Intra-Operative CT-Free Examination System for Anterior Cruciate Ligament (ACL) Reconstruction

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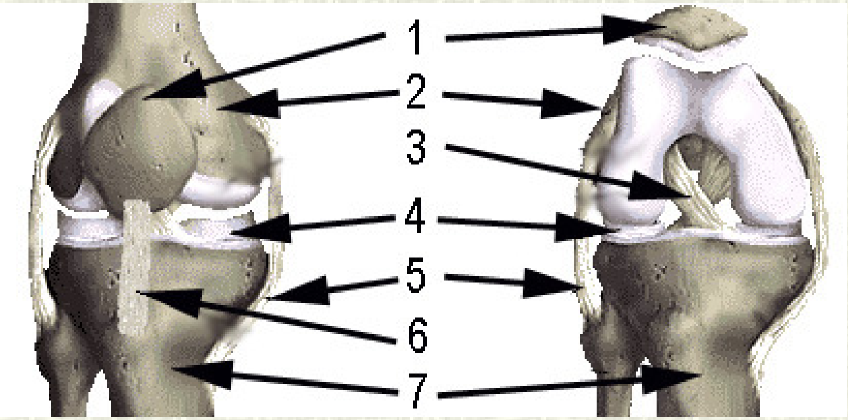
Overview

- *ACL reconstruction problem & CT-Free navigation approach*
- *Physical simulation of the ACL graft*
- *ACL Surgery using the OrthoPilot navigation system from Aesculap*
- *Experimental Results*
- *Conclusion & Perspectives.*

Context of our Work

- **The ACL is often injured or broken by a pivoting or twisting movement.**
- **In some cases, the damaged ACL has to be replaced by a *strong biologic substitute.***
- **Our work has the aim of helping the surgeon with this replacement.**

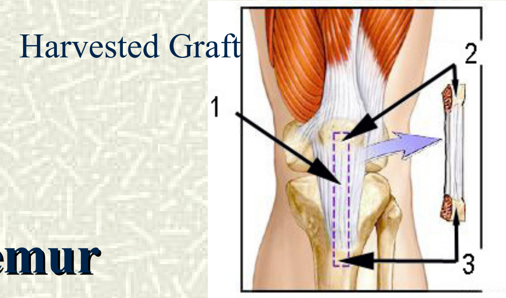
1. Patella
2. Femur
3. ACL
4. Meniscus
5. Collateral Ligaments
6. Patella Tendon
7. Tibia

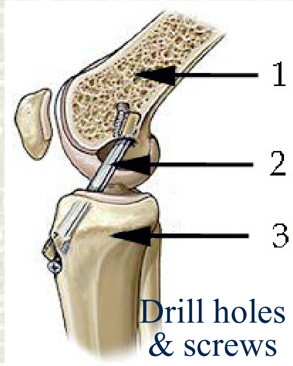


ACL Reconstruction

- **Procedure :**
  1. **A *natural graft* is first harvested**
  2. **2 bone tunnels are then drilled in the tibia and the femur**
  3. **The graft is then inserted and fixed using screws**

  (it takes about nine months for the reconstructed graft to completely heal)



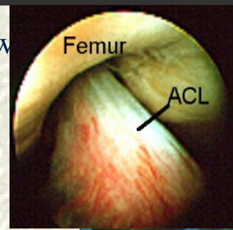


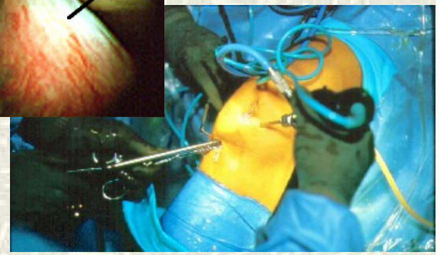
- **Main difficulties :**
  - **Best Graft placement ⇔ Mainly « isometric behavior »**
  - **Even in the best case, the graft is subjected to stress during leg flexion (graft is bigger than the original ACL, hence contact exists with bones & surrounding ligaments)**

  => Good Positioning & Orientation of the tunnels for the graft is VITAL

CT-Free navigation for ACL reconstruction

Camera View





Arthroscopic Examination

OrthoPilot Workstation
(Aesculap-Bbraun)

1. **Acquisition (per-operatively) of patient's knee kinematics & local geometry** *(« anatomic landmarks »)*

2. **Graft is harvested. Its shape & size is given to the navigation system**

3. **A physical model of the ACL graft is used to predict failures** *(using generic bio-mechanical data)*

4. **Tunnels are drilled, Graft is inserted and fixed**

   => Using geometric & physical simulation for interactively guiding the surgeon (Graft placement & Tunnels navigation)

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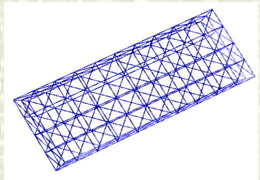
Data Acquisition (per-operatively)

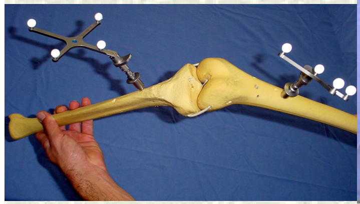
- **The dimensions of the ACL graft is obtained**
  - Patient specific
  - General form of the graft is like a beam



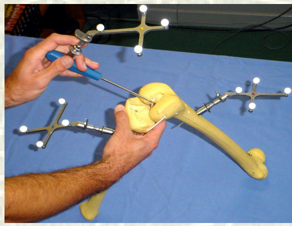
Simple Beam Mesh

- **Patient's knee kinematics & local geometry (specific anatomic landmarks) are obtained**
  - Patient specific and surgeon dependant
  - A set of transformations between the tibia with respect to a fixed femur

Kinematics Acquisition



Specific Landmark Acquisition

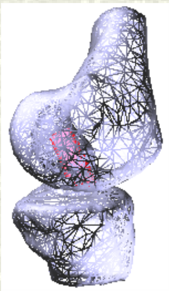


ACL Graft Physical Model

- **Problem : *Calculate stress from deformation***

- **Approach : *Volume Distribution Method (VDM)***
  - Inspired from the Long Element Method (LEM) *[Sundaraj-Laugier-Costa:Iros01]*
  - Objects that can be assimilated to an « elastic skin filled with some incompressible fluid » *(a priori adapted to most of biological tissues)*

- **Basic Idea**
  - Given a geometrical mesh, a displacement of any node causes a change in volume
  - This change in volume is distributed to the other nodes using Pascal's Principle and Volume Conservation principle



$$\begin{cases} B_i \frac{\Delta V_i}{V_i} + \sum_i \frac{B_{ij}}{V_i}(\Delta V_i - \Delta V_j) - \Delta P = \rho_i g \delta_i + P_{envi} \\ \sum_i \Delta V_i = 0 \end{cases}$$

$\Delta P = P_{fluid} - P_{atm}$

$\Delta V_i \approx A_i \cdot \Delta L_i$

=> n+1 variables

B_i : Bulk modulus (normal stress)

B_{ij} : Connectivity bulk modulus (shear stress)

ρ : Fluid density

δ_i : High of liquid column at node i

Model Simulation

- **Static Formulation** *($P_{ext} = P_{int}$)*
  - Sufficient for the ACL (ligaments exhibit negligeable viscoelastic effects)

  => Solving K . ΔL = R   where K is sparse, R = Pressure & Gravity effects
- **Boundary Condition**
  - Pascal's Principle
- **Node Constraints**
  - Fixed, Free, Contact & Displaced

$$\mathbf{A} = \begin{pmatrix} \frac{E_1^x}{L_1^x} & .. & \frac{-k_N^j}{A_N^x} & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \vdots & .. & \vdots & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{-k_1^j}{A_1^x} & .. & \frac{E_N^x}{L_N^x} & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \frac{E_1^y}{L_1^y} & .. & \frac{-k_N^j}{A_N^y} & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \vdots & .. & \vdots & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \frac{-k_1^j}{A_1^y} & .. & \frac{E_N^y}{L_N^y} & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{E_1^z}{L_1^z} & .. & \frac{-k_N^j}{A_N^z} & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & \vdots & .. & \vdots & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{-k_1^j}{A_1^z} & .. & \frac{E_N^z}{L_N^z} & 1 \\ A_1^x & .. & A_N^x & A_1^y & .. & A_N^y & A_1^z & .. & A_N^z & 0 \end{pmatrix} \quad \mathbf{x} = \begin{pmatrix} \Delta L_1^x \\ \vdots \\ \Delta L_N^x \\ \Delta L_1^y \\ \vdots \\ \Delta L_N^y \\ \Delta L_1^z \\ \vdots \\ \Delta L_N^z \\ -\Delta P \end{pmatrix} \quad \mathbf{B} = \begin{pmatrix} d_1^x g_1^x h_1^x \\ \vdots \\ d_N^x g_N^x h_N^x \\ d_1^y g_1^y h_1^y \\ \vdots \\ d_N^y g_N^y h_N^y \\ d_1^z g_1^z h_1^z \\ \vdots \\ d_N^z g_N^z h_N^z \\ 0 \end{pmatrix}$$

- **Resolution Method**
  - Nonlinear Analysis (K changes for larges deformations)
  - Iterative Bi-Conjugate Gradient

Model Generation

⌗ Geometrical Model

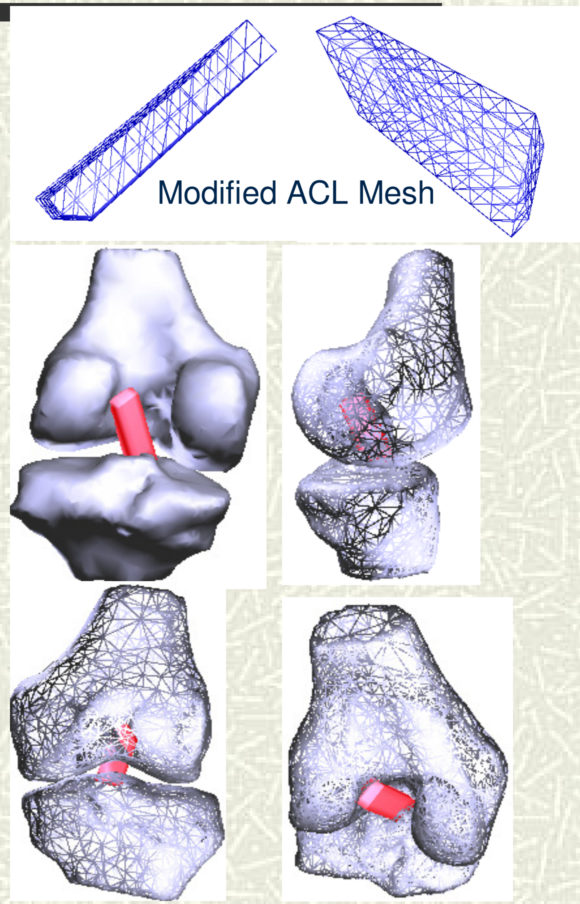
- A simple beam shape tapered at the ends
- Ends are fixed at the femoral and tibia tunnel outlets
- Generic mesh of the tibia and femur

  => for 3D visualization

⌗ Physical Model

- Knee kinematics as position boundary conditions
- VDM deformable model for simulation

  => Bulk modulus B_i and connectivity bulk modulus B_{ij} are obtained from the literature



Positioning with respect to a generic mesh of the femur and tibia

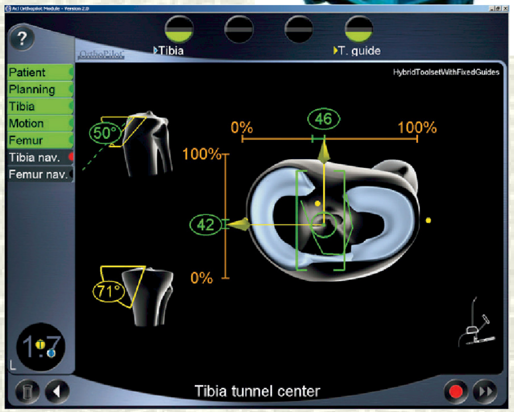
Model Generation (2)

PHYSICAL DATA OF THE VIRTUAL ACL GRAFT*

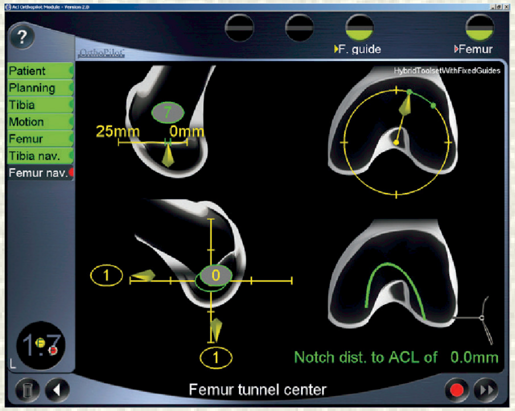
Height (H)	5mm	
Width (W)	10mm	
Length (L)	25mm	
Cross Section Area (A)	50mm^2	
Surface Area (S)	850mm^2	
Volume (V)	1250mm^3	
Resolution (Q)	138 elements	
Bulk Modulus (B_i)	0.3 x 10^6 Nm^{-2}	=> Normal stress
Connectivity Bulk Modulus (B_{ij})	4.0 x 10^3 Nm^{-2}	=> shear stress
Angle of Flexion (θ)	0° - 90°	

Navigation principle (OrthoPilot)

- **Position and orientation of diode markers are read by infra-red cameras**
- **Patients knee is flexed**
- **Spatial transformations are read at 1.5° intervals**
- **OrthoPilot solves the geometrical problem and proposes a solution to the surgeon**

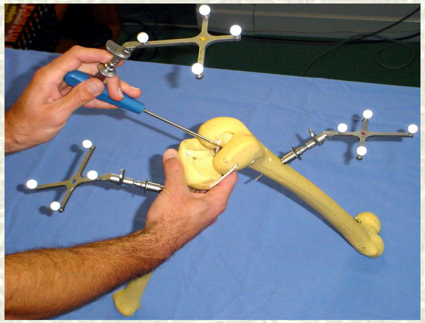


Tibia tunnel navigation



Femur tunnel navigation

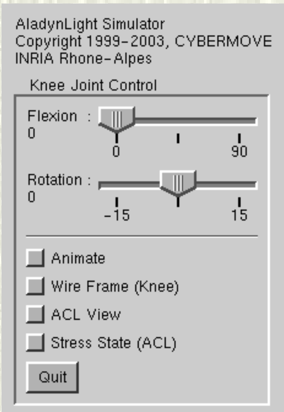
Clip vidéo



Implementation

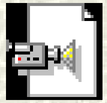
- OrthoPilot navigation system from Aesculap
- AlaDyn3D dynamic simulator
- Linked through a serial interface for data transfer
- Graphical User Interface (GUI) has two views
  - 3D Deformation and Stress
  - Control Station

3D Rendering

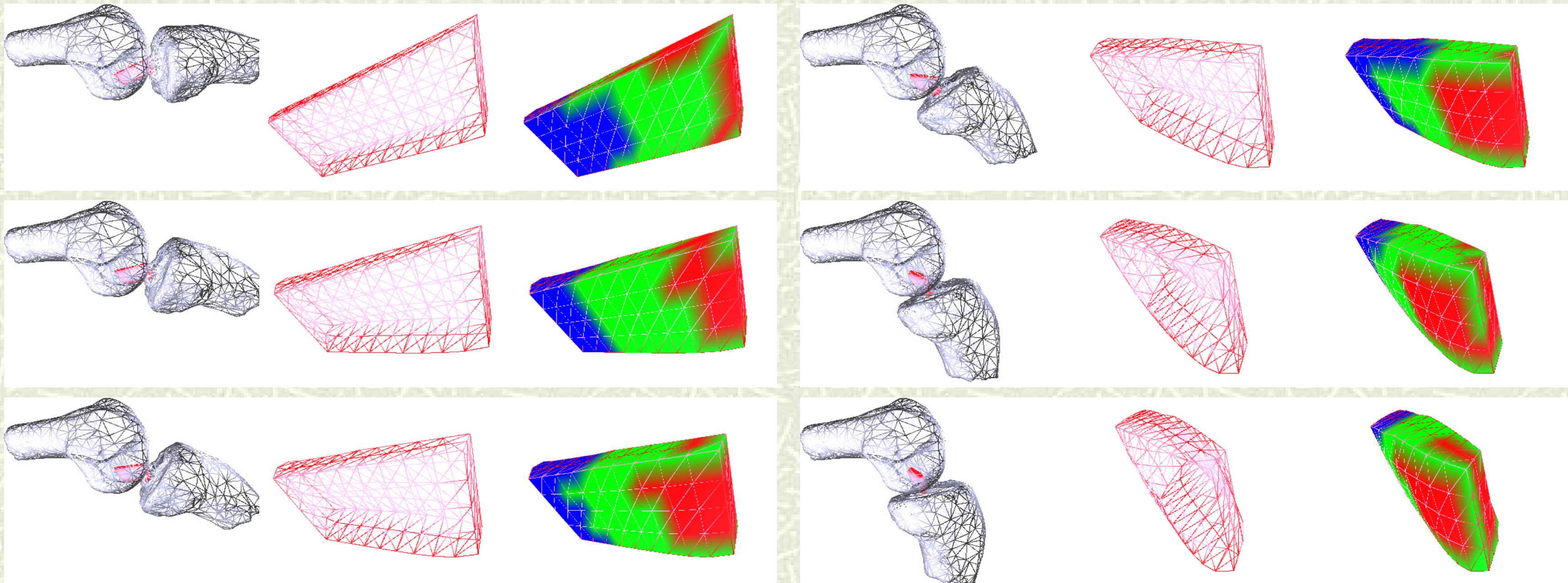


Control station

Experimental Results


Clip vidéo

- **Input Data & Setup**
  - *Using a sample set of transformations from OrthoPilot's database (knee flexed from 0° - 90°)*
  - *Using a sample position, orientation and dimension of the ACL graft from the database*
- **Deformation & Stress** (simulation results from 10° to 90°)



Conclusion & Perspectives

Conclusion

- A prototype medical simulator has been developed as an help to the ACL reconstruction
- This simulator includes geometric, kinematics, and physical data processing
- These data can be used by the surgeon for choosing a good surgical solution (graft placement & tunnels placement and orientation)

Perspectives

- Perform cadaveric and clinical tests to validate the physical model
- Consider interactions of the ACL graft with the bones and surrounding ligaments
- Improve the GUI for surgery environment