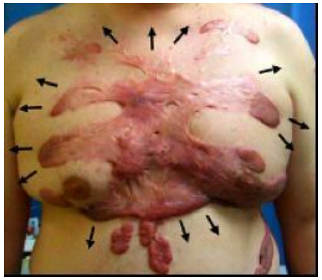
Propriétés mécaniques de la peau et incertitudes en biomécanique.

Aflah ELOUNEG,

Arnaud LEJEUNE, Jérôme CHAMBERT, Emmanuelle JACQUET

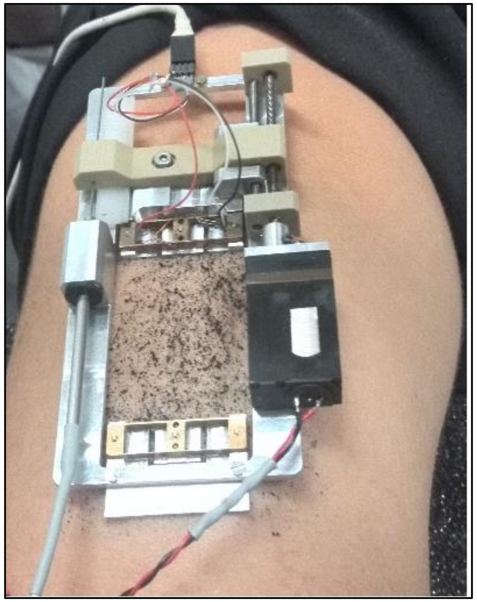
Context



Keloid chest scar formation
(Ogawa 2008)

Keloid shoulder scar formation
(Ogawa 2008)

Butterfly-shaped keloid (x=15mm, y=47mm)
(Chambert et al. 2019)



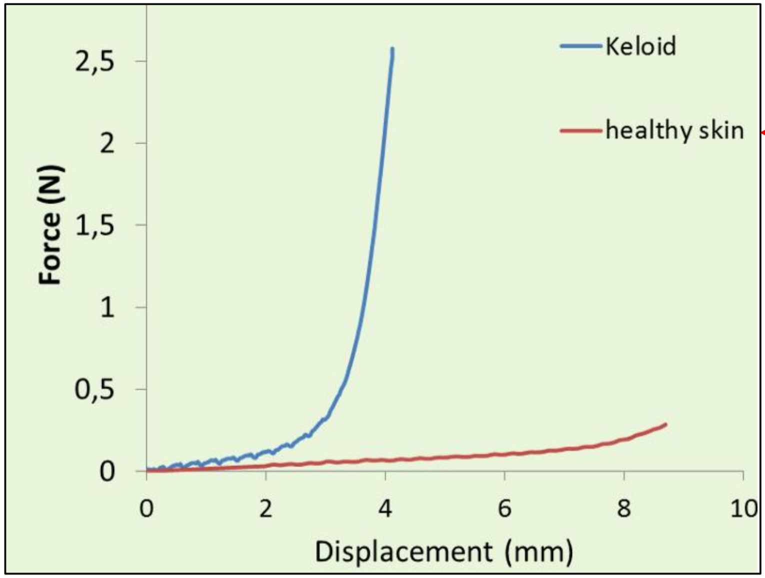
DIC Speckle pattern
(Chambert et al. 2019
Jacquet et al. 2017)

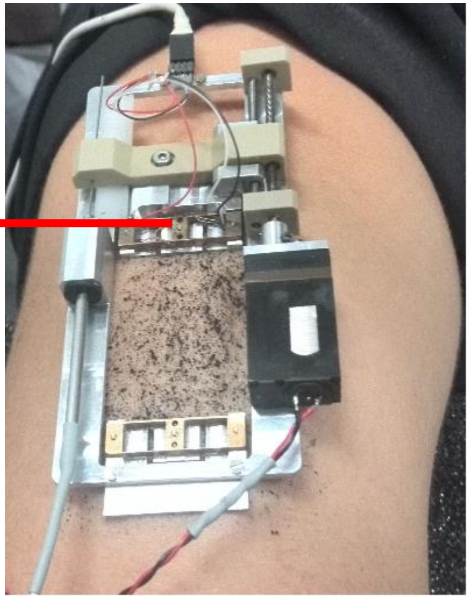
Outlines:

- Uniaxial tensile test on keloid-healthy skin
- FEniCS framework of the inverse problem
- Validation
- Uncertainties
- Conclusion and perspectives

Uniaxial tensile test on keloid-healthy skin

Experimental data





DIC Speckle pattern (Jacquet et al. 2017)

Uniaxial tensile test on keloid-healthy skin

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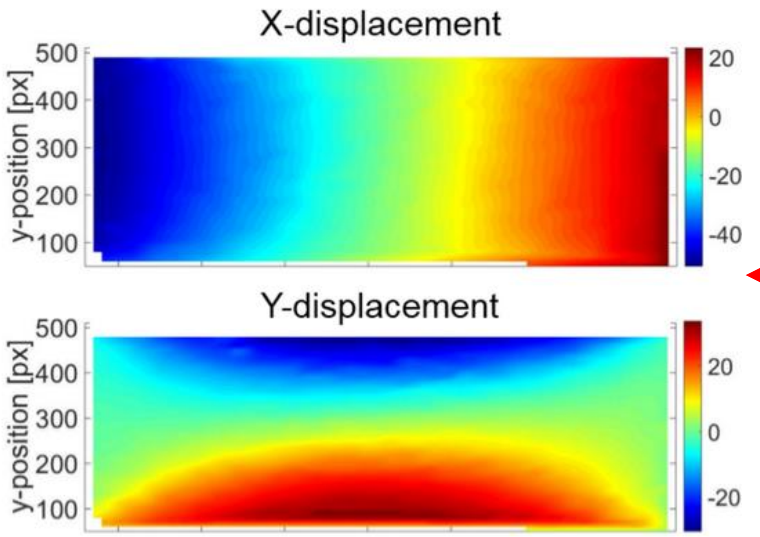

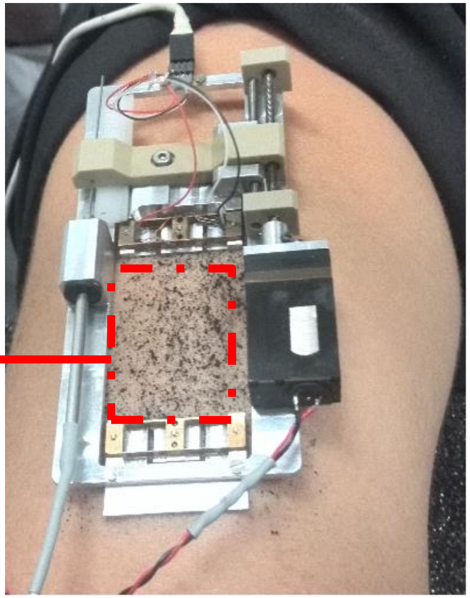

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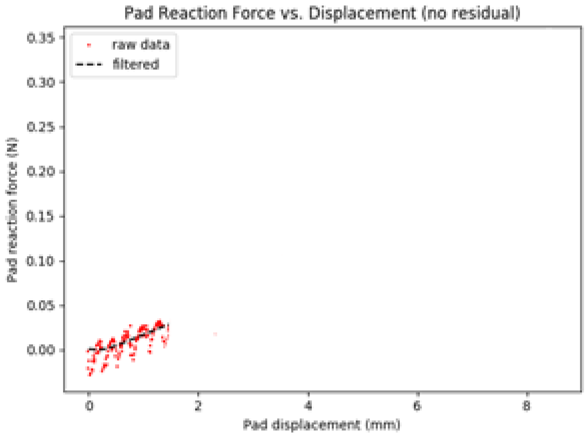
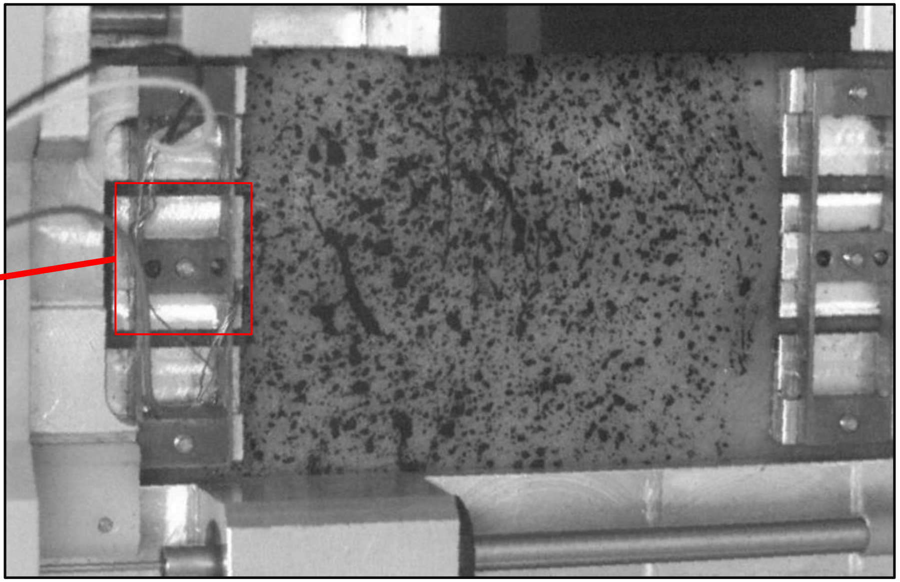
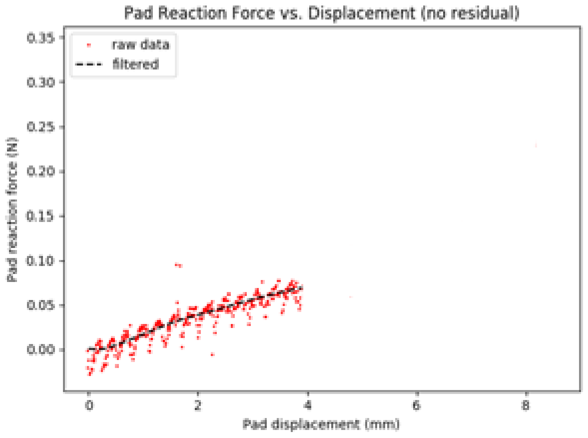
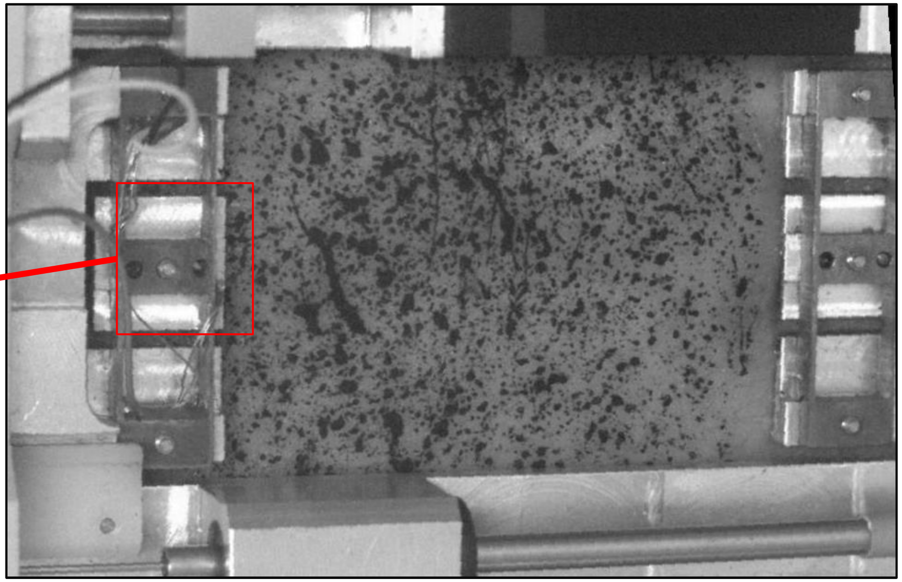




Experimental data: **Force-Displacement** and **DIC (Digital Image Correlation)**

Uniaxial tensile test on keloid-healthy skin





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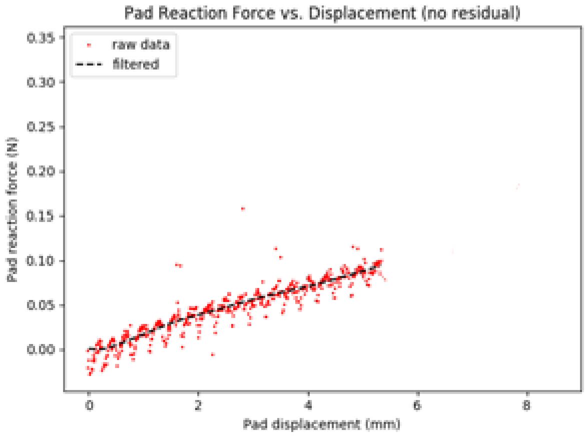

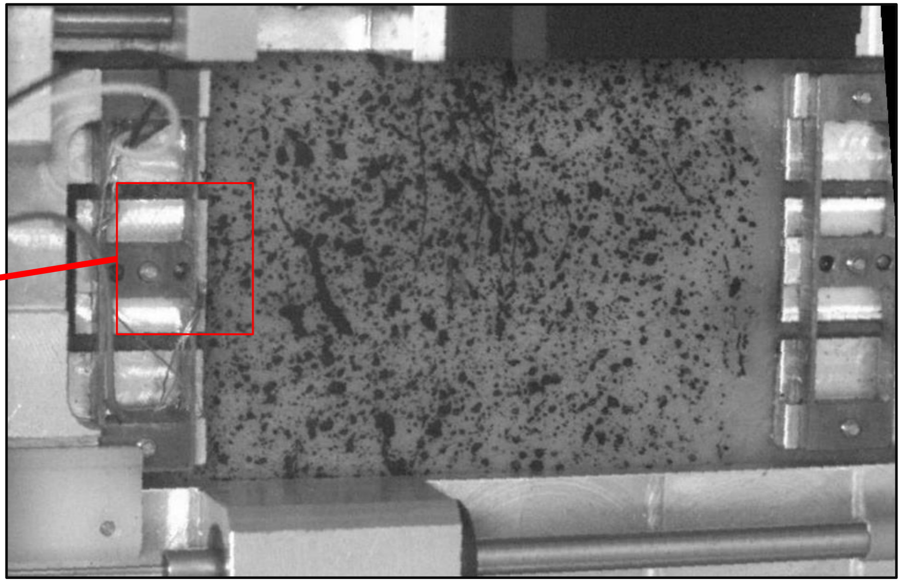

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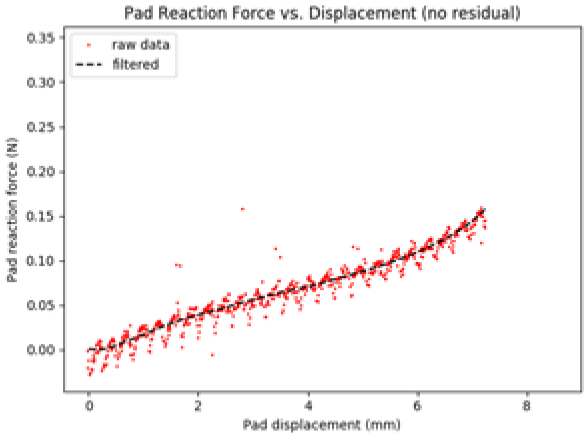

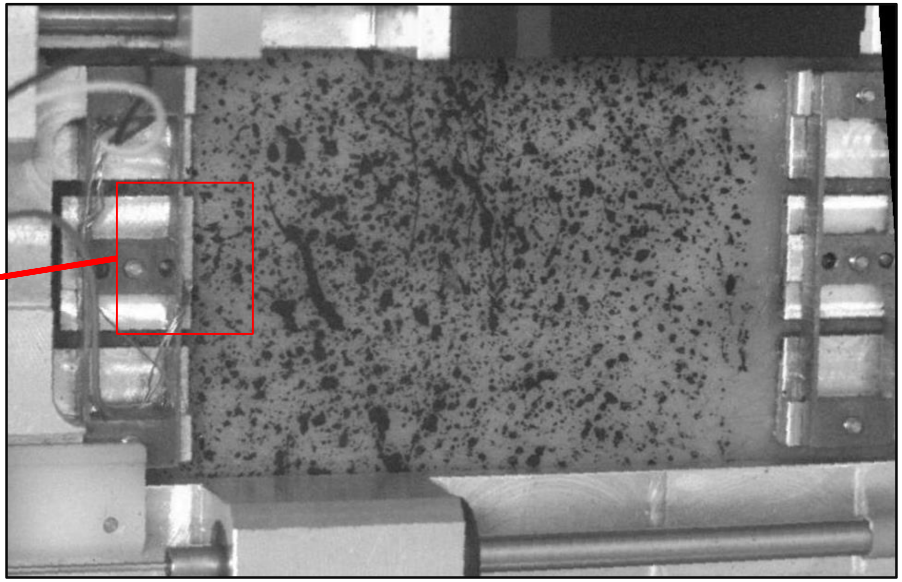

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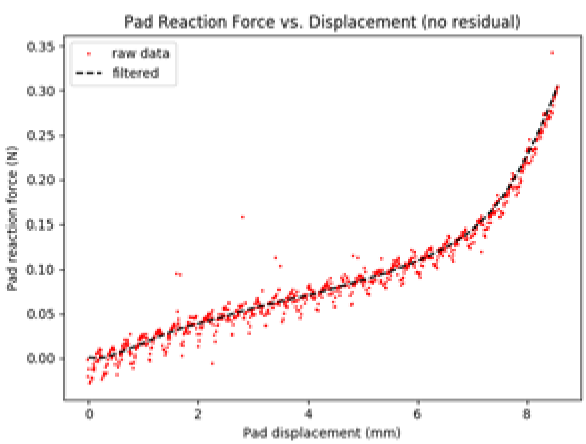

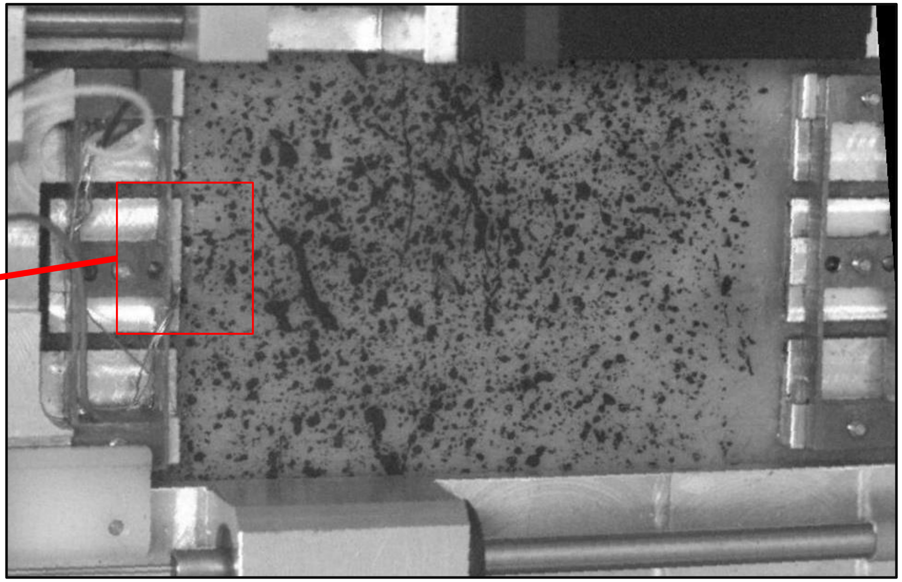

Experimental data: <u>Force-Displacement</u> and <u>DIC (Digital Image Correlation)</u>

FEniCS framework of the inverse problem

FEniCS PROJECT

$$\boldsymbol{\theta} = \{\boldsymbol{\theta}_{keloid}, \boldsymbol{\theta}_{healthy\ skin}\}$$

$$\boldsymbol{\theta} = \arg_{min} J^{(k)}(\boldsymbol{\theta}, \boldsymbol{\lambda})$$

$$J(\boldsymbol{\theta}, \boldsymbol{\lambda}) = \sum_{k=1}^{N_{frames}} \int_{\Gamma_{u_{msr}}} \left\| \boldsymbol{u}_{fem}^{(k)}(\boldsymbol{\theta}) - \boldsymbol{u}_{msr}^{(k)} \right\|^2 dx + \boldsymbol{\lambda} \int_{\Gamma_{f_{msr}}} \left\| \boldsymbol{f}_{fem}^{(k)}\left(\boldsymbol{u}_{fem}^{(k)}; \boldsymbol{\theta}\right) - \boldsymbol{f}_{msr}^{(k)} \right\|^2 dx$$

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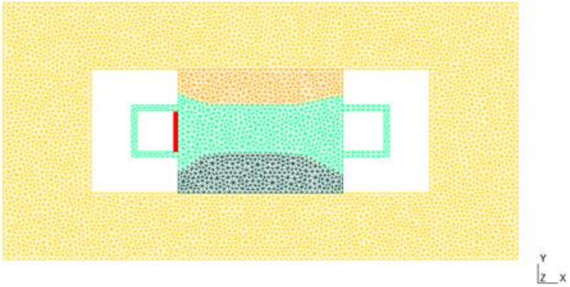

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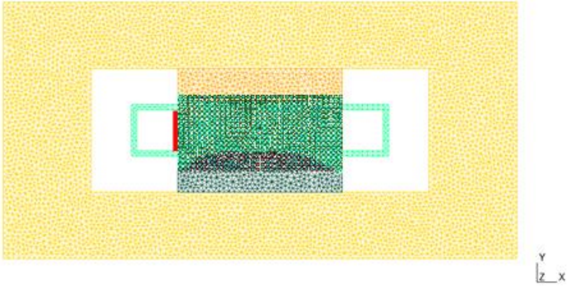

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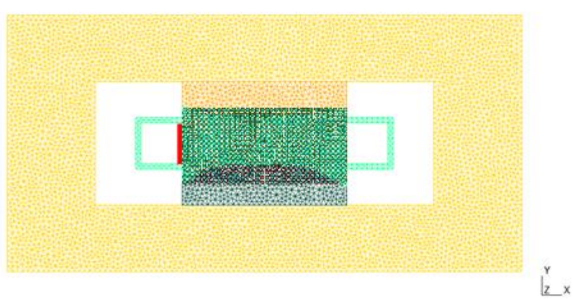

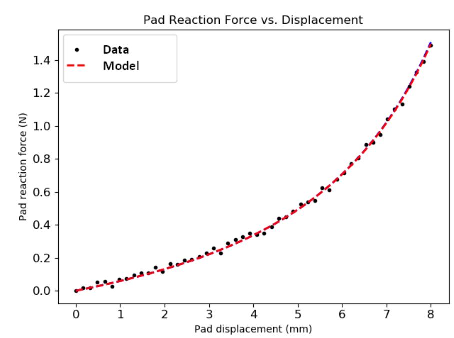

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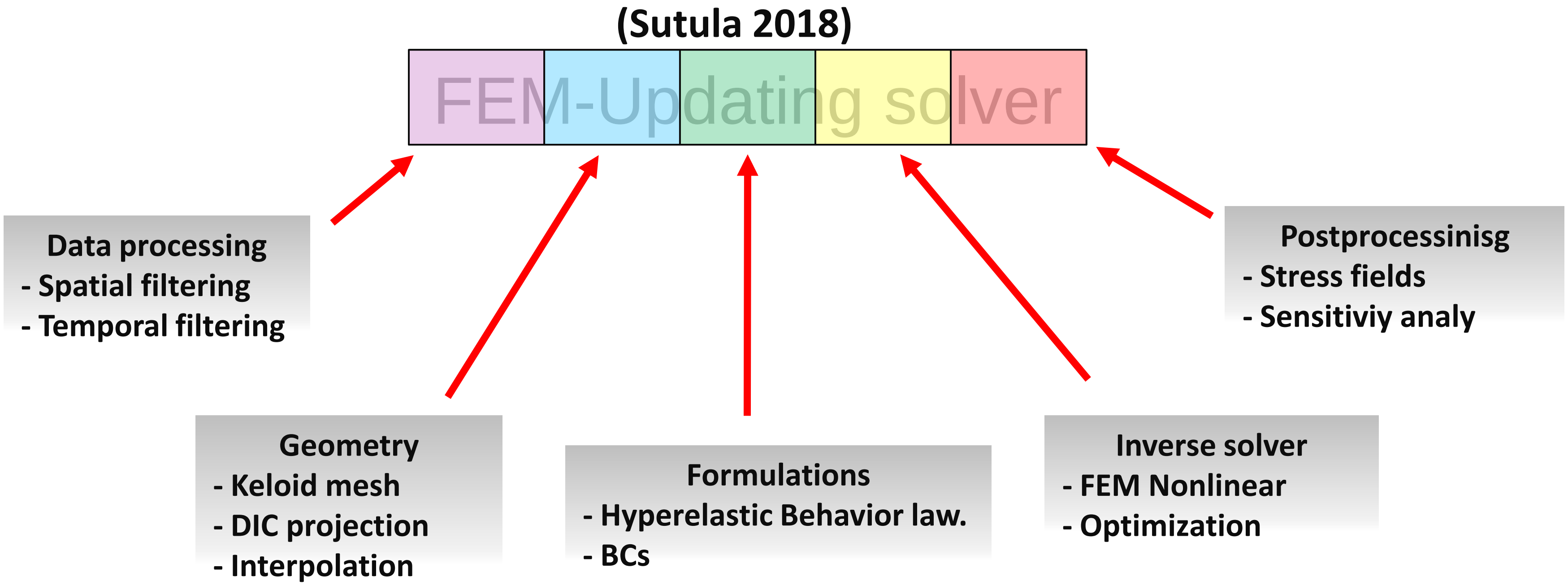


FEniCS framework of the inverse problem

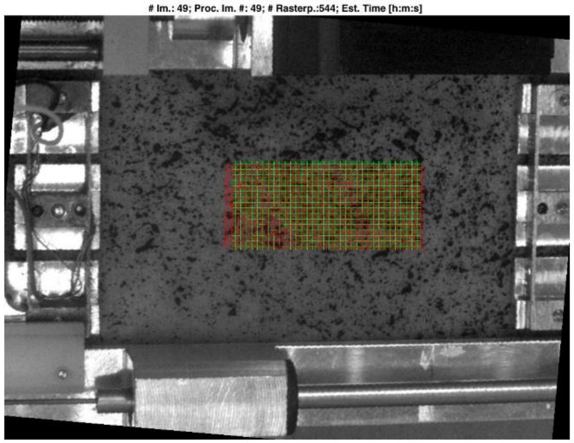
Experimental data:
- Force measurements
- Displacement fields (DIC)

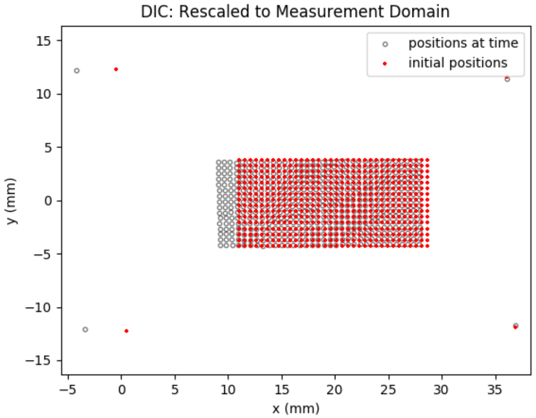
→ FEM-Updating solver

FEniCS framework of the inverse problem

FEM-Updating solver

Filtering data





FEniCS framework of the inverse problem

FEM-Updating solver

Filtering data

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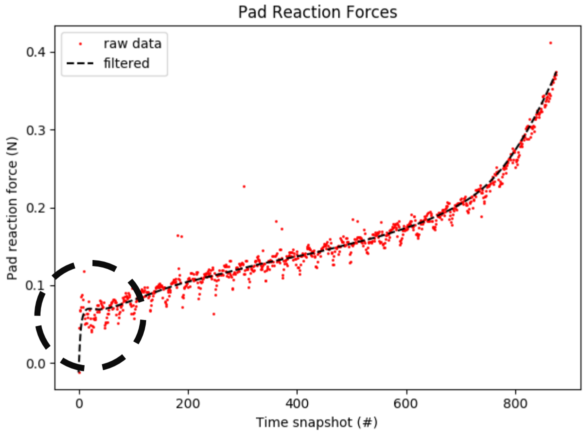

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FEM-Updating solver

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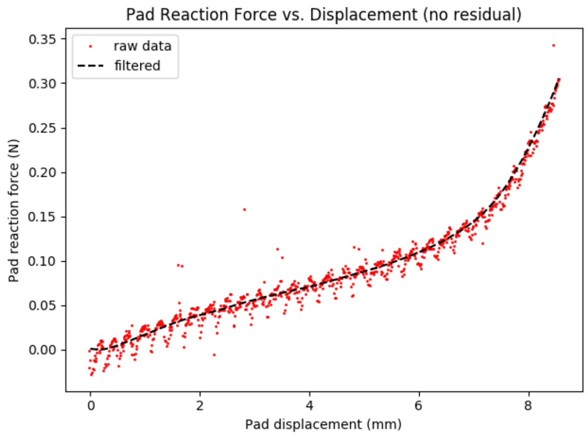

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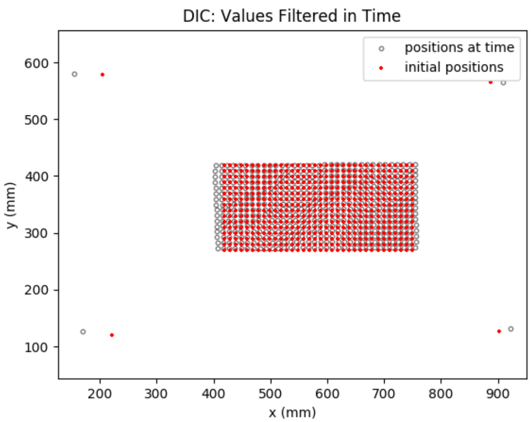
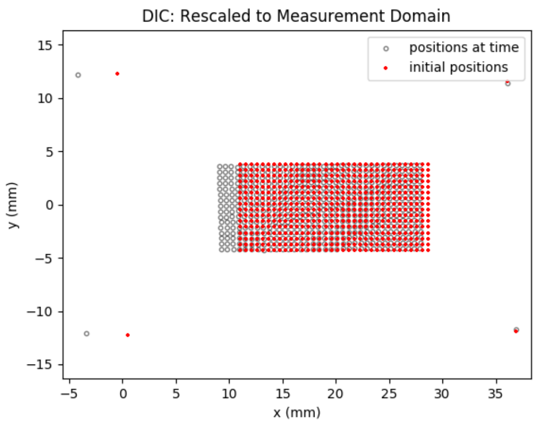
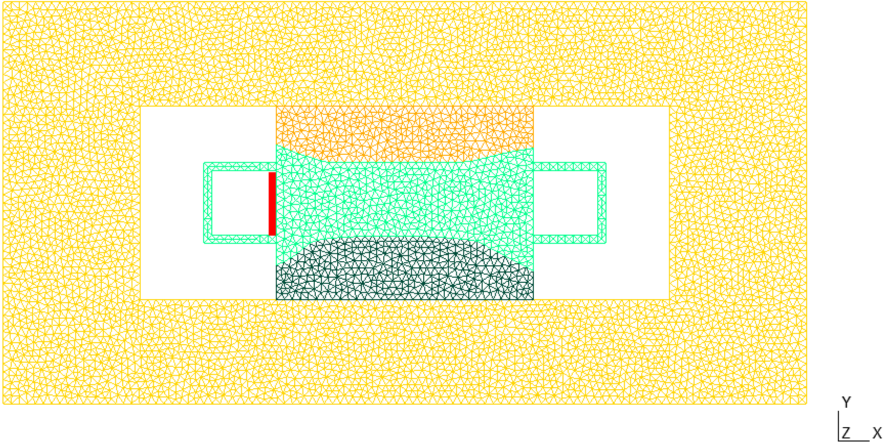




FEniCS framework of the inverse problem

FEM-Updating solver

Importing keloid-healthy skin geometry



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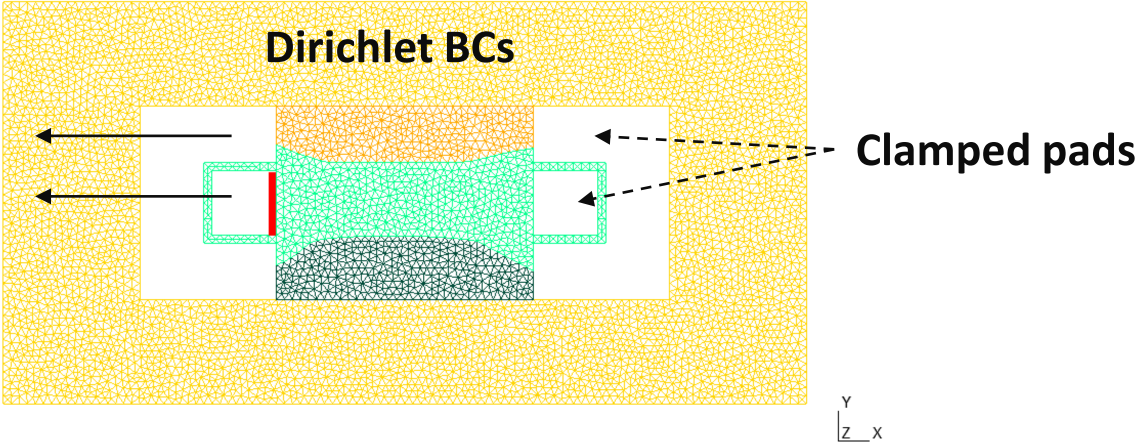

FEniCS framework of the inverse problem

FEM-Updating solver

Implementing hyperelastic models

Strain energy density as function of invariants

Soft tissue model: **Neo-Hookean, Ogden, Gent, Yeoh …**

Hypothesis:

Same model on both keloid and healthy domains.

FEniCS framework of the inverse problem

FEM-Updating solver

Estimating parameters

Inverse solver

Nonlinear FEM solver

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FEniCS framework of the inverse problem

FEM-Updating solver

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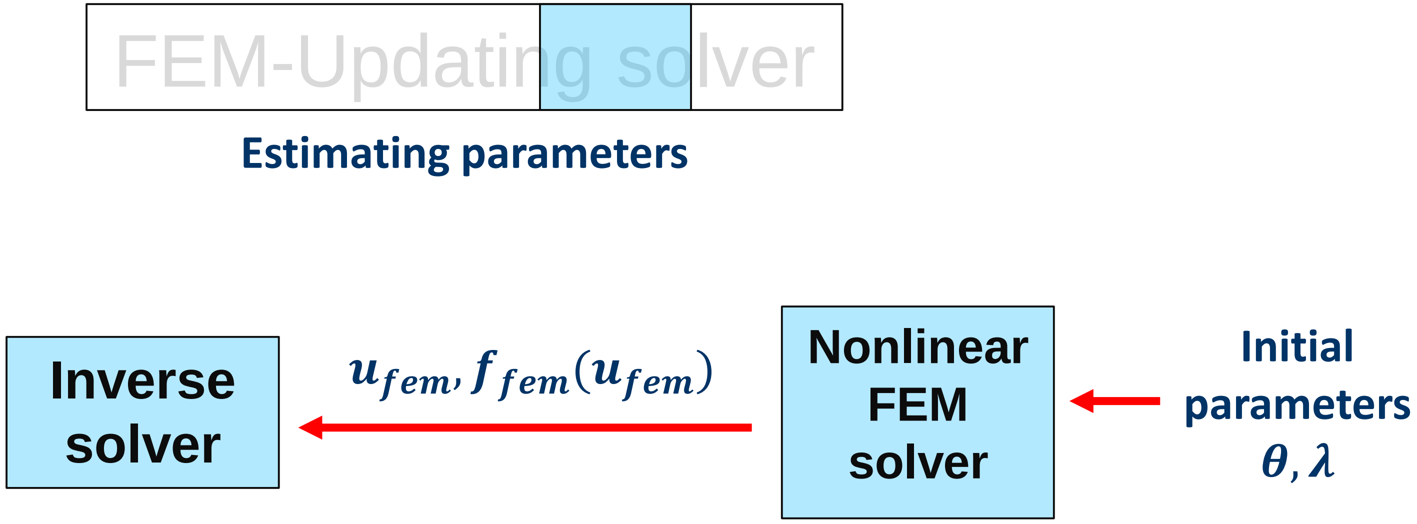
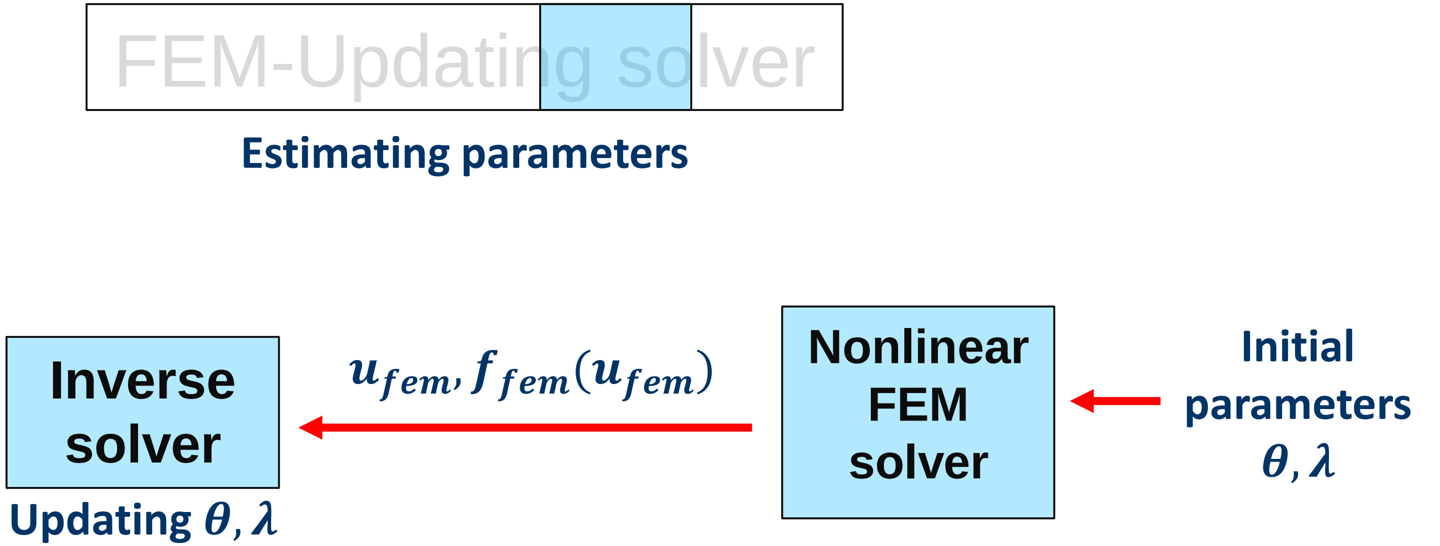
Nonlinear FEM solver

Initial parameters
θ, λ

FEniCS framework of the inverse problem



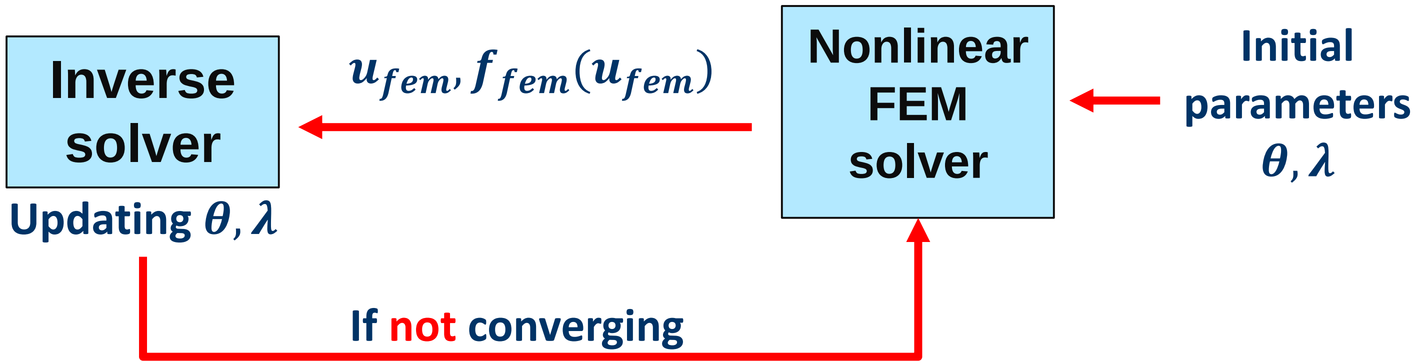
FEniCS framework of the inverse problem



FEniCS framework of the inverse problem

FEM-Updating solver

Estimating parameters



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FEniCS framework of the inverse problem

FEM-Updating solver

Estimating parameters

If converging final parameters θ, λ

Inverse solver

Updating θ, λ

$u_{fem}, f_{fem}(u_{fem})$

Nonlinear FEM solver

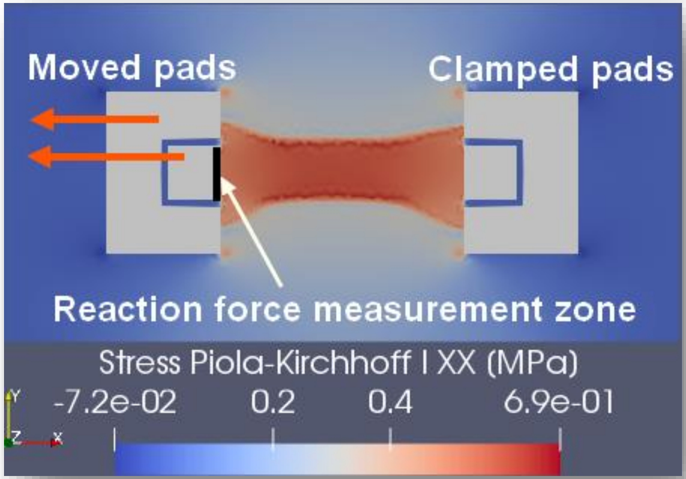
Initial parameters θ, λ

FEniCS framework of the inverse problem

FEM-Updating solver

Postprocessing

- **Stress fields (Cauchy, Piola-Kirchhoff I).**
- **Sensitivity analysis.**



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FEM-Updating solver

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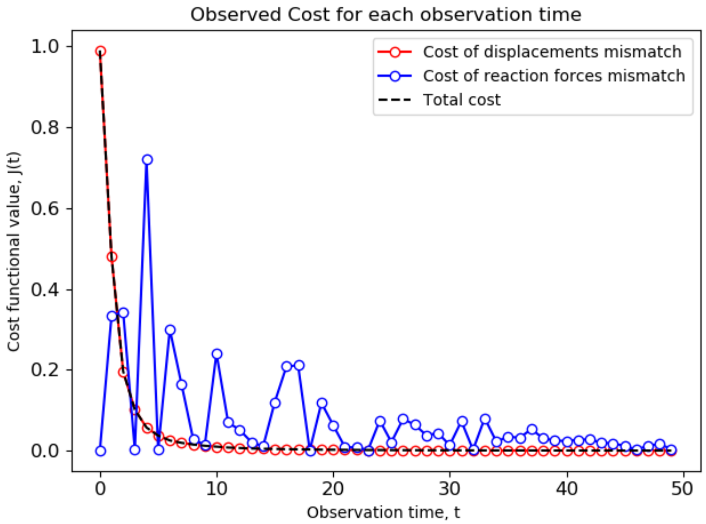

Validation using dummy data

Material parameters (arbitrary)

Validation using dummy data

* Displacement fields
* Reaction force

← FEM nonlinear solver ← Material parameters (arbitrary)

Gent model

$$\psi(\mu, j_m, I_1) = -\frac{\mu}{2} j_m \, ln\left(1 - \frac{I_1 - 3}{j_m}\right)$$

$$I_1 = Tr(FF^T)$$

Validation using dummy data

Material parameters (arbitrary)

FEM nonlinear solver

* Displacement fields
* Reaction force

Noise generator (Gaussian distribution)

Dummy data

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$$X_{noise} = X + \delta X; \qquad \delta X \sim \mathcal{N}\left(0, s^2\right)$$

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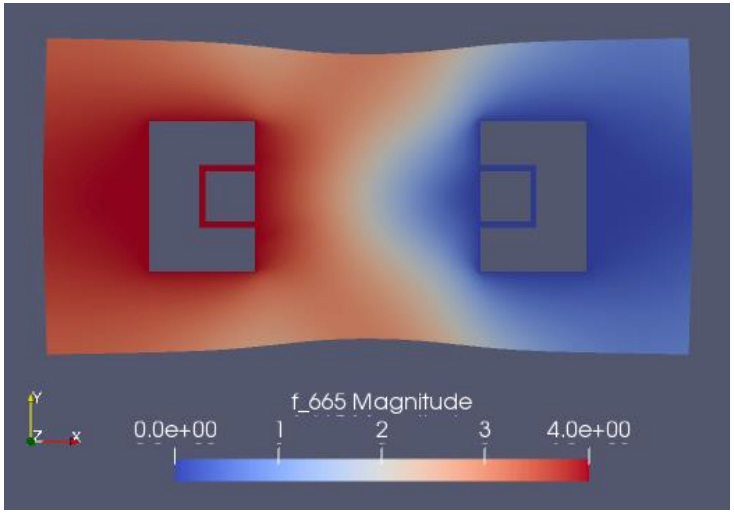

Displacement field

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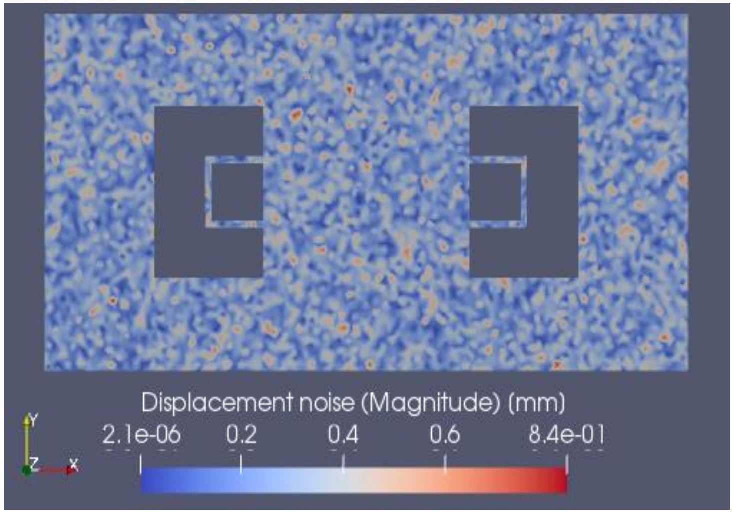

Noised displacement field

$$s_{DIC} = 0.05\ mm$$

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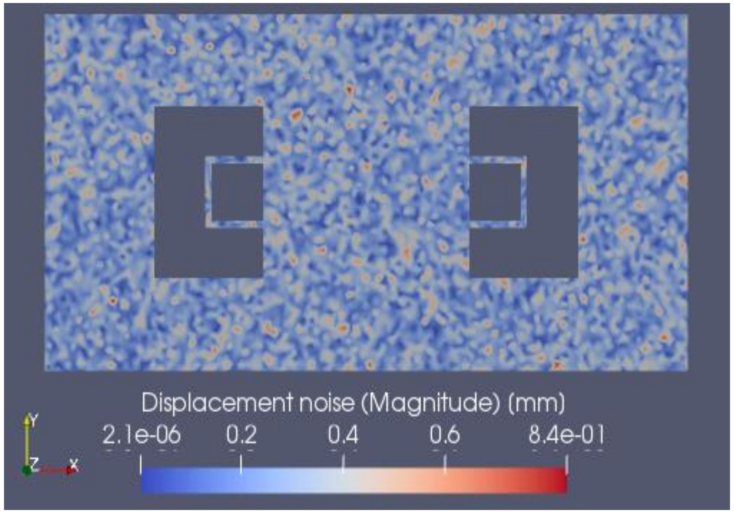

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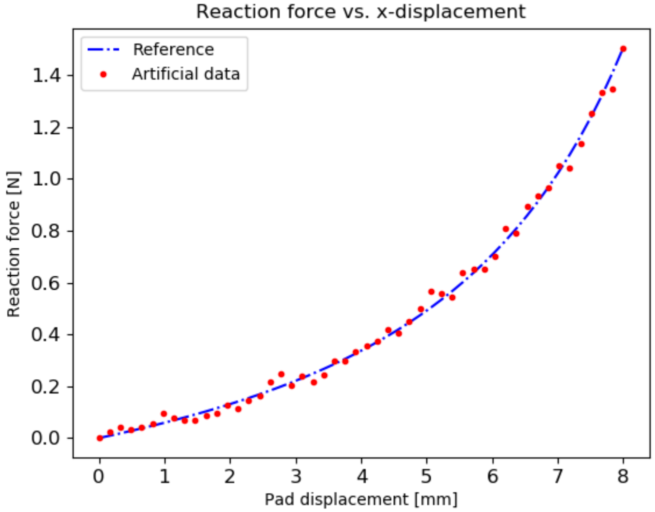
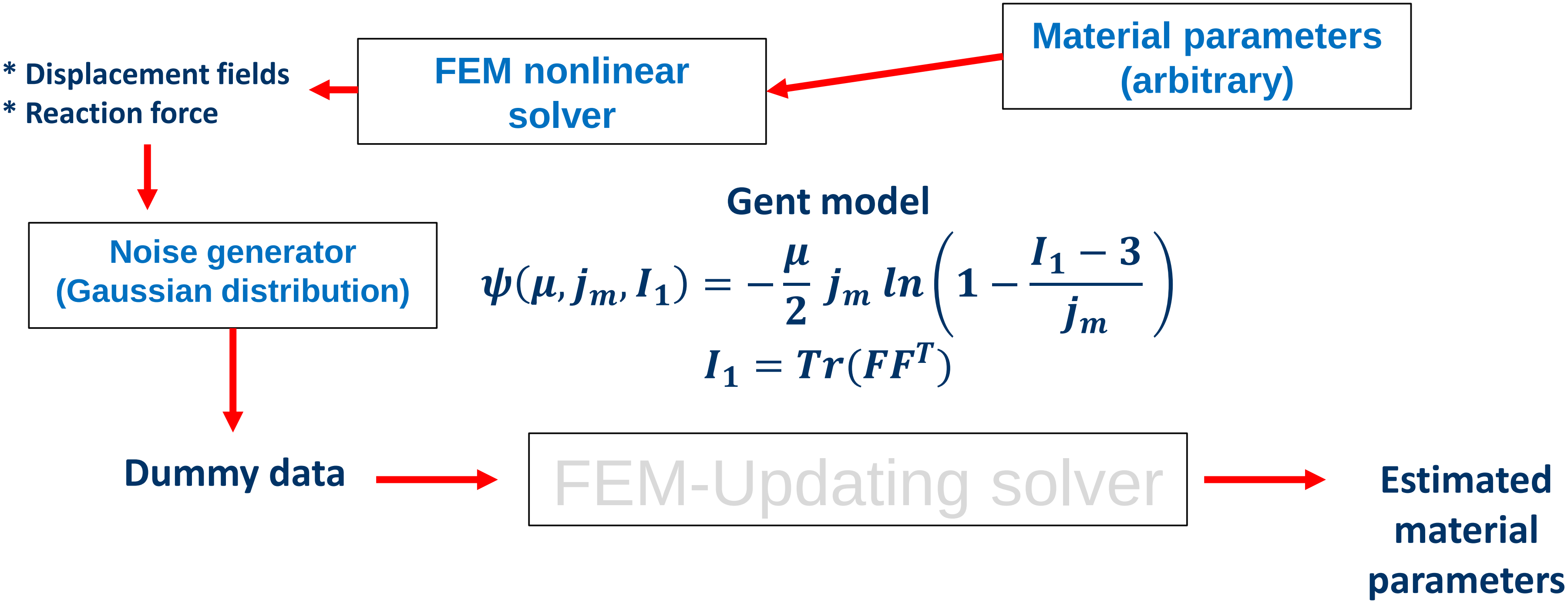


Noised reaction forces

$$s_{force} = 0.03\ N$$

Validation using dummy data



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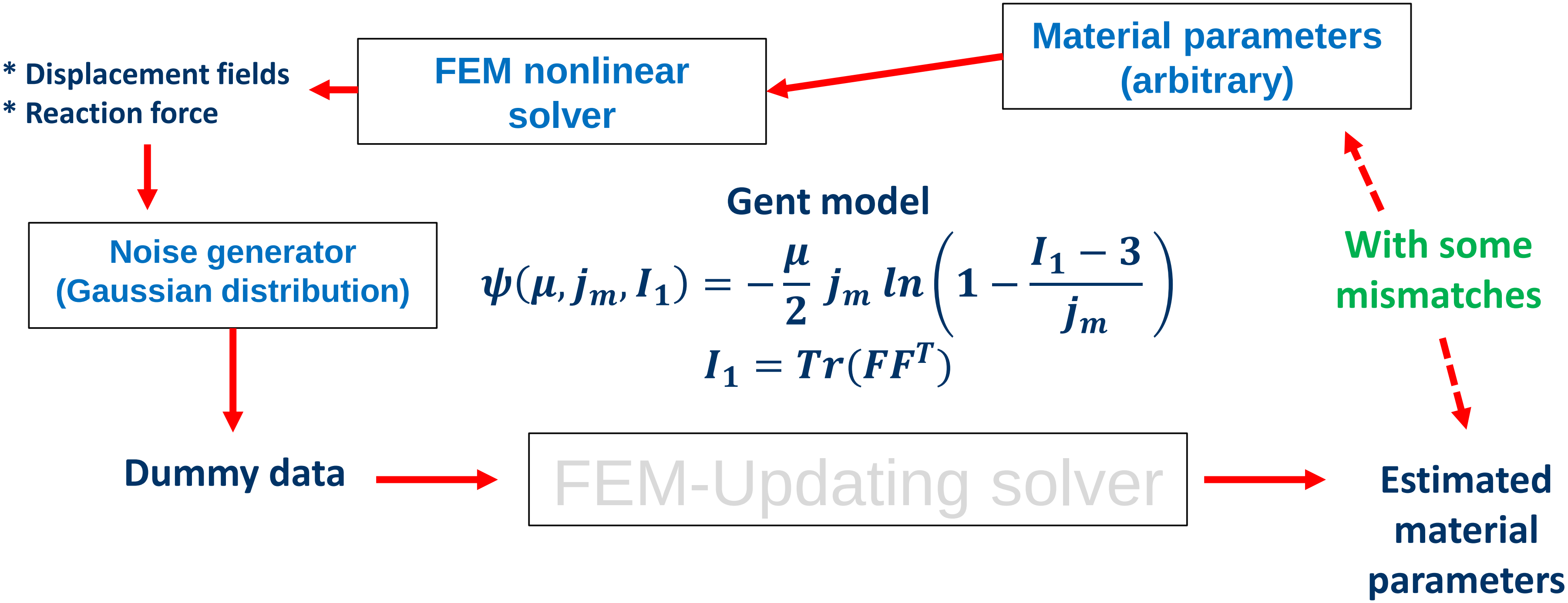

Uncertainties

Hyperelastic behavior law

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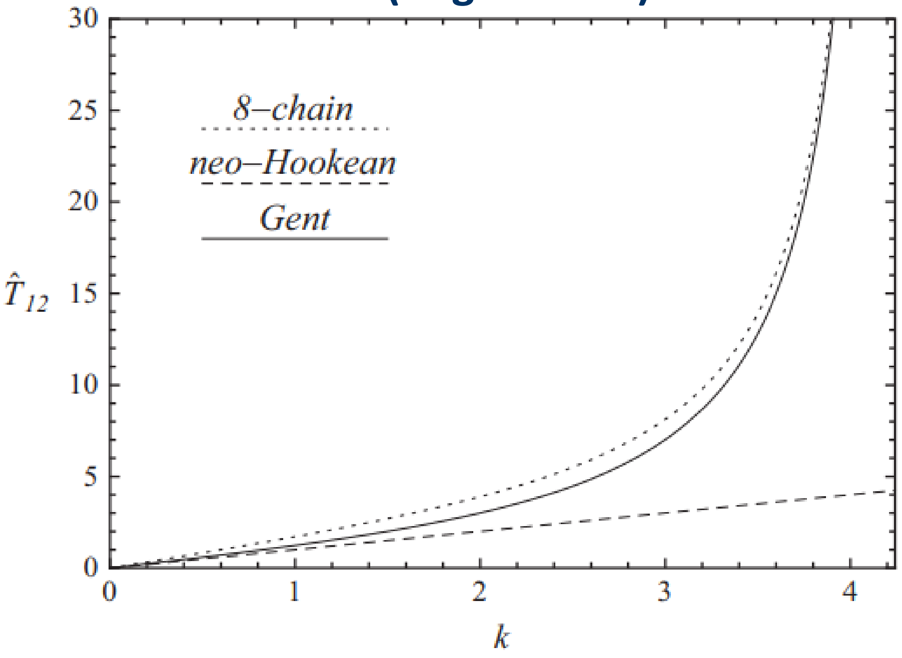
Stress/strain curve (Puglisi 2015)



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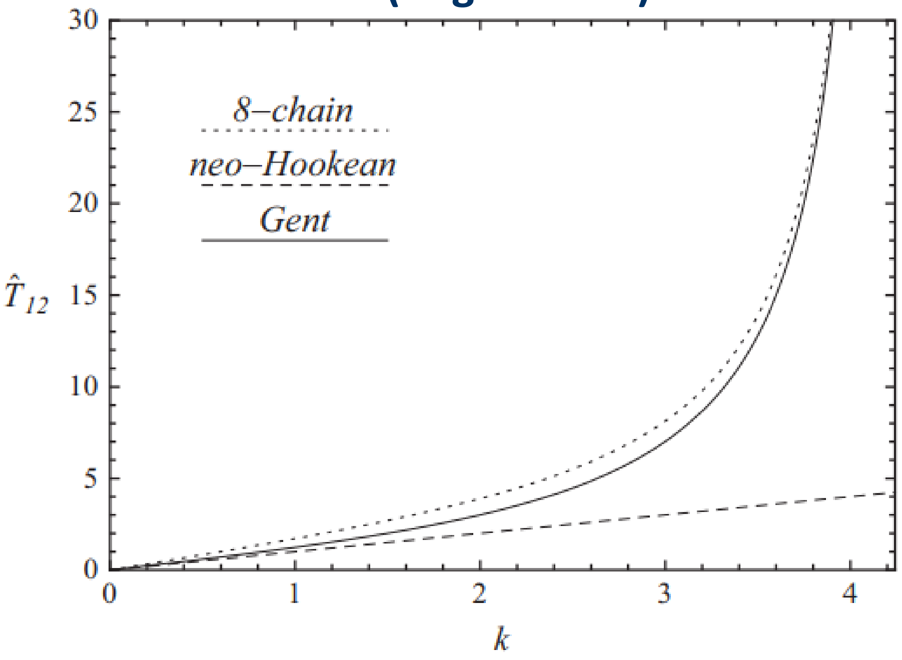

Uncertainties

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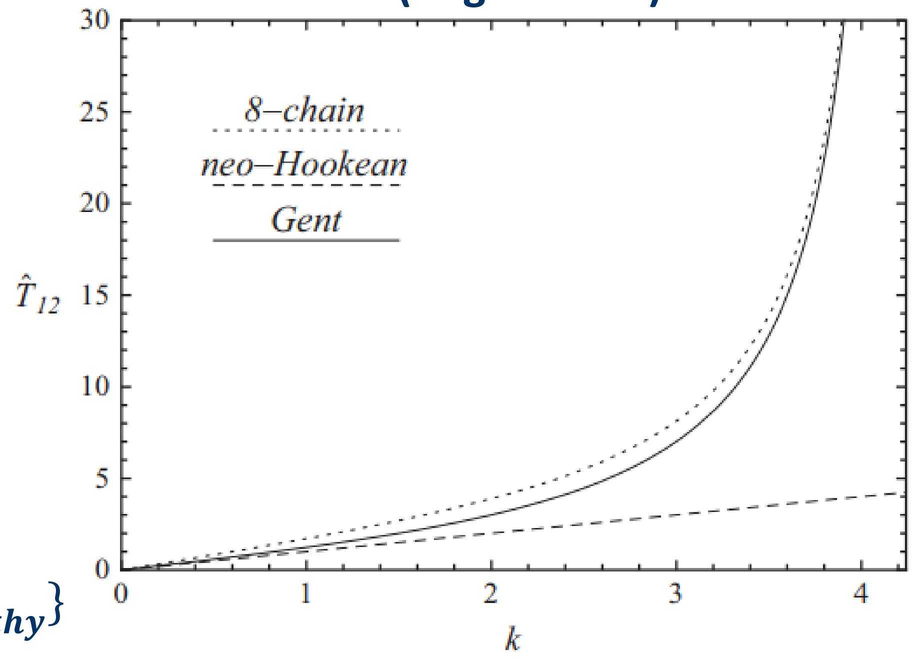
Hypothesis : the same behavior law in both materials keloid/healthy-skin

$$\theta_{model} = \{\mu_{keloid}, j_{m_{keloid}}, \mu_{healthy}, j_{m_{healthy}}\}$$

Stress/strain curve (Puglisi 2015)



Uncertainties

- **Measurement standard variations.**
- **Number of DIC frames.**
- **Geometrical sensitivity**

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$$s_{DIC} = 0,15\ mm \quad \equiv \quad relative\ error\ 3\%$$

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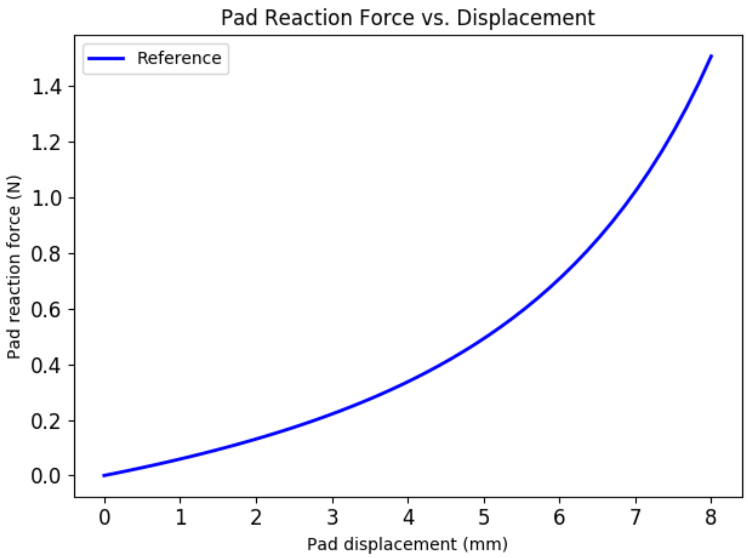

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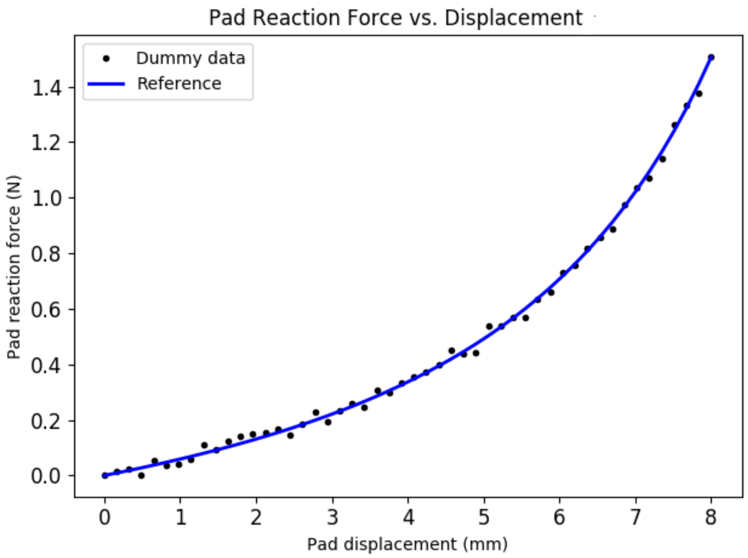

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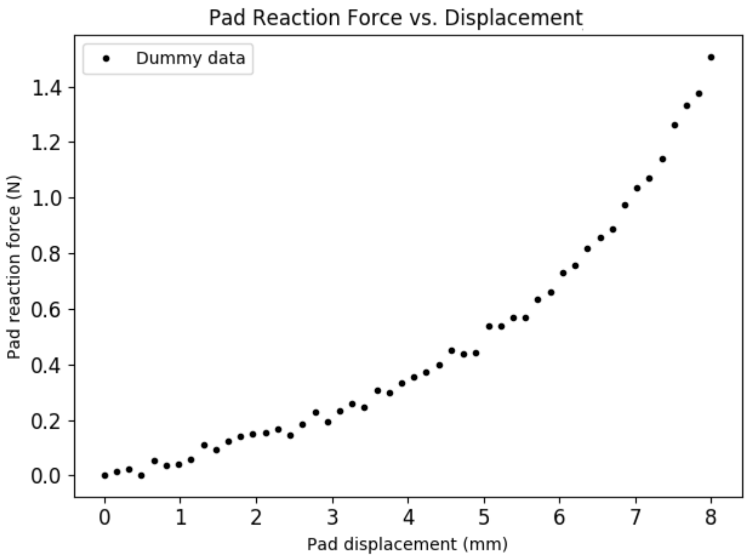


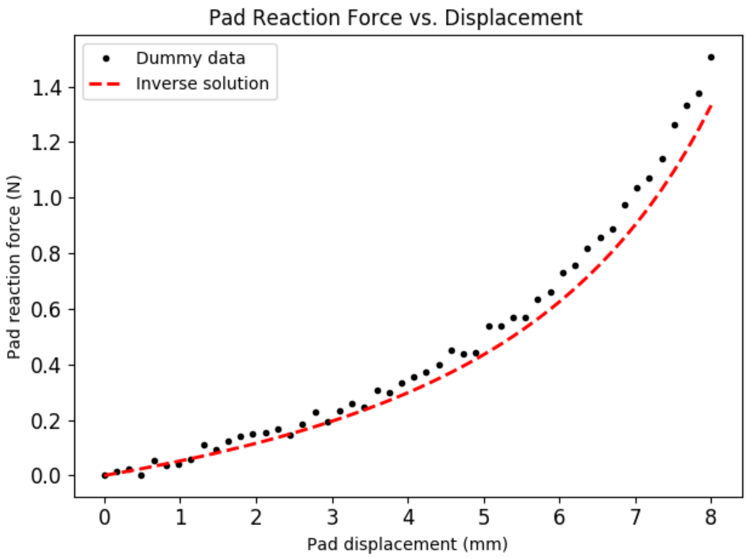
Uncertainties

$$X_{noise} = X + \delta X; \qquad \delta X \sim \mathcal{N}(0, s^2)$$

$s_{force} = 0,02\ N \equiv$ *relative error* 3%

$s_{DIC} = 0,15\ mm \equiv$ *relative error* 3%

	θ_{exact}	$\theta_{estimated}$	$\varepsilon_{relative}$
μ_{keloid}	$50\ kPa$	$44,4\ kPa$	11%
$j_{m_{keloid}}$	0, 2	0, 201	0, 8%
$\mu_{healthy}$	$16\ kPa$	$14,42\ kPa$	9, 8%
$j_{m_{healthy}}$	0, 4	0, 399	0, 5%



Uncertainties

- Measurement standard variations.
- Number of DIC frames.
- Geometrical sensitivity

$$\mu_{keloid}$$

$$X_{noise} = X + \delta X; \qquad \delta X \sim \mathcal{N}(0, s^2)$$

$s_{force}[N]$

$s_{DIC}[mm]$	0,01 (~1,5%)	0,02 (~3%)	0,03 (~4,5%)	0,04 (~6%)	0,05 (~7,5%)
0,1 (~2%)	0,2%	6,8%	11%	12,4%	18,7%
0,15 (~3%)	1,7%	11,1%	15,2%	18,3%	25,9%
0,2(~4%)	3%	5,6%	13,9%	16,8%	37%

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Uncertainties

- Measurement standard variations.
- Number of DIC frames.
- Geometrical sensitivity

$$j_{m_{keloid}}$$

$$X_{noise} = X + \delta X; \qquad \delta X \sim \mathcal{N}(0, s^2)$$

$s_{force}[N]$

$s_{DIC}[mm]$	0,01 (~1,5%)	0,02 (~3%)	0,03 (~4,5%)	0,04 (~6%)	0,05 (~7,5%)
0,1 (~2%)	**0,7%**	**0,5%**	**0,2%**	**1,2%**	**1,5%**
0,15 (~3%)	**2%**	**0,8%**	**0,9%**	**0,4%**	**0,3%**
0,2(~4%)	**1%**	**1,3%**	**0,6%**	**2,7%**	**0,2%**

Uncertainties

- Number of DIC frames.
- Measurement standard variations.
- Geometrical sensitivity

$$\mu_{healthy}$$

$$X_{noise} = X + \delta X; \qquad \delta X \sim \mathcal{N}(0, s^2)$$

$s_{force}[N]$

$s_{DIC}[mm]$	0,01 $(\sim 1,5\%)$	0,02 $(\sim 3\%)$	0,03 $(\sim 4,5\%)$	0,04 $(\sim 6\%)$	0,05 $(\sim 7,5\%)$
0,1 $(\sim 2\%)$	2%	0,8%	10%	11%	19%
0,15 $(\sim 3\%)$	2%	9,8%	17,8%	17,8%	25%
0,2 $(\sim 4\%)$	6,7%	5,9%	12%	18,4%	39%

Uncertainties

- Number of DIC frames.
- Measurement standard variations.
- Geometrical sensitivity

$$j_{m_{healthy}}$$

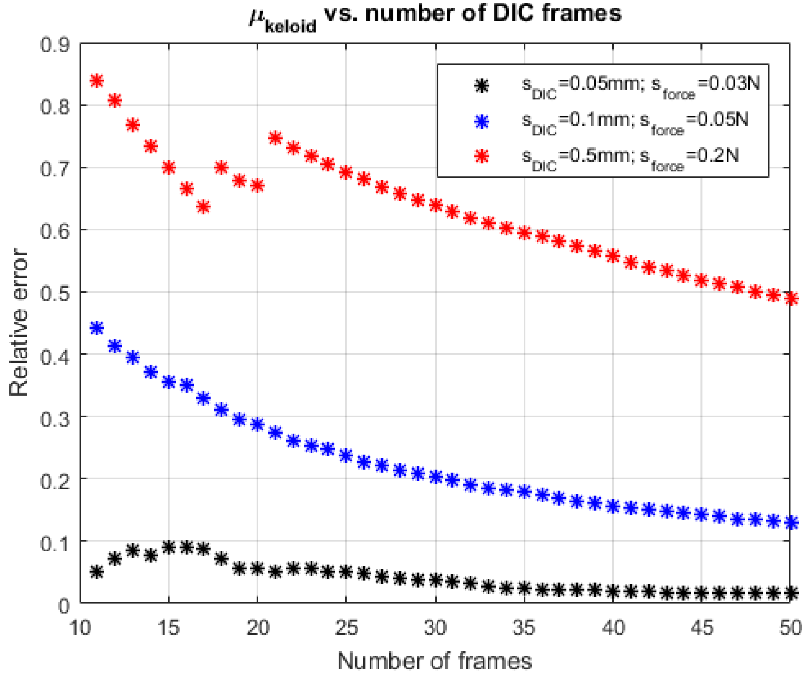
$$X_{noise} = X + \delta X; \qquad \delta X \sim \mathcal{N}(0, s^2)$$

$s_{force}[N]$

		0,01 ($\sim 1,5\%$)	0,02 ($\sim 3\%$)	0,03 ($\sim 4,5\%$)	0,04 ($\sim 6\%$)	0,05 ($\sim 7,5\%$)
$s_{DIC}[mm]$	0,1 ($\sim 2\%$)	**0,3%**	**0,5%**	**0,2%**	**1,4%**	**1,3%**
	0,15 ($\sim 3\%$)	**1,6%**	**0,1%**	**0,8%**	**0,2%**	**0,3%**
	0,2($\sim 4\%$)	**0,9%**	**0,5%**	**0,8%**	**2,6%**	**2,6%**

Uncertainties

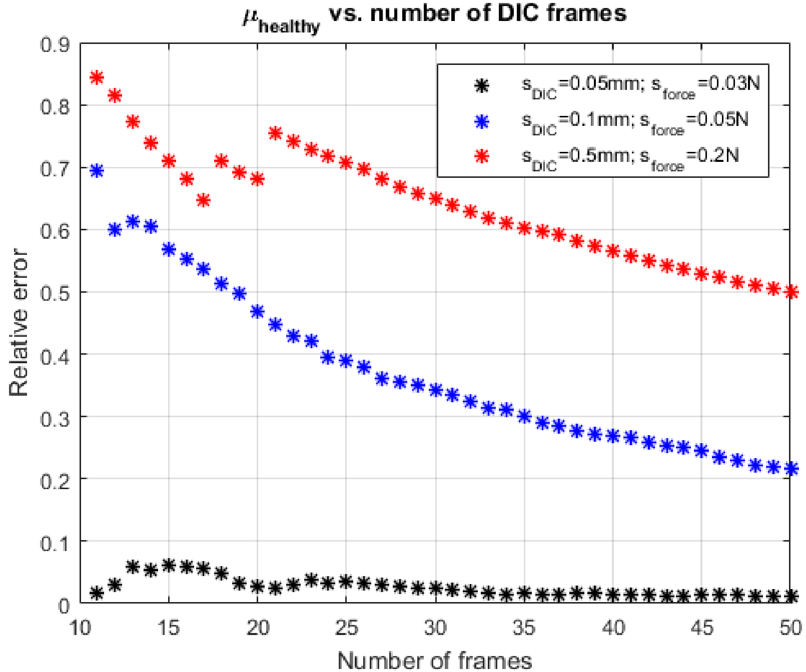
- Measurement standard variations.
- Number of DIC frames.
- Geometrical sensitivity



μ_{keloid}

Uncertainties

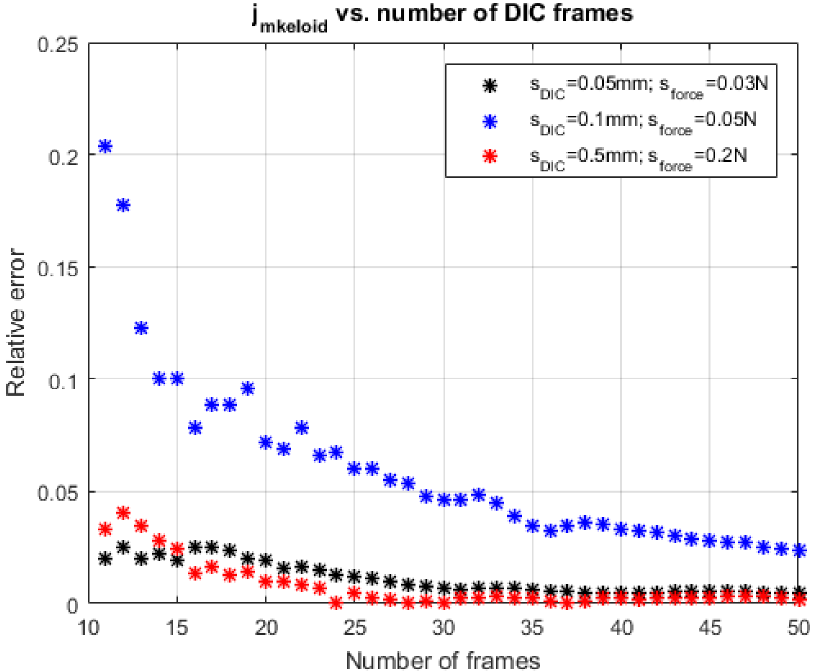
- **Measurement standard variations.**
- **Number of DIC frames.**
- **Geometrical sensitivity**



$\mu_{healthy}$

Uncertainties

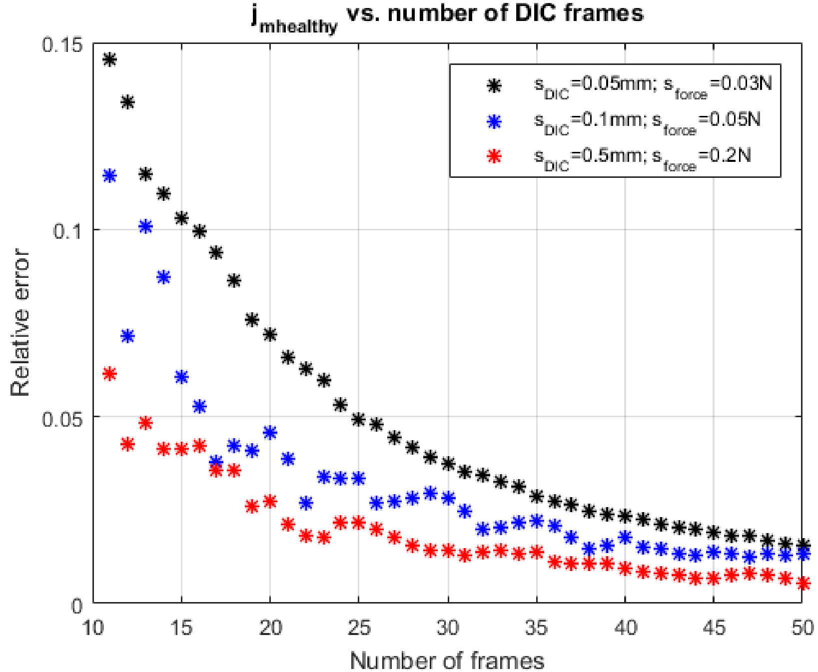
- **Measurement standard variations.**
- **Number of DIC frames.**
- **Geometrical sensitivity**



$j_{m_{keloid}}$

Uncertainties

- **Measurement standard variations.**
- **Number of DIC frames.**
- **Geometrical sensitivity**

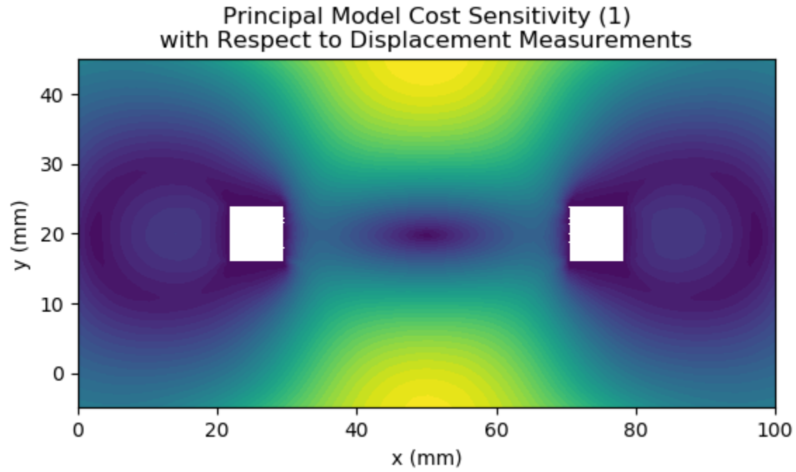


$j_{m_{healthy}}$

Uncertainties

- Measurement standard variations.
- Number of DIC frames.
- Geometrical sensitivity

$$\int_{\Omega} \frac{\left(u_{exact} - u_{estimated}\right)^2}{\left(u_{exact}\right)^2} dx$$



Conclusion and perspectives

An operational numerical tool for mechanical characterization on bi-material soft tissue by combining force measurement and Digital Image Correlation.

Conclusion and perspectives

An operational numerical tool for mechanical characterization on bi-material soft tissue by combining force measurement and Digital Image Correlation.

- **To apply the tool on real data with controlled uncertainties.**
- **To extend it by automating DIC processing.**
- **To exploit the results and conceive a clinical solution of prevention against keloid growth.**

Thank you for your attention !

Questions ?