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Experimental and numerical assessment of the mechanics of keloid-skin composites undergoing large deformations

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CHRU Besançon centre hospitalier régional universitaire

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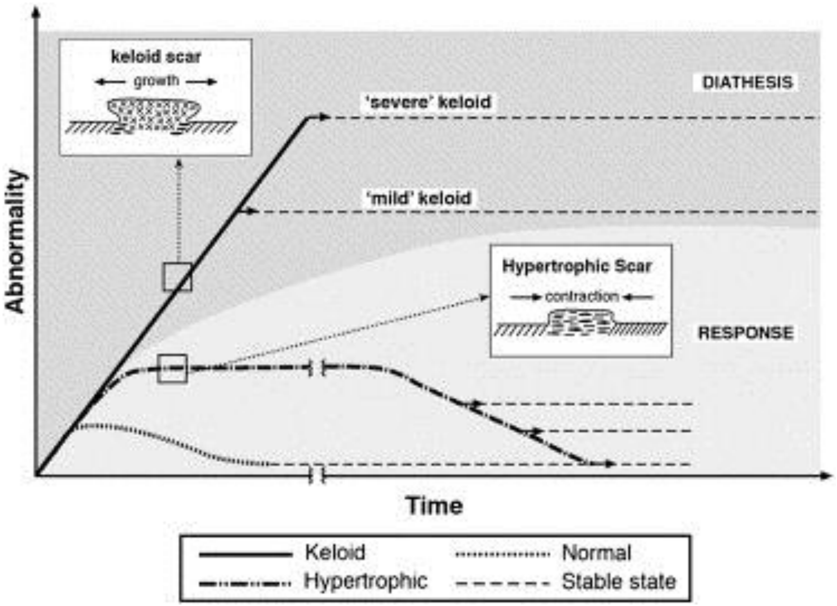
keloid scars (1)

“A **keloid scar** is defined as a dermal tumour that spreads beyond the margin of the original wound, that continues to grow over time, that does not regress spontaneously, that often recurs after excision, and has been present for at least 1 year.“ (Suarez Pozos, 2014)

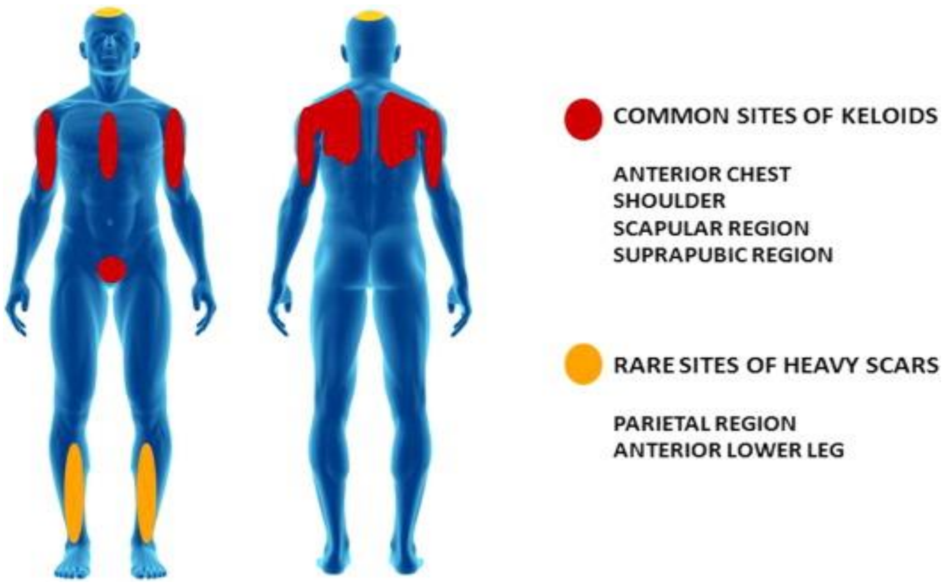


Keloid’s growth (Burd, 2008)

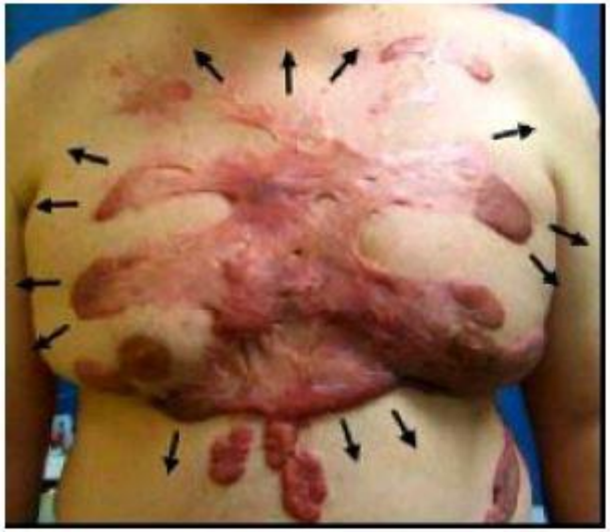
Sternal keloid
(Patel et al., 2010)

Upper arm keloid
(Ogawa et al., 2011)

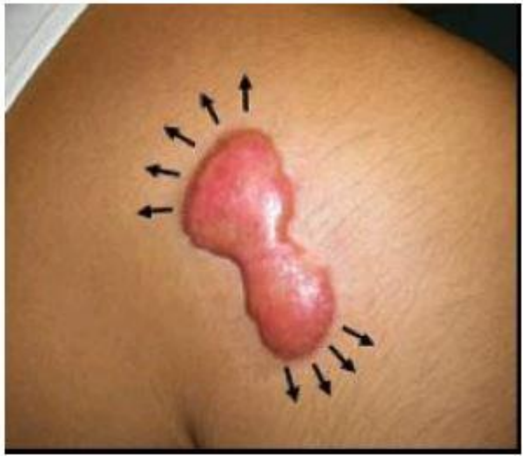
keloid scars (2)



Common sites of keloid appereance (Ogawa , 2011)



Crab's clow shape keloid (Ogawa, 2008)



Butterfly shape keloid (Ogawa, 2008)

- Biologic, genetic and mechanical causes
- Pathogenesis still not well understood
- No existing optimal treatment method

goal of the project

Hypothesis: mechanical forces are responsible of keloid's extension

- Develop a method to predict keloid mechanical behaviour
- Investigate the stress field in and around the keloid and directions of growth
- Design a patient-specific device to prevent keloid's growth

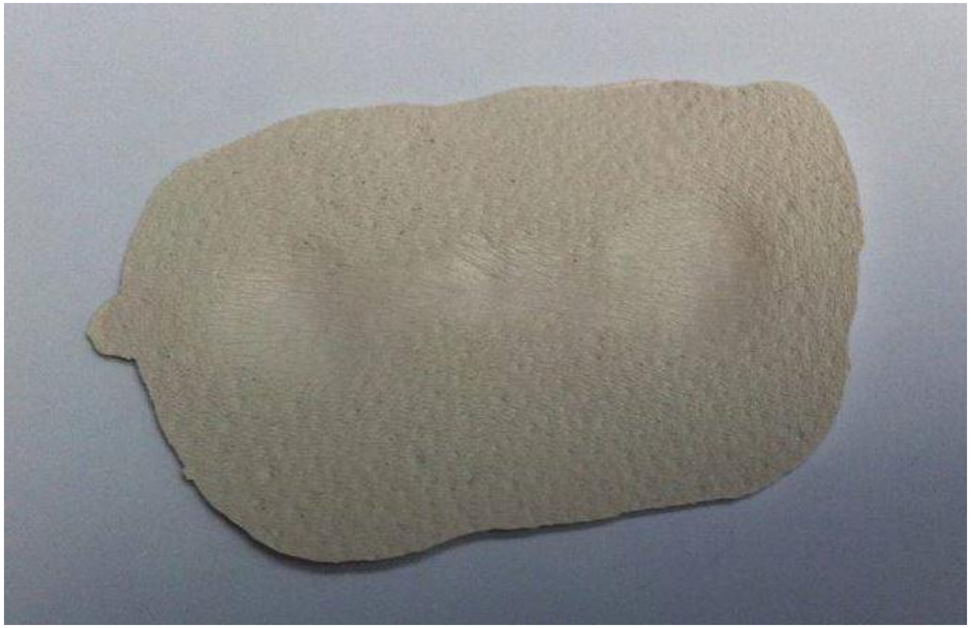


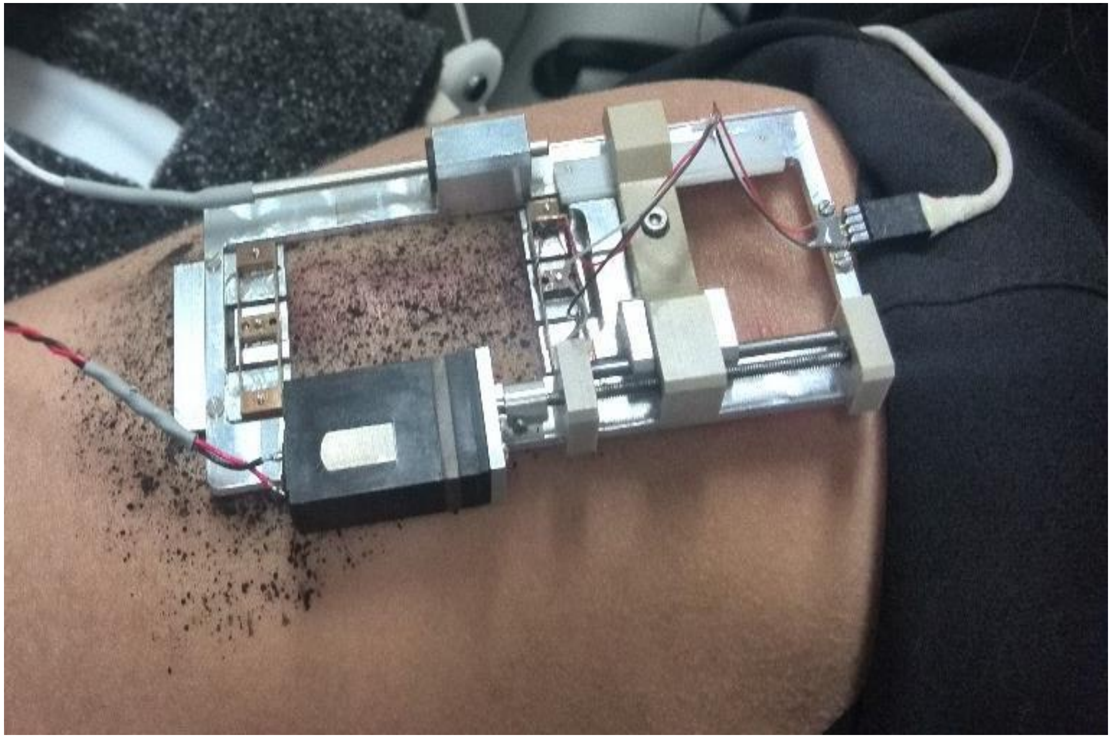
Photo of the keloid's specimen silicon molding

aim of the present study

Develop a 3D FEM model of a real keloid starting from experimental data collected during a clinical study on a volunteer's specimen.

a clinical study on a keloid specimen (1)

Ultra-light extensiometer: uniaxial extension

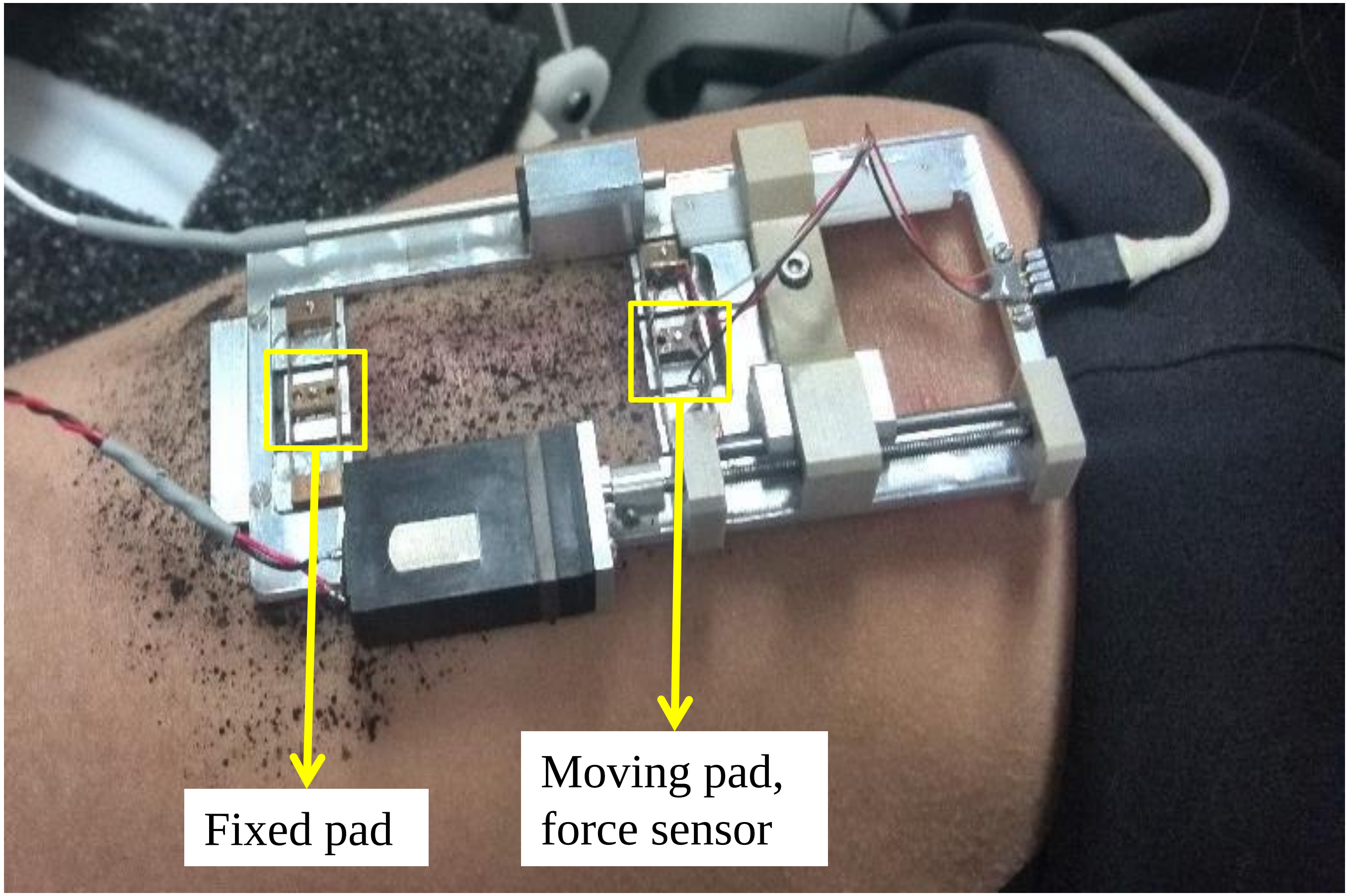


A photo taken during the clinical study

Keloid specimen

a clinical study on a keloid specimen (2)

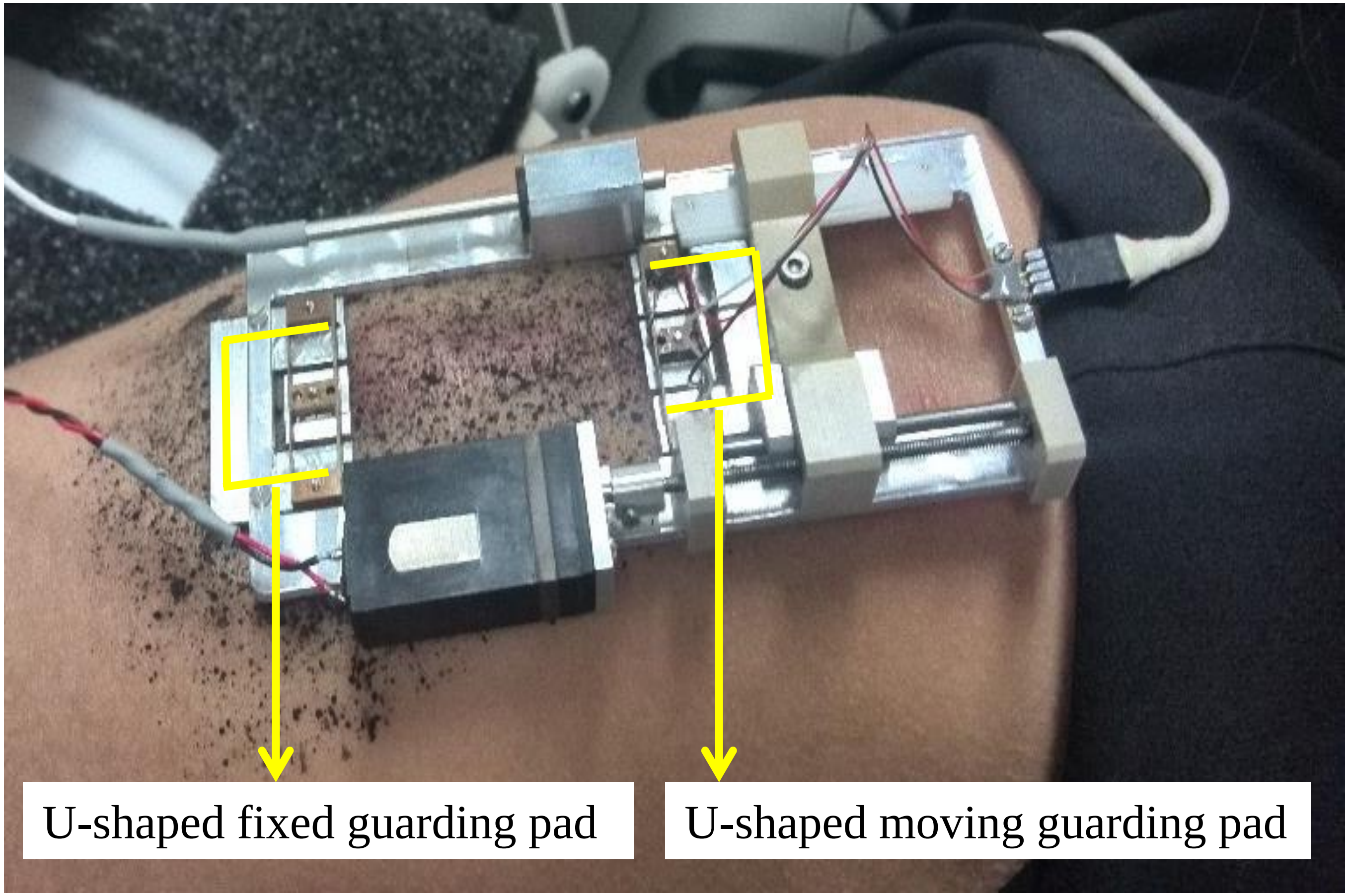
Ultra-light extensiometer: uniaxial extension



A photo taken during the clinical study

a clinical study on a keloid specimen (2)

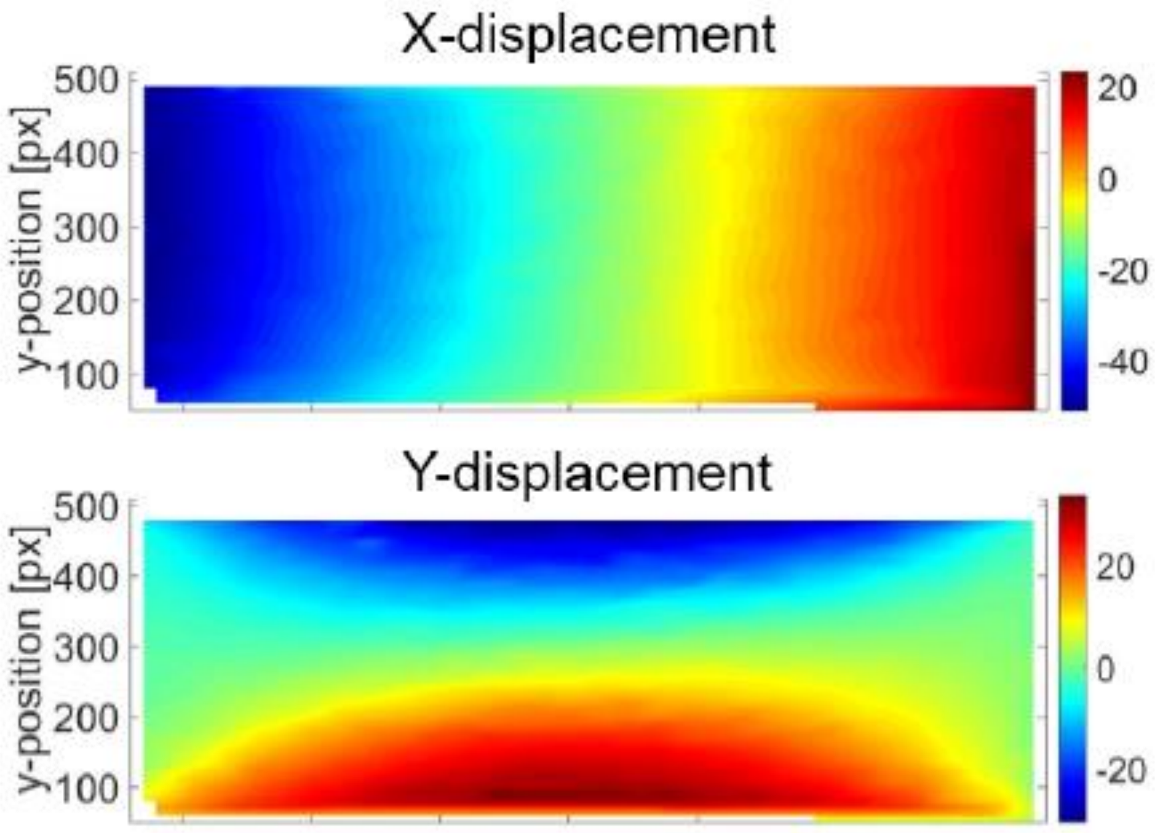
Ultra-light extensiometer: uniaxial extension



A photo taken during the clinical study

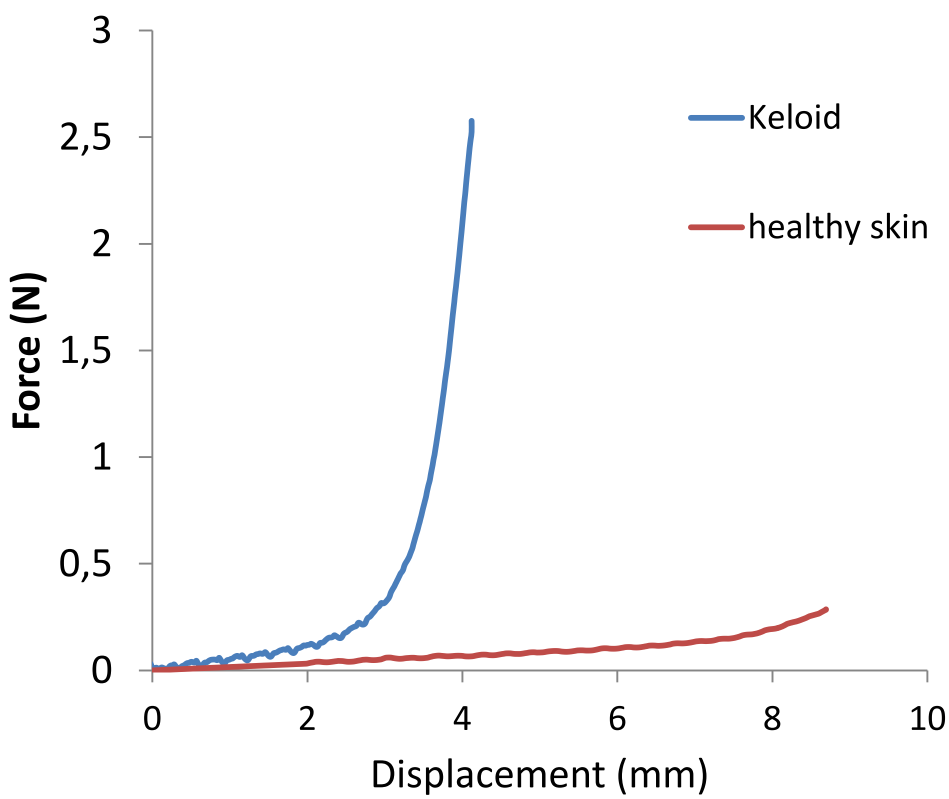
a clinical study on a keloid specimen (3)

Ultra-light extensiometer: uniaxial extension



Displacement fields following the tensile axis X and the transverse axis Y for an example with only healthy skin

a clinical study on a keloid specimen (4)



Hypothesis:

- constant keloid thickness e_0
- constant healthy skin thickness e_0'
- uniform strain over both keloid and healthy skin

$$\sigma = \frac{F}{d \cdot e_0}; \quad \varepsilon = \frac{L - L_0}{L_0}$$

parameters identification: hyperelasticity(1)

Mechanical parameters identification: ANSYS® Material Curve Fitting

Least squares fitting hypothesizing a **uniaxial traction**:

$$E = \sum_{i=1}^{N} \left(\sigma_i^{exp} - \sigma_i^{p}(c_j)\right)^2$$

Hypothesis about keloid and healthy skin materials:

- Ideally elastic (no visco-elasticity)
- Isotropic
- Homogeneous
- Incompressible
- **Hyperelastic** (nearly incompressible $K = 570\ MPa$)

W strain density energy function $\xrightarrow{\frac{\partial}{\partial C}}$ **Stress σ_i^p**

parameters identification: hyperelasticity(2)

Mechanical parameters identification: ANSYS® Material Curve Fitting

Mooney-Rivlin 5 parameters model

$$W = W(c_{10}, c_{01}, c_{20}, c_{11}, c_{02}, \mathrm{d}, \mathrm{I}_1, \mathrm{I}_2, \mathrm{I}_3)$$

c_{10}, c_{01}, c_{20}, c_{11}, c_{02} material constants
d compressibility parameter
I_1, I_2, I_3 invariants of the Cauchy-Green tensor

Mooney-Rivlin 5 parameters (MPa)		
	Keloid	Healthy skin
C10	- 0.97	- 0.01
C01	0.98	0.02
C20	912.30	9.34
C11	-1953.40	- 21.36
C02	1048	12.24

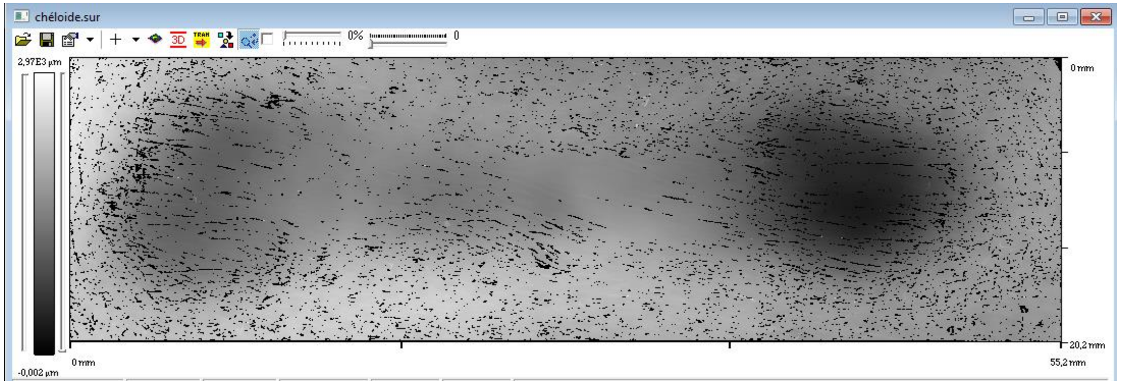
Ogden 2nd order model

$$W = W(\mu_1, \alpha_2, \mu_2, \alpha_2, d_1, d_2, \bar{\lambda}_p (p = 1,2,3))$$

μ_1, α_1, μ_2, α_2, material constants
d_1, d_2 compressibility parameters
$\bar{\lambda}p$ (p = 1,2,3) principal stretches of the deviatoric part of the deformation gradient tensor

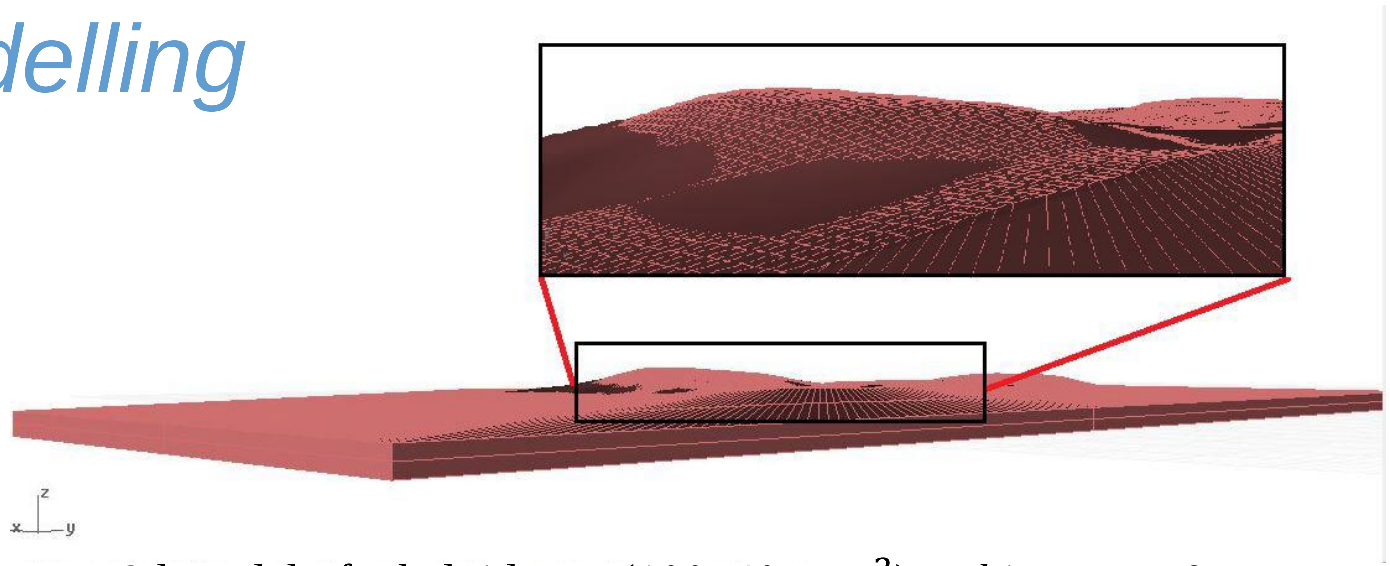
Ogden 2° order (MPa)		
	Keloid	Healthy skin
μ_1	5.07 E-06	9.40 E-09
α_1	83.03	64.38
μ_2	7.20	0.01
α_2	0.01	4.90

image processing



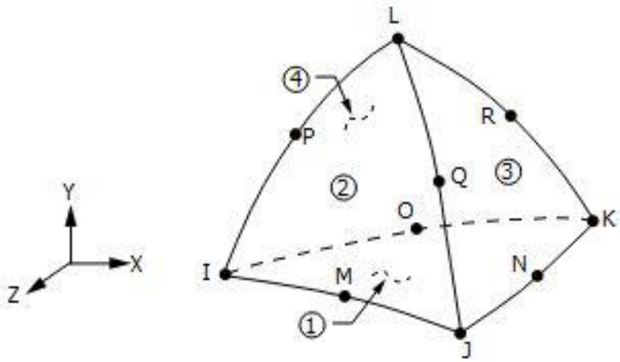
Alicona Infinite Focus ® : image of the silicon molding (55x20 mm^2)

CAD modelling



3d model of a keloid scar (100x40 mm^2) , *Rhinoceros* ©

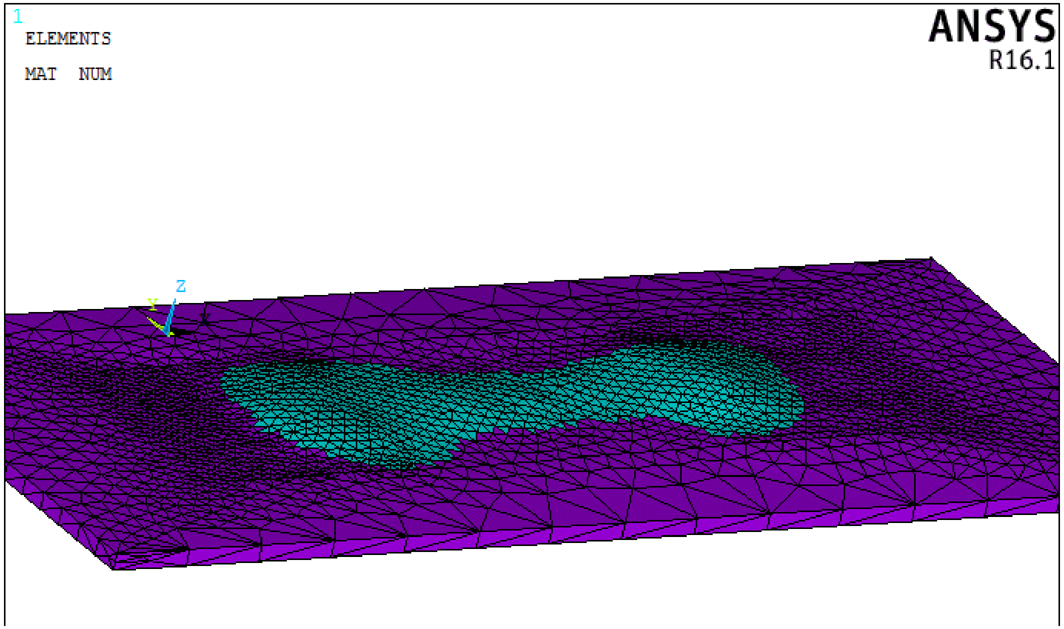
FEM modelling (1)



Geometry of element SOLID187 ANSYS®

Element SOLID187

- Quadratic tetrahedra
- Translations x, y, z directions
- Unstructured meshes



An example of mesh, element size (0.9-1.1) mm

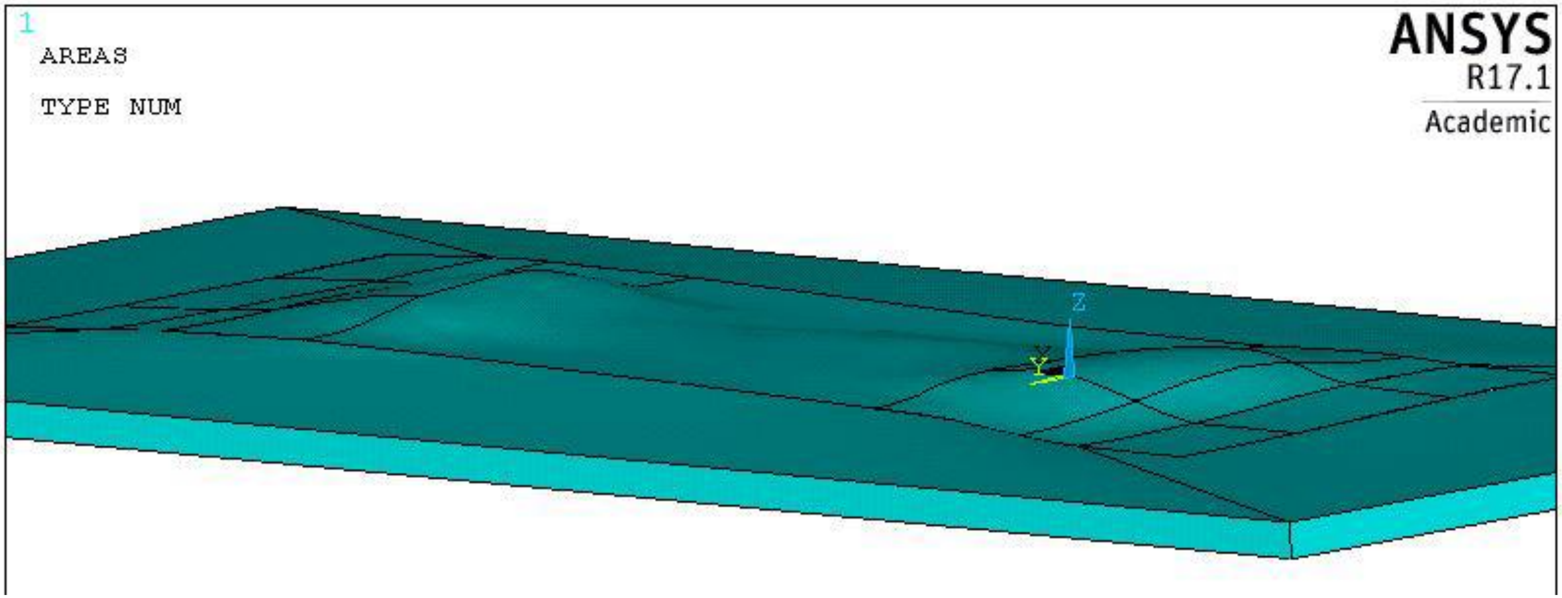
Composite keloid / healthy skin

FEM modelling (2)

Boundary conditions ➔

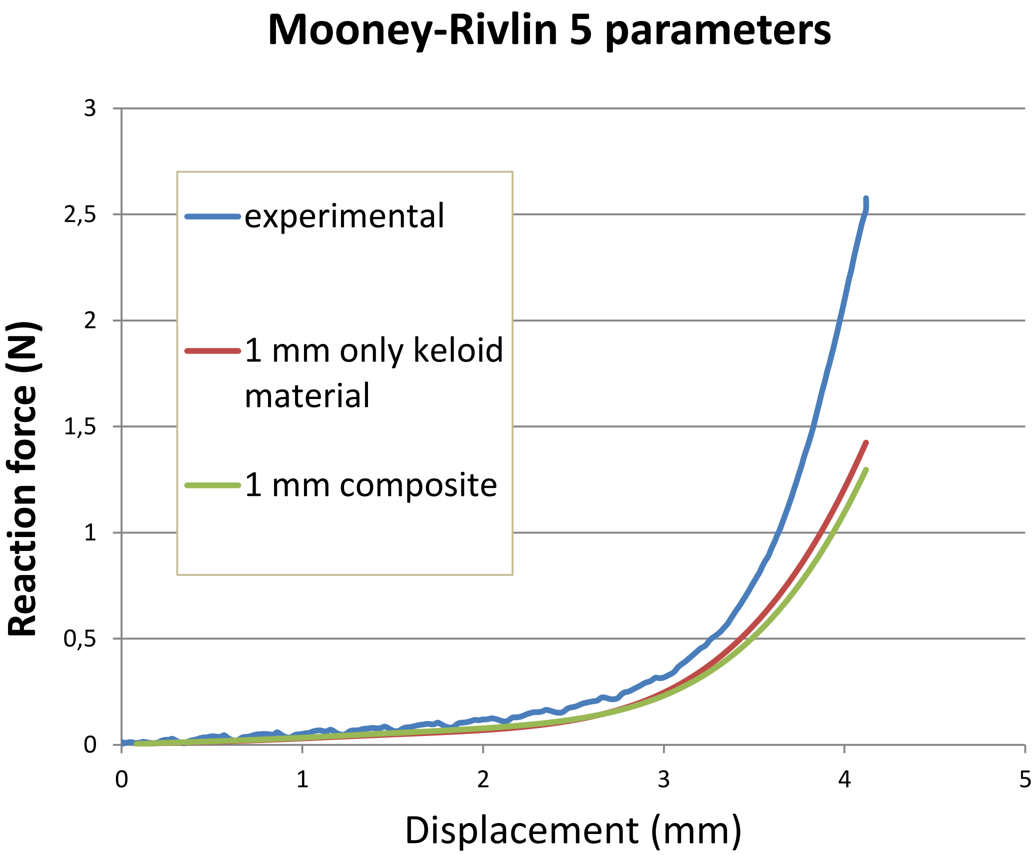
- Moving pads: $u_x = -4.119\ mm;\ u_y = u_z = 0$
- Fixed pads: $u_x = u_y = u_z = 0$
- Dermis: $u_z = 0$

Nonlinear analysis ➔ Newton-Raphson linearization method



Dirichlet boundary conditions applied on some surfaces of the model

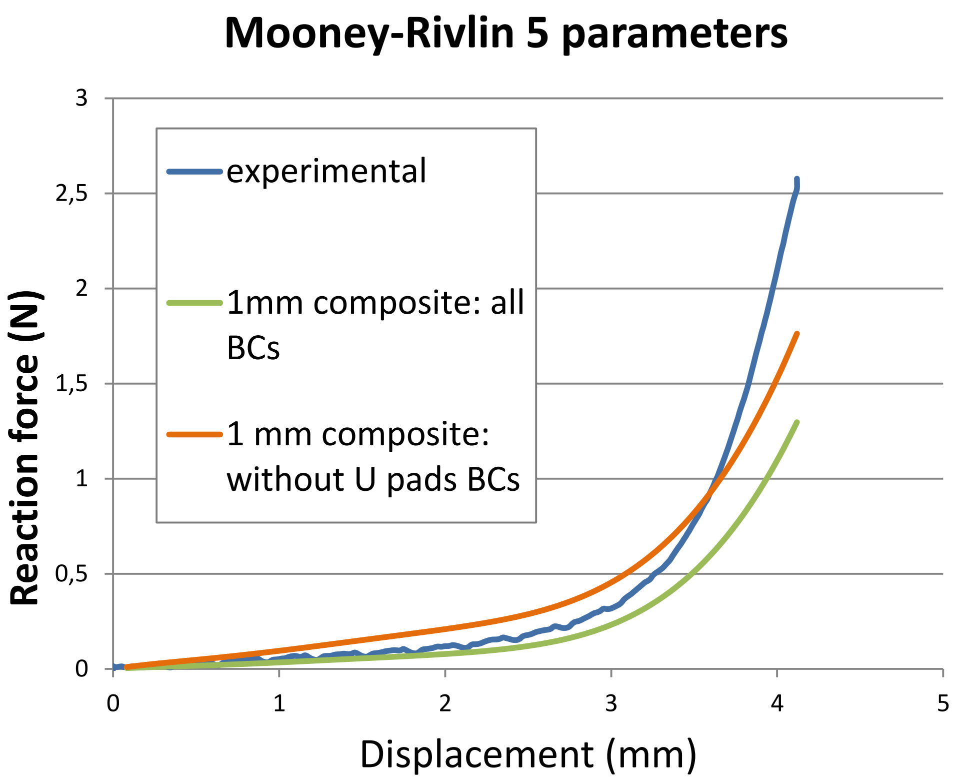
results and discussion (1)



- Numerical curves fit well experimental curve up to about 3 mm
- Composite model is less stiff because of the contribution of healthy skin around the keloid

results and discussion (2)

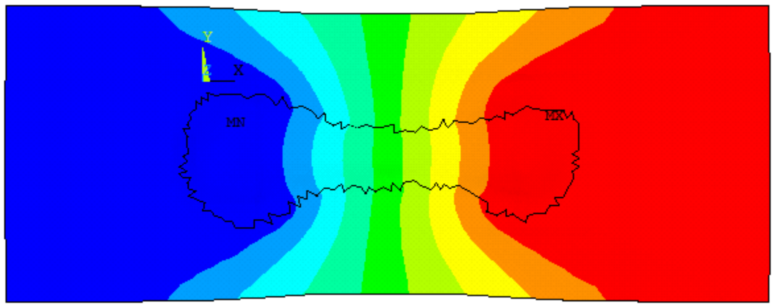
U-shaped guarding pads boundary conditions



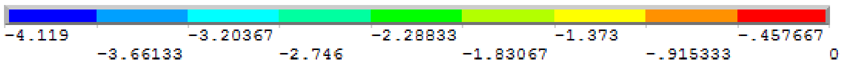
Correlation coefficients:

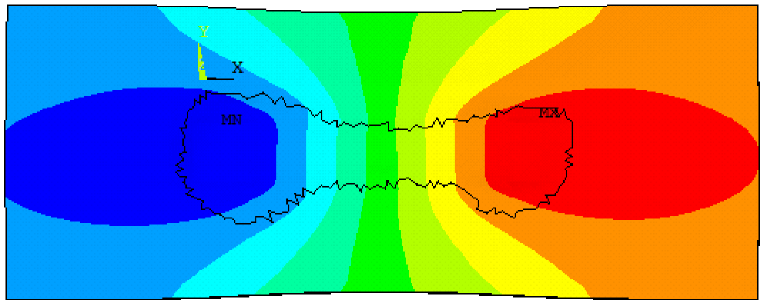
All BCs ➔ r = 0.9877

Without U pads BCs ➔ r = 0.9729



u_x field *with* guarding pads BCs





u_x field *without* guarding pads BCs

prospects (1)

- Constant keloid and healthy skin thickness
- Uniform strain
- Only uniaxial extension

→

- Uncertainty quantification and sensitivity analysis about mechanical parameters in FEniCS ©

- Absence of experimental data about the interface keloid / healthy skin

→

- Need data from OCT, echography, cutometry test

- Isotropy

→

- Pre-tension
- Anisotropic models

prospects (2)

- Boundary conditions
    - Effect of dermis underneath the model
    - Study of sensibility
    - Tests on a phantom fabricated using a developed mold
- Estimate of the experimental stress field with Digital Image Correlation
    - Comparison with numerical results

Thank you for your attention

Marco Sensale

results and discussion (3)