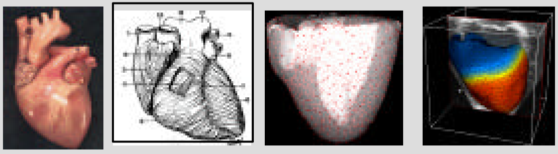
Physiology-Based Deformable Model to Segment Cardiac Images



H. Delingette,

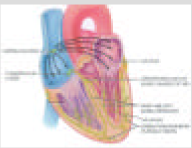
M. Sermesant, Y. Coudière, Nicholas Ayache

France-Singapour Conference 2002

INRIA - 2004 Route des Lucioles, 06902 Sophia-Antipolis , France
Herve.Delingette@inria.fr

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion



Electro-Mechanical Heart Model

- From ***passive*** to ***active*** biomechanical model
  - Triggered by ECG
  - Adjusted from Image Measurements
- Advantages
  - more robust (can “beat” with partial image info)
  - provide both electrical and biomechanical functional information
  - can simulate electrical and mechanical pathologies and specific surgery

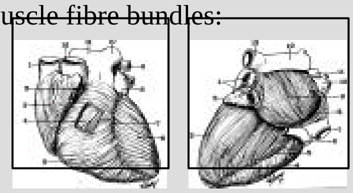
---

Pluridisciplinary project

- ICEMA
  - INRIA:Caiman, Epidaure, Macs, Sinus, Sosso
  - Philips, King’s College (D. Hill)
- Following the pioneering work of
  - Mc Culloch et al.,
  - Mc Veigh et al.,
  - Papademetris, Sinusas, Duncan et al.,
  - P. Hunter, Young et al., ...

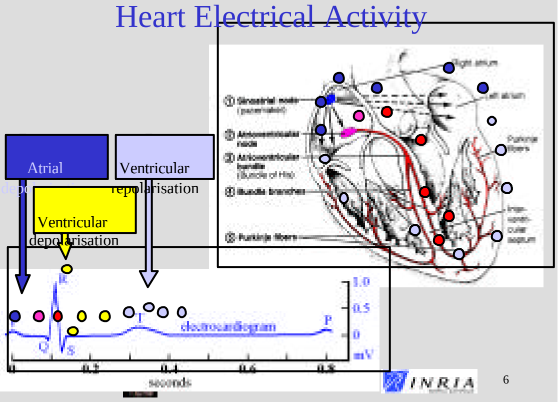
Myocardium Properties

The myocardium is composed of muscle fibre bundles:



It is an active non-linear viscoelastic anisotropic incompressible material.

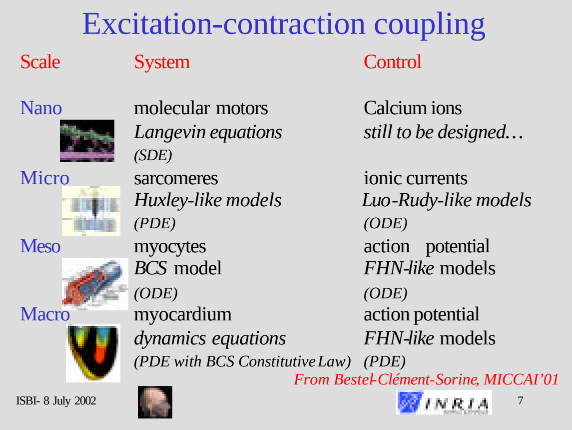
Heart Electrical Activity



Atrial depolarisation

Ventricular repolarisation

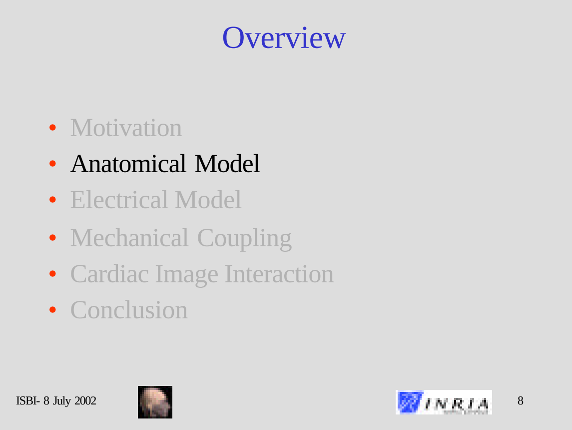
Ventricular depolarisation



Excitation-contraction coupling

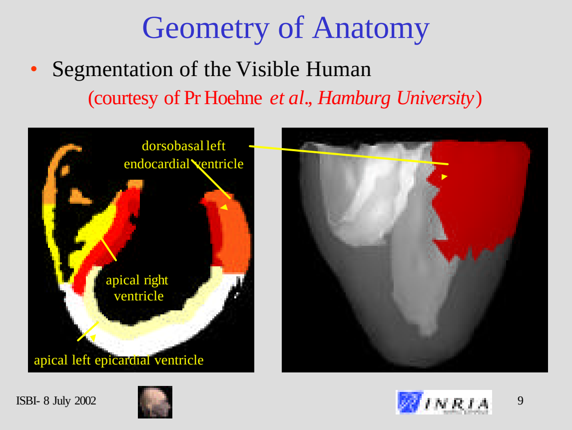
Scale	System	Control
Nano	molecular motors *Langevin equations* *(SDE)*	Calcium ions *still to be designed…*
Micro	sarcomeres *Huxley-like models* *(PDE)*	ionic currents *Luo-Rudy-like models* *(ODE)*
Meso	myocytes *BCS* model *(ODE)*	action potential *FHN-like* models *(ODE)*
Macro	myocardium *dynamics equations* *(PDE with BCS Constitutive Law)*	action potential *FHN-like* models *(PDE)*

From Bestel-Clément-Sorine, MICCAI'01



Overview

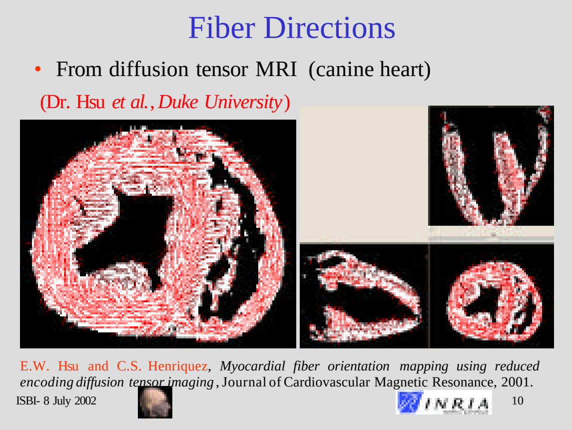
- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion



Geometry of Anatomy

- Segmentation of the Visible Human

(courtesy of Pr Hoehne *et al*., *Hamburg University*)

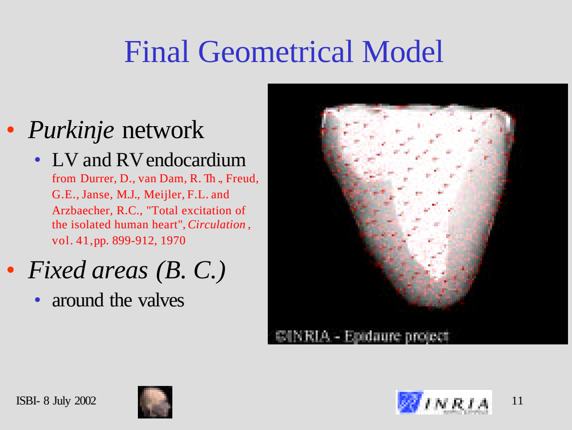


Fiber Directions

- From diffusion tensor MRI (canine heart)

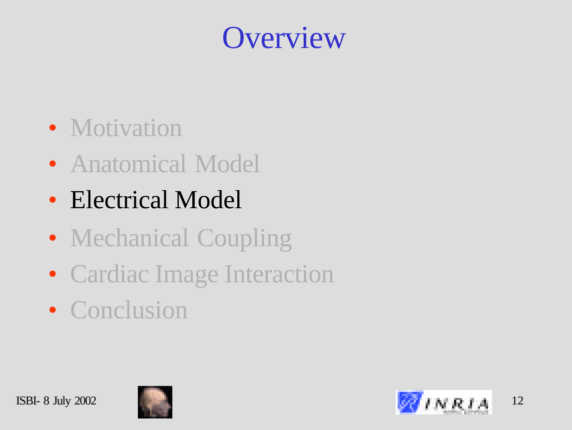
(Dr. Hsu *et al.*, *Duke University*)

E.W. Hsu and C.S. Henriquez, *Myocardial fiber orientation mapping using reduced encoding diffusion tensor imaging*, Journal of Cardiovascular Magnetic Resonance, 2001.



Final Geometrical Model

- *Purkinje* network
  - LV and RV endocardium
    from Durrer, D., van Dam, R. Th., Freud, G.E., Janse, M.J., Meijler, F.L. and Arzbaecher, R.C., "Total excitation of the isolated human heart", *Circulation*, vol. 41, pp. 899-912, 1970
- *Fixed areas (B. C.)*
  - around the valves



Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion

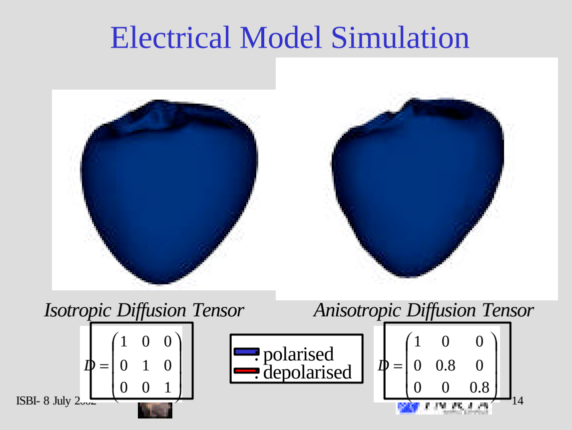
Electrical Model

- Action potential u computation: 2 variables FitzHugh-Nagumo *Reaction-Diffusion* system

$$\begin{cases} \dfrac{\partial u}{\partial t} = div(D\nabla u) + f(u) - z \\ \dfrac{\partial z}{\partial t} = b(u - cz) \end{cases}$$

u action potential
D diffusion tensor
f ionic current
z repolarization variable
b repolarisation rate
c repolarisation decay

Or R. Aliev and A. Panfilov : A Simple Two-variable Model of Cardiac Excitation, *Chaos, Solitons & Fractals*, Vol 7, No 3, pp. 293-301,1996



Electrical Model Simulation

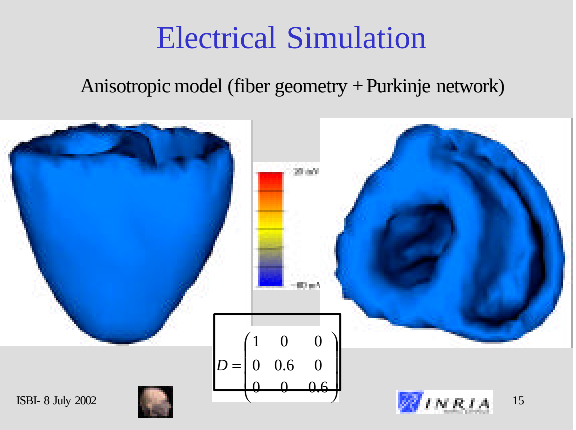
Isotropic Diffusion Tensor

$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Anisotropic Diffusion Tensor

$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.8 & 0 \\ 0 & 0 & 0.8 \end{pmatrix}$$

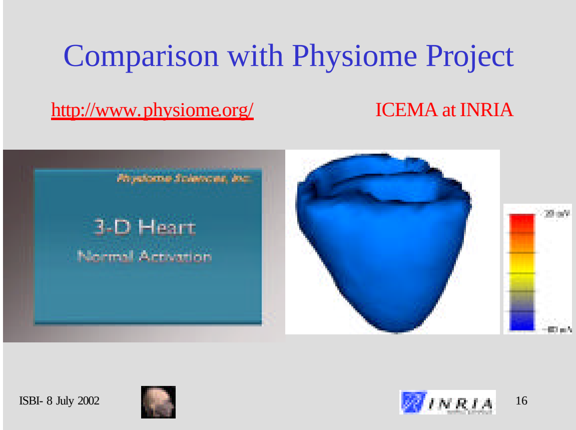
🟦 : polarised
🟥 : depolarised



Electrical Simulation

Anisotropic model (fiber geometry + Purkinje network)

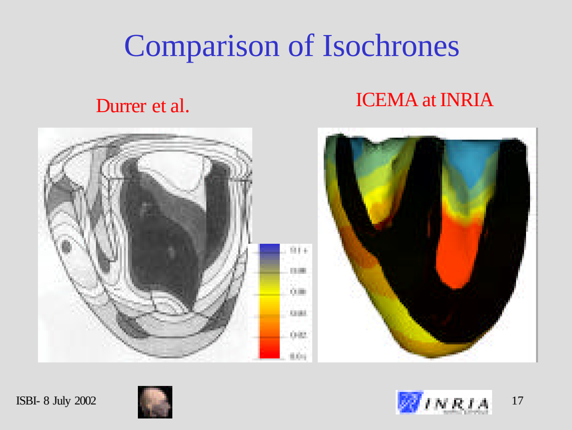
$$D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0.6 & 0 \\ 0 & 0 & 0.6 \end{pmatrix}$$



Comparison with Physiome Project

http://www.physiome.org/

ICEMA at INRIA



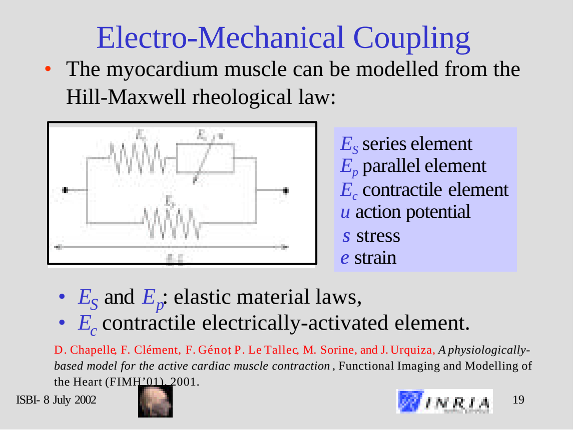
Comparison of Isochrones

Durrer et al.

ICEMA at INRIA

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion



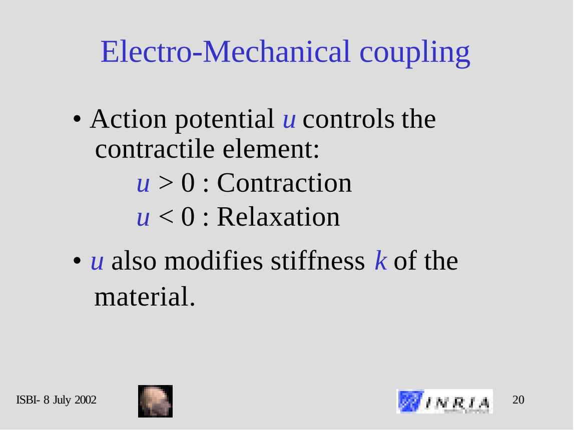
Electro-Mechanical Coupling

- The myocardium muscle can be modelled from the Hill-Maxwell rheological law:

E_S series element
E_p parallel element
E_c contractile element
u action potential
s stress
e strain

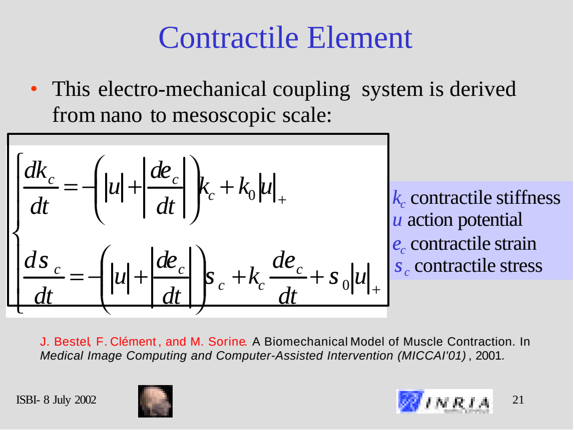
- E_S and E_p: elastic material laws,
- E_c contractile electrically-activated element.

D. Chapelle, F. Clément, F. Génot, P. Le Tallec, M. Sorine, and J. Urquiza, *A physiologically-based model for the active cardiac muscle contraction*, Functional Imaging and Modelling of the Heart (FIMH'01), 2001.



Electro-Mechanical coupling

- Action potential u controls the contractile element:
  - $u > 0$: Contraction
  - $u < 0$: Relaxation
- u also modifies stiffness k of the material.



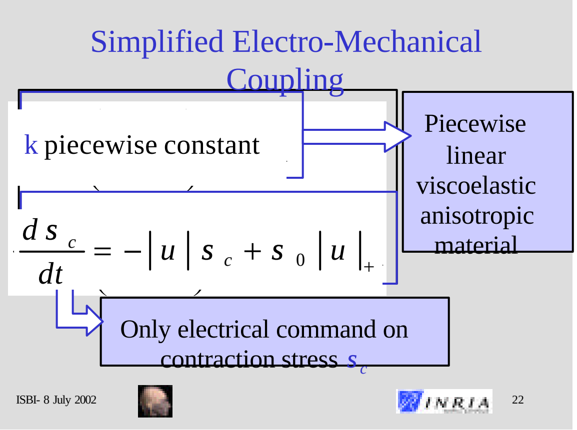
Contractile Element

- This electro-mechanical coupling system is derived from nano to mesoscopic scale:

$$\begin{cases} \dfrac{dk_c}{dt} = -\left(|u| + \left|\dfrac{de_c}{dt}\right|\right) k_c + k_0 |u|_+ \\ \dfrac{ds_c}{dt} = -\left(|u| + \left|\dfrac{de_c}{dt}\right|\right) s_c + k_c \dfrac{de_c}{dt} + s_0 |u|_+ \end{cases}$$

k_c contractile stiffness
u action potential
e_c contractile strain
s_c contractile stress

J. Bestel, F. Clément, and M. Sorine. A Biomechanical Model of Muscle Contraction. In *Medical Image Computing and Computer-Assisted Intervention (MICCAI'01)*, 2001.



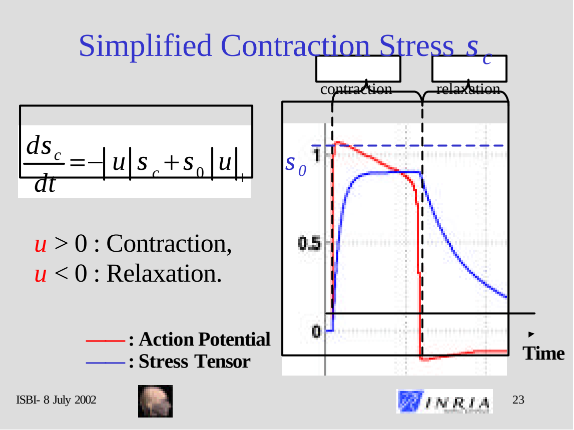
Simplified Electro-Mechanical Coupling

k piecewise constant

$$\frac{ds_c}{dt} = -|u| s_c + s_0 |u|_+$$

Piecewise linear viscoelastic anisotropic material

Only electrical command on contraction stress s_c

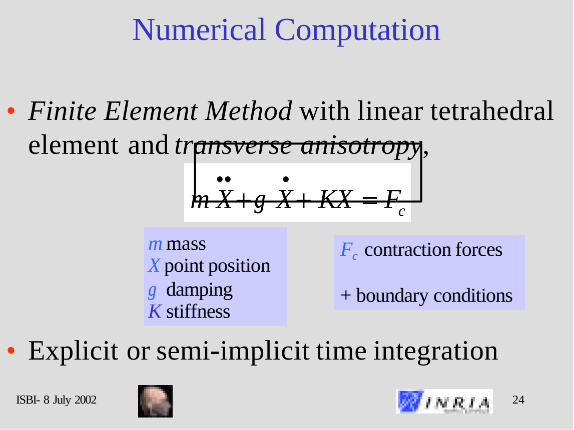


Simplified Contraction Stress s_c

$$\frac{ds_c}{dt} = -|u| s_c + s_0 |u|_+$$

$u > 0$: Contraction,
$u < 0$: Relaxation.

: Action Potential
: Stress Tensor



Numerical Computation

- *Finite Element Method* with linear tetrahedral element and *transverse anisotropy*,

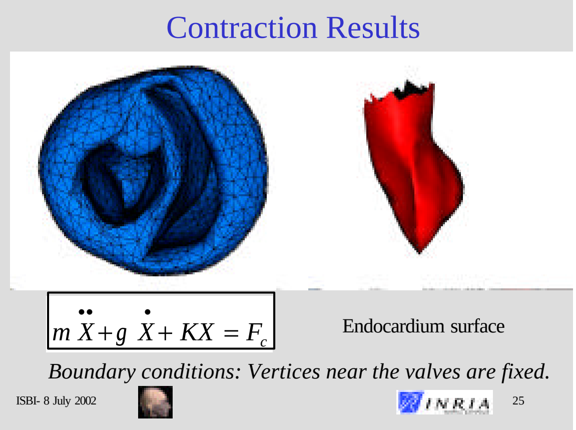
$$m\ddot{X} + g\dot{X} + KX = F_c$$

m mass
X point position
g damping
K stiffness

F_c contraction forces

+ boundary conditions

- Explicit or semi-implicit time integration



Contraction Results

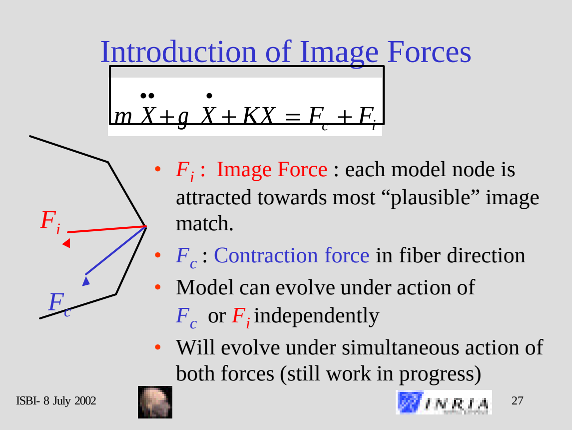
$$m\ddot{X}+g\dot{X}+KX=F_c$$

Endocardium surface

Boundary conditions: Vertices near the valves are fixed.

Overview

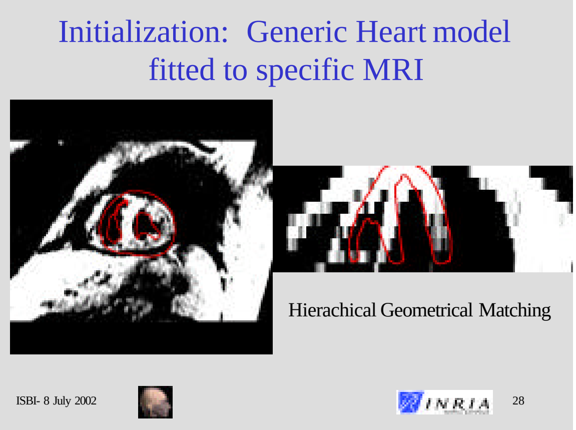
- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction (in progress)
- Conclusion



Introduction of Image Forces

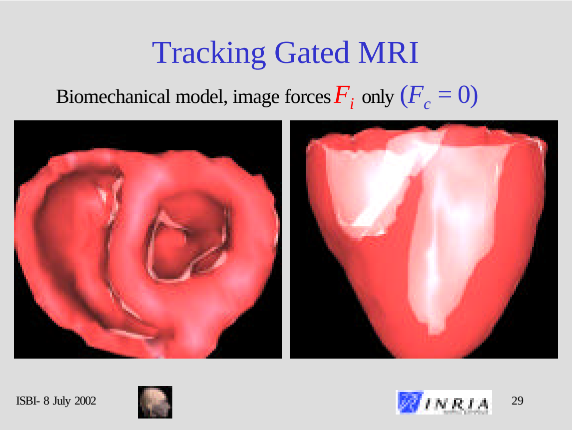
$$m\ddot{X}+g\dot{X}+KX=F_c+F_i$$

- F_i : Image Force : each model node is attracted towards most “plausible” image match.
- F_c : Contraction force in fiber direction
- Model can evolve under action of F_c or F_i independently
- Will evolve under simultaneous action of both forces (still work in progress)



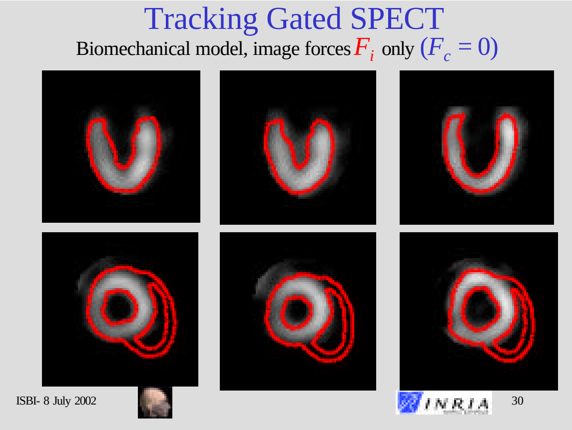
Initialization: Generic Heart model fitted to specific MRI

Hierachical Geometrical Matching



Tracking Gated MRI

Biomechanical model, image forces F_i only $(F_c=0)$

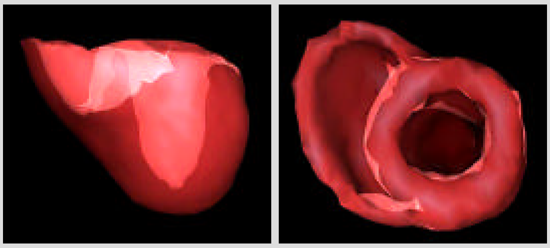


Tracking Gated SPECT

Biomechanical model, image forces F_i only $(F_c=0)$

Tracking Gated Spect

Biomechanical model, image forces F_i only $(F_c = 0)$



Combining Image and Contraction Forces

- Requires additional data
  - D. Hill et al., Electrical measurements and tagged MRI in the same heart, work in progress
  - E. McVeigh et al., Measurement of ventricular wall motion, epicardial electrical mapping and myocardial fiber angles in the same heart, in FIMH'01, 2001.
- First experiments planned by the end of 2002

Simulating RF Ablation

- Collaboration with D. Hill (King 's College)
- Simulate electrical pathologies like fibrillation, arrhythmia, reentry, and radiofrequency surgery.

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion

Summary

- From Geometric to **Passive** and **Active** Biomechanical Models
- A simplified electro-mechanical model of the heart controlled through ECG and 4-D images
- Current development allows independant electro-mechanical simulation or image tracking. Coupling to be integrated soon!

Credits & References

- M. Sermesant, H. Delingette, N.A, Y. Coudière, J.A Desideri An Electro-Mechanical Model of the Heart for Cardiac Image Analysis, MICCAI'01 (+Update at ISBI'02).
- J. Bestel, F. Clément, and M. Sorine. A Biomechanical Model of Muscle Contraction, MICCAI'01
- N. Ayache, D. Chapelle, F. Clément, Y. Coudière, H. Delingette, J.A. Désidéri, M. Sermesant, M. Sorine and J. Urquiza, Towards Model-Based estimation of the cardiac electro-mechanical activity from ECG signals and ultrasound images, FIMH'01