Measuring the mechanical properties of human skin in vivo using digital image correlation & nonlinear finite element modeling

Sam Evans, Rachel Groves, Jamal Mahmud, Sion Coulman*, James Birchall*

School of Engineering, *School of Pharmacy
Cardiff University
Introduction

• Many engineering applications for a model of skin
• Detailed, layered, 3D models for localised effects (eg needles, shaving)
• Membrane model more efficient for large areas of skin
Property identification

• Need to identify properties for use in a constitutive model
• Quick, non-invasive measurements needed because of wide variations in properties
• Can use a model to measure the properties as well as to predict deformation
FE model

- 2D plane stress model with unaligned mesh
- Incompressible Ogden material model, with tension field wrinkling & prestretch$^1$
- Hager – Zhang nonlinear conjugate gradient solver

Computational measurements

“Consider a nonlinear material with large strains... The task of interpreting the experimental tensile test then becomes nontrivial... Probably this task will eventually be taken over by computer-aided experiment, 'back-calculating' by trial and error using finite elements...”

- Bruce Irons, 1980
Digital image correlation

Subsets matched in other camera view and later images
Optimisation

• Hager – Zhang solver and simple model gives reliable solution <0.5s
• Many iterations possible
• Simplex optimisation (Matlab fminsearch)
• Stochastic optimisation (Alexandre Delalleau, Pierre Fabre)
Improved stochastic algorithm

• Random points within bounds
• Fit regression plane through best points
• Randomly generate new points around regression plane
• Effectively changes the axes for the bounding box to suit the problem
Discussion

• The skin stiffens dramatically at low loads but not so much at high loads
• A single Ogden model doesn't fit all loads perfectly
• Identification based on a single frame is as effective as using multiple frames
• Some uncertainty remains
Conclusions

• Hager – Zhang algorithm is excellent for highly nonlinear models
• Simplex optimisation can be misleading
• Modified stochastic method works well but there is some inherent uncertainty when identifying three parameters
Two layer model of skin indentation

- Indentation using various indenters and needles
- Multi-layer model incorporated both the epidermis (0.06mm) and dermis (1.74mm)
- Epidermis assumed to be stiffer than the dermis because of the stratum corneum
- Ogden parameters optimised to match
Results for the multilayer FEBio model

Epidermis Ogden parameters:
Bulk modulus=1N/mm²
\( \alpha = 2, \ \mu = 0.005 \) with a Young’s Modulus of 0.01N/mm²

Dermis Ogden parameters:
Bulk modulus=0.75N/mm²
\( \alpha = 1.5, \ \mu = 0.005 \) with a Young’s Modulus of 0.0075N/mm²
Conclusions

• Very delicate measurements of skin behaviour are possible in vivo
• Can identify properties of multiple layers
• Microneedle penetration tests offer the possibility of measuring fracture properties – almost impossible to do in any other way