Numerical Simulation of Anisotropy Directions of Human Skin at the Macroscopic Scale

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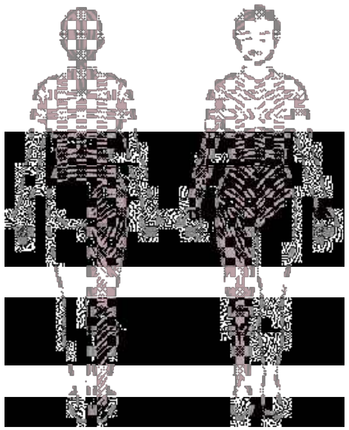
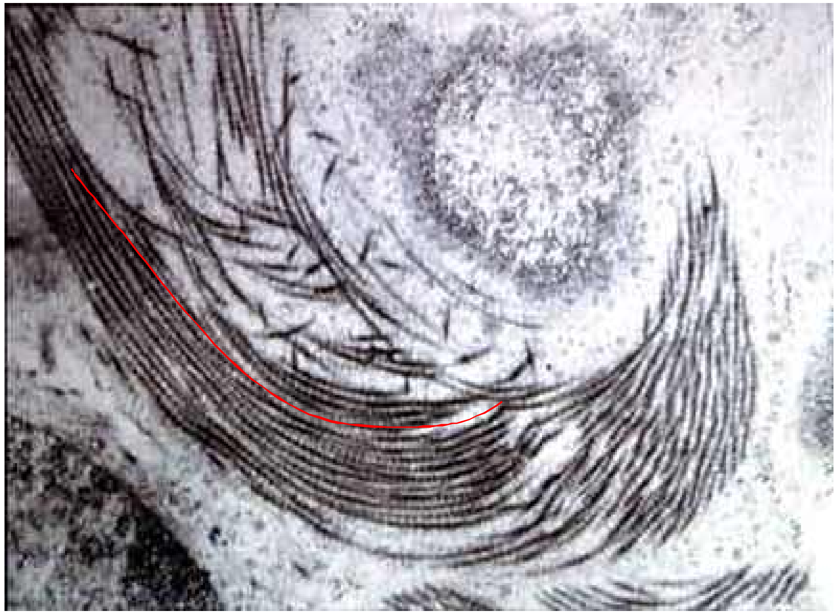


Motivation

Collagen fibers govern the anisotropy of soft tissue



Electron micrograph of collagen fibrils in the rat oviductal wall[1]

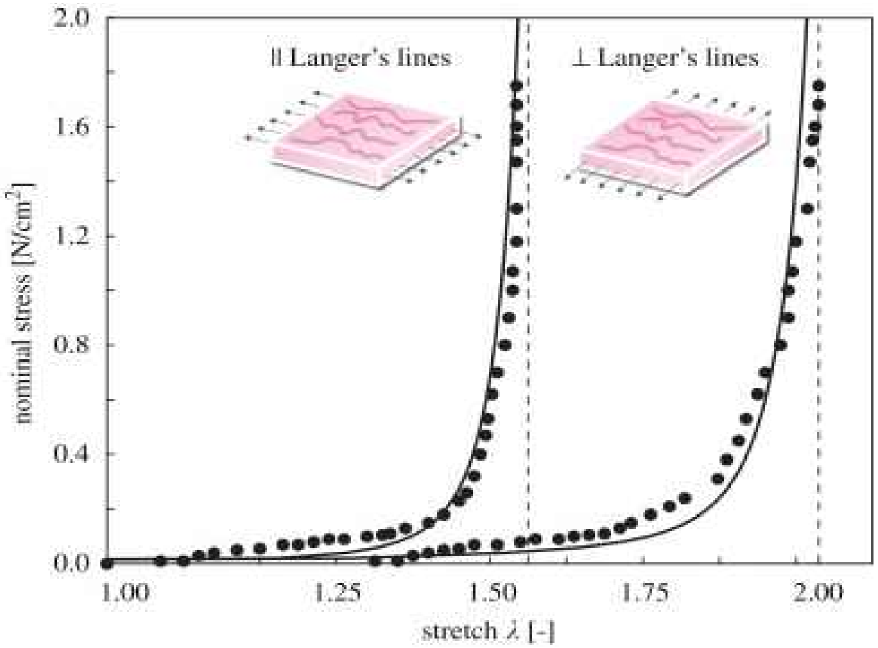
- Mechanical properties of soft tissue [2]
  - Non-linearity
  - Anisotropy
  - Softening and preconditioning
  - Pre-stress
  - Viscoelasticity

1. http://millette.med.sc.edu/Lab
2. Fung, Y.C., Biomechanics: Mechanical Properties of Living Tissues. Springer, 2nd edition. (1993)

Motivation

Collagen fibers govern the anisotropy of soft tissue

- Mechanical behavior of Collagen fibers.



Uniaxial tension test of rabbit skin[1,2]

- **Collagen → strength**
- **Elastin → elasticity**

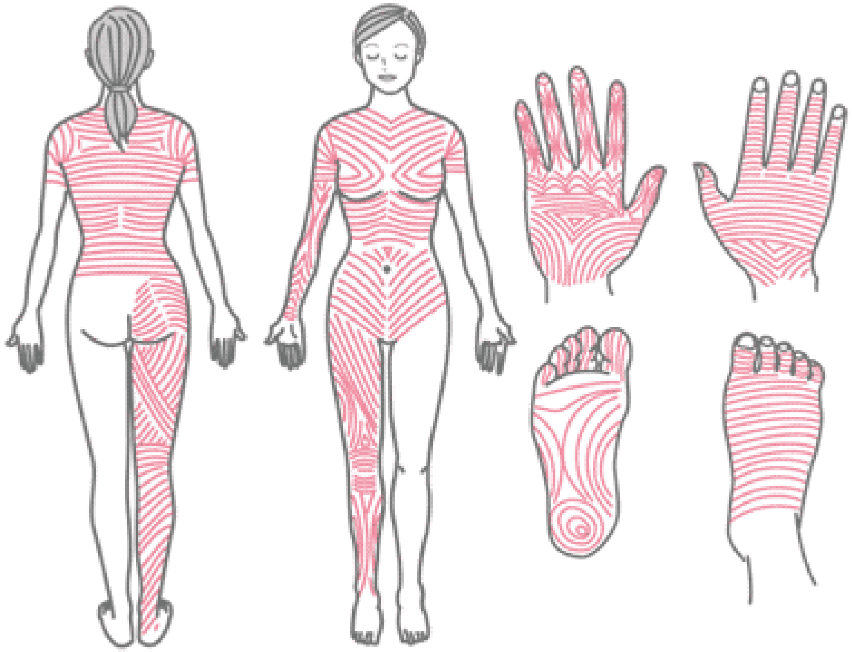
1. Y. Lanir, Y.C. Fung, Two-dimensional mechanical properties of rabbit skin II experimental results, J. Biomech. 7 (1974) 171–182.
2. Tepole et al. Stretching skin: The physiological limit and beyond. International Journal of Non-linear Mechanics, 47(2012) pp938-949.

Motivation

The anisotropy directions of skin at macro scale

Langer's Lines[1]

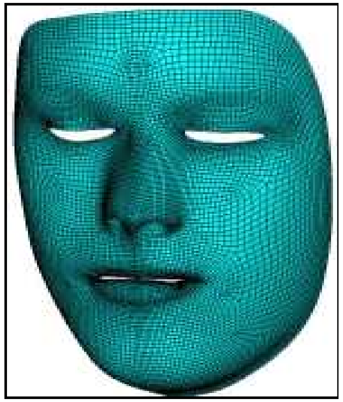
- Topological lines for mapping the preferred directions of skin
- The natural orientation of collagen fibers in the dermis

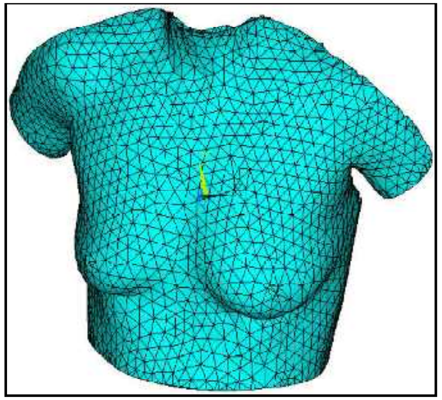


Langer's Lines[2]

1. Langer, K. 'On the anatomy and physiology of the skin'. British Journal of Plastic Surgery(1861)
2. http://www.beltina.org/health-dictionary/langers-lines-skin.html

Goals





- Automatically generate the anisotropy directions for a skin model
  - I. Approaches to calculate anisotropy directions of skin.
    - Heat conduction-based method.
    - Sketch-based Laplacian smoothing method.
  - II. Implementation to the Langer's lines of skin model.
    - Mechanical simulation of skin.

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- Heat conduction-based method
- Sketch-based Laplacian smoothing method

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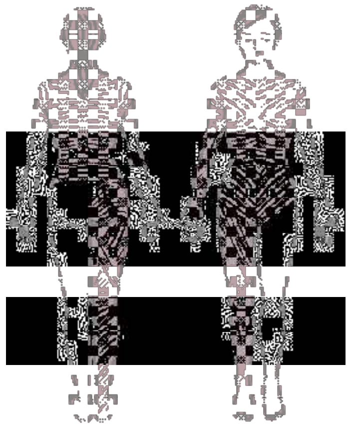
(4) Conclusions



Anisotropy directions calculation methods

Data Acquisition: CT-scan or 3D- surface scan

↓

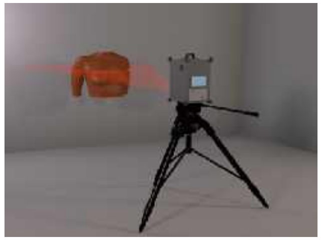
Modeling: FE meshing

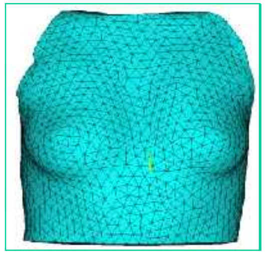
↓ ↓

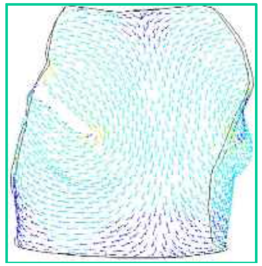
Heat conduction-based method | **Sketch-based Laplacian smoothing method**

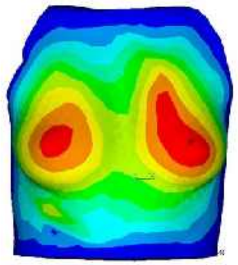
↓ ↓

mechanical simulation with calculated anisotropy directions





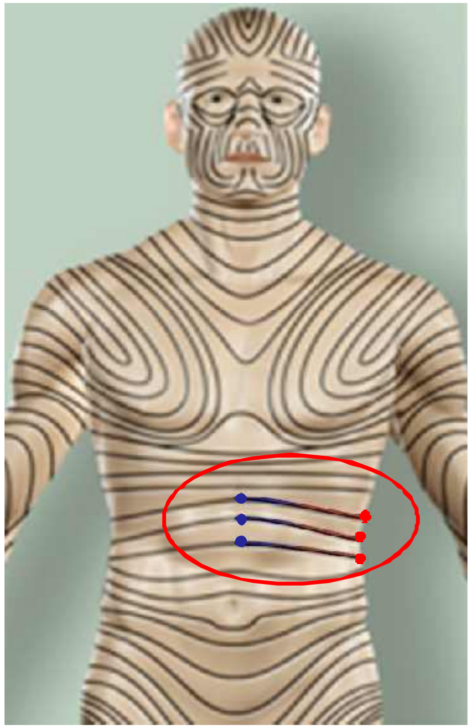




Anisotropy directions calculation methods

Heat conduction-based method (Method I)

Langers' lines of skin[1]



The heat flux on the abdominal region.

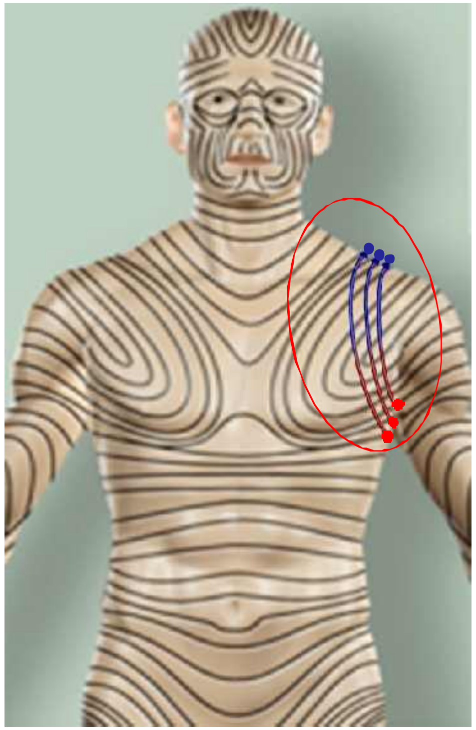
The heat transfers from high temperature to low temperature.

- high temperature
- low temperature

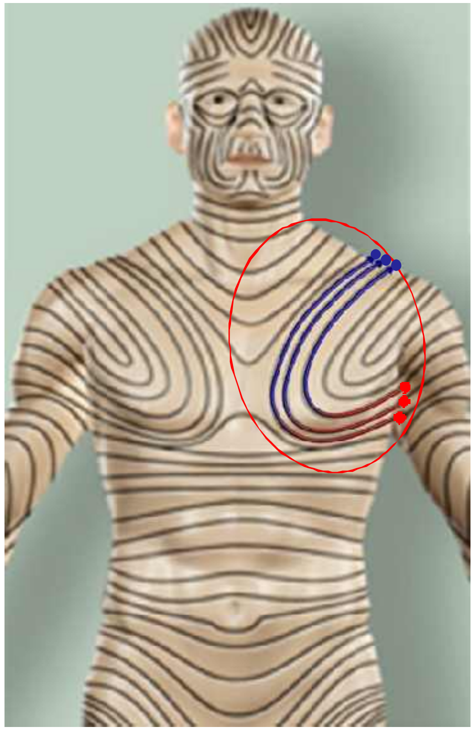
1. http://www.med-ars.it/galleries/langer.htm

Anisotropy directions calculation methods

Heat conduction-based method (Method I)



Heat flux on the shoulder region



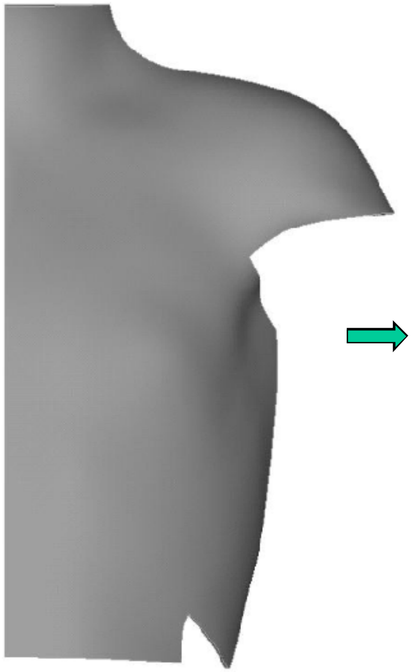
Heat flux with split
on the shoulder region

At some regions with curved skin tension lines more control is needed to get the desired curvatures.

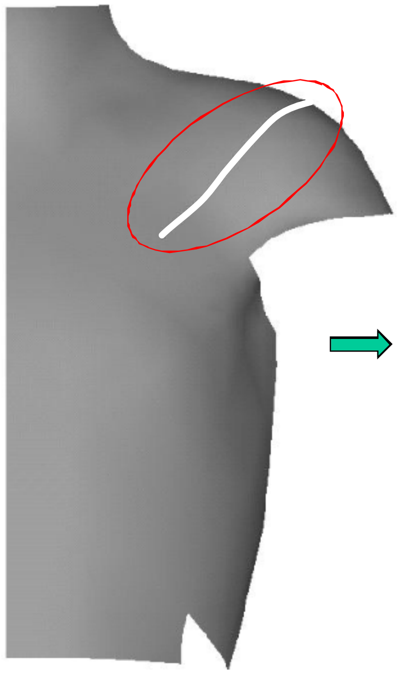
- high temperature
- low temperature

Anisotropy directions calculation methods

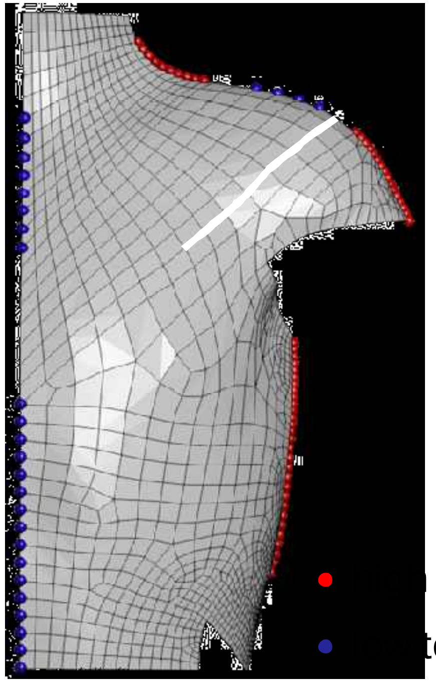
Heat conduction-based method(Method I)



Skin model



Skin model with split on the shoulder



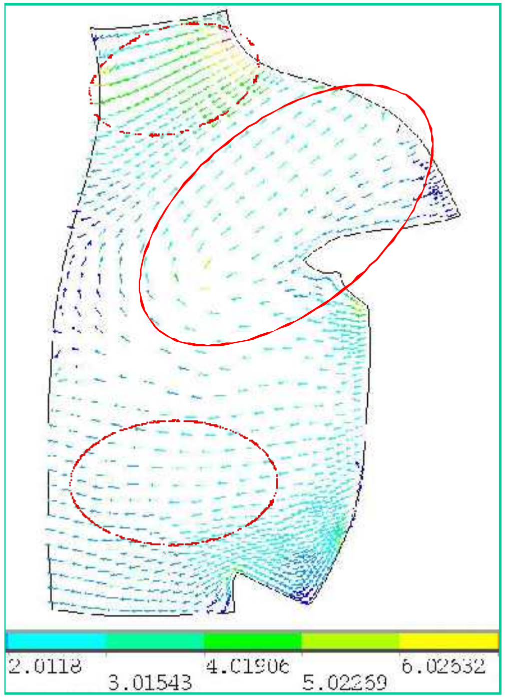
temperature

temperature

Skin model with temperature boundary conditions

Anisotropy directions calculation methods

Heat conduction-based method (Method I)



Numerical results for anisotropy directions of man skin

The Langer's lines of the skin

- ANSYS steady state thermal conduction analysis

Element type: shell 131

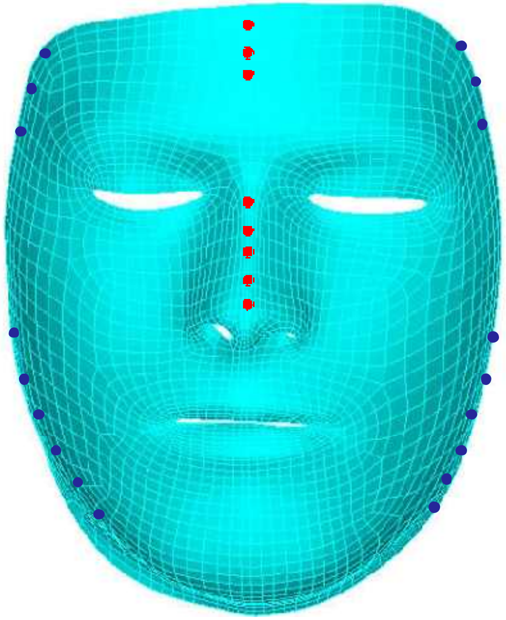
Thermal conductivity: KXX=1

High temperature: $T_h = 1$

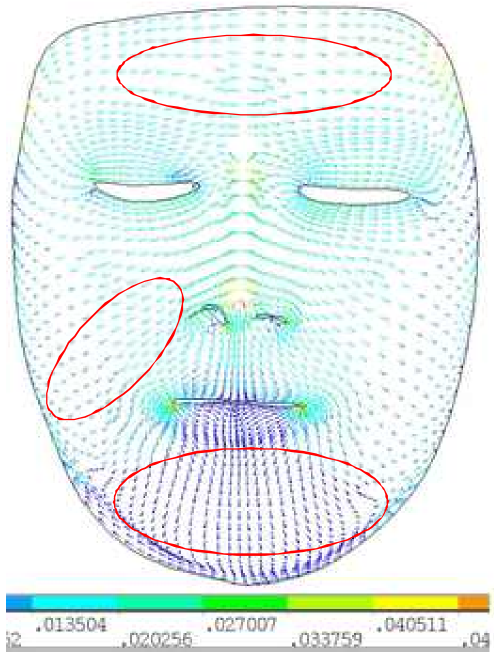
Low temperature: $T_l = 0$

Anisotropy directions calculation methods

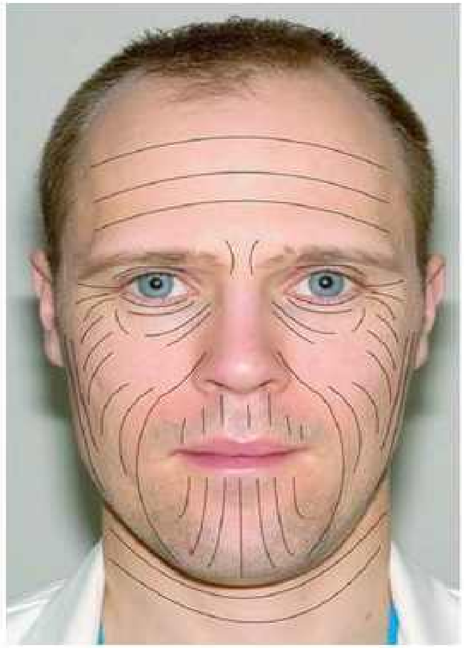
Heat conduction-based method (Method I)



face model with temperature boudaries



Numerical results for anisotropy directions of face model



Langers' lines on the face model[1]

1. Richard Baker et al. Cutaneous Scarring: A Clinical Review, Dermatology Research and Practice, (2009)

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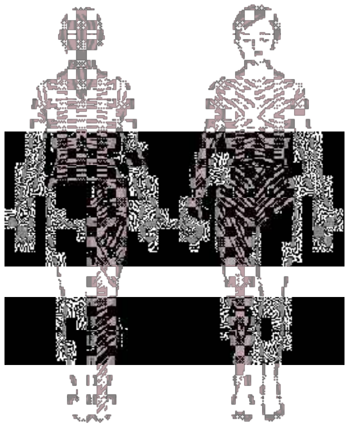
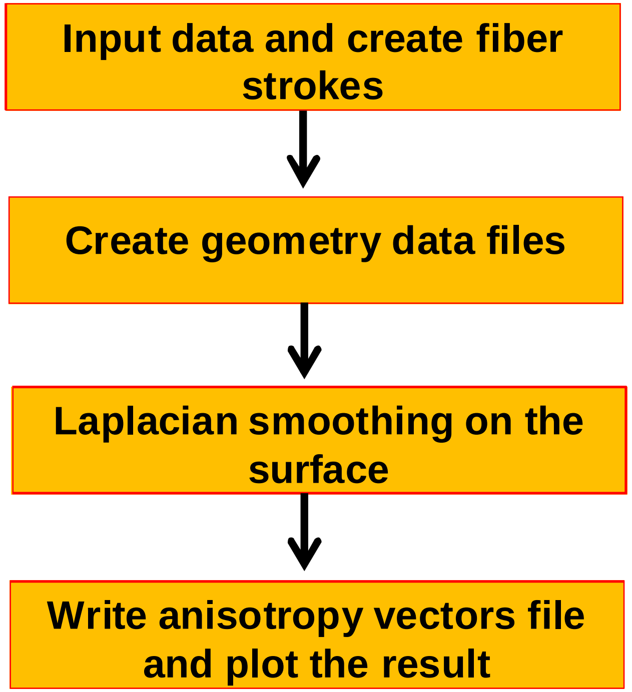


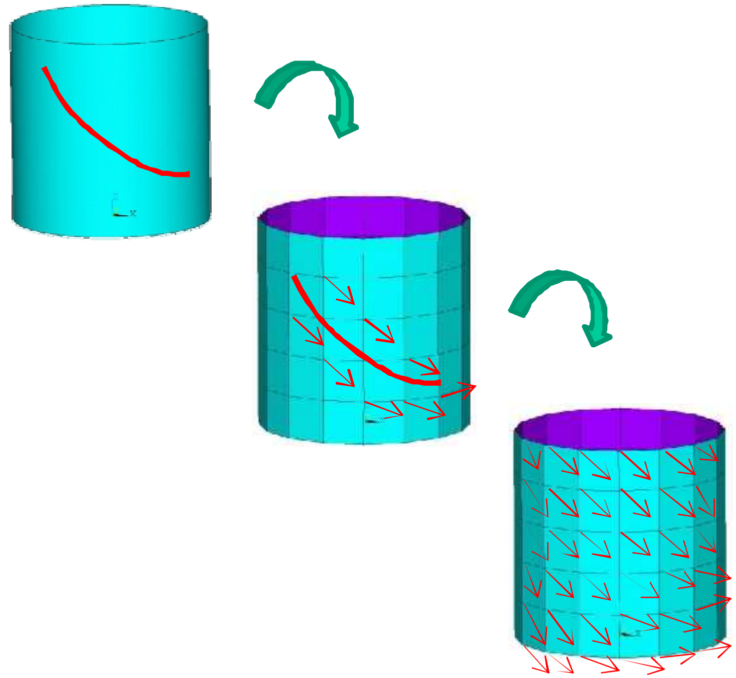
Anisotropy directions calculation methods

Sketch-based Laplacian smoothing method (Method II)

- The sketch-based method for modeling fiber orientations: interpolates the vector field with the Laplacian smoothing method based on given strokes drawn by user[1,2].



Calculation flow chart



1. Sorkine O et al. Laplacian surface editing. (2004)
2. Takayama et al. The Journal of Physiological Sciences. (2008)

Anisotropy directions calculation methods

Sketch-based Laplacian smoothing method (Method II)

- The Laplacian smoothing: minimizing the difference between anisotropy vectors in the least-squares sense under given constraints [1,2].

$$\left.\begin{array}{l} \mathrm{L}\mathbf{V} \approx \mathbf{0} \\ \mathrm{C}\mathbf{V} = \mathbf{V}^c \end{array}\right\} \rightarrow \left\| \begin{bmatrix} \mathrm{L} \\ \mathrm{C} \end{bmatrix} \mathbf{V} - \begin{Bmatrix} \mathbf{0} \\ \mathbf{V}^c \end{Bmatrix} \right\|^2 = 0$$

L is the matrix defining the relation between neighboring nodes.

C is the matrix describing the constraint in nodes of FE model.

$\mathbf{V}$ is the set of all anisotropy vectors of the FE model.

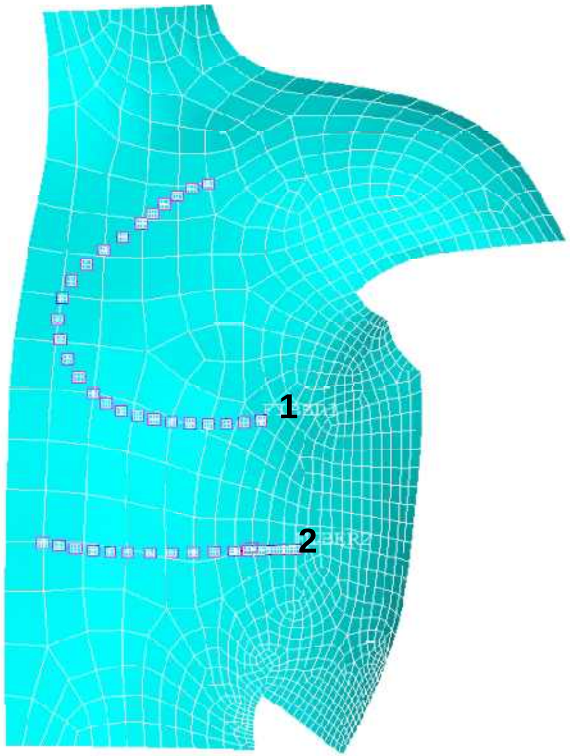
$\mathbf{V}^c$ is the set of constraint anisotropy vectors according to user-defined strokes.

1. Sorkine O et al. Laplacian surface editing. (2004)
2. Takayama et al. The Journal of Physiological Sciences. (2008)

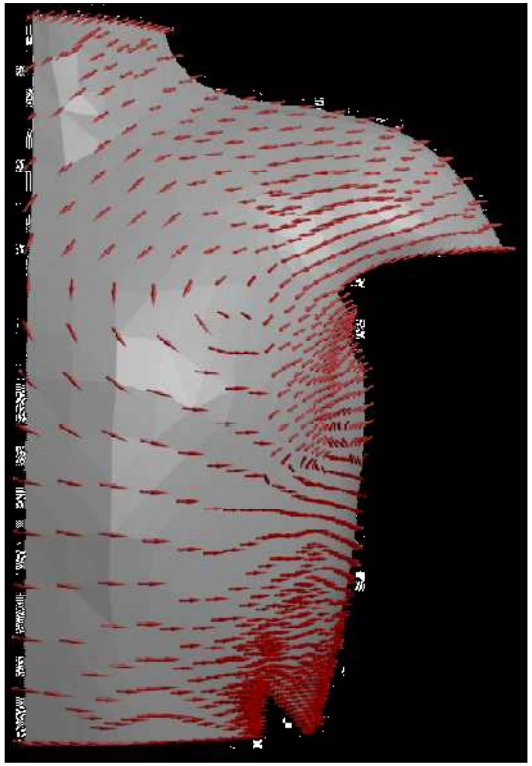
Anisotropy directions calculation methods

Sketch-based Laplacian smoothing method (Method II)

- The sketch-based method numerical results (ANSYS and Matlab).



the man skin model with
2 fibers

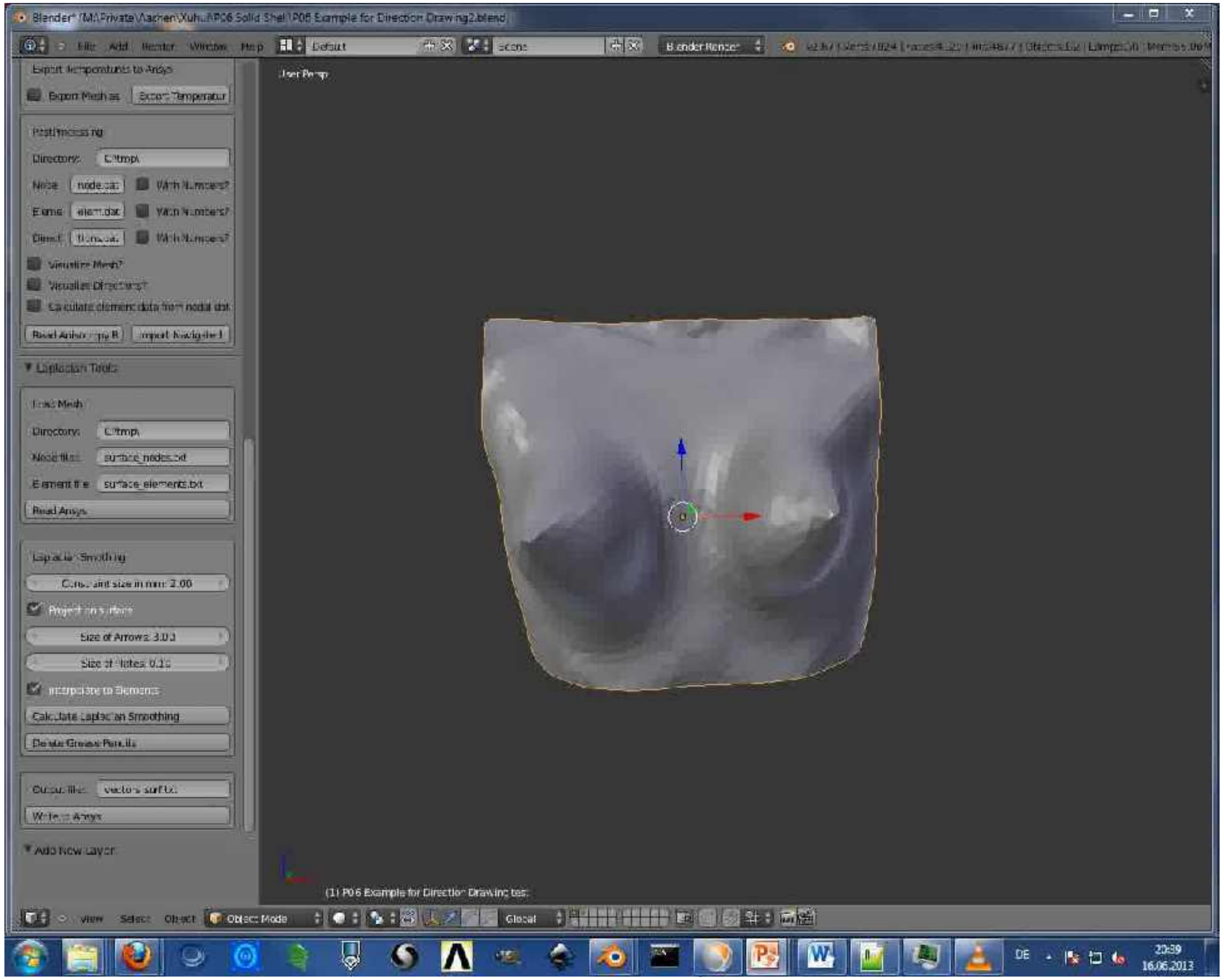


Numerical results for anisotropy
directions on the skin

Anisotropy directions calculation methods

Sketch-based Laplacian smoothing method (Method II)

- The sketch-based method numerical results (Python and Blender).



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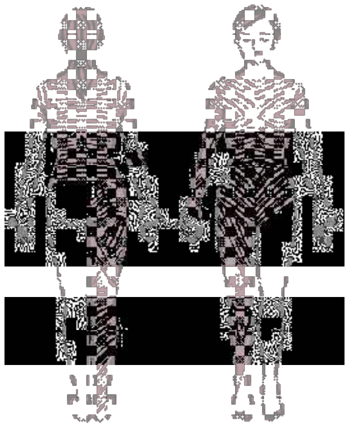
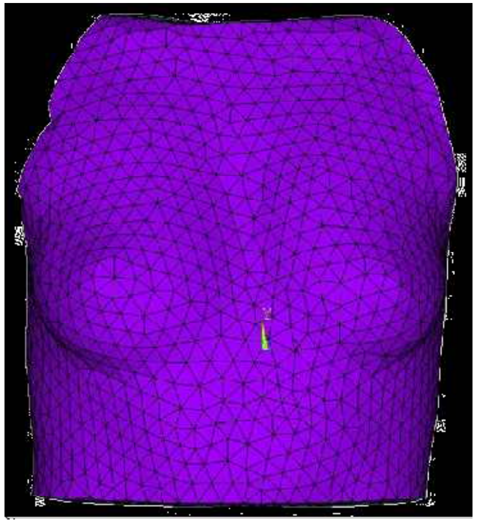
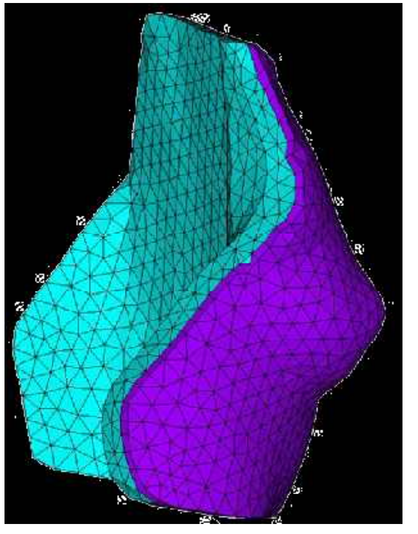


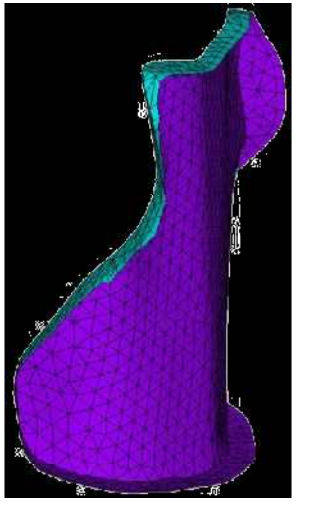
Mechanical Simulation on Skin

The geometry file of female breast model



Dermis and ground tissue (solid elements)





fixed boundary (shell elements)

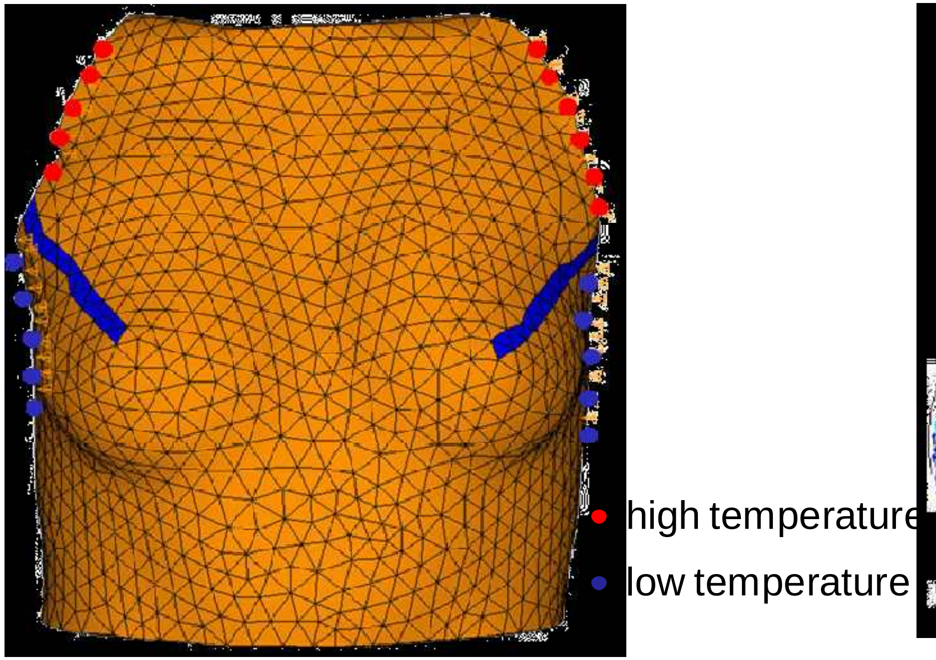
Breast model:

- **Dermis** is assumed as an anisotropic material with collagen fibers.
- **Ground tissue** is assumed as an isotropic material attributing the force on the dermis.
- **Fixed boundary** attribute the boundary conditions, i.e. the displacements are equal to zero.

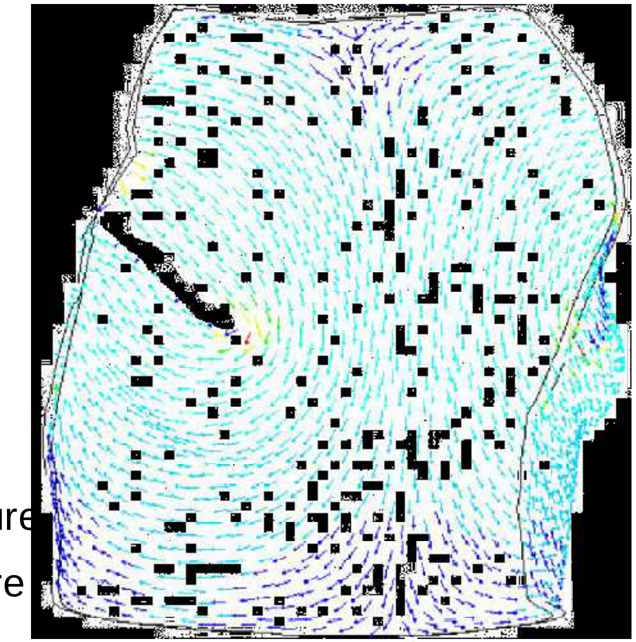
Mechanical Simulation on Skin

Heat conduction-based method (Method I)

- Calculation the anisotropy directions within dermis.



Temperature boundaries



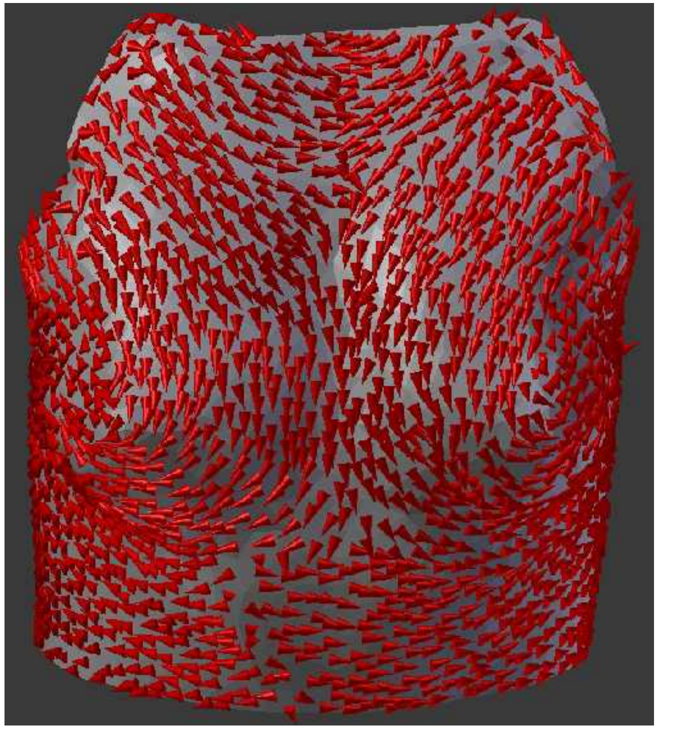
Anisotropy directions of skin

Mechanical Simulation on Skin

Sketch-based Laplacian smoothing method (method II)

- Calculation the anisotropy directions within dermis.

User-defined strokes



Anisotropy directions of skin

Mechanical Simulation on Skin

Material properties of breast model

- Simulation the deformation of breast model under gravity with Polyconvex model[1].

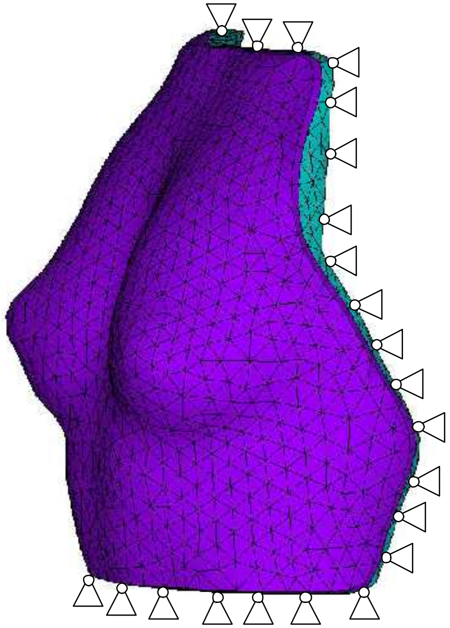
Strain energy function of polyconvex model:

$$\psi = \frac{\mu}{4}\left\{ \frac{1}{\alpha}\left[e^{\alpha(\bar{I}-1)} - 1\right] + \frac{1}{\beta}\left[e^{\beta(\bar{J}-1)} - 1\right] \right\}$$

Material properties:

	μ(mPa)[2]	α	β	w
skin	3.85e-3	1	3.84	0.621
Ground tissue	2.34e-3	1	3.84	0

density	1e-9 (kg/mm^3)
acceleration	9810 (mm/s^2)

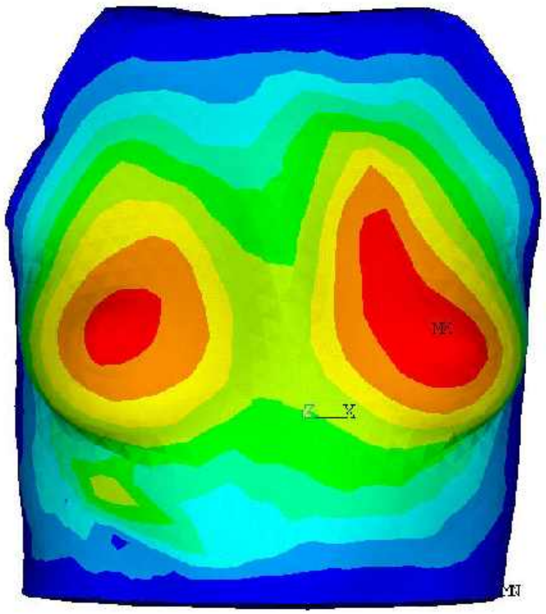


Body force and boundary conditions

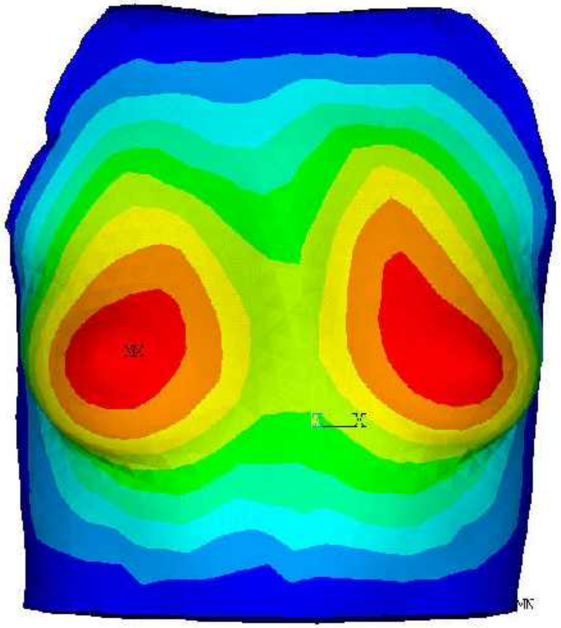
1. Ehret, A.E. and Itskov, M., A polyconvex hyperelastic model for fiber-reinforced materials in application to soft tissues. Journal of Material Science 42: 8853-8863,2007.
2. A. Samani et al, Physics in medicine and biology (2007)

Mechanical Simulation on Skin

- Comparison on the deformations of breast model



Displacement of method I
(maximal displacement 5.80973mm)

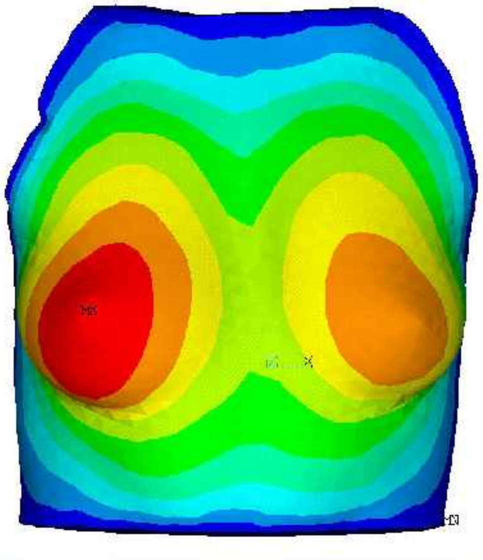


Displacement of isotropic material
(maximal displacement 11.7024mm)

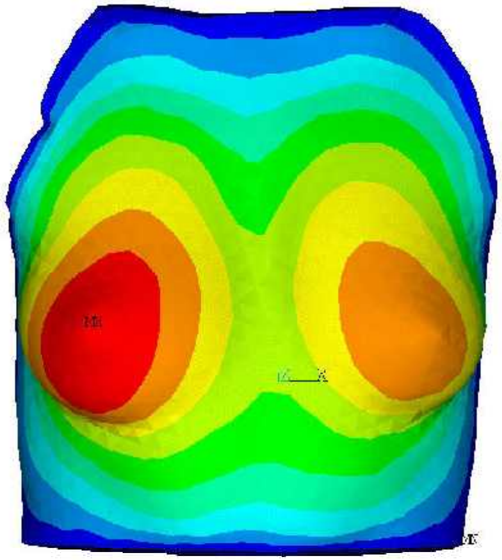
Ø The anisotropy directions attribute the stiffness of breast model.

Mechanical Simulation on Skin

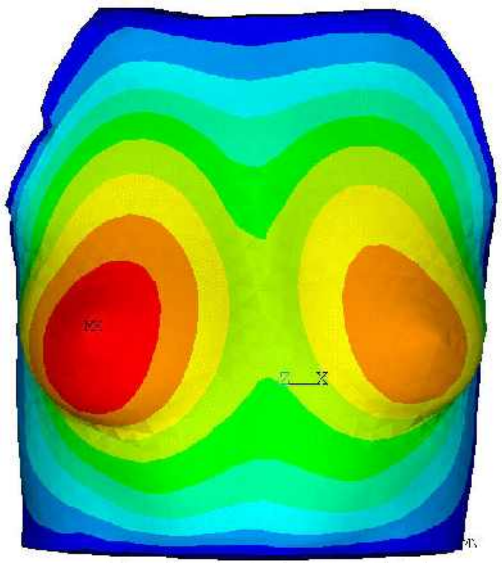
- Comparison on the deformations of breast model with orthotropic model.



Displacement of method I
(Umax=17.8697mm)



Displacement of method II
(Umax=17.9161mm)



Displacement of isotropy material model (Umax=18.3708mm)

- Ø The anisotropy directions attribute the stiffness of breast model.
- Ø These two methods both can calculate the anisotropy directions effectively.

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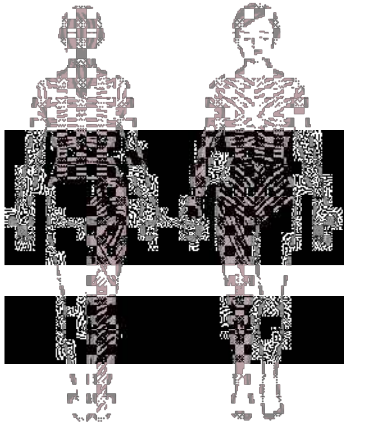

Comparison of the two methods

- **Heat conduction-based method**
- Advantages
  - Only ANSYS software is needed for anisotropy direction calculation and further mechanical simulations.
  - Anisotropy directions distribute smoothly and consistently.
- Disadvantages
  - The finite element model may be split in several parts.
  - Definition of the temperature boundaries needs engineering experience.

- **Sketch-based Laplacian smoothing method**
- Advantages
  - It is easy and fast to get the anisotropy directions and even can be used without engineering experience.
  - It allows maximal control over the anisotropy directions
- Disadvantages
  - The implementation process should combine ANSYS and Matlab or Python.
  - The directions don't distribute smoothly enough.

Conclusion

- **Summary**
  - Prediction of the anisotropy directions of soft tissue is feasible.
  - Good agreement with the Langer's line data in human skin.
  - Mechanical simulation of skin under gravity with anisotropy directions.
- **Future work**
  - Experimental validation of numerical anisotropy result.
  - Simulation on skin model considering the properties of muscle.
  - Simulation on the incision deformation.

Thank you!