Predicting Tumour Location by Simulating Large Deformations of the Breast using a 3D Finite Element Model and Nonlinear Elasticity

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Outline

- Motivation and Modelling Procedure
  - Why a model would extremely clinically useful
  - Modelling procedure
- Simulations
  - Finite elasticity
  - The three types of simulation
  - Results
- Conclusions and Further Work

Motivation for a Deformable Model of the Breast

- Huge difference in breast shape between different scenarios
  - MRI - patient lies prone
  - Mammography - breast is forcibly compressed, various directions of compression
  - Surgery - patient lies supine
- Matching tumour location is an important but difficult problem
- A patient-specific anatomically accurate deformable model can be used to simulate breast shape and predict tumour location

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The Model can be used to:

- Predict tumour location during surgery/biopsy..
- Match MRI with mammograms..
- Match different types of mammogram, e.g. CC with e.g MLO..
- Perform temporal matching..
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..a host of potential uses!

Modelling Procedure

Mesh Generation

- Build 3D mesh geometry from MR images
- Form thin skin elements and interior elements
- Segment MR images into **fat**, **fibroglandular** or **tumour**
- Assign a tissue to each element

Boundary Conditions

- Assume the pectoral muscle stays fixed

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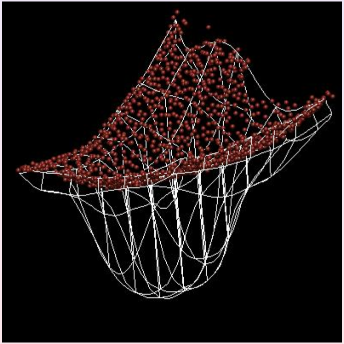

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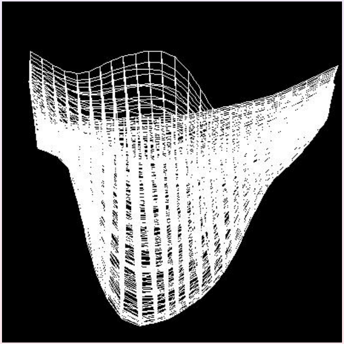

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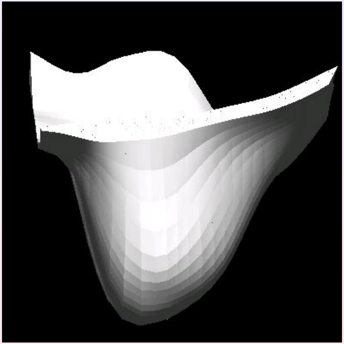

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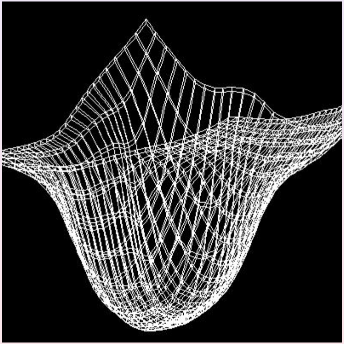

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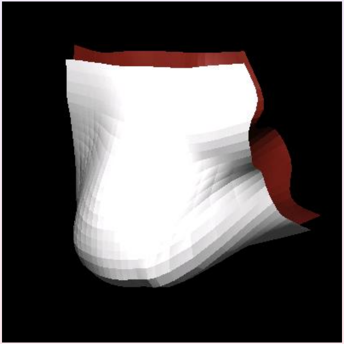

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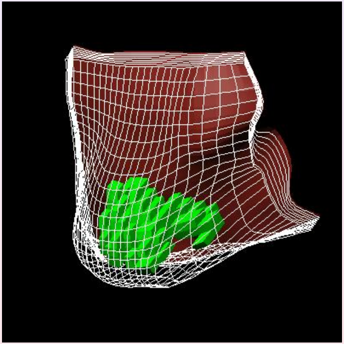

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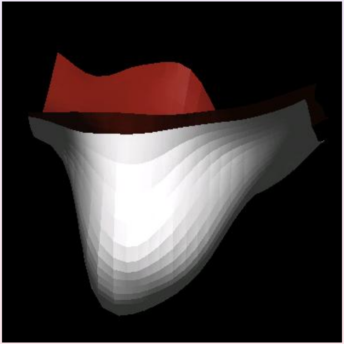

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Modelling Assumptions

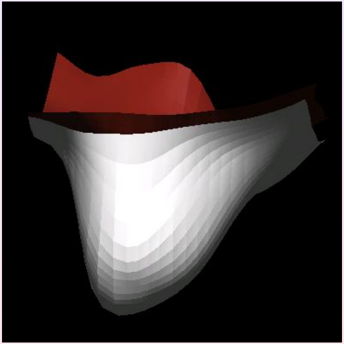
- Assume tissues are isotropic
- Assume tissues are incompressible
- Assume hyperelasticity

Determine Tissue Material Laws

- Must be determined experimentally

Simulations

- Normal nonlinear deformations
- 'Backward' deformations...
- Constrained deformations...



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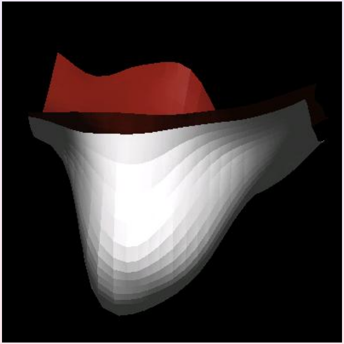

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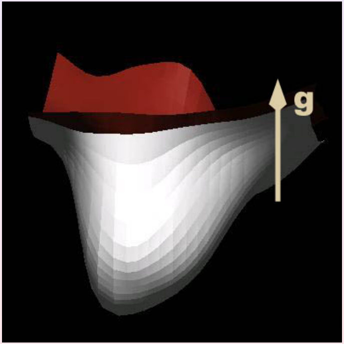

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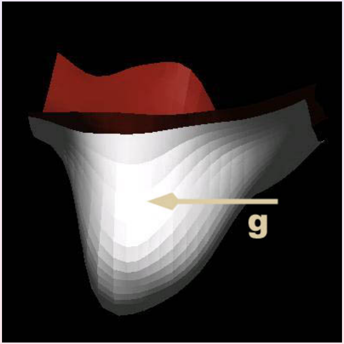

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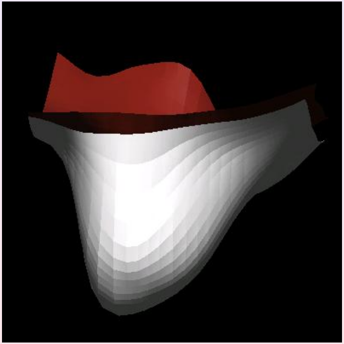

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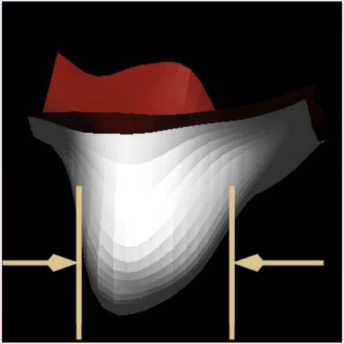

Nonlinear Elasticity

- Nonlinear elasticity theory generally needed in bio-mechanical simulations
- Two types of nonlinearity: strain is quadratic, and tissue stress-strain relationships are no longer assumed to be linear
- Leads to highly nonlinear equations which can be slow to solve computationally
- We assume hyperelasticity, which means stress is dependent on strain only (not history of strain, or strain rate)

The Forward and Backward Problems

The Forward Problem

- Normal nonlinear deformation
- Given undeformed state, require deformed state

The Backward Problem

- A mesh formed from MR images will be in a *gravity-loaded state*
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- Have to solve an inverse finite deformation calculation
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The Contact Problem

- Simulation of mammography
- Here we have to solve a deformation problem with inequality constraints
- Formulate equations as an energy minimisation and add a penalty function

$$\min \int_{\text{breast}} (\text{total energy})\, dV_0 + \int_{\text{skin}} \frac{P}{2} \left([d(\mathbf{x})]_+\right)^2 dS_0$$

- P is the penalty parameter, $[d(\mathbf{x})]_+$ a positive quantity which measures violation of the constraint (required to be zero)
- P needs to be very large for accurate results
- Better method is the Augmented Lagrangian Method:

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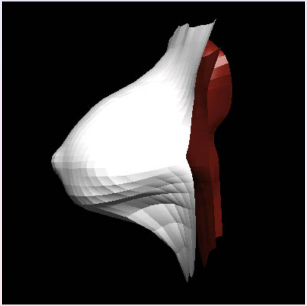
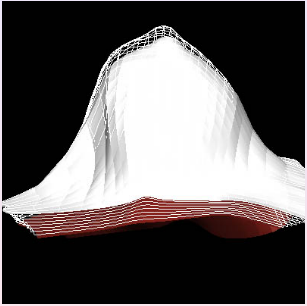
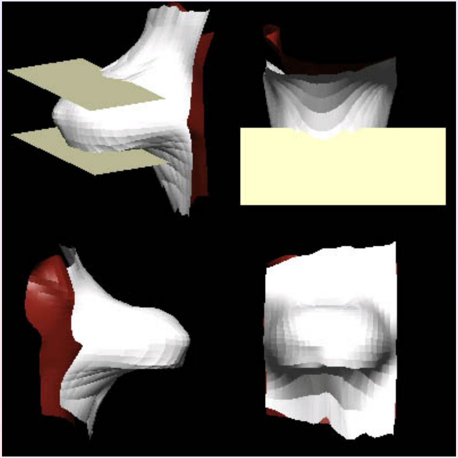


initial mesh



reference state (wireframe)
and supine breast shape (surface)

Simulations (cont)



Simulation of CC mammographic compression

Conclusions and Further Work

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- Have shown modelling breast deformation with nonlinear elasticity is computationally tractable
- Discussed the three types of simulation necessary
- Used a patient-specific model to simulate surgical and mammographic breast shape

Further Work

- Validation using patient data and phantom studies
- Include transverse isotropy
- Include effect of friction
- Model skin as a membrane
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- This research is funded by the EPSRC, UK