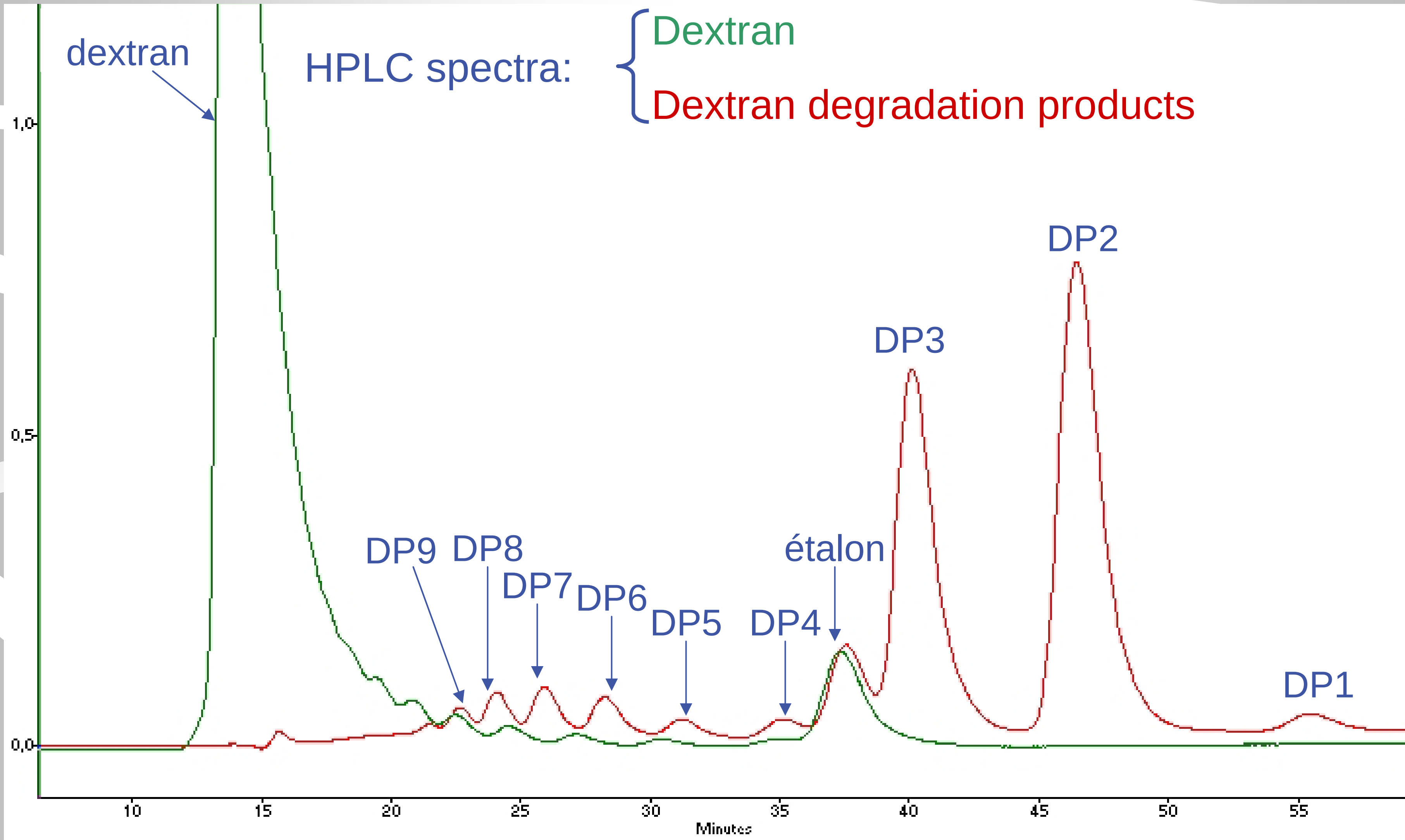
- Glucose polymer
  - More than 50% of α(1→6) links 
  - bacterial origin
  - enzymatic synthesis and degradation
  - bio-compatible

Energy Creation: degradation

- Dextranase

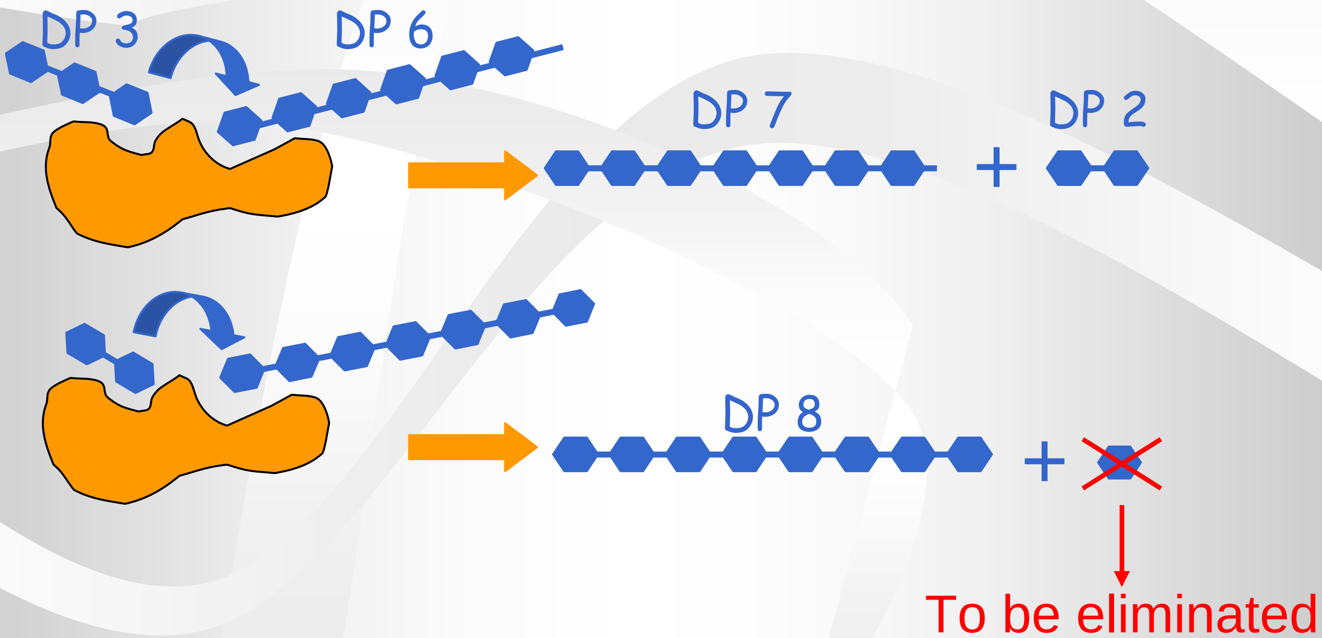


Energy Creation: degradation



Energy Creation: synthesis

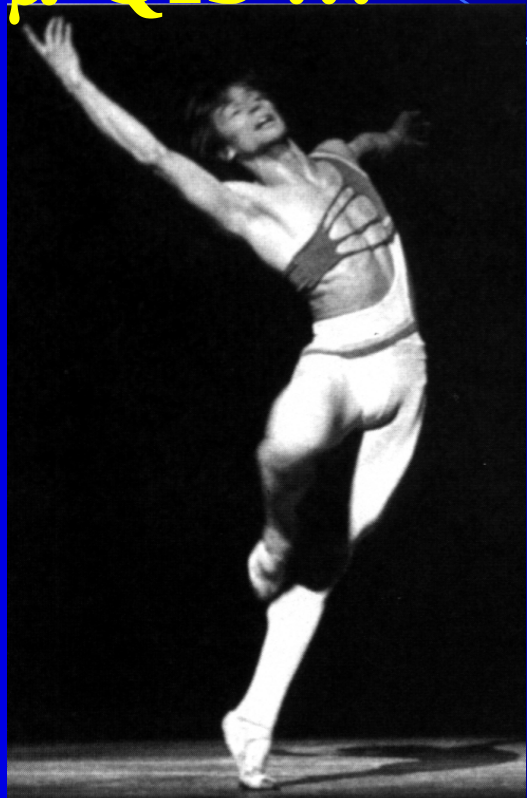
- Dextransucrase



Osmotor: Status

- Demonstrator (Osmotor V1) ready for tests
- Consumes Dextran and produces glucose
- Quantification of Power/Mass to be performed. First results lead to hope about 4 W/kg (human heart uses some Watts)
- Osmotor (V2) will use encapsulated mammal cells capable of transforming glucose into sucrose. A lot of research ahead!

- **From CAMI to QIS …**
- **From QIS to μ-QIS …**



- Prosperous future for the marriage between *Surgical Art* and *Information Technology*！