A Simscape Based Mesostructural Model of Skin Mechanics

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Skin is the outermost layer of our bodies, as well as the **largest organ**. It acts as a first **protective barrier** against **external agents** such as heat, light, infection, and injury. Skin carries a vast network of nerves, glands and vessels that enable sensing of heat, touch, pressure and pain, and is also a **crucial interface** that regulates our body temperature and stores water and lipids in order to maintain a healthy metabolism [1].

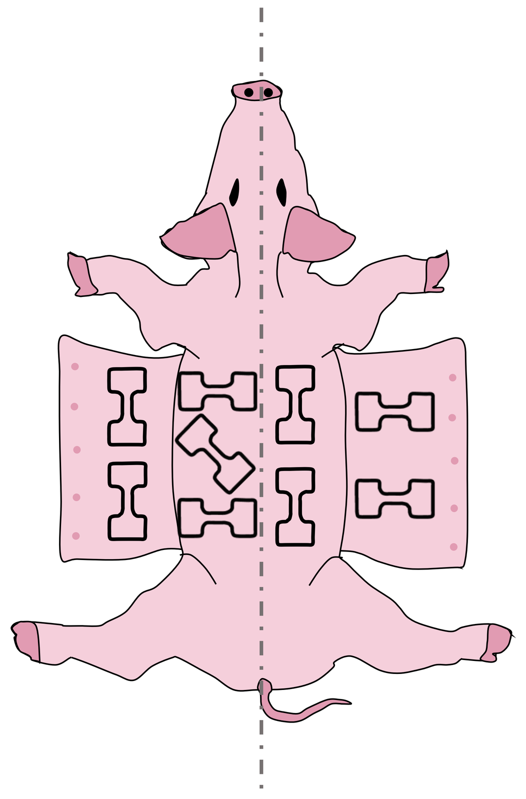
In order **to fulfill** such a broad range of **functions throughout an individual's life**, skin must be able **to withstand and recover from tremendous deformations** as well **as mitigate tear propagation** that can occur during **growth, movement, and potential injuries that affect its integrity**.

As a result, **characterizing the viscoelastic behavior of skin** and **understanding the underlying mechanisms of deformation at different levels of scale is essential** in a large spectrum of applications such as surgery, cosmetics, forensics, biomimicry and engineering of protective gear or artificial grafts, for example.

Although a fair amount of research has focused on skin's non-linear elastic and viscoelastic properties at various structural levels [2,3], proposed models often neglect said levels of complexity and lean towards a phenomenological approach rather than **a micromechanical model**. Other models accounting for fiber dispersion in skin are generally limited by their complexity and inadaptability, The **present study proposes a new framework** to describe skin mechanics, using a Simscape physical component model [4] which enables rapid parameter identification and offers malleability via its block-based structure. Interactions between constitutive elements are simulated using a microstructural Finite Element Model.

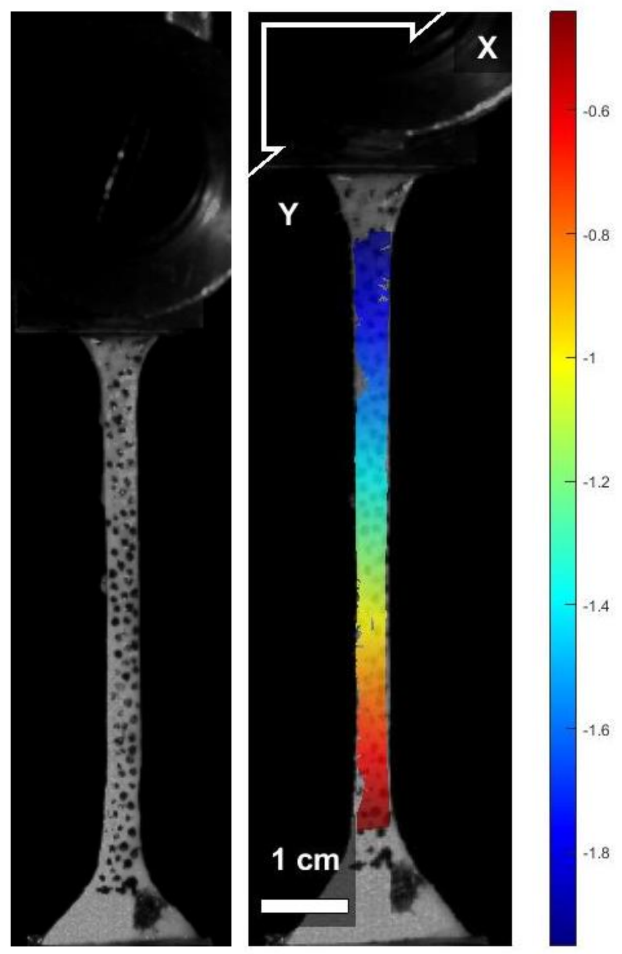
Experimental Methods

Two 9 weeks old piglets were sacrificed and their skin was surgically excised. The fat layer was removed with a scalpel and ASTM D412 Type B [5] samples were obtained using a cutting die. Cuts from the back and the belly were performed in two distinct directions: along the direction of the spine (longitudinal cut), and perpendicular to it (transverse cut). Skin was tested fresh.



Setup for tensile tensing

DIC analysis of a pig skin sample in tension. 2D mapping of the vertical displacement

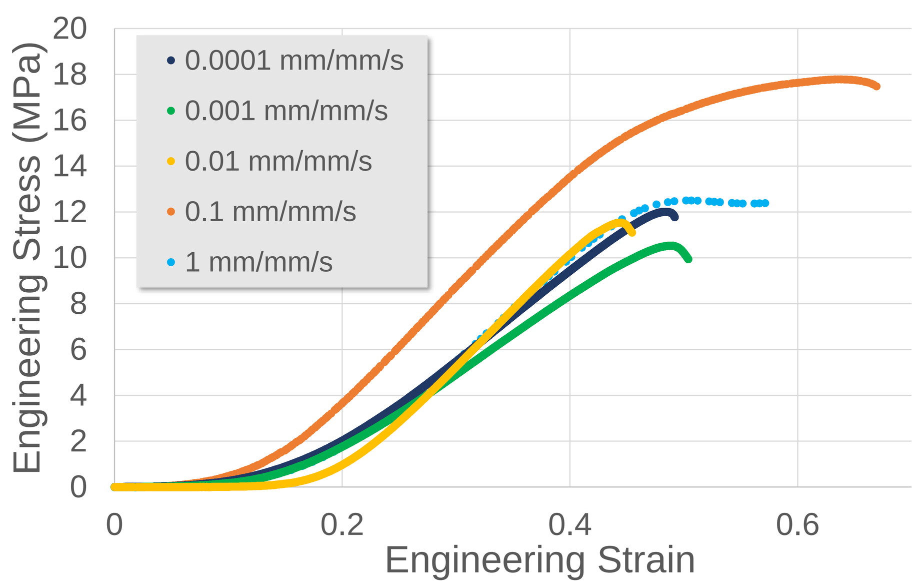


Samples were speckled and tensile tests were recorded using a Phantom v120 High-Speed Camera (resolution:512x512; frame rates: 10fps, 20fps, 80fps).

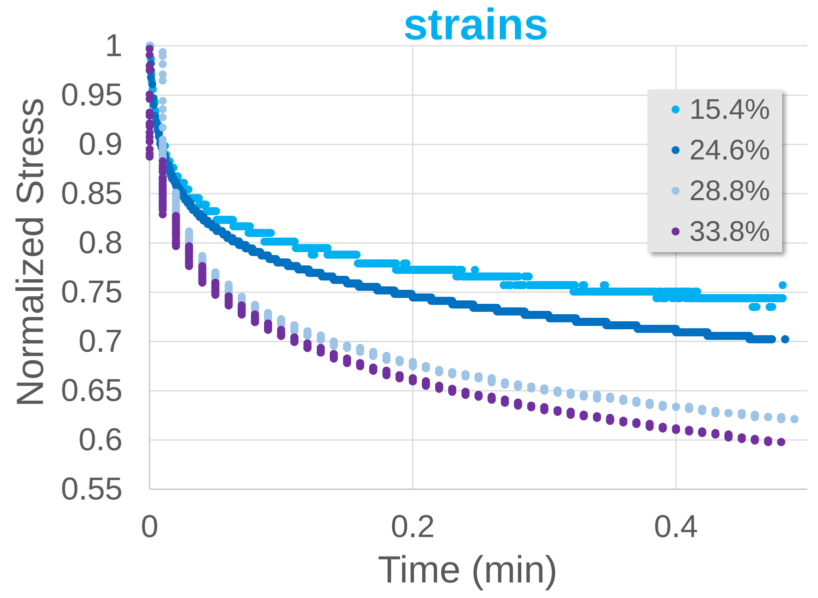
The Matlab software Ncorr 2.1 [6] was used to perform DIC and estimate sample slipping.

Experimental Results

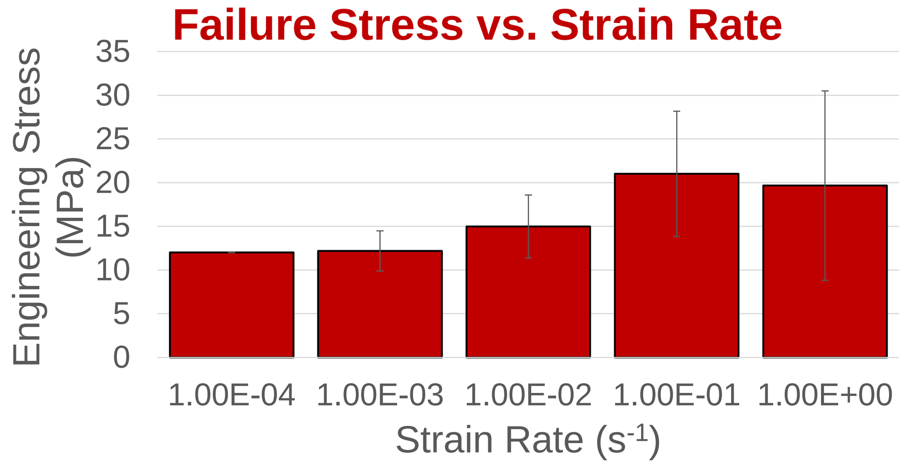
Strain Rate Sensitivity of Pig Skin



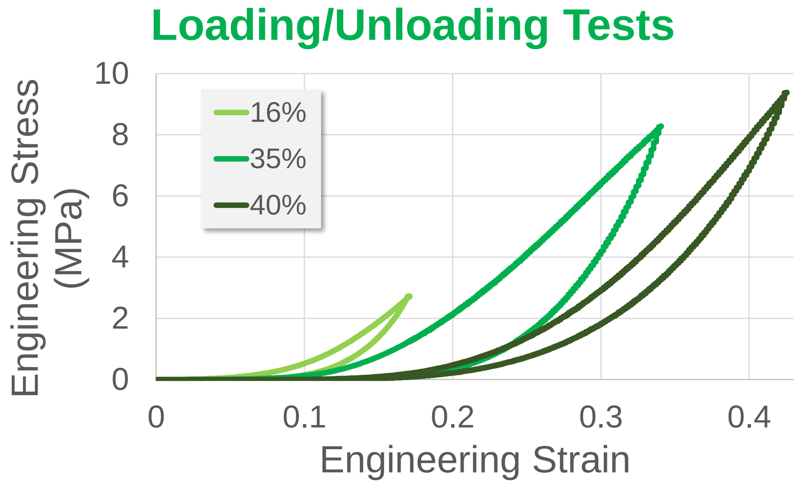
Stress Relaxation at increasing strains



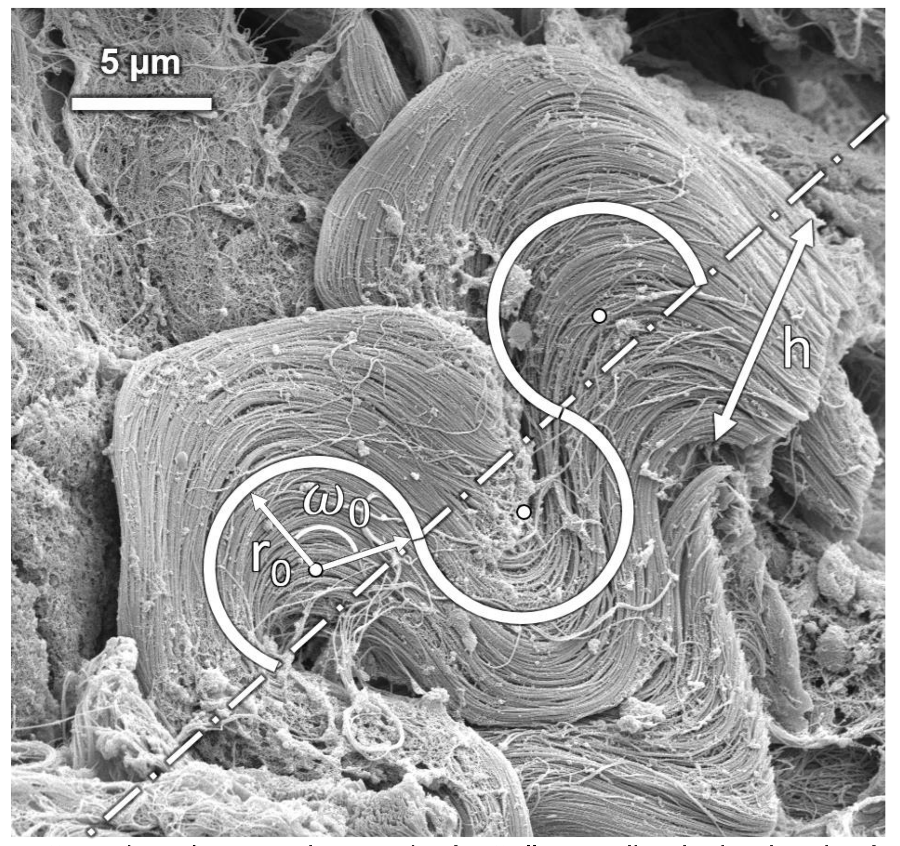
Failure Stress vs. Strain Rate



Loading/Unloading Tests



Mesostructural Simscape Model



Scanning Electron Micrograph of a Collagen Fiber in the dermis of pig skin

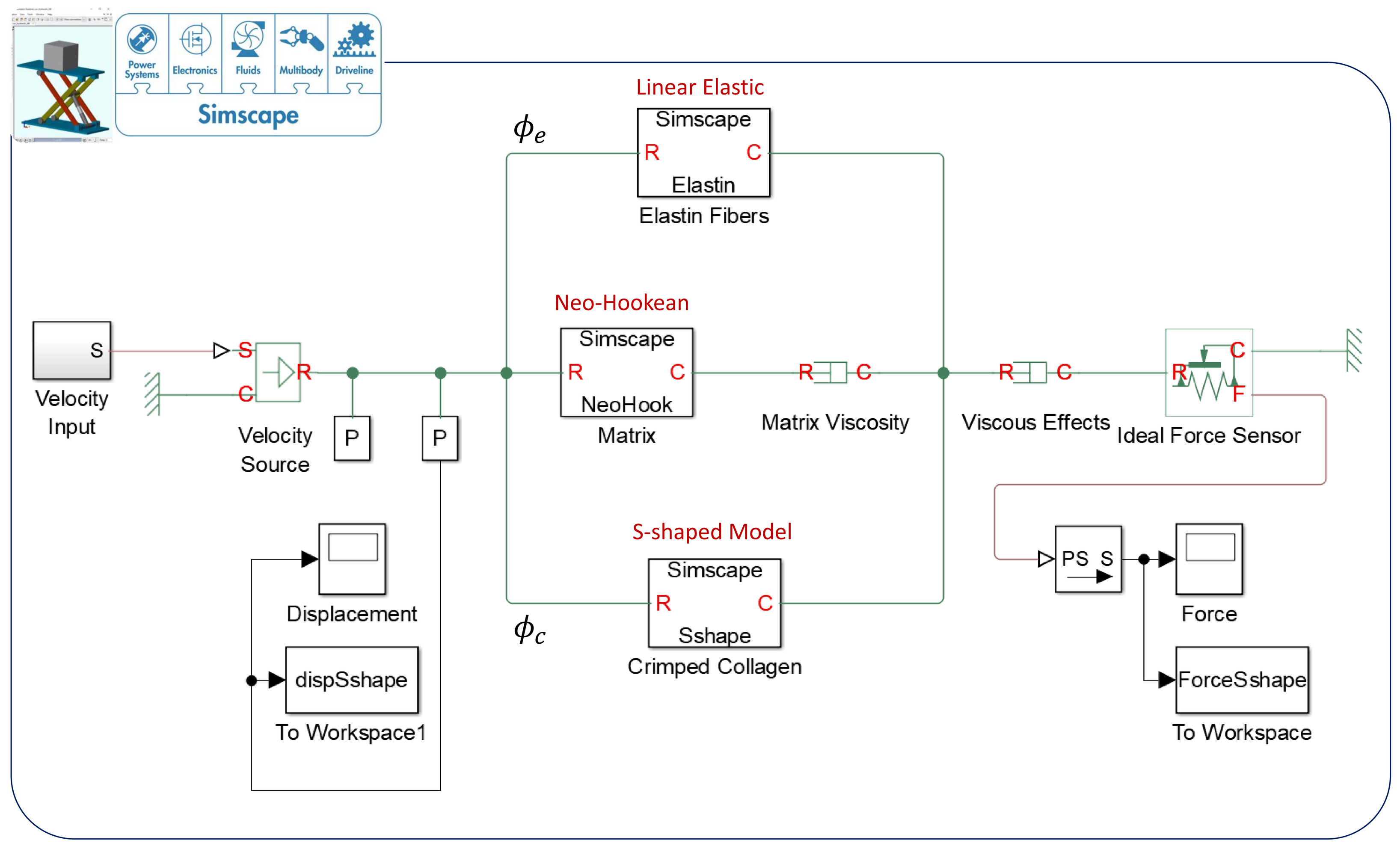
The principal load-bearing component of skin is the dermis, composed of collagen (~30% v.f.) [7,8], elastin (~2% v.f.) [7,8] and a soft viscoelastic matrix. Collagen fibrils form bundles, which are initially crimped. We describe the waviness of the fibers using a semi-circular model [9], with:

- r_0: initial radius
- ω_0: crimp angle
- h: fiber thickness

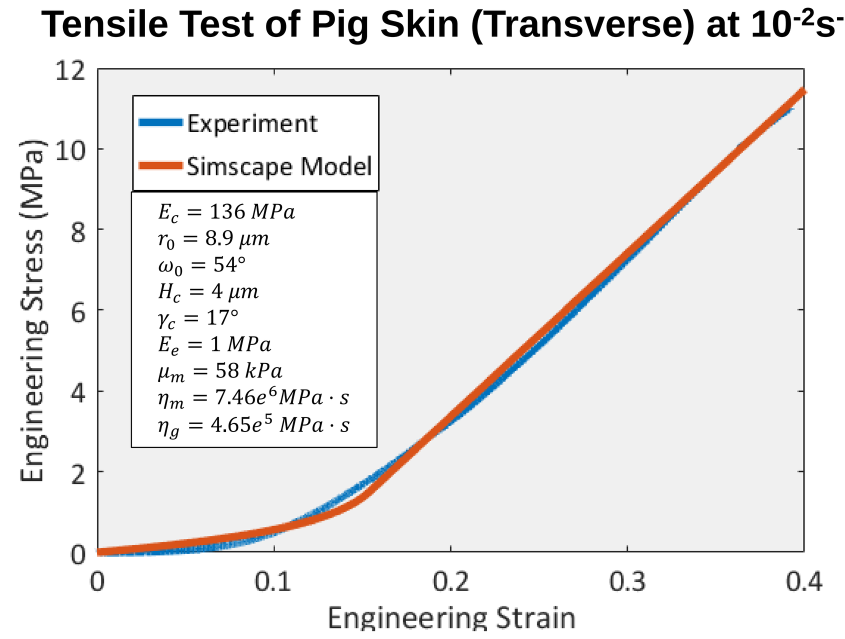
The deformation of such a fiber is expressed by:

$$\sigma = \int_0^{\varepsilon_c} E_{app}(\varepsilon) d\varepsilon$$

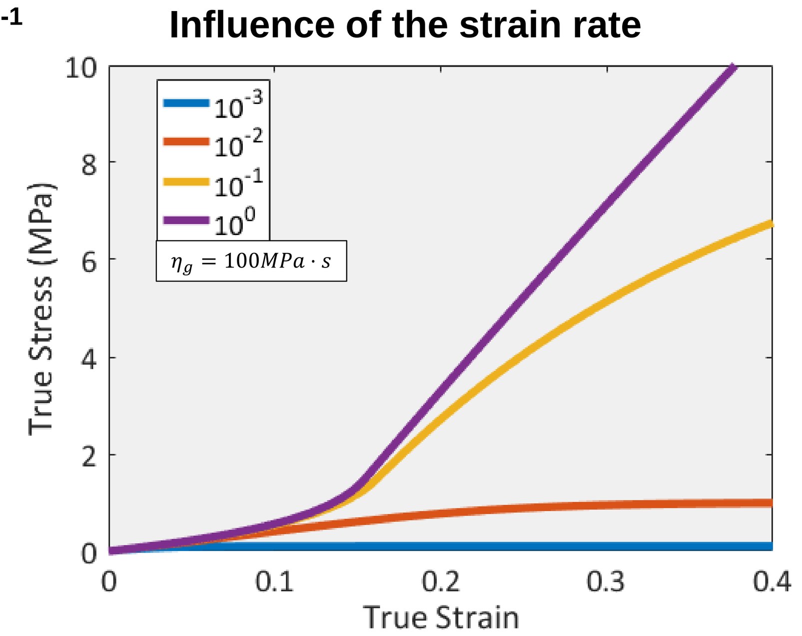
Where E_{app} is the apparent Young's Modulus along the axis of tension, defined by the structural parameters listed above.



Tensile Test of Pig Skin (Transverse) at $10^{-2}s^{-1}$



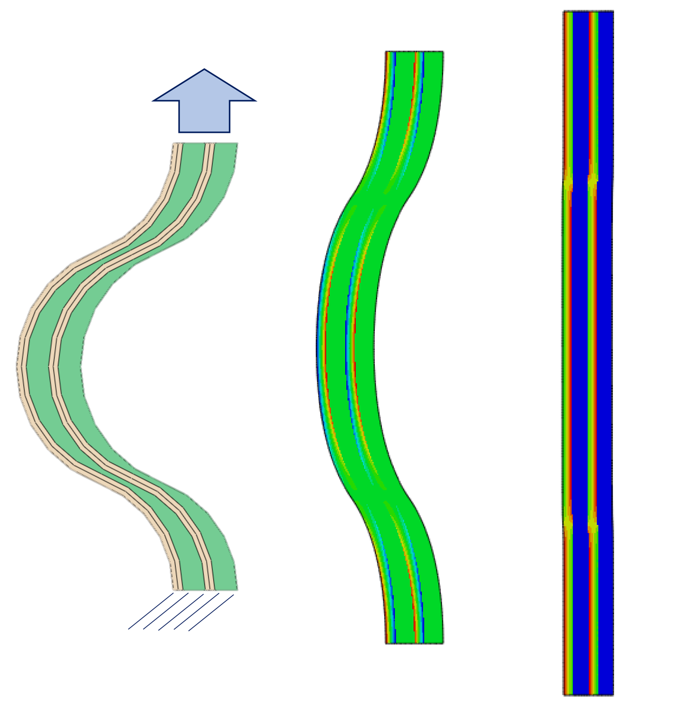
Influence of the strain rate



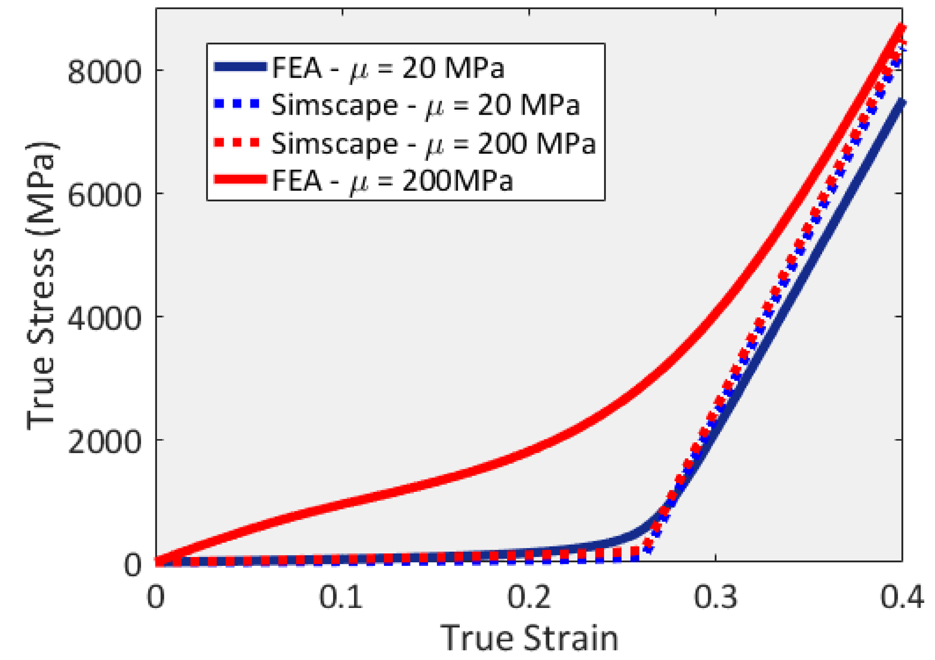
Modeling Interactions Between Components

Periodic Representative Volume Element in tension (Abaqus Finite Element Model)

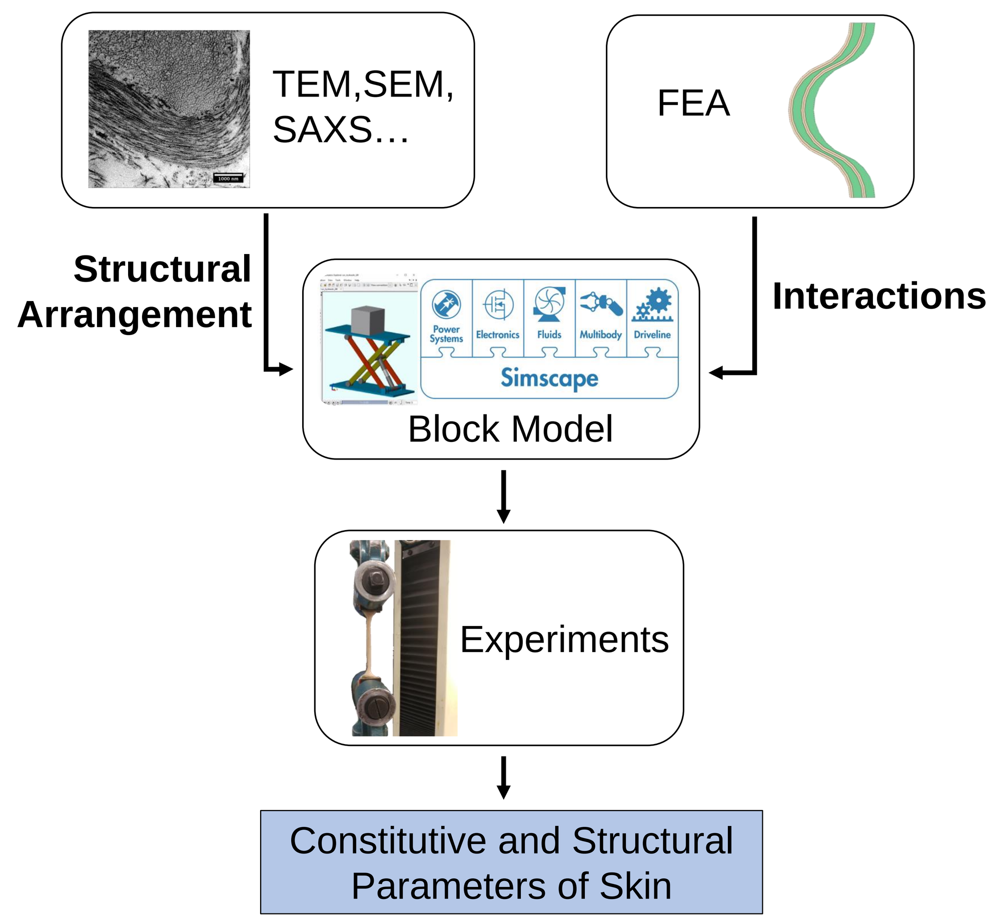
- Crimped Collagen Fibers spaced apart with a given distance
- Embedded in a hyperelastic matrix



Averaged Stress vs. Strain in the RVE for different values of μ (E=200GPa)



Conclusions and Future Work



- In the block model, elements can be easily rearranged, modified.
- Resolution is very fast with the Parameter Estimation Module
- Can be applied to a broad range of loading conditions
  - Strain Rate Sensitivity
  - Stress Relaxation & Creep
  - Cyclic Loading
- Limited to uniaxial tests
- Necessity to better understand the structural arrangement in the dermis → TEM, SEM, Confocal Imaging…
- Some more in-depth energy dissipative processes can be added
  - -Friction
  - -Shear-Lag [10]
  - -Damage evolution [11,12]
  - → FEA, Molecular Dynamics.

Acknowledgements

Support from a Multi-University Initiative through the Air Force Office of Scientific Research (AFOSR-FA9550-15-1-0009) to the University of California Riverside with a subcontract to the University of California San Diego.

References

[1] G. J. Tortora, B. Derrickson, Principles of Anatomy and Physiology, John Wiley and Sons, Inc., 2009.
[2] W. Li, Biomed. Eng. Lett. 5 (2015) 241–250.
[3] G. Limbert, Proc. R. Soc. A Math. Phys. Eng. Sci. 473 (2017)
[4] https://www.mathworks.com/products/simscape ; [5] https://www.astm.org/Standards/D412; [6] http://ncorr.com
[7] J.W.Y. Jor, M.P. Nash, P.M.F. Nielsen, P.J. Hunter, Biomech. Model. Mechanobiol. 10 (2011) 767–778.
[8] R. Meijer, L.F. a. Douven, C.W.J. Oomens, Comput. Methods Biomech. Biomed. Engin. 2 (1999) 13–27
[9] W. Yang, V.R. Sherman, B. Gludovatz, E. Schaible, P. Stewart, R.O. Ritchie, M.A. Meyers, Nat. Commun. 6 (2015) 6649.
[10] S.E. Szczesny, D.M. Elliott, Acta Biomater. 10 (2014) 2582–2590
[11] W. Li, X.Y. Luo, Ann. Biomed. Eng. 44 (2016) 3109–3122.
[12] M.B. Rubin, S.R. Bodner, Int. J. Solids Struct. 39 (2002) 5081–5099