Medical Imaging, Simulation and Robotics

Medical Simulators and Soft Tissue Modelling

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2015-2016   v4.0

Medical Intervention Simulation
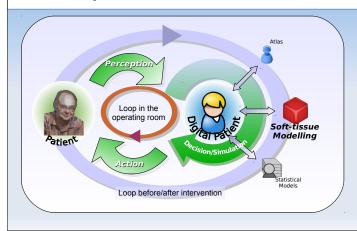
Chapter 1. Introduction

TiMC

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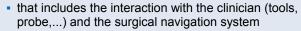
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Outline

- Chapter 1. Introduction
- Chapter 2. Medical simulators
- Chapter 3. Soft Tissue Simulation
- Chapter 4. Validation
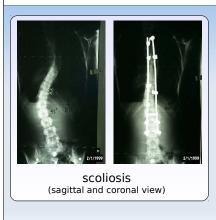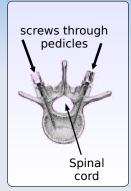

Perception – Decision – Action

Challenge

- Simulation of
  - deformable/soft tissue
  - accurate and precise
  - patient-specific
  - that includes the interaction with the clinician (tools, probe,...) and the surgical navigation system
  - in interactive time

Acc+ Prec-   Acc- Prec+

▶ Build a digital patient as close as possible to the real patient

▶ Use (hence measure) soft-tissue patient-specific constitutive law"

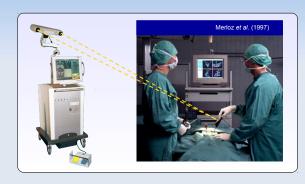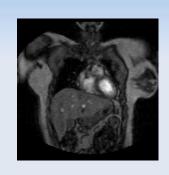# A typical case in CAMI: spine surgery

scoliosis
(sagittal and coronal view)

screws through pedicles

Spinal cord

Surgery planning on the CT scan

Per-operative Surgical Guiding

Merloz *et al.* (1997)

more difficult: soft tissue
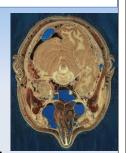

(Segars et al, 2001)

Context

- From "Visible Human" (1995)
  → "Virtual Physiological
     Human" (Physiome, 2005...)
- International Consortium:
  physiome.org
- European: VPH NoE
- National:
  - GDR STIC-Santé CNRS- INSERM
  - Labex CAMI
  - ...

Context

- In Rhône-Alpes
  - Research labs in Lyon, St Etienne, Annecy, Grenoble
  - Business: regional cluster i-care
    http://www.i-carecluster.org/

Context

- In Grenoble
- Healthcare Industry represents:
  - 4.1 billion euros of revenue
  - More than 700 companies, 11 000 jobs in the industry (20 000 in R-A), 200 state-owned laboratories and major European research institutes
- → Networks
  - Business: Medic@lps
    http://www.medicalps.eu/
  - ECCAMI.com Excellence Center for CAMI
    http://www.eccami.com/

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Grenoble INP ensimag

Medical Intervention Simulation

Chapter 2. Medical simulators

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Outline

Why medical simulators?

- Surgical procedures become more and more complex
- Surgical gestures become more and more complex
  - Coordination hands/vision (imaging) difficult
  - Minimally-invasive surgery: no direct view
- From generic to patient-specific

Classical Learning

- Always existed since... ever
  and still a big part of the medical studies

école de Chirurgie LADAF

From anatomical specimens...

- Anatomical specimens (animal or human, including body parts) are
  - Expensive
  - Not always easy to obtain
  - Have ethical issues and
  - Do not have the same physical properties as living tissues

  → Simulators aiming at *learning a technique*

  = learning simulators

...to learning simulators

- Medical simulators for learning the best way to diagnose or cure
  - Acquire knowledge
  - Acquire know-how (procedure, technique, gesture...)
- Medical simulators can be
  - Mechanical
  - Digital (including virtual reality, augmented reality, mechatronics, ...)
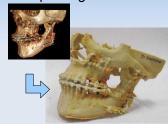
Mechanical simulators

- Stereolithography
- 3D printing

[copyright 2010, Amber Simpson]

Bespoke Modeling (3DSystems)
2013 from DICOM to 3D

→ patient specific but limited in terms of use

Mechanical simulators

- Complete environment (situation learning)

VIRGIL, Chest Tube Insertion
CIMIT, Boston,MA

Laerdal SimMan ®

Mechanical simulators

- Endoscopy or laparoscopy simulators

Simulab TraumaMan

LaproTrain

Other examples in obstetrics

Madame Du Coudray's machine
~1750

Noelle Simulator (Société Gaumard), Eggert (2007)

Limitations

- Mechanical learning simulators have a limited
  - Physical realism (especially for soft tissue)
  - Context / gesture
- Cost
- Pedagogy not controlled (no digital record of what happened)

Digital simulators

- Digital simulators
  - Are more flexible and can be reused
  - Can simulate generic pathological case but also patient-specific pathologies
  - Are multi-sensory (visual feedback, force feedback...)
  - Can record events/what happened

  → Digital medical simulators are
     not limited to learning simulators

Focus: soft tissue simulation

- Including soft tissue simulation in medical simulators implies dealing with
  - Displacements (natural, forced by a tool...)
  - Deformations (constitutive equations, parameters...)
  - Short term physiological evolutions (e.g. bleeding)
  - Long term physiological evolutions (e.g. change in elasticity due to change in cell type)

Medical simulator feature list

- Medical simulator have to include
  - Modeling (soft tissue deformations)
  - Interaction (sensors, force feedback)
  - Graphics (medical image simulation / 3D environment)
  - Event recording = trace what happened
    - For usage study, quality control
    - For pedagogy: skill assessment, learning path, exercises, validation of the gesture,...

  + Validation (accuracy/precision of the simulation)

Different types of simulator

- Four types of medical digital simulators should be distinguished
  - Learning simulators
  - Understanding simulators
  - Planning simulators
  - Per-operative simulators

Learning Simulators

- Aim at
  - Learning an intervention technique or gesture
  - Replacing anatomical specimen and mechanical simulators
- Need to include
  - Force feedback and tissue deformation ("visuo-haptic simulators")
  - Small subset of generic tissue behaviour

  simbionix lap mentor

Understanding Simulators

- Also called morpho-dynamic simulator
- Aim at
  - Understanding a phenomenon/pathological case
    → Classical meaning of "model" in science
  - Helping to diagnose a specific patient and to choose a specific treatment
- Need to include
  - 3D deformations and interactions with environments of tissues
  - Some pathological behavior at a "high" level of modeling

Planning Simulators

- Aim at
  - Define the operative strategy
  - Plan an intervention
    → anticipate a functional/anatomical effect
- Need to include
  - Patient specific data (tissue properties, disease)
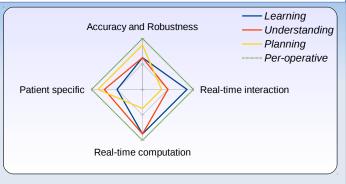 - Medical level validation

Per-operative simulators

- Also called «the grail»
- Aim at
  - Simulating the complete environment and intervention
  - Unity of place
  - Unity of time
- Need to include...
  - ...everything!
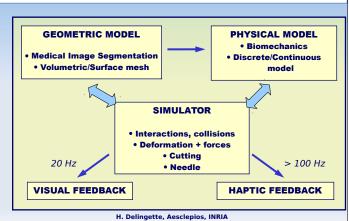
Different types of challenges

- Real-time interaction with the user
- Real-time computation of tissues
- Accuracy and robustness
- Patient-specific fidelity

Needed features

- Different types ▶ different approaches!

Digital Simulators

H. Delingette, Aesclepios, INRIA

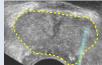## Rigid structures or soft tissue?

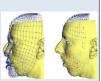- Bony structure simulators

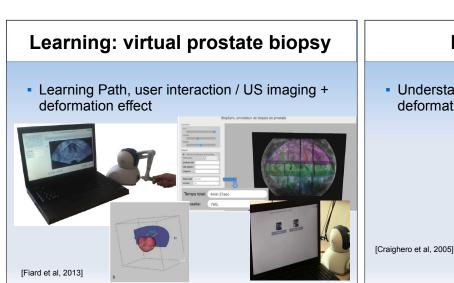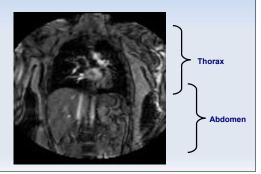- Soft tissue simulators

Work in progress at TIMC-IMAG

- Learning
  - Prostate biopsy
- Understanding
  - Respiratory motions
- Planning
  - Breast cancer radiotherapy
- Per-Operative
  - Brain-shift

Learning: virtual prostate biopsy

- Learning Path, user interaction / US imaging + deformation effect

[Fiard et al, 2013]

Respiratory Motion

- Understand organ displacements and deformations

[Craighero et al, 2005]

Thorax

Abdomen

Understanding hemidiaphragm

- Aim: understanding raised hemi-diaphragm
- Half the diaphragm is paralyzed
- Paradoxical movements
  - Very small volume intake

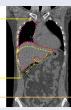

imagingpathways.health.wa.gov.au

[Promayon Baconnier, 2008]

Issues of Respiratory Motions

- Dose planning and control
- Interventional Radiology, puncture, biopsy
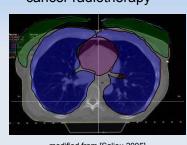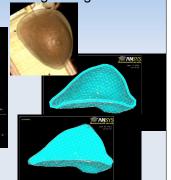 - → Reaching target organ

[Hostettler, 08]

Biomechanical breast modelling

- Aim: improve patient positioning during breast cancer radiotherapy

modified from [Saliou 2005]

[Vallier et al, 2013]

Per-Operative: Low-cost brain shift compensation

- Aim: replacing the high cost intra-operative MRI by 2.5D US images + biomechanical model.
- Grail: estimate brain shift deformations from 2.5D localized US images + model

[Ferrant 2002]

2.5D localized US → Doppler effect

[Bucki et al, 2007]

Medical Intervention Simulation

Chapter 3. Soft Tissue Simulation

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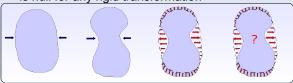Emmanuel Promayon – 21 Oct 2015 - Emmanuel.Promayon@imag.fr

Outline

Deformable model

- Analytical models (e.g. ODE)
  or purely geometrical models
  or statistical models
  - are not applicable to specific case/patient
  - cannot finely define loads and interactions needed to model a medical intervention
- In this lecture, we only focus on the so called "biomechanical model"

Deformable model...

- A soft tissue is considered as an elastic object
- Elasticity =
  - property of an object to come back to its initial shape (rest shape) once external constraints end
  - physical response of an object, expressed as forces, to external solicitations (force, imposed displacements)
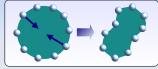 - is null for any rigid transformation

...to biomechanical model

- Continuous mechanics
  → Finite Element Method for best accuracy

- Computer Graphics animation
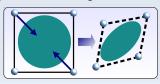 → Approximation for best visual rendering

... for CAMI

- But in CAMI, we need to be visually *and* physically correct (be nice + be true)
  → not so simple !

- To be taken into account
  - Correct physical properties
  - Specific environment influence (other tissues/organs, surgical tools, needles, ...)
- ► verification & validation is mandatory!

Characterization of deformations

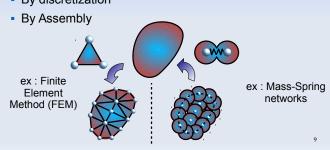- Nodal approaches using geometrical nodes (DOF)
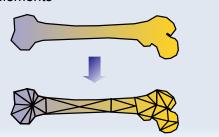

- Global approaches using control nodes, e.g FFD

Nodal approaches needed

- Nodal approach are needed for biological simulator
- Two families
  - By discretization
  - By Assembly

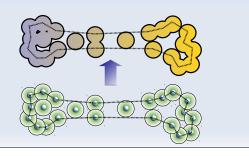ex : Finite Element Method (FEM)

ex : Mass-Spring networks

9

Nodal approach by discretisation

- From global to local
  - e.g. Finite Element Method
- Discretization of a continuous domain into a set of discrete elements

10

Nodal approach by assembly

- Nodal approach by assembly (from local to global), e.g. particle systems, Mass-spring network
- Des particules portant la physique sont regroupées

11

Nodal approaches needed

- Nodal approach by discretisation (from global to local), e.g. Finite Element Method

continuous
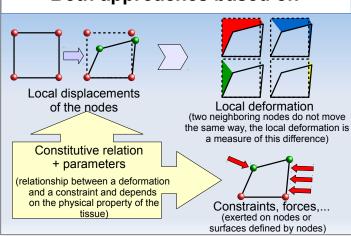
  discretization of a continuous domain into a set of discrete elements

- Nodal approach by assembly (from local to global), e.g. particle systems, Mass-spring network

discrete

Both approaches based on

Local displacements of the nodes

Local deformation
(two neighboring nodes do not move the same way, the local deformation is a measure of this difference)

Constitutive relation + parameters
(relationship between a deformation and a constraint and depends on the physical property of the tissue)

Constraints, forces,...
(exerted on nodes or surfaces defined by nodes)

Modeling steps

Define the geometry

(generally using a mesh, segmented from medical images)

Model the deformation

(choose approach)

Choose the the constitutive relation and parameter values

Define the interactions and loads (Boundary Conditions)

Solve

i.e. find the numerical solution

Outline

Physics principles

- Materials in physics
  - are deformed by stress acting on them
  - are under stress once deformed
- Strain
  = deformation of material in response to stress
- Stress ↔ Strain

The physics of soft-tissues

Displacements

Geometry

Deformations (strain)

Loads (boundary conditions)
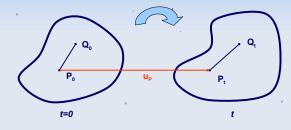
Materials and Constitutive equation

Constraints (stress)

Outline

From displacements...
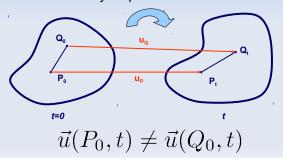
- Elementary displacement of a particle in the system

Q_0

P_0

u_P

Q_t
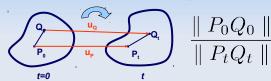
P_t

t=0

t

$$\vec{u}(P_0, t) = \vec{P_0 P_t}$$

… to strain

- Deformation of the system (strain) based on the fact that two neighboring points do not have the same elementary displacement
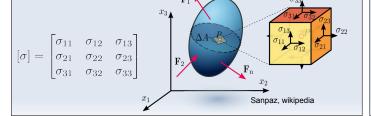

$$\vec{u}(P_0, t) \neq \vec{u}(Q_0, t)$$

From strain...

- Deformation of the system (strain) is a normalized measurement, e.g.

$$\frac{\parallel P_0 Q_0 \parallel}{\parallel P_t Q_t \parallel}$$

- Deformation is a 3x3 *tensor* that measures the deformation in all directions

… to stress

- Constraints (stress) = all forces applied on a given internal or external area (force / area) = N/m² = Pa
- Material stress measures the average force acting on a surface
- As for the strain, the stress is usually measured using a 3x3 *tensor*

$$[\sigma] = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

Sanpaz, wikipedia

Strain Tensor

- Deformation express by strain tensor $[\varepsilon]$
  - Describes the system stress locally on a volume element
  - ex: Green-Lagrangian (others exist)

$$[\varepsilon] = \frac{1}{2}([G] + [G]^T + [G]^T[G])$$

  with $[G] = [grad\,\vec{u}]$ (3x3)

Stress Tensors

- Stress tensor $[\sigma]$
  - Describes all the stress applied locally on a volume element
  - Internal force (in our case resisting the deformation)
  - Express as a function of deformation (strain tensor)
  - This function defines the *material behavior*

Continuum Mechanics Problem

- Considering Newton's second law

$$\sum (F_i + F_e) = m\gamma$$

$$div([\sigma]) + F = m\gamma$$

- Local equilibrium

$$div([\sigma]) + F = 0$$

- The expression of the tensors $[\sigma]$ and $[\varepsilon]$ are expressed as function of the displacements **u** and the applied forces **F**
- They depends on the constitutive equation

Outline

-

Material behavior
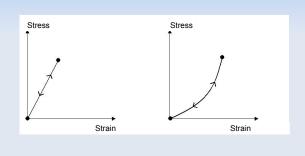
- The material behavior is determined by
  - The constitutive equation
  - The material properties

Material behavior: Constitutive Equation

- The **constitutive equation**
  - = Relation/function between stress and strain
- *It is a modeling choice*
  - Hypothesis about the material behavior
  - More than often dictated by processing power and available data

Constitutive law

- **Elasticity** can be linear or non linear

Constitutive law

- **Viscoelasticity** change the behavior depending on the stress/loading velocity

Constitutive law

- Plasticity, fracture

Constitutive law

- **Isotropy** = same behavior for all directions
- **Anisotropy**

Material behavior: Material properties

- The material **properties**

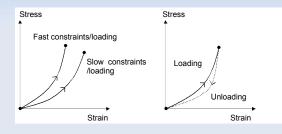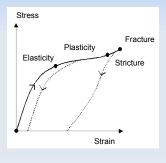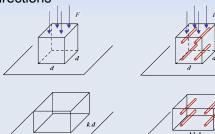 = parameters of the constitutive law
- *The material has to be characterized*
  - Parameters are estimated/approximated by experiments/probing...
  - … Which is not always possible/practical/relevant

Parameters

- Linear elasticity can be expressed either as
  - Young modulus E and Poisson ratio ν
  - Lamé parameters λ μ (shear modulus)
- Lamé parameters are directly used in the expression of the strain / stress relationship
- Young modulus and Poisson ratio are more intuitively understand

$$\lambda = \frac{\nu E}{(1 + \nu)(1 - 2\nu)} \qquad \mu = \frac{E}{2(1 + \nu)}$$

- Beware for ν = ½ or near ½!

Material parameters

- For linear isotropic elasticity
  - Young modulus : rigidity

  $$E = \frac{\sigma}{\varepsilon}$$

  - Poisson ratio ν : compressibility

  $$\nu = -\frac{\partial \varepsilon_z}{\partial \varepsilon_x}$$

  - + Plasticity, viscosity,...

PAR, Wikipedia

Human soft-tissue

- Bulk modulus μ is strongly heterogeneous between 0.1 KPa to 10.000 Kpa
- 60-70% of water → quasi incompressible
- λ is therefore very high ~ 1.000.000 kPa

Constitutive equation and material parameters in CAMI

- Living tissues are extremely complex!
  - non-homogeneous, anisotropic
  - non-linear constitutive law
  - viscosity, creep,...
  - structures, fluids,...
- Living tissues are extremely difficult to characterize (impossible?)
  - In vivo different than in vitro
  - Elastography (image) / solicitation
    → inverse problem
  - Patient specific (high variability, pathology, cancer,...)

Simplifying hypothesis

- It is sometimes impossible/unpractical to use very complex law
    - Computing power
    - Precise knowledge
- Hypothesis can be simplified by considering only small deformations (<10% or <5%)
    - Mechanical linearity
    - Geometrical linearity

Outline

Finite Element Methods

- Continuum mechanics can be applied on theoretical/analytical problems, but not on complex problem with a specific geometry
- The Finite Element Method (FEM) provides a numerical approximation of the solution
- It is a matricial formulation of the continuous mechanics

FEM for programmers

Gennadiy Nikishkov

Programming Finite Elements in Java™

Springer
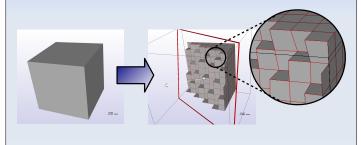
- "The FEM is a computational technique ~~for solving problems~~ *to find approximate solutions* that are described by partial differential equations or can be formulated as functional minimization"
- "A domain of interest is represented as an assembly of finite elements."

FEM Applied to Solid Mechanics Problems

- 7 steps
- From discretization of the solid to post-processing
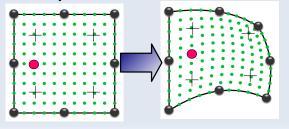
Step 1: Discretize the solid

- The physical domain has to be discretized
    - Nodes
    - Elements (e.g. triangle in 2D, tetrahedra in 3D)

Step 2: Determine interpolation functions

- Interpolation functions over one reference element
  → any equation system solved at the nodes can provide solutions by interpolation anywhere in the body

Step 3: Choice of mechanical behavior

- Choose a material behavior
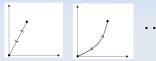 → define a constitutive equation
- Choose the simplifying hypothesis

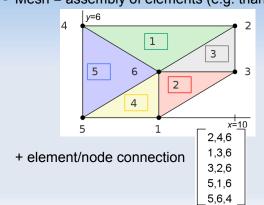- Compute the tensors and stiffness **matrix** of the reference element

$$[K_e][U_e] = [F_e] \qquad [K_e] = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix}$$
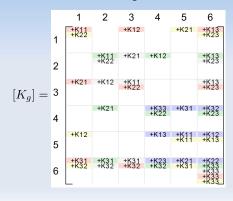
Step 4: Assemble the elements

- Mesh = assembly of elements (e.g. triangles)

+ element/node connection

$$\begin{bmatrix} 2,4,6 \\ 1,3,6 \\ 3,2,6 \\ 5,1,6 \\ 5,6,4 \end{bmatrix}$$
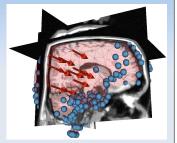
Step 4: Assemble the elements

- That will lead to one big matrix

Step 5: define BC and loads

- Loads are defined for example
  - To impose a null displacement in one direction (sliding), guarantee symmetry of the problem
  - To impose full null displacement (nodes cannot move)
  - To impose external forces (user, external pressure...)

Step 6: Solve the system

- Apply the virtual work principles
- The system to solve is equivalent to
  - linear case equilibrium

$$[K_g][U_g] = [F_g]$$

  - dynamic case

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{F\}$$
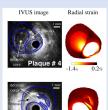
- With
  - K = stiffness matrix
  - M = mass matrix, C = inertia matrix
  - F = external forces, u = displacements
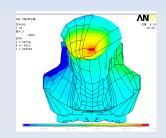
Step 6: Solve the system

- The system is solved numerically using, e.g.
  - Conjugate Gradient when linear
  - Newton-Raphson when non-linear
- The solution is computed on the nodes in terms of
  - Displacements
  - Strain
  - Stress

Step 7: Post-processing

- Once all the displacements are known, the strain and stress can be computed *everywhere* on the domain

Great online lecture

- Excellent interactive FEM lecture (in french)
 - http://www.utc.fr/~mecagom4/

Pros/Cons

- Pros
  - very strong physics, formalism
  - direct link with material properties
  - generally accurate
  - solution = displacement, but stress and strain can be computed as well
- Cons
  - considered slow
  - generally not dynamic
  - sometimes divergent (no numerical solution)
  - topology change (cutting) and contacts are difficult to model, sometimes simplification is too much

Other methods based on FEM

- Pre-computing displacements and then linearly combine them for the resolution (Cotin et al)
- Adaptative meshing (Debunne et al)
- Explicit FEM (Etzmuß, Müller, Nesme...)
  - Solve element by element and propagate
  - Polar decomposition (separate rigid and pure deformation)
- Other approaches includes "mix" between FEM and discrete methods (ex: Mass-Tensor, Delingette)

Outline

- Chapter 1. Introduction
- Chapter 2. Medical simulators
- Chapter 3. Soft Tissue Simulation
  - Introduction to biomechanics
  - Continuous models
  - Discrete models
- Chapter 4. Validation

Numerous discrete model

- Discrete model also called "physically-*based*"
- Three families
    - Implicit surfaces
      skeleton + border functions
    - Particle systems / point based
      nodes = Newtonian particles
    - Particle networks
      nodes + mesh / neighborhood relationships
      e.g. mass-spring network

Mass-Spring: the most popular

- Early age: mass-spring networks initially developed for the simulation of the facial expressions

(Platt and Badler, 1981) (Terzopoulos and Waters, 1990) (Lee et al., 1995)
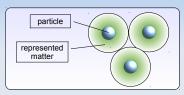
Popularity explained

- Popularity certainly due to
    - Simple to implement
    - Very fast simulation
    - Dynamic simulation
    - Small or large deformation (but beware of precision!)

Principles
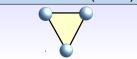
- Object are defined using Newtonian particles
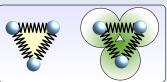
- Each particle has
    - a position in 3D
    - a mass
    - a neighborhood

Principles

- Neighborhood relationships usually (but not always) defined a network (mesh)

- A spring is associated with each neighborhood relationship

Newtonian physics

- Elasticity is thus simply expressed as a distance criterion between particles (which dynamics is determined by the spring)
- Particle movements derived from the Newton's second law, expressed as the differential equation

$$\mathbf{F} = m\ddot{\mathbf{X}}$$

- Applied forces depend on position, velocity and time

$$\ddot{\mathbf{X}} = \frac{\mathbf{F}(\mathbf{X}, \mathbf{V}, t)}{m}$$

Different kind of forces

- Constants
  e.g. : gravity $\mathbf{F} = m \cdot \mathbf{G}$
- Position or Time dependent
  e.g. force field (magnetics,...)
- Velocity-dependent
  e.g. viscosity of the medium $\mathbf{F} = -k_{visc} \cdot \mathbf{V}$
- Point-to-point
  e.g. spring linking to particles $F = k_e \cdot (L - L_0)$
- Interaction
  e.g. user manipulation, contact...

Constraints
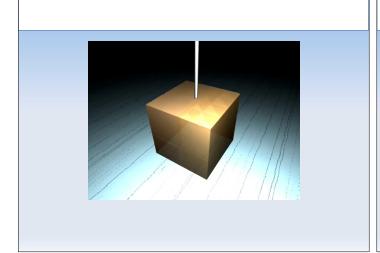
- Not everything can/should be expressed as forces
  - collision with objects
  - attachment between objects, joint
  - other properties (e.g. incompressibility)
- Constraints can also be added easily (same way we added forces)
- Constraints can impose displacement or velocity, can be enforced or mixed with forces
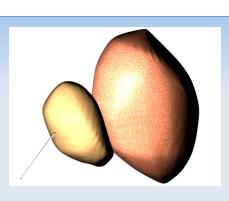
Solving
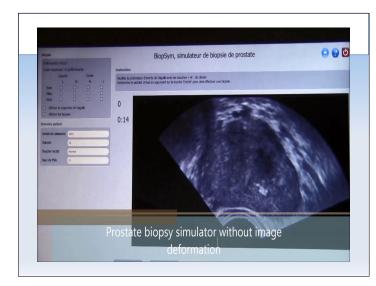
- The mechanical equilibrium is solved the same way
- Without any assembly → faster
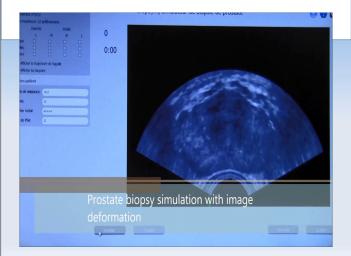
Pro/Cons

- Pros
  - fast
  - "construction set"
    - easy to model complex interaction
    - easy to mix different kind of properties (elastic, rigid, ...)
- Cons
  - not strongly linked with continuum mechanics

  ▶ Verification & validation is even more strongly needed

Prostate biopsy simulator without image deformation

Prostate biopsy simulation with image deformation

Université Joseph Fourier GRENOBLE

UNIVERSITÉ DE GRENOBLE

Grenoble INP ensimag

Medical Intervention Simulation

Chapter 4. Validation

TIMC

Université J. Fourier - TIMC-IMAG / CNRS UMR 5525
Emmanuel Promayon – 21 Oct 2015 - Emmanuel.Promayon@imag.fr

CNRS

Outline

- Chapter 1. Introduction
- Chapter 2. Medical simulators
- Chapter 3. Soft Tissue Simulation
- Chapter 4. Validation
  - Verification and Validation
  - Validation of soft tissue simulations
  - Validation of medical simulators
  - Patient-specific models

Validation

- 4 types of simulators
  - Learning
    - interaction is more important
    - simulation does not have to be exact or patient-specific
  - Others
    as the clinician will base his decisions on the simulator results, validation is essential
- Validation of the
  - Physical realism
 - Parameters (even for continuous model)
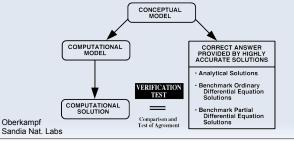
Validation
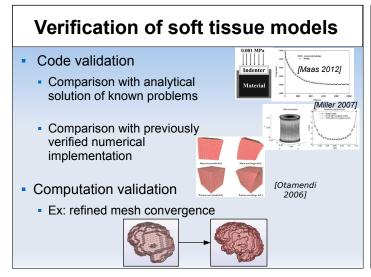
- In medical literature, validation is nearly always the main point
- Elsewhere, it is too often in the "to do" list of the "future works" section!
- Why?
  - Not so easy to do or organize
  - Can show negative results! (not easy to publish a paper finishing by "the validation section proved that the simulation are not accurate enough!")

V&V

To model = describe reality using equations

Reality
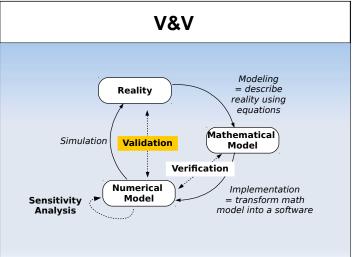
Simulate   Validation   Mathematical Model

Verification

Sensitivity Analysis   Numerical Model

Implement = transform math model into a software

[Deram 2012]

Verification of soft tissue models

- Verification
  - Mathematical point of view
  - Ensure that the mathematical model solve the mathematical problem with enough precision / accuracy

CONCEPTUAL MODEL

COMPUTATIONAL MODEL

CORRECT ANSWER PROVIDED BY HIGHLY ACCURATE SOLUTIONS
- Analytical Solutions
- Benchmark Ordinary Differential Equation Solutions
- Benchmark Partial Differential Equation Solutions

COMPUTATIONAL SOLUTION

VERIFICATION TEST

Comparison and Test of Agreement

Oberkampf
Sandia Nat. Labs

Verification of soft tissue models

- Code validation
  - Comparison with analytical solution of known problems
  - Comparison with previously verified numerical implementation

[Maas 2012]

[Miller 2007]

[Otamendi 2006]

- Computation validation
  - Ex: refined mesh convergence

V&V

Reality

Modeling = describe reality using equations

Simulation **Validation** **Mathematical Model**

Verification

Sensitivity Analysis **Numerical Model**

Implementation = transform math model into a software

Validation of soft tissue models

- Aim
  - Ensure the numerical solution can be used for medical decision

REAL WORLD

CONCEPTUAL MODEL

COMPUTATIONAL MODEL

COMPUTATIONAL SOLUTION

VALIDATION TEST

Comparison and Test of Agreement

EXPERIMENTAL DATA
· Unit Problems
· Benchmark Cases
· Subsystem Cases
· Complete System

Oberkampf
Sandia Nat. Labs

Outline

Four different types of comparisons

- How easy is it?
- Beside theoretical comparison, the most popular way is by **comparison with data**
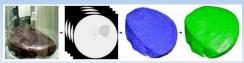
V&V of soft tissue models

- Four types of comparisons
  1. *comparison with in silico* data
     - Comparison with other validated numerical simulations
       ~ Verification

  2. *In vitro* experiments

[Kerdok 2003]

Four different types of comparisons

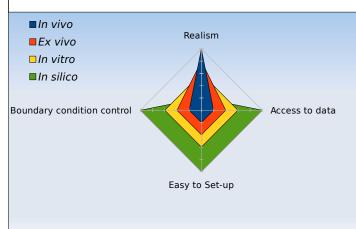3. *Ex vivo* experiments

[Shi 2005]

4. *In vivo*

[Mollemans 2007]

How easy is it?

- 4 criteria (Deram 2012)
  - **Access to data/parameters**
    how easy it is to access data/parameters
  - **Boundary condition control**
    how easy it is to known/control the boundary conditions
  - **Set-up**
    how easy is it to organize/set up the validation
    (acquisition chain, data analysis...)
  - **Realism**
    how close to reality is the experiment? How close is it to
    comparing with reality ?

Validation levels

- ■ *In vivo*
- ■ *Ex vivo*
- ■ *In vitro*
- ■ *In silico*

Example: *in vitro* comparison

- Experimental validation
  - Needs a real physical model
    ► difficult to control the material properties of a
    build object
  - Needs a control of experimental condition
    ► difficult to be really precise (error in building or
    assembling, position or force control, friction
    condition...)
- Examples
  - Truth Cube
  - Ad hoc phantoms

Example: truth-cube design

- Truth Cube (Kerdok and al., 2003)

- Silicon cube of supposedly known mechanical
  properties (elasticity, contractility)
- Build layer by layer
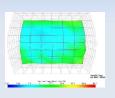- Each layer has 7x7 Teflon beads

Example: truth-cube experiments
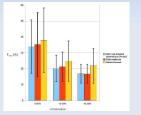
- Indentation/compression controlled by CT scan

- Bead positions segmented
  ► local displacement/deformation in the cube

Example: truth-cube simulations

- Simulation of the experiments and comparisons of the real displacements with simulated ones

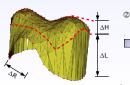- Possible comparison of different models

Example: *In vivo* comparison

- Comparison with medical data are not easy
- Possible if
  - Clinicians need control exams (you cannot ask for a post-operative CT scan if there is no clinical needs!) e.g. maxillofacial surgery (CT scan)

  - Non-invasive data acquisition e.g. respiratory movements (dynamic MRI)

Example: dynamic MRI

respiratory signal

ΔH

ΔL

ΔR

End of inspiration model ≈ real data

Important question

- Considering a given application, the Soft Tissue Simulation is the last step
- What is the needed precision
  → it depends on the application and intended use

Example : Prostate Cancer detection

- Biopsy and TRUS echography
  - Images with low resolution
  - Prostate *is* deforming
  - 2D / 3D projection
  - Usually pre-operative MRI

- Koelis
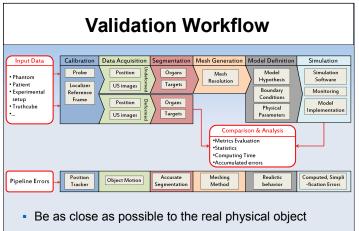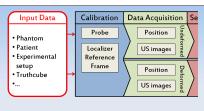 - Planning Mapping Localization
  - ANR ProsBot

Aim of the simulator

- Create a patient-specific biomechanical model
- Interaction TRUS probe / prostate
- Simulation of the deformations
- Per-operative simulator
- Interaction between US images and model
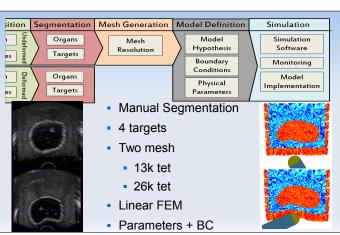- V & V needed before including it in the final medical device

Validation Workflow

- Be as close as possible to the real physical object
- Everything can be directly used in clinical conditions
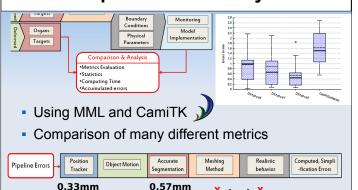
Acquisition

- US volume acquisition
  - With deformation
  - Without deformation (with displacements)
  - Trajectory are recorded for V&V (3D tracker)
- Realistic phantom

Simulation

- Manual Segmentation
- 4 targets
- Two mesh
  - 13k tet
  - 26k tet
- Linear FEM
- Parameters + BC

Comparison and analysis

- Using MML and CamiTK
- Comparison of many different metrics

| Position Tracker | Object Motion | Accurate Segmentation | Meshing Method | Realistic behavior | Computed, Simpli -fication Errors |

0.33mm   0.57mm   X ⟷ X

X = Error accumulated in the final error

Test on 120 simulation

- Estimation of required precision in the model

Workflow Step	Parameter	Value		
		Prostate	Surroundings	Walls
Mesh Generation	Mesh Resolutions (number of tetrahedra)	4,202 18,083	6,781 21,419	1,912 1,912
Model Definition	Young Modulus (kPa)	50 100	13 50	50 100
	Poisson Ratio	0.45 0.40		
Simulation	SOFA FEM implementation (method name)	Small Large Polar SVD		

X4 Acquisition

Initial Results

- 3 Linear FEM method (SOFA)
  - 2 mesh
  - Parameter study
  - 4 experiments (lots of displacement)
  - 1.74 +/- 0.66 mm

- Accumulated errors
  - Potentially 50% comes from the simulation

Outline

Training simulator now required

- All surgical training programmes should incorporate simulation
  "Simulation as the new paradigm" Am. Coll of Surgeons 2008

- "La formation par les méthodes de simulation en santé doit être intégrée dans tous les programmes d'enseignement des professionnels de santé à toutes les étapes de leur cursus (initial et continu). Un objectif éthique devrait être prioritaire : « jamais la première fois sur le patient ». "
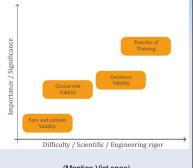 Proposition 1, Rapport "Simulation" Haute Autorité de Santé, jan. 2012

Validating teaching simulators

- From the Mentice Vist product spec
  - "Validation of a product is an essential **quality assurance process**, particularly for products that will be used for medical purposes such as training."
  - "In medicine, validation studies should establish **evidence** that provides a high degree of assurance that a product, service or system **accomplishes its intended requirements**."

4 steps

- Face and content validity
- Construct validity
- Concurrent validity
- Transfer of skills

(Mentice Vist spec)

Step 1

- Face and content validity

  = The simulator is a true representation of the real-life task

- "Preliminary validation evaluating if a device looks, feels, behaves, teaches, trains and assesses what it is supposed to."

Step 2

- Construct validity

  = the simulator can accurately reflect **differences** in performance

- "Probably best summarised by the question "are we measuring or assessing what we think we're measuring?" It is a type of validation that is based on the accumulation of evidence from numerous studies confirming the identification and differentiation of levels of performance, skill, experience or ability."

Step 3

- Concurrent validity
- "This can be said to have been demonstrated if there is a high concordance between two tests that purport to measure the same thing. For example, we would expect an endovascular specialist who is very experienced in endovascular procedures to perform well on a full-physics virtual reality simulator which simulated the same procedures."

  → The simulator should gives better score for better skills

Step 4

- Transfer of skills
- " The most crucial validation test of a simulator is whether what has been trained on the simulator transfers to the in vivo operating environment."

  → Clinicians trained with the simulator are better than the clinicians that did not use the simulator (for simular experience)
- "One to one correspondance assessment of patient specific data (e.g., mission rehearsal) is the ultimate assessment of transfer of training."

Example: Mantice Vist

- Endovascular/catheter simulator

Validation studies

| Study	Journal	VIST module	Face validity	Construct validity	Training potential	Transfer of training
Dayal R, et al. (n=21)	J Vasc surg 2004	Carotid	√	√	√	
Hsu JH, et al. (n=29)	J Vasc surg 2004	Carotid	√	√	√	
Nicholson WJ, et al. (n=100)	Simulation in Healthcare 2006	Carotid	√		√	
Aggarwal R et al. (N=20)	Eur J Vasc Endovasc Surg 2006	Renal		√	√	
Chaer RA et al. (n=20)	Ann Surg 2006	Illiac/SFA				√
Berry M et al. (n=12)	Cardiovasc Intervent Radiol 2006	Illiac	√		√	√
Gallagher et al. (n=94)	EuroIntervention 2006	Coronary	√	√	√	Mission rehearsal
Patel AD et al (n=20)	JACC 2006	Carotid	√		√	
Cates et al (n=1)	JAMA 2007	Carotid	√		√	Mission rehearsal
Van Herzeele et al (n=47)	J Vasc Surg 2008	Illiac		√	√	
Glaiberman CB et al (n=63)	J Vasc Interv Radiol 2008	Renal		√	√	
Van herzeele et al (n=21)	Eur J Vasc Endovasc Surg 2009	Carotid		√	√	

Outline
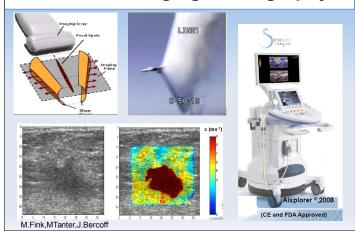
In vivo measurements

- *Ex vivo* measurements are important for building simulators but are different to *in vivo* measurements (Kerdok et al. 2006)
  - Vascularization
  - Temperature
  - Elasticity..

- To be patient-specific
  → measure the properties *in vivo* and *in situ*

Two main approaches

- Elastography: imaging deformation (MR or US)
  - Image of the organ before and after a controlled stress → deformation (generally ultrasound)
  - Measure the tissue local displacement
- Direct mechanical test (indentation or aspiration)
  - Direct mechanical stress/probing
  - Measure of the tissue deformation or response using force sensors (identation) or camera (aspiration)
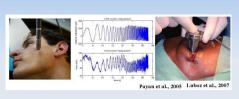
  → Inverse problem gives the model parameters

Magnetic Resonance Elastography

(from R. Willinger, Univ. Strasbourg)

Ultrasonic Imaging Elastography

M.Fink,MTanter,J.Bercoff

Aixplorer ©,2008
(CE and FDA Approved)

Mechanical Probing

- External measurements   commercial

Payan et al., 2005 Luboz et al., 2007

- Internal tissue/organ measurements
  - Indentation
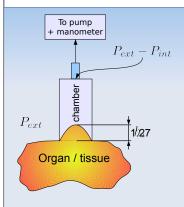 - Aspiration

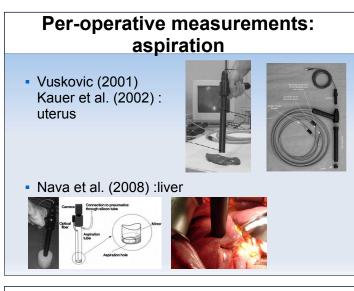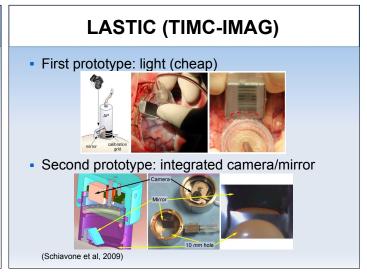Carter et al. (2001) (liver)

In vivo is difficult

- Cannot create tissue damage
- Per-operative use implies
  - Sterilization
  - Ergonomics and functional (bulk, time,...)
- Most difficult: sterilization
  - Aggressive process : T140° for 20min, steam, high-pressure, heat, chemicals (liquid, gaz, plasma...)
  - Fragile parts (electronics, sensor) could easily be dammaged
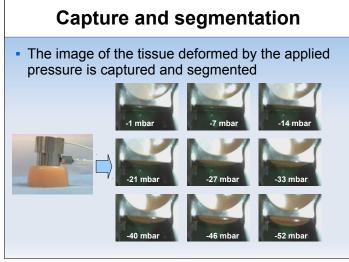 - Everything has to be sterile (even parts not in the field, because of projection risks)

Aspiration/suction : principles

To pump + manometer

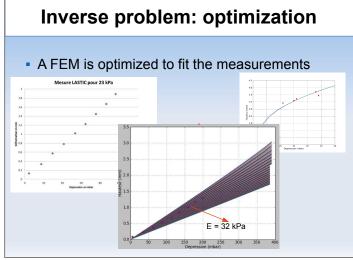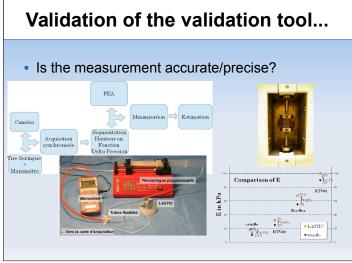$P_{ext} - P_{int}$

chamber

P_{ext}

1/27

Organ / tissue

- In contact
- Negative pressure P_{int} applied in the chamber → tissue is "aspired"
- Aspired height h_i is measured (mirror)
- As the device is fixed by suction, measurements are independent of the natural movements (beathing, heart beat...)

Per-operative measurements: aspiration

- Vuskovic (2001)
  Kauer et al. (2002) :
  uterus

- Nava et al. (2008) :liver

LASTIC (TIMC-IMAG)

- First prototype: light (cheap)

- Second prototype: integrated camera/mirror

(Schiavone et al, 2009)

Capture and segmentation

- The image of the tissue deformed by the applied pressure is captured and segmented

-1 mbar	-7 mbar	-14 mbar
-21 mbar	-27 mbar	-33 mbar
-40 mbar	-46 mbar	-52 mbar

Inverse problem: optimization

- A FEM is optimized to fit the measurements

E = 32 kPa

Validation of the validation tool...

- Is the measurement accurate/precise?

Conclusion

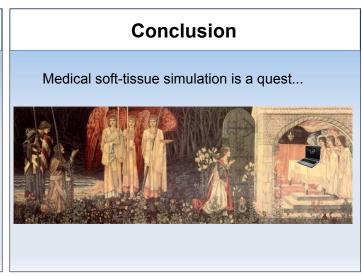Medical soft-tissue simulation is a quest...

Acknowledgements

- PhD students
  - J. Sarrazin, S.Y Selmi, M. Bailet, A. Deram, M. Marchal
- Colleagues
  - V. Luboz, Y. Payan, M. Chabanas, J. Troccaz, C. Fouard
- And more...