Biomechanics for computer-assisted surgery

Yohan Payan
TIMC-IMAG Laboratory
Computer Assisted Medical Intervention Group
CNRS, University of Grenoble, France
Yohan.Payan@imag.fr
TIMC
Computer Aided Medical Intervention

Main goal: “to assist the clinician and the surgeon in the realization of diagnostic or therapeutic intervention, in the most accurate and minimally-invasive way”
Computer Aided Medical Intervention

spinal column

vertebra
(face and sagittal view)
Computer Aided Medical Intervention

scoliosis

screws through pedicles

Spinal cord
Computer Aided Medical Intervention

Planning onto the scanner exam
Computer Aided Medical Intervention

Per-operative surgical guiding:

Merloz et al. (1997)
Computer Aided Medical Intervention

What about soft organs?
Computer Aided Medical Intervention
Computer Aided Medical Intervention

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

- A “fast” generation of the patient-specific biomechanical model of the organ
- The possibility to estimate the patient-specific constitutive behavior of the organ
- An almost real-time computation of the deformations simulated by the model
## Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Intra-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td>A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
## Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Pre-operative computer Aided System</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A “fast” generation of the patient-specific biomechanical model of the organ</td>
<td>++</td>
</tr>
<tr>
<td>The possibility to estimate the patient-specific constitutive behavior of the organ</td>
<td>++</td>
</tr>
<tr>
<td>An almost real-time computation of the deformations simulated by the model</td>
<td>+</td>
</tr>
</tbody>
</table>
Outline

• Introduction

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

• Intra-operative Computer Aided Device: Neurosurgery

• Discussion
Orthognathic surgery is directed to patients suffering from malformations of the lower part of the face.
Orthognatic surgery

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

Bones cuttings and repositioning:
Orthognatic surgery

Bones cuttings and repositioning:
Orthognatic surgery

Bones cuttings and repositioning:
Orthognatic surgery

Bones cuttings and repositioning:
Orthognatic surgery

Bones cuttings and repositioning:
Orthognatic surgery

Bones cuttings and repositioning:
Orthognatic surgery

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

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

- Levator labii superioris
- Alaeque nasi
- Levator labii superioris
- Zygomaticus minor
- Zygomaticus major
- Masseter
- Risorius
- Muscle platysma
- Depressor anguli oris
- Mentalis
- Orbicularis oris
- Depressor labii inferioris
- Levator anguli oris
- Buccinator
Face modeling in the maxillo-facial literature

Keeve et al., 1996, 1998

Gladilin et al., 2003

Roth et al., 1998

Zachow et al., 2000

Koch et al., 1998, 1999
Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Pre-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>• The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>• An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
Our modeling strategy

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

1. Manual elaboration of a “generic” (atlas) Finite Element model
Generic Finite Element face model

Outer layer (Dermis)

Inner layer (Hypodermis)

Chabanas et al. (2003), *Medical Image Analysis*
Simulation:
Activation of Zygomaticus major
Conformation of the generic model to patient morphology

Patient skin surface segmented from CT (Marching cube)
Conformation of the generic model to patient morphology

- Outer nodes of the generic mesh (blue points)
- Patient skin surface segmented from CT (Marching cube)
Our modeling strategy

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

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

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

The registration algorithm (Szeliski & Lavallée, 1996):

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

Displacement vectors on each cube vertex

- Minimization: distance + regularity criteria
Conformation of the generic model to patient morphology
Conformation of the generic model to patient morphology
Confromation of the generic model to patient morphology
**Computer Aided Medical Intervention**

<table>
<thead>
<tr>
<th>Pre-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>• The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>• An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
Finite Element Simulations of the bone repositioning consequences

Medical Image Analysis.
### Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Pre-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>• The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>• An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
Trying to characterize the face rheology

In vitro indentation experiment
Trying to characterize the face rheology

Modeling assumptions: Yeoh strain energy

\[
[\sigma] = \frac{\partial W}{\partial E} \quad W = a_{10} (I_1-3) + a_{20} (I_1-3)^2
\]
Trying to characterize the face rheology

Modeling assumptions: Yeoh strain energy

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

\[ a_{10} = 190 Pa \]
\[ a_{20} = 90 Pa \]

Gerard J.M., Ohayon J., Luboz V., Perrier P. & Payan Y. (2005), Medical Engineering & Physics
Finite Element Simulations of the bone repositioning consequences

Medical Image Analysis.
## Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Pre-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>•</strong> A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td><strong>•</strong> The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td><strong>•</strong> An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
Finite Element Simulations of the bone repositioning consequences
Finite Element Simulations of the bone repositioning consequences
Simulations validations: comparisons with post-operative CT data
Simulations validations: comparisons with post-operative CT data
Face modeling for the study of speech production

Nazari et al. (2010)
## Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Pre-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td>A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
Trying to characterize the face rheology

In vivo indentation experiment

TeMPeST: Ottenmeyer, 2002
Use of micro-camera ST Microelectronics 2MPixels (1600x1200), < 1 cm³

Schiavone et al., 2010
LASTIC

a Light Aspiration device for in vivo
Soft Tissue Characterization

TIMC-IMAG Laboratory
France
Light Aspiration Device: estimation of the constitutive law

- Finite Element Analysis + Optimisation (Schiavone et al., 2010)
Estimation of the constitutive law
Estimation of the constitutive law
Outline

• Introduction

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

• Intra-operative Computer Aided Device: Neurosurgery

• Discussion
Intra-operative Computer Aided Device: Neurosurgery

The “Brain-Shift” problem
Intra-operative Computer Aided Device: Neurosurgery

The “Brain-Shift” problem
The “Brain-Shift” problem

Two solutions to solve this problem:

1. The « expensive » solution: intraoperative MRI
The “Brain-Shift” problem

Two solutions to solve this problem:

1. The « expensive » solution: intraoperative MRI

2. A « low cost » solution:

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

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

   - applying this 3D transform as boundary conditions to a real-time 3D biomechanical model of the patient brain.
Intra-operative Computer Aided Device: Neurosurgery

Before surgery

Angio-MRI

Patient-specific Finite Element model
Intra-operative Computer Aided Device: Neurosurgery

During surgery

Intra-operative 2D Doppler US localized in 3D
Intra-operative Computer Aided Device: Neurosurgery

Echographie Doppler 2D ou 3D
Intra-operative Computer Aided Device: Neurosurgery
Intra-operative Computer Aided Device: Neurosurgery
Intra-operative Computer Aided Device: Neurosurgery
Brain Shift

Intra-operative Computer Aided Device: 
Neurosurgery

Bucki et al., 2012
## Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Intra-operative computer Aided System</th>
</tr>
</thead>
</table>
| A “fast” generation of the patient-specific biomechanical model of the organ | ++++
| The possibility to estimate the patient-specific constitutive behavior of the organ | ++++
| An almost real-time computation of the deformations simulated by the model | ++++
# Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th><strong>Intra-operative computer Aided System</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>• The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>• An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
## Computer Aided Medical Intervention

<table>
<thead>
<tr>
<th>Intra-operative computer Aided System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• A “fast” generation of the patient-specific biomechanical model of the organ</td>
</tr>
<tr>
<td>• The possibility to estimate the patient-specific constitutive behavior of the organ</td>
</tr>
<tr>
<td>• An almost real-time computation of the deformations simulated by the model</td>
</tr>
</tbody>
</table>
Light Aspiration Device: LASTIC V1

Towards pomp + manometer

\( \Delta P \)

Grid

Mirror

View from the camera

Schiavone et al., 2008
Light Aspiration Device: LASTIC

Aspiration: in vivo measurement of patient brain elasticity

Schiavone et al., 2009
Pressure ulcers prevention

Pressure ulcers prevention for paraplegic persons
Over-pressures: healthy person
Over-pressures: healthy person

Perception → Analyze → Action
Over-pressures: healthy person

Perception → Analyze → Action
Over-pressures: healthy person
Over-pressures: paraplegics

Perception

Action

Analyze
Over-pressures: paraplegics
Perception multi-sensory intégration Action

Coupling device

Artificial sensor

Stimulator

Perceptual supplementation

provide information dedicated to one sensory modality through another modality
Valid sensory canal → Perception → Analyze → Action

Over-pressures: paraplegics

Artificial sensor
Pressure ulcer prevention

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

An Utility / Utilisability / Acceptability Study
What kind of artificial sensor?

Tekscan Inc.

Xsens Inc.

Vista Medical Inc.
What kind of artificial sensor?

• Conclusions of the Utility / Utilisability / Acceptability Study:
  
  • The pressure mat has to be low cost.
  
  • The pressure mat has to be comfortable (on or around the cushion)
  
  • The pressure mat has to be washable
What kind of artificial sensor?

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

100% textile
What kind of artificial sensor?

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

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

Three questions:

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

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

- How to alert the person in case of a risk?
When deciding that there is a risk for PU?

\[ \varepsilon : \text{déformations internes} \]

\[ \varepsilon_i < \varepsilon_m \]
Pressions d’interface

- déformations internes < $\varepsilon_i$
- $\varepsilon_i$ < déformations internes < $\varepsilon_m$
- déformations internes > $\varepsilon_m$

Conséquences de l’ischémie
- défaut d’oxygénation
- accumulation de toxines
- diminution du pH

si durée > 2h

Conséquences des déformations
- rupture de la membrane
- perméabilité
- dégradation du cytosquelette

si durée > 10 mn

Tissu sain

Escarre

$\varepsilon_i$ : seuil de déformations « ischémiques » (env. 20%)
$\varepsilon_m$ : seuil de déformations « mécaniques » (env. 50%)

D’après Loerakker, 2011
When deciding that there is a risk for DPU?

- How to estimate the deformations thresholds $\varepsilon_i$ and $\varepsilon_m$ from the measured pressures at the buttocks / cushion interface?

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

---

Linder-Ganz et al., 2009
Contexte

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

Origines : Diabète \(\rightarrow\) angiopathie et neuropathie

Causes : marche et interaction pied/chaussure \(\rightarrow\) micro-traumatismes répétés
Contexte

Chiffres :

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

Un pied amputé toutes les 30s à cause du diabète
Des coûts exhorbitants pour les systèmes de Santé
48 milliards $ / an aux USA ; 3 milliards £ / an en UK

Contexte

Prévention :

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

Mesure :

BioFoot® insoles  F-Scan®, Tekscan  Pedar shoes LilaBox
Contexte

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

- Tricotage d’une chaussette monocouche sur Métier Chaussant.

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

- Unité Centrale miniaturisée et liaison radio.
Résultats du projet

- Modèle biomécanique patient-spécifique du pied.
Résultats du projet

- **Anatomie du pied**: 26 os, 33 articulations et plus de 100 muscles, tendons et ligaments, ainsi qu’un réseau de vaisseaux sanguins, nerfs, peau et tissus mous.
Perrier et al., 2014
Résultats du projet

- Modèle biomécanique « patient-spécifique » du pied.

Calcanéum Patient 1

Calcanéum Patient 2
Outline

• Introduction

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

• Intra-operative Computer Aided Device: Neurosurgery

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

• PhD students:

• Clinicians:

• Co-authors: