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

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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

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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

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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

1. Evans, S. L., On the implementation of a wrinkling, hyperelastic membrane model for skin and other materials. CMBBE 12(3): 319-332.

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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

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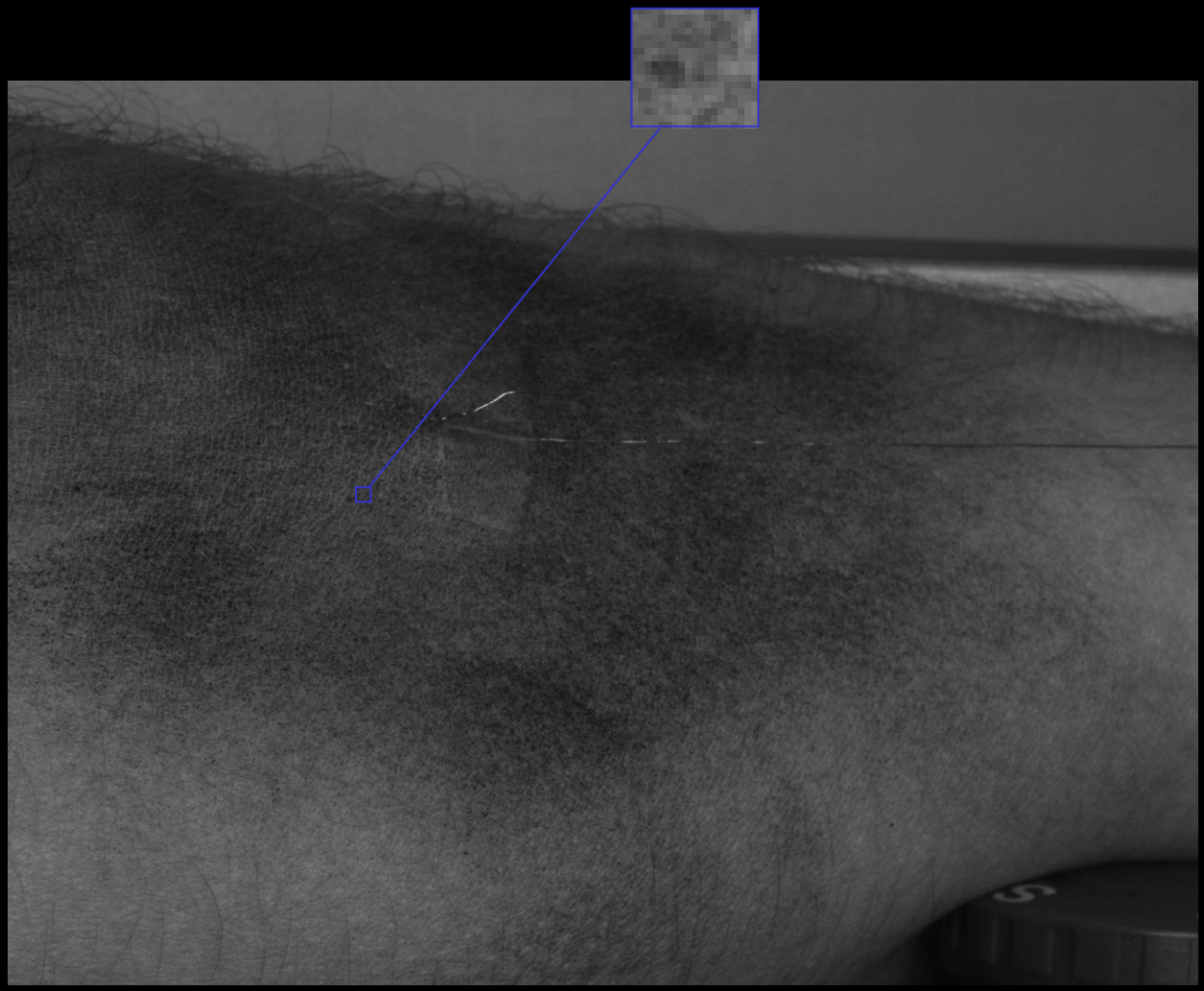
Digital image correlation



Subsets matched in other camera view and later images

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Vic-3D 2006 - (skin4.v3d) - [Plot: sk4-211_0.out]

File Edit Project Calibration Data Plot Window Help

2D 3D

Plotting tools

Axes | Contour | Color map | Vector

X: -46.9263 - 47.6254

Y: -31.8411 - 33.2823

Z: -15.2767 - 6.47933

Auto-rescale coordinates

Z-scale 0.3

Apply

Project

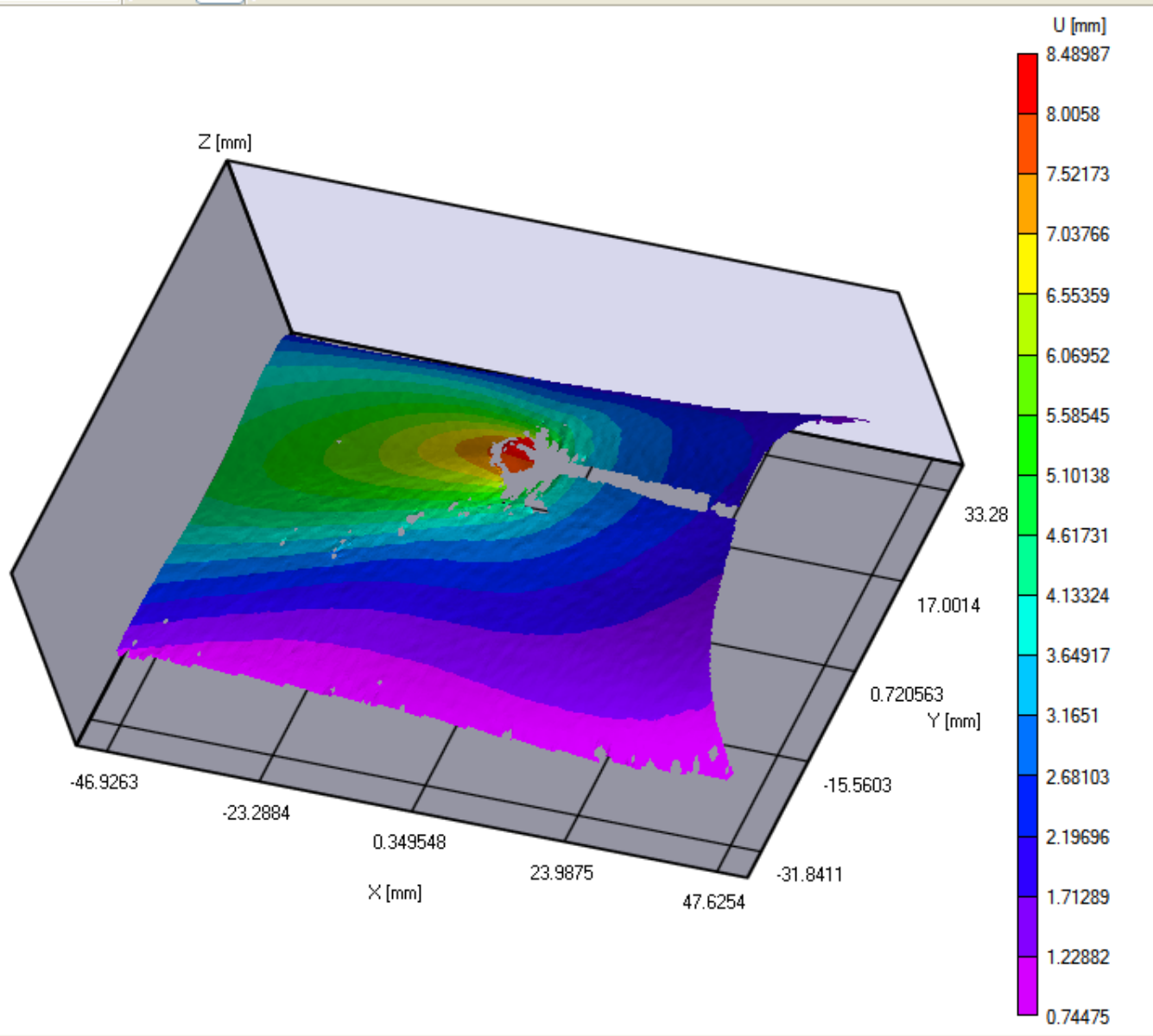
Images | Data | Calibration

Current data

- sk4-192_0.out
- sk4-193_0.out
- sk4-194_0.out
- sk4-195_0.out
- sk4-196_0.out
- sk4-197_0.out
- sk4-198_0.out
- sk4-199_0.out
- sk4-200_0.out
- sk4-201_0.out
- sk4-202_0.out
- sk4-203_0.out
- sk4-204_0.out
- sk4-205_0.out

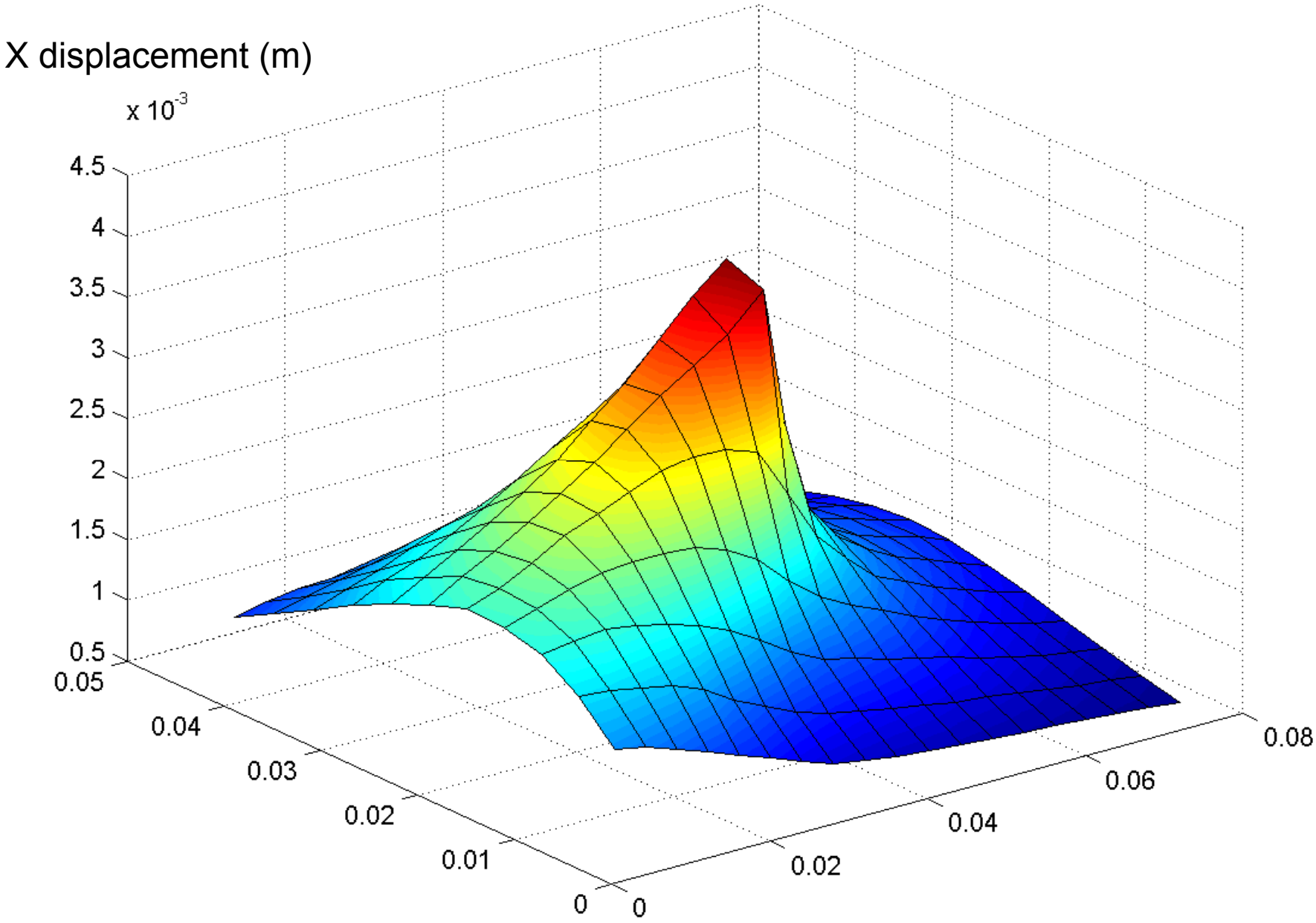
Animation tools

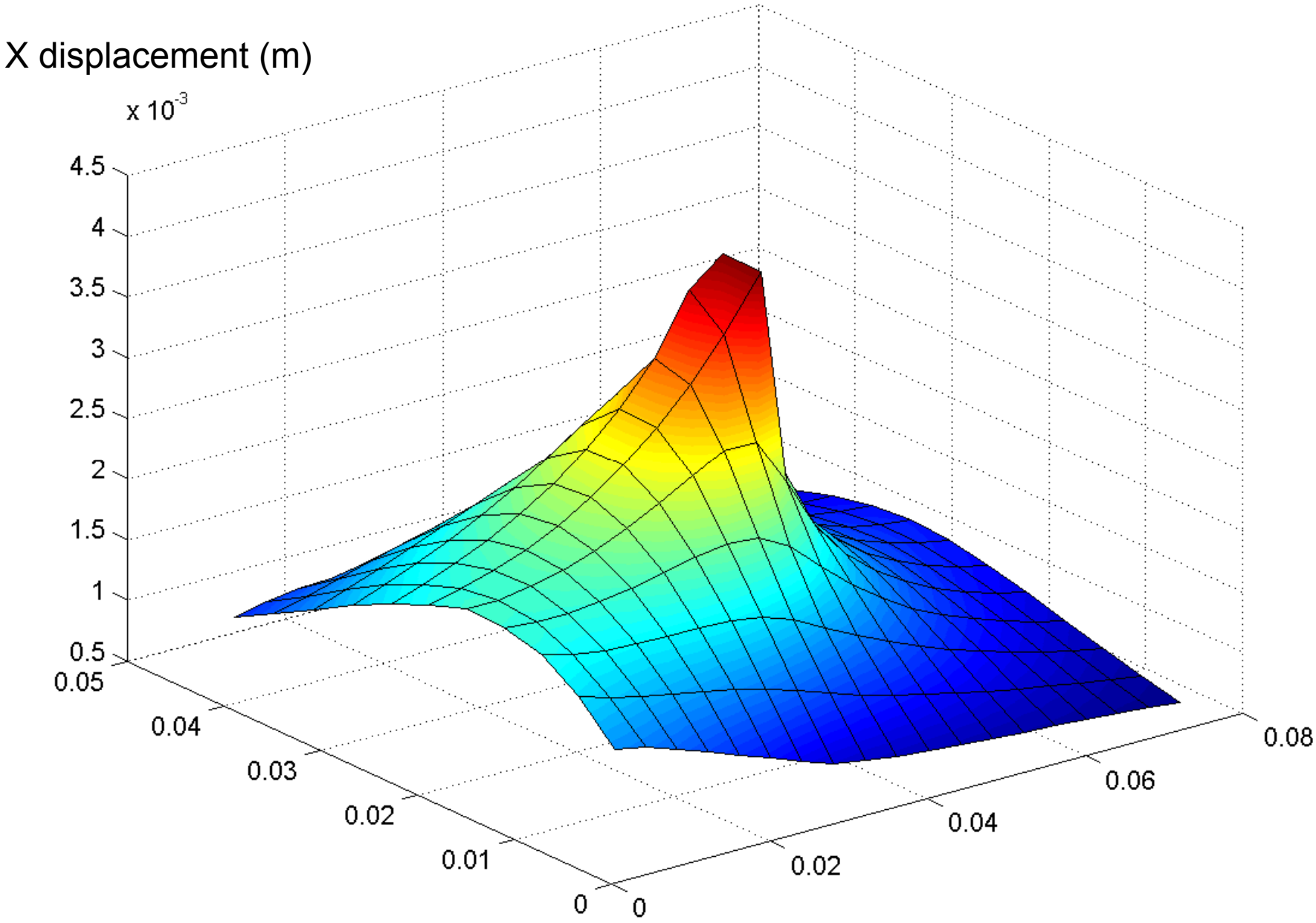
100

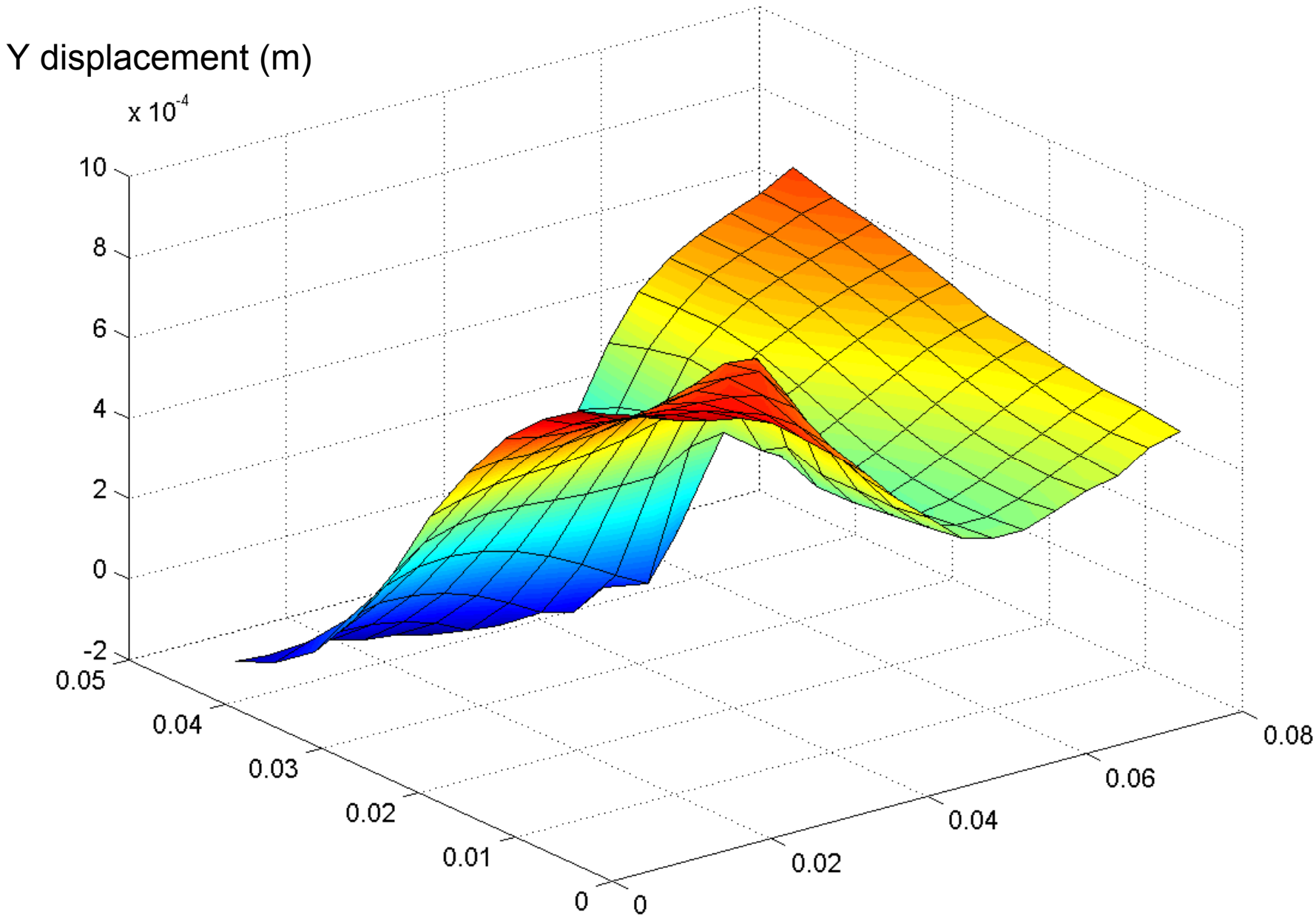


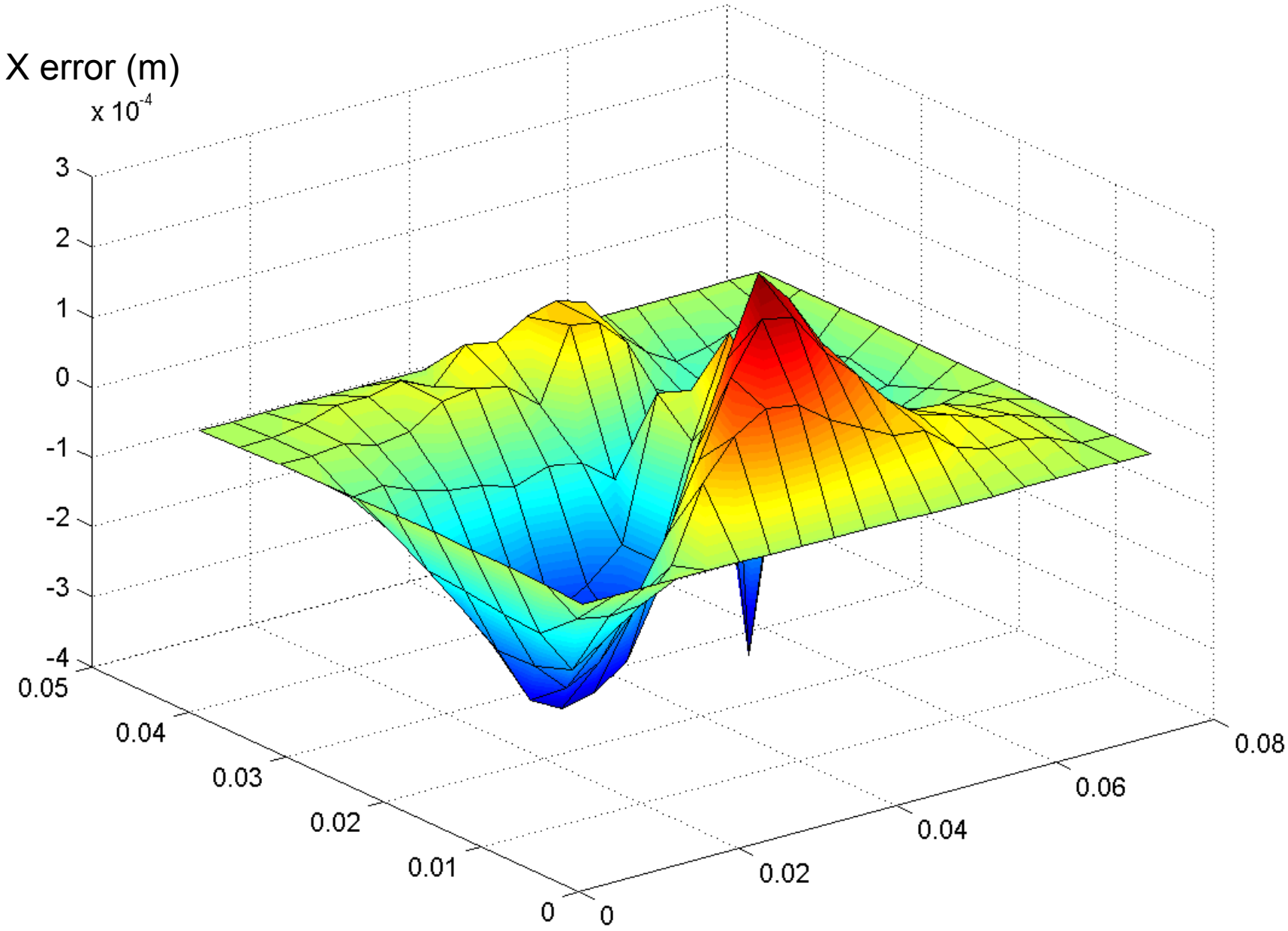
(187, 878) 46

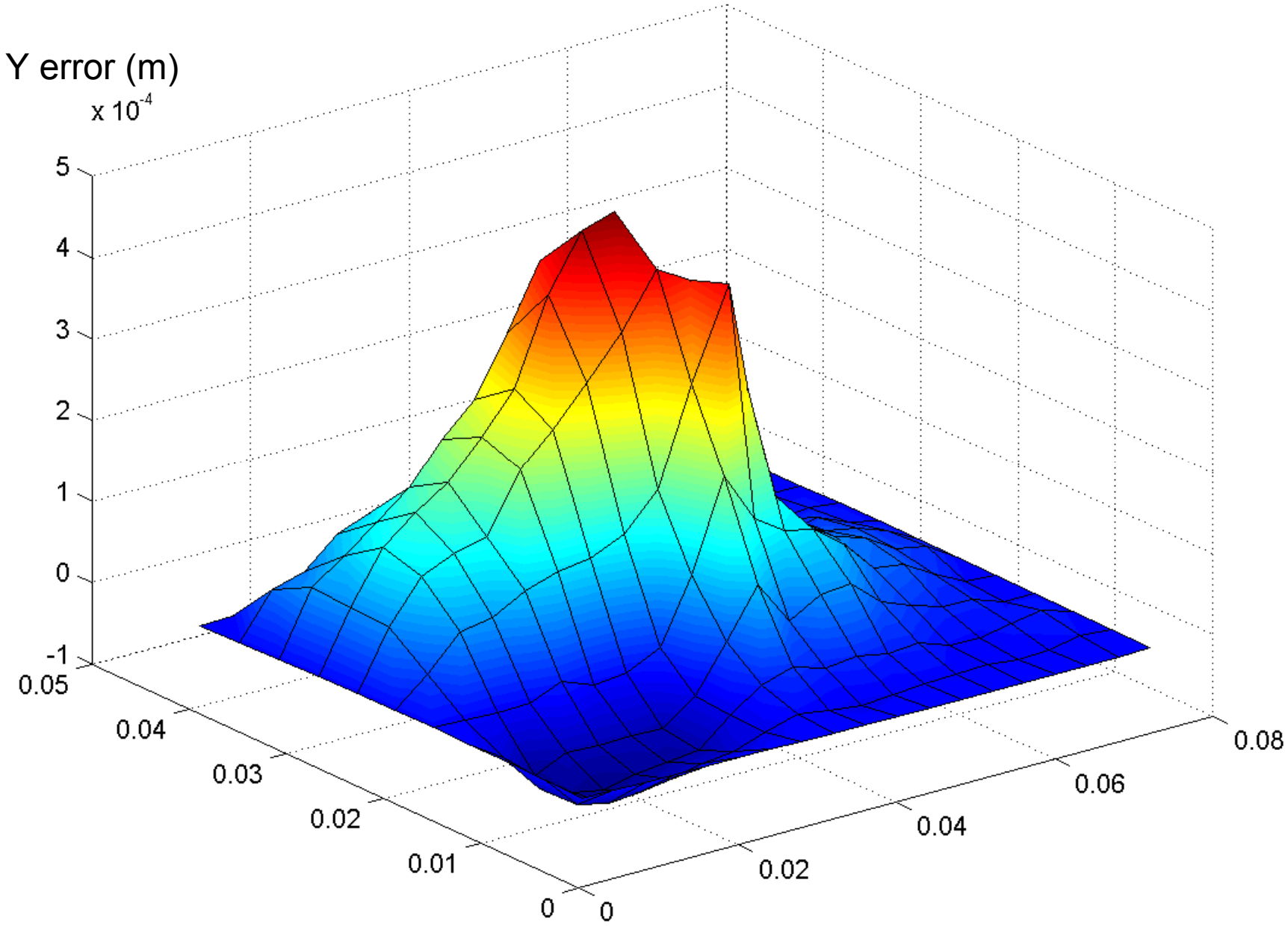
start | Papers | Meditech Arup Sam.p... | Vic-3D 2006 - (skin4.... | EN | 10:26


X displacement (m)
x 10^-3
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08


X displacement (m)
x 10^-3
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08


Y displacement (m)
x 10^-4
10
8
6
4
2
0
-2
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08


X error (m)
x 10^-4
3
2
1
0
-1
-2
-3
-4
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08


Y error (m)
x 10^-4
5
4
3
2
1
0
-1
0.05
0.04
0.03
0.02
0.01
0
0
0.02
0.04
0.06
0.08

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)*

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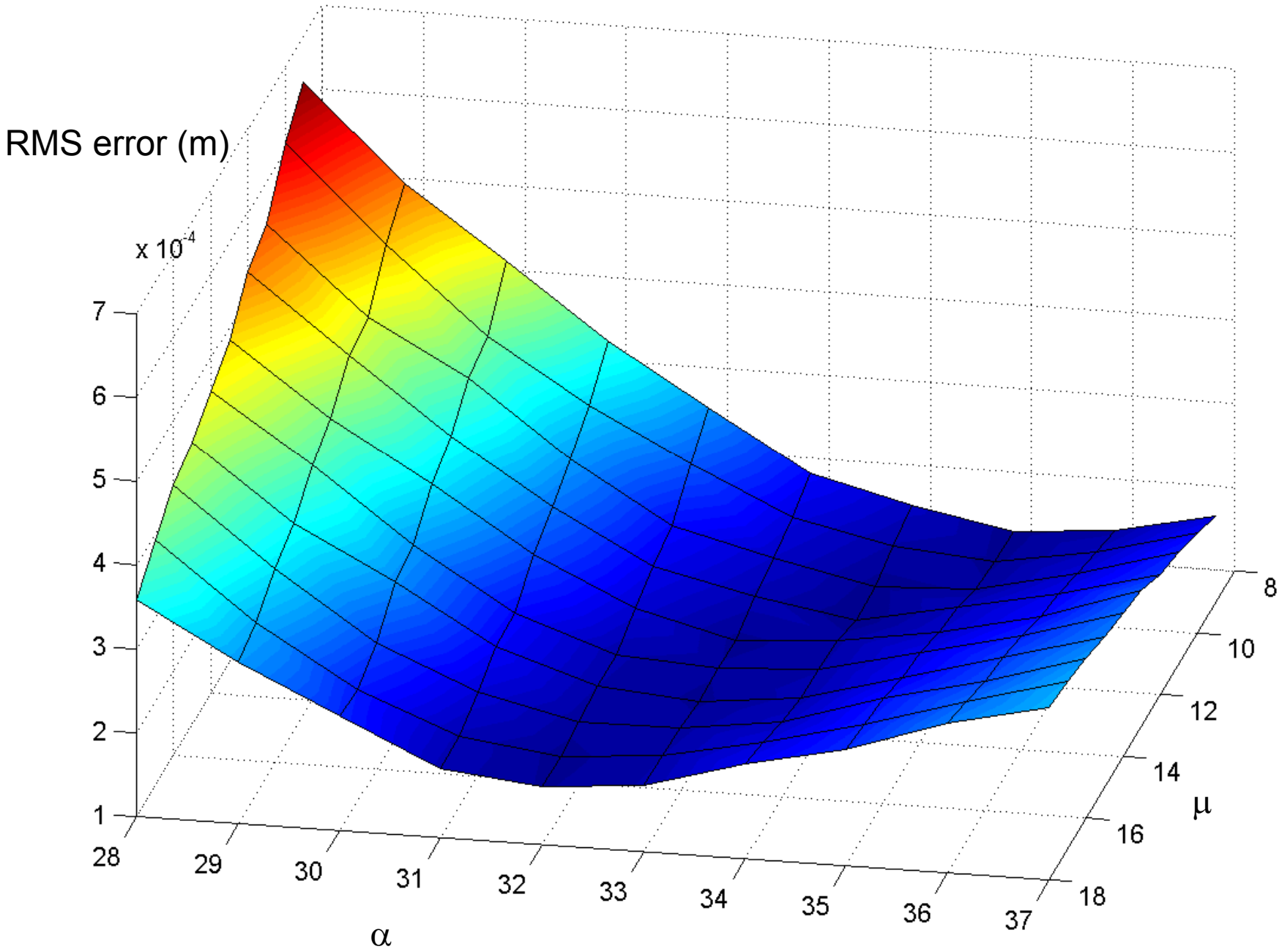
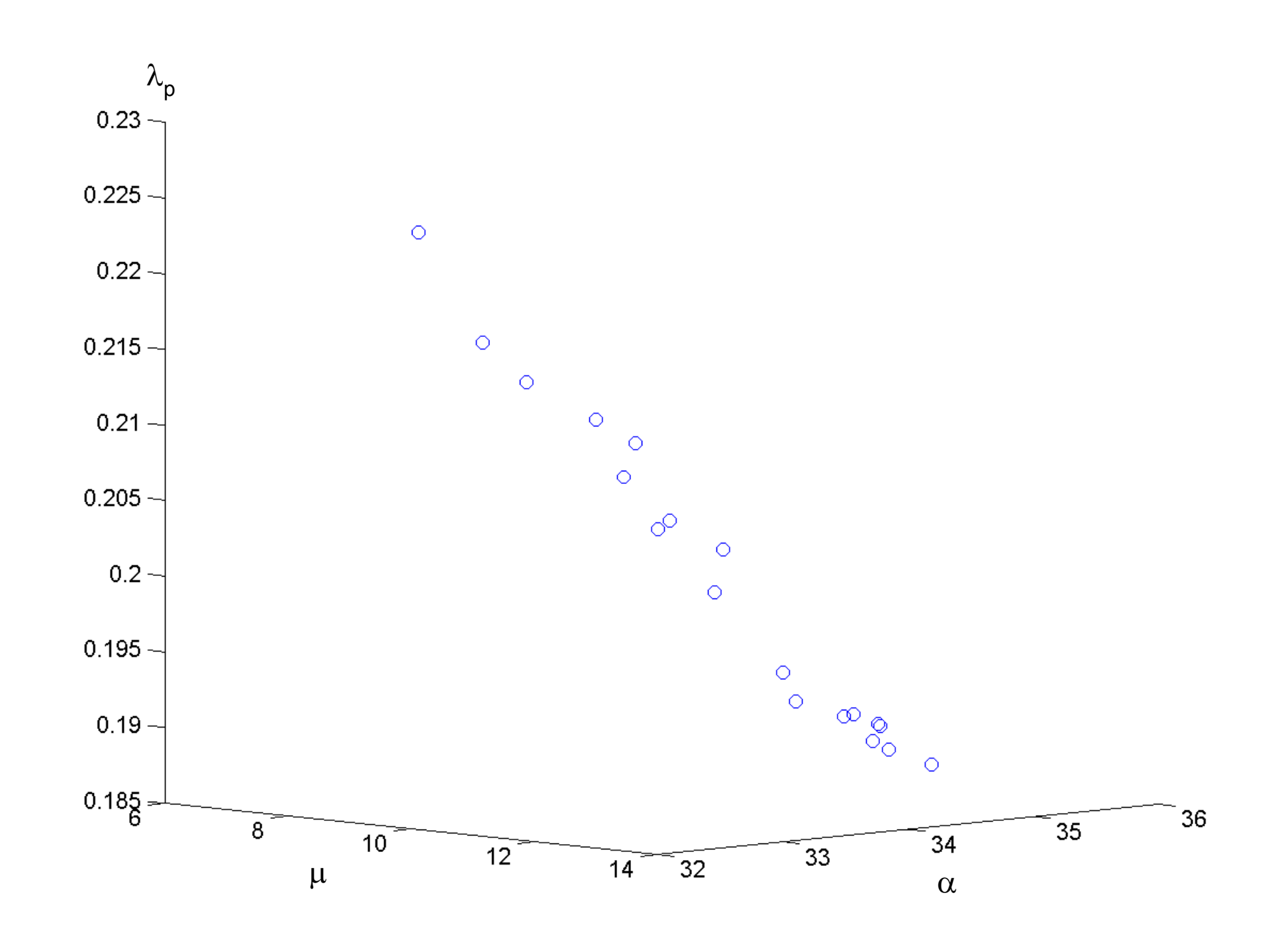
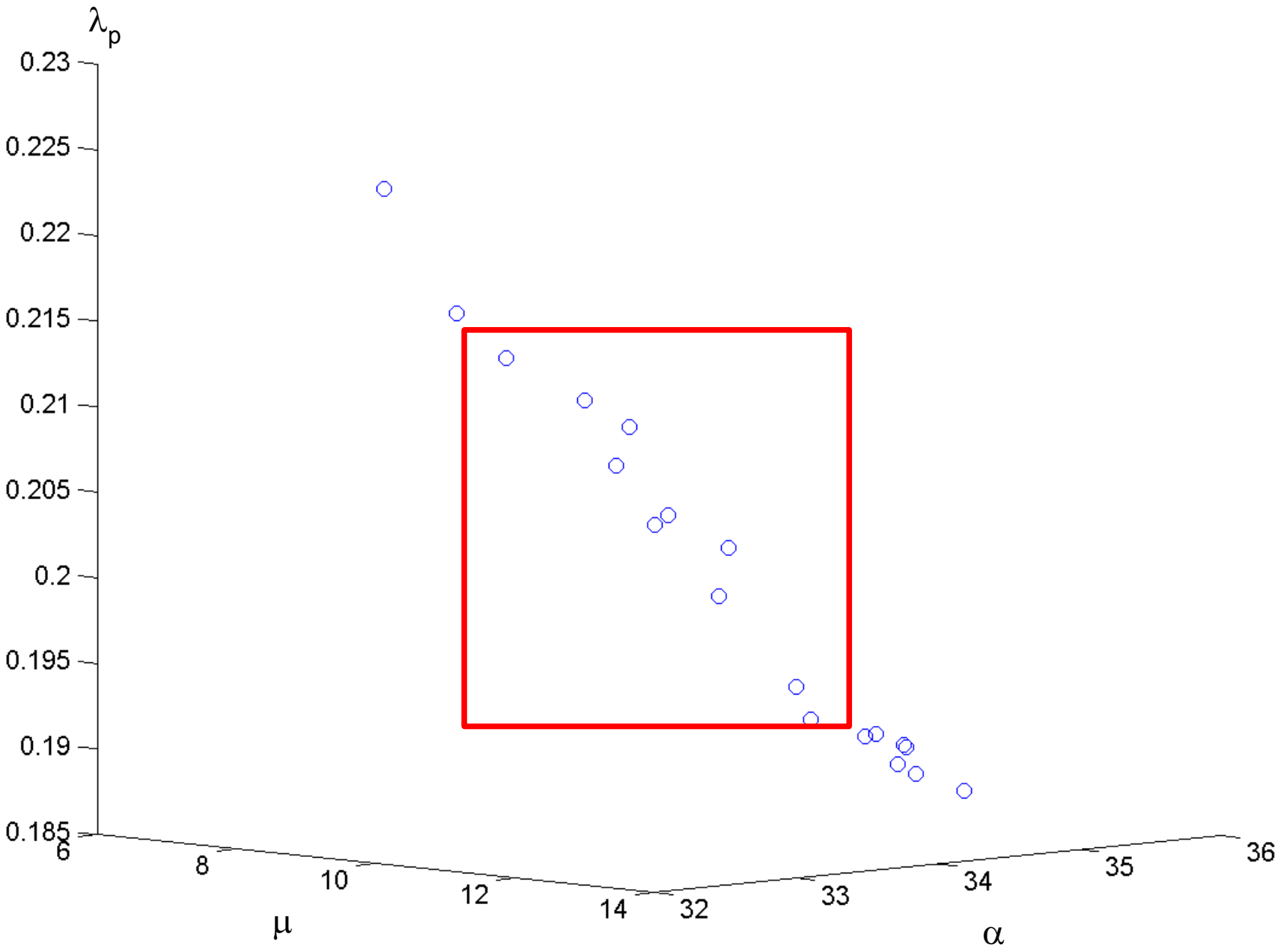

RMS error (m)
x 10^-4
7
6
5
4
3
2
1
28
29
30
31
32
33
34
35
36
37
α
8
10
12
14
16
18
μ


λp
0.23
0.225
0.22
0.215
0.21
0.205
0.2
0.195
0.19
0.185
6
8
10
12
14
μ
32
33
34
35
36
α


λ_p
0.23
0.225
0.22
0.215
0.21
0.205
0.2
0.195
0.19
0.185
6
8
10
12
14
μ
32
33
34
35
36
α

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

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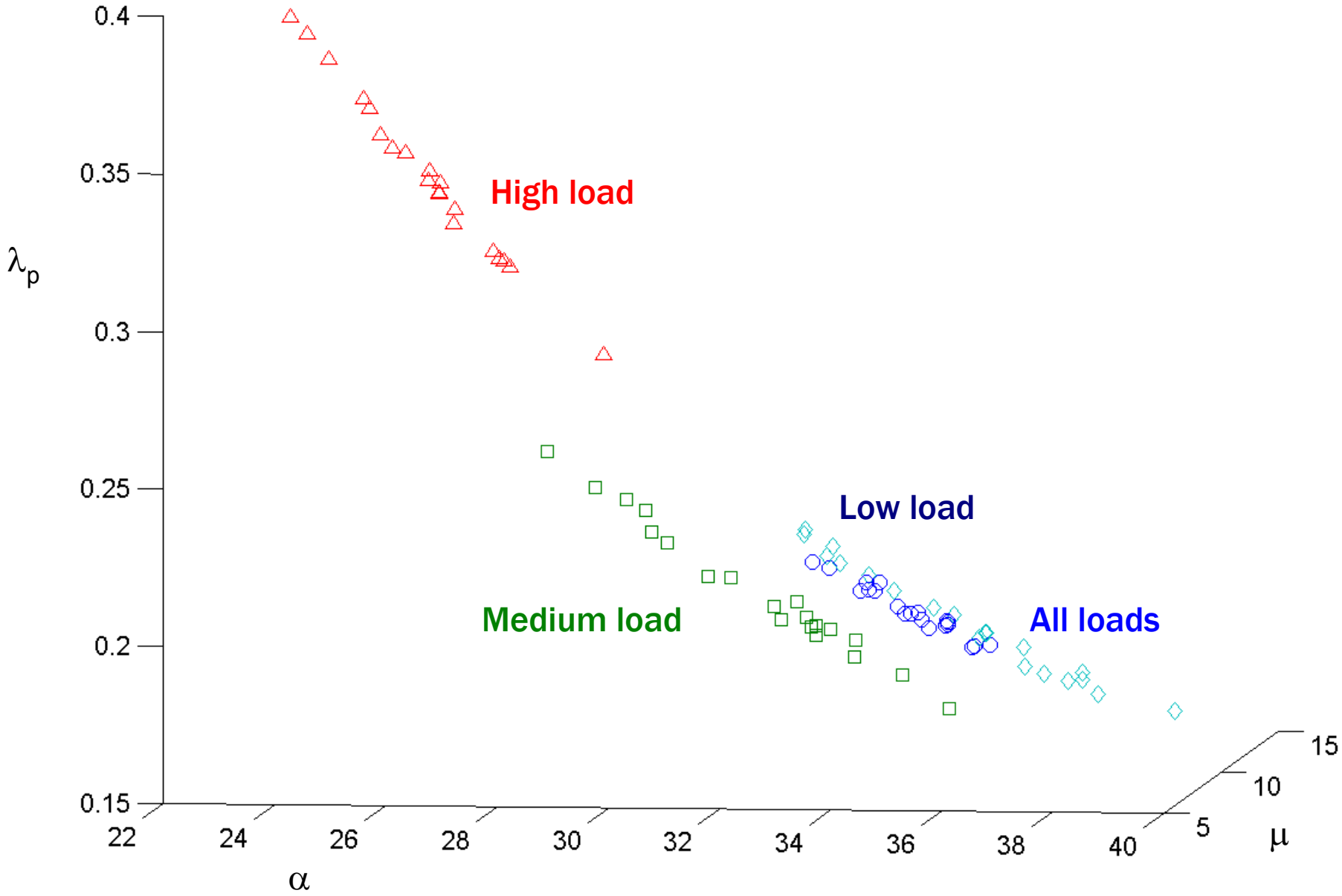
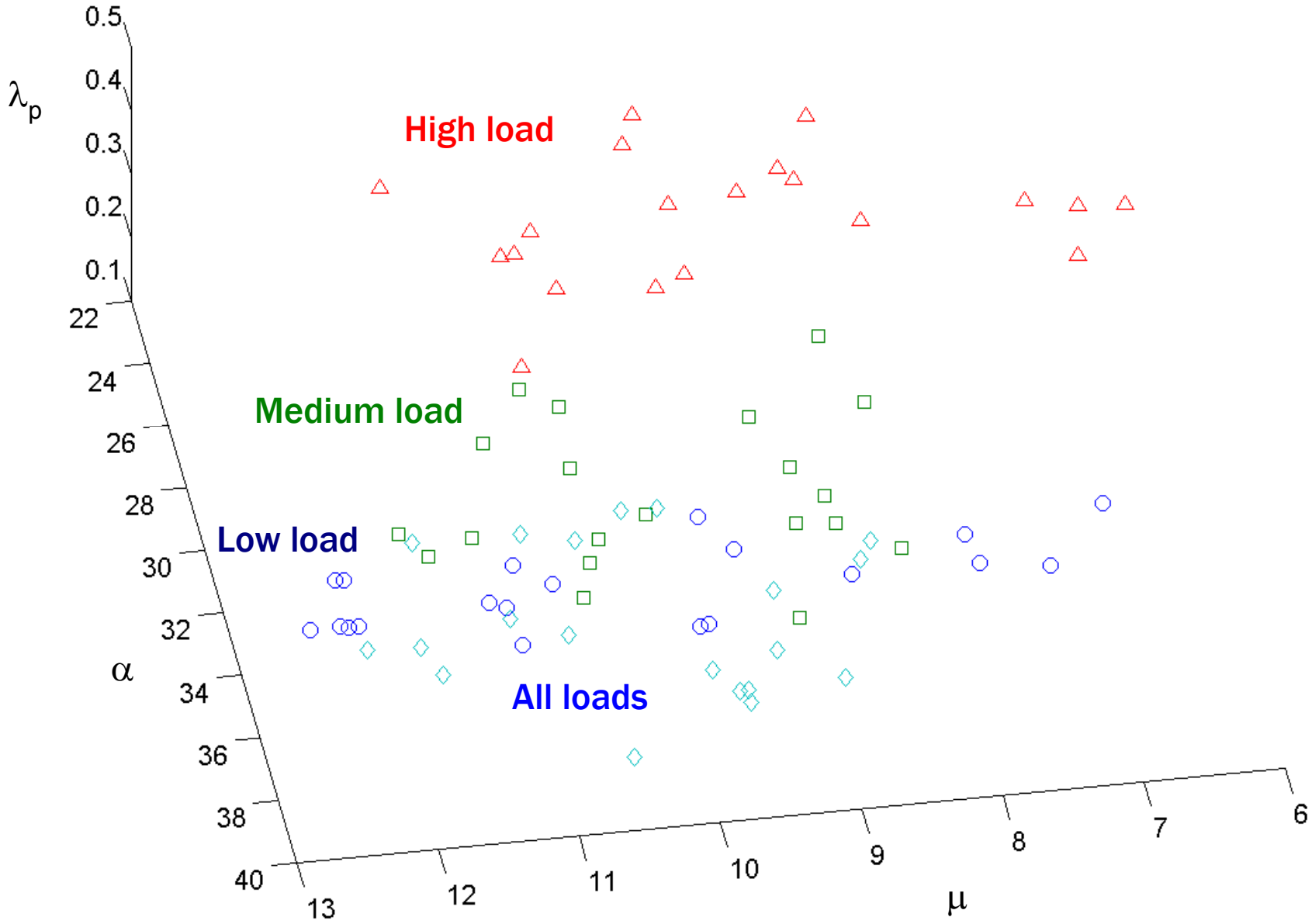

0.4
0.35
0.3
0.25
0.2
0.15
λ_p
High load
Low load
Medium load
All loads
22
24
26
28
30
32
34
36
38
40
α
5
10
15
μ


High load
Medium load
Low load
All loads
λ_p
0.5
0.4
0.3
0.2
0.1
α
22
24
26
28
30
32
34
36
38
40
μ
13
12
11
10
9
8
7
6

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

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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

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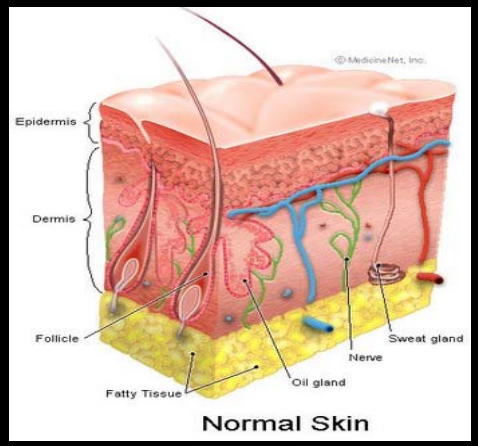
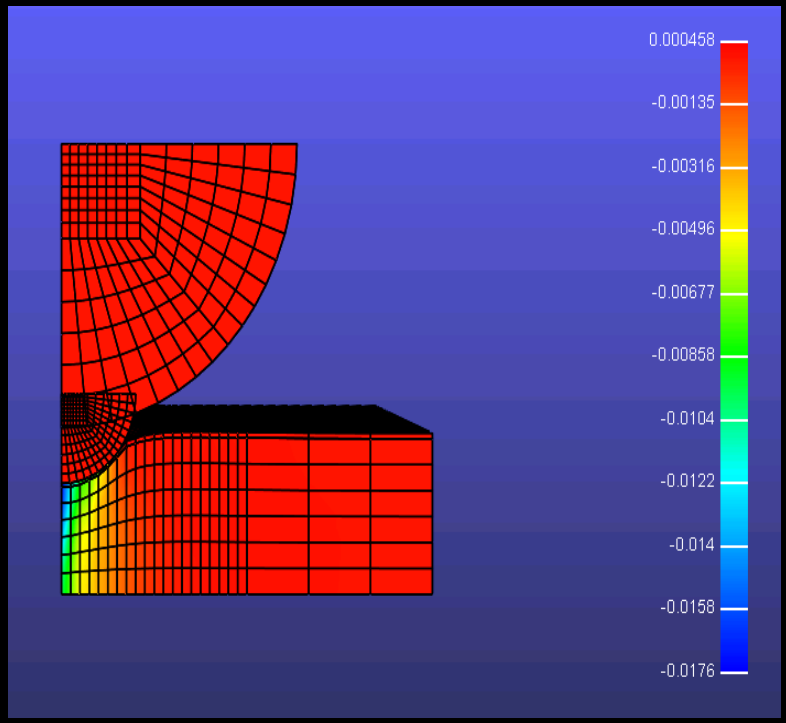


Two layer model of skin indentation



- 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

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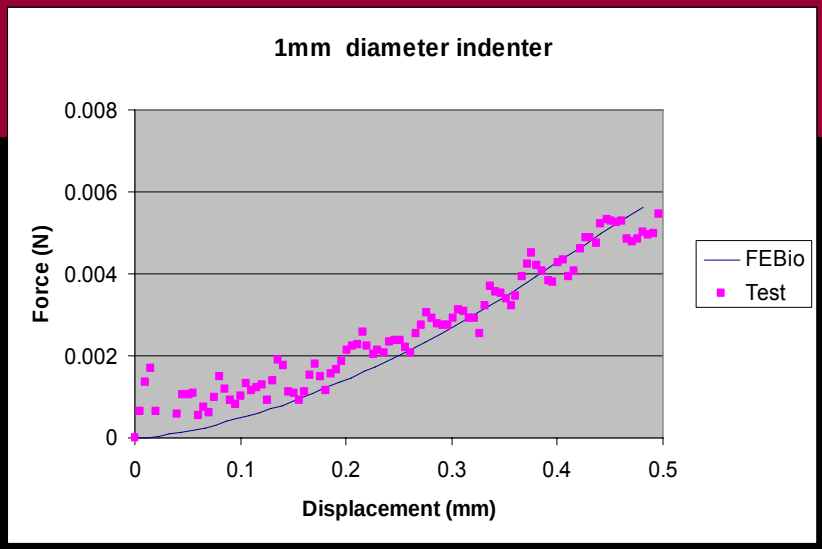
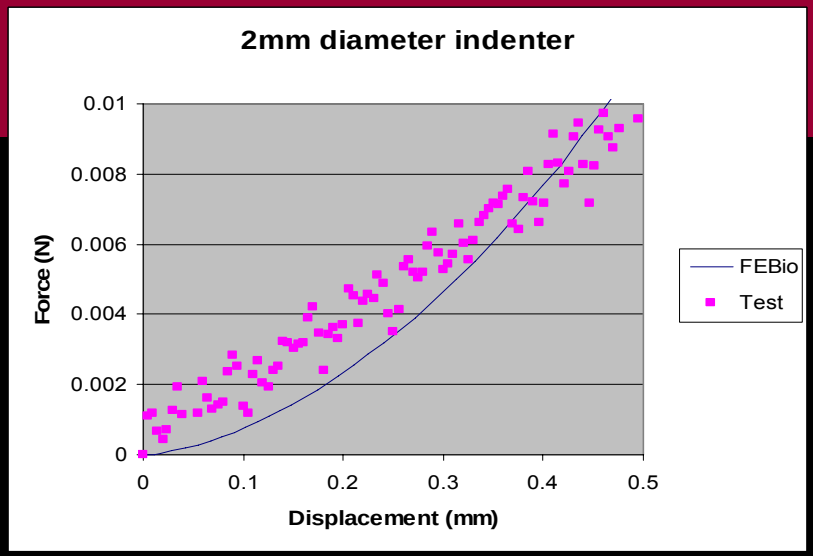




Epidermis Ogden parameters:

Bulk modulus=1N/mm²

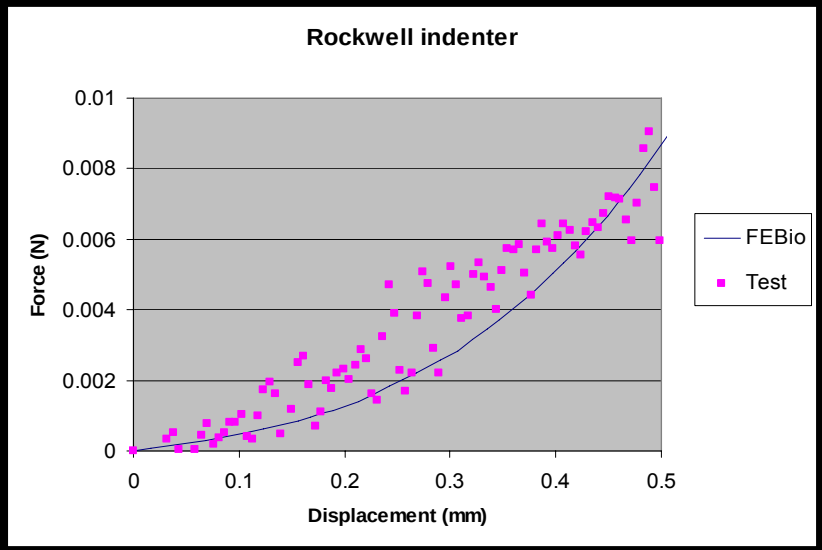
α = 2, μ = 0.005 with a Young's Modulus of 0.01N/mm²

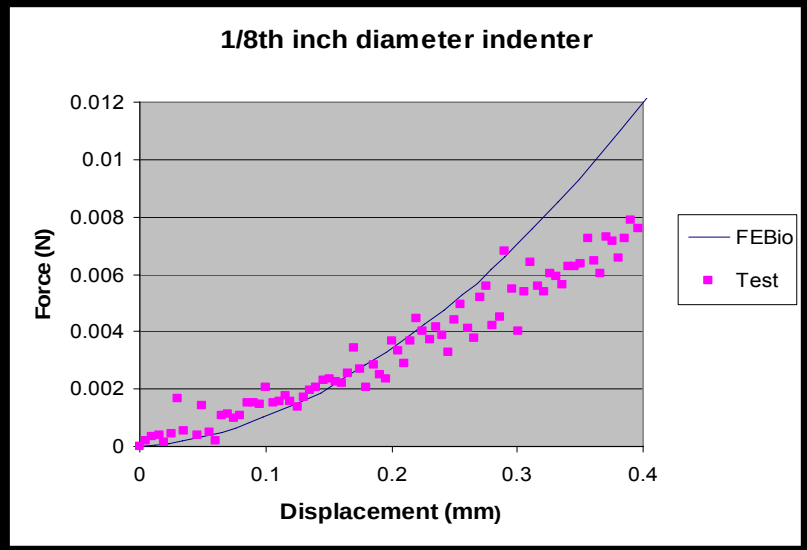
Results for the multilayer FEBio model

Dermis Ogden parameters:

Bulk modulus=0.75N/mm²

α = 1.5, μ = 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

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