A Biomechanical Properties Overview of Skin and Muscle Tissue

Literature review
by
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Outline

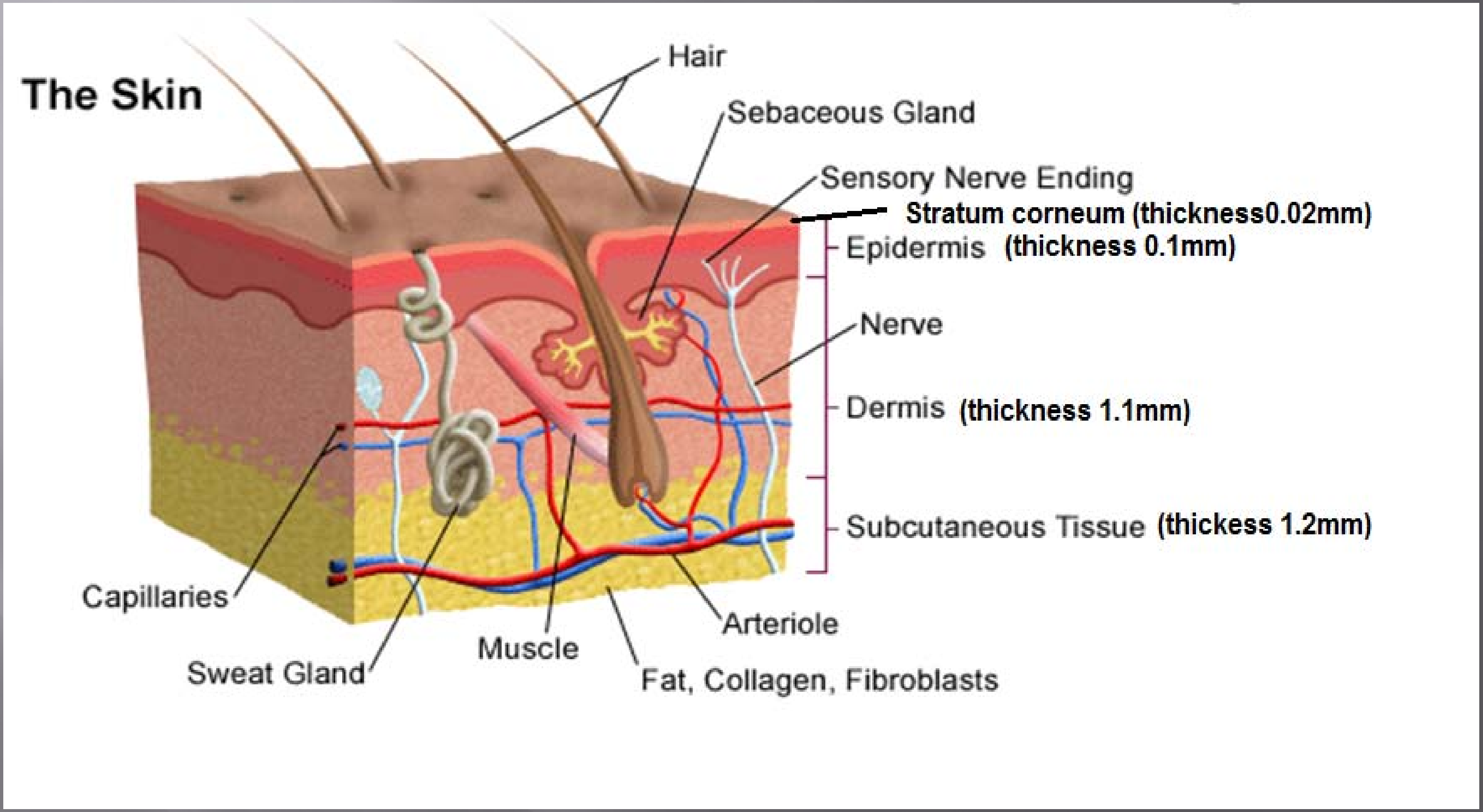
- Skin
  - Skin functionalities / Skin anatomy
  - Mechanical properties of skin
  - Basic properties of collagen and elastin
  - Viscoelastic properties of skin
    - Viscous and elastic spring constants
  - Finite element modeling of skin deformation
  - Skin mechanical properties measuring devices
    - Suction and torsion devices
  - Skin mechanical failure
    - Hypertrophic scar tissue
    - Stretch mark tissue
  - Tissue engineering
  - Animal skin mechanics
    - Rhinoceros and eel skin material properties
- Muscle tissue: skeletal muscle, cardiac muscle, and smooth muscle
  - Hierarchical organization of skeletal muscle
  - Hills functional model
  - Cardiac mechanics
  - Mechanical properties of smooth muscle

Skin functionalities

- Heaviest single organ of the body (16% of total body weight)
- 1.2-2.3 m^2 of surface area contacting external environment
- Skin on the back is 4mm thick and scalp skin is 1.5mm thick
- 3 major layers: epidermis, dermis, and hypodermis layer
- Epidermis layer's mechanism- prevent water loss, thermal control, and UV protection
- Skin is heterogeneous, anisotropic and a non-linear viscoelastic material

Ross, Michael. Histology: A text and Atlas. Pensylvania: Wojciech Pawlina, 2003.

Skin anatomy



http://cancer.stanford.edu/information/cancerDiagnosis/images/ei_0390.gif

Epidermis

- Keratinocyte: are structural protein components, they play a role in forming the epidermal wall barrier
- Langerhans': are antigen-producing cells in the epidermis layer
- Melanocyte: produces melanin (pigments in skin)
- Merkel's cell: cells in the epidermis layer which relates to sensory in skin

Ross, Michael. Histology: A text and Atlas. Pensylvania: Wojciech Pawlina, 2003.

Dermis

- A proteoglycan matrix
- Collagen fibers (type I and type III): are responsible for mechanical properties of skin
- Elastic fibers: giving elasticity of skin
- Blood vessels: providing oxygen and nutrients
- Nervous system : having sensory purpose

Ross, Michael. Histology: A text and Atlas. Pensylvania: Wojciech Pawlina, 2003.

Mechanical properties of skin

- Depends on the nature and organization of:
  - Dermal collagen and elastic fibers network
  - Water, proteins and macromolecule embedded in the extracellular matrix
  - with less contribution by epidermis and stratum corneum

Agache P, “ Mechanical properties and Young’s modulus of human skin in vivo”, Arch Dermatol Res 1980: 269: 221-232

Collagen molecules

- 300 nm long and 1.5 nm in diameter
- Tropocollagen triple helix- consist of three polypeptide strands
- Quaternary structure (stabilized by hydrogen bonds)
- 29 types of collagen
- E along fiber ~ 1000 MPa
- UTS ~ 50-100 MPa

http://en.wikipedia.org/wiki/Collagen

Fung, Y.C, " Biomechanics: mechanical properties of living tissue" 2nd ed. Springer(1993)

Types of collagen

- Collagen I: skin, tendon, vascular, ligature, organs, bone (main component of bone)
- Collagen II: cartilage (main component of cartilage)
- Collagen III: reticulate (main component of reticular fibers), commonly found alongside type I.
- Collagen IV: basis of cell basement membranes
- Collagen V: Cells surfaces, hair and placenta

Elastin

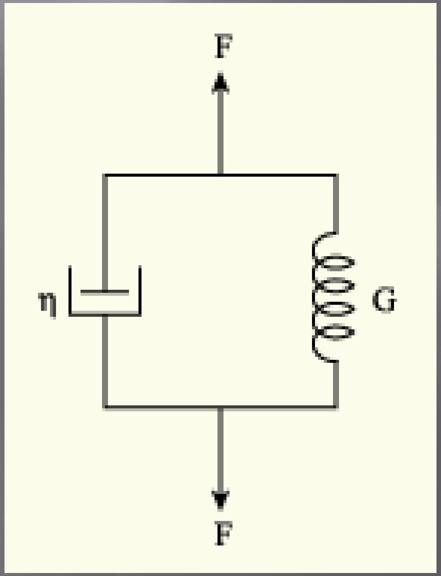
- Protein fibrillin and amino acids (glycine, valine, alanine, and proline)
- Providing elasticity- tissue are able to retract back to its shape after deformation
- Location- blood vessels (Windkessel effect), lungs, skin, bladder and elastic cartilage…
- E ~ 0.6 MPa

http://en.wikipedia.org/wiki/Elasin

Fung, Y.C, “ Biomechanics: mechanical properties of living tissue” 2nd ed. Springer(1993)

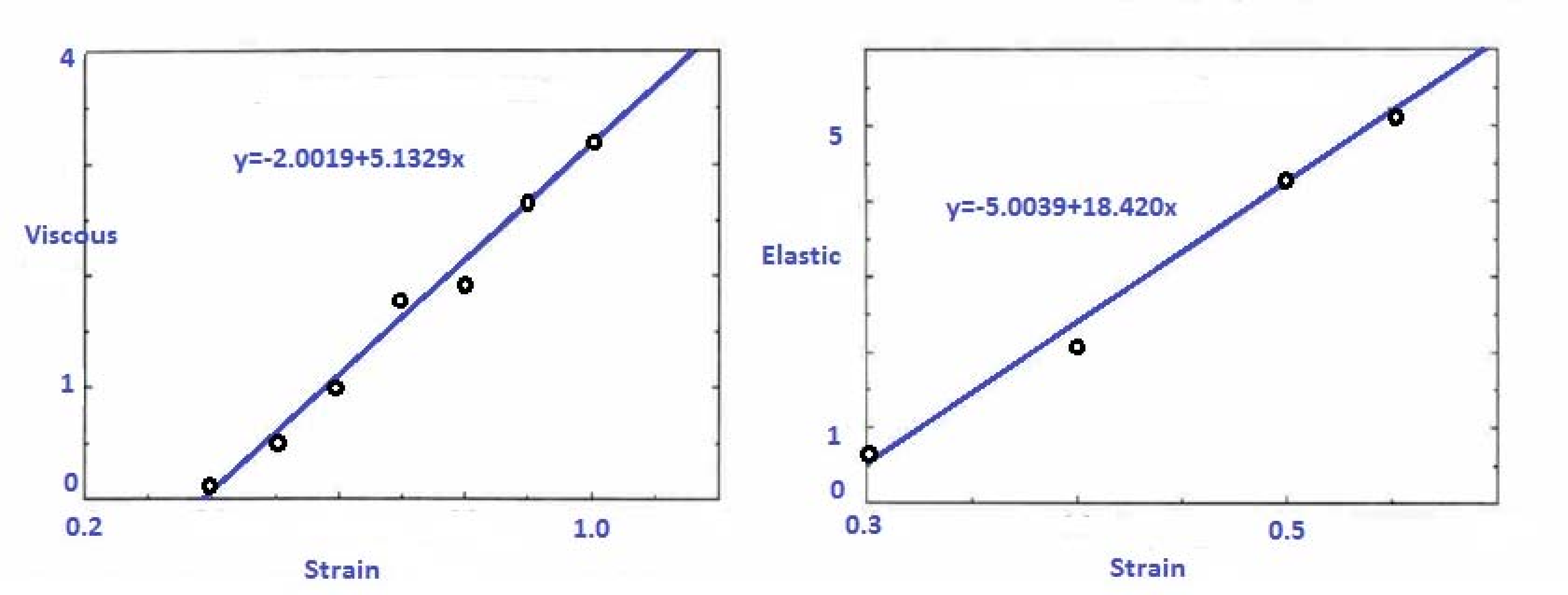
Viscoelasticity

- Skin exhibit both viscous and elastic characteristics when undergoing deformation



http://en.wikipedia.org/wiki/Viscoelasticity

Viscoelastic properties of skin



Mechanical behavior of skin and tendon are different!
This is due to differences in collagen types self-assembly, i.e. tilt angle of collagens (orientation), fiber length, volume fraction of the Fibers, collagen molecular stretching

Silver, " Viscoelastic properties of human skin and processed dermis", Skin research and technology 2001:7:18-23

Elastic and viscous spring constants

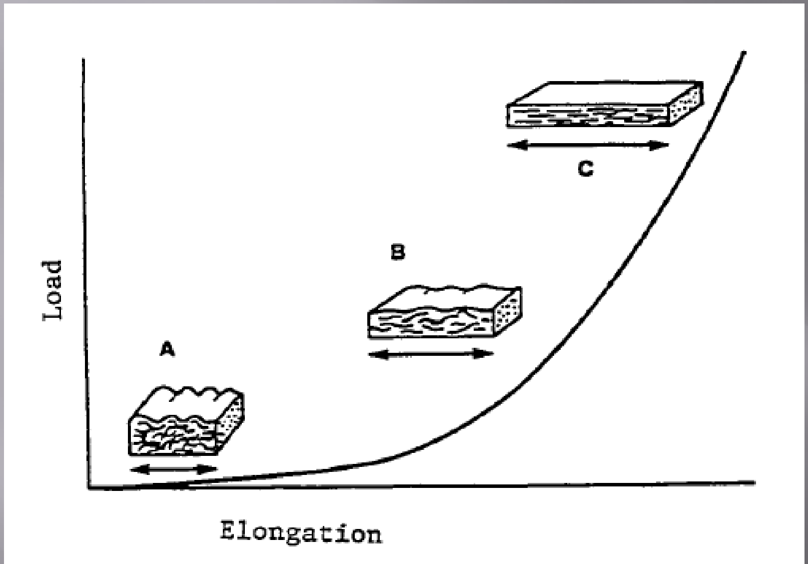
TABLE 1. Slopes of the incremental stress-strain curves

Sample	Slopes (MPa)			Fibril length (μm)
	Initial elastic	Final elastic	Viscous	
Human skin	0.10	18.8	5.13	54.8
Alloderm®	0.10	18.4	7.05	63.7
Processed dermis	0.10	17.6	4.35	48.8

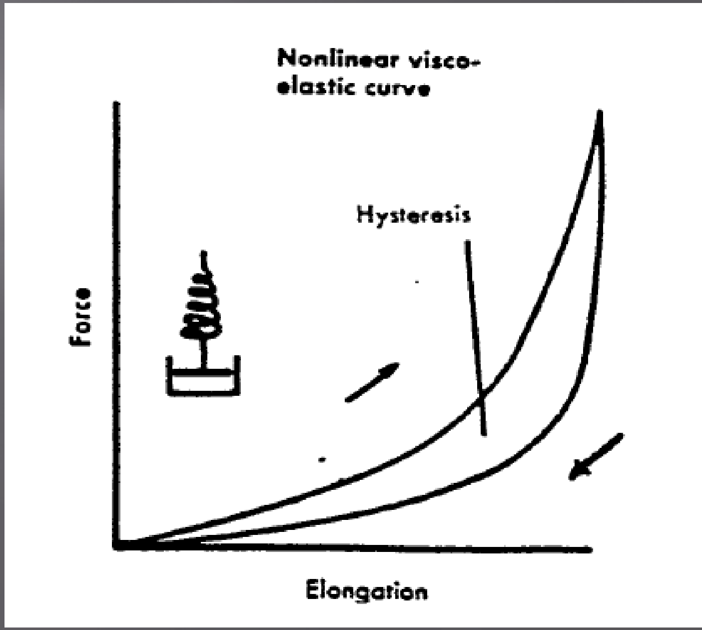
* Calculated using a fibril diameter of 80 nm.

Silver, " Viscoelastic properties of human skin and processed dermis", Skin research and technology 2001:7:18-23

Skin stretching mechanics

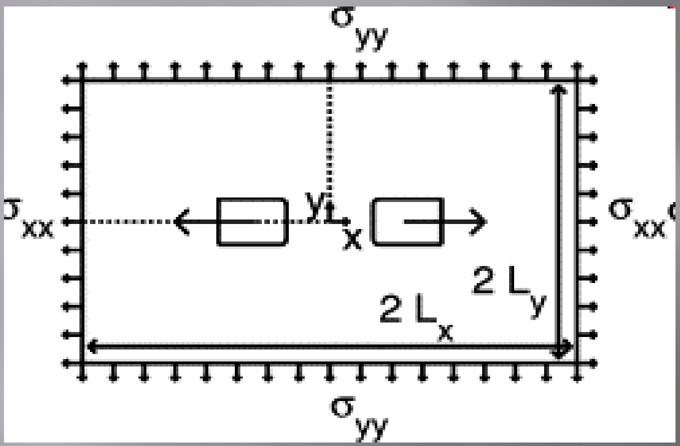


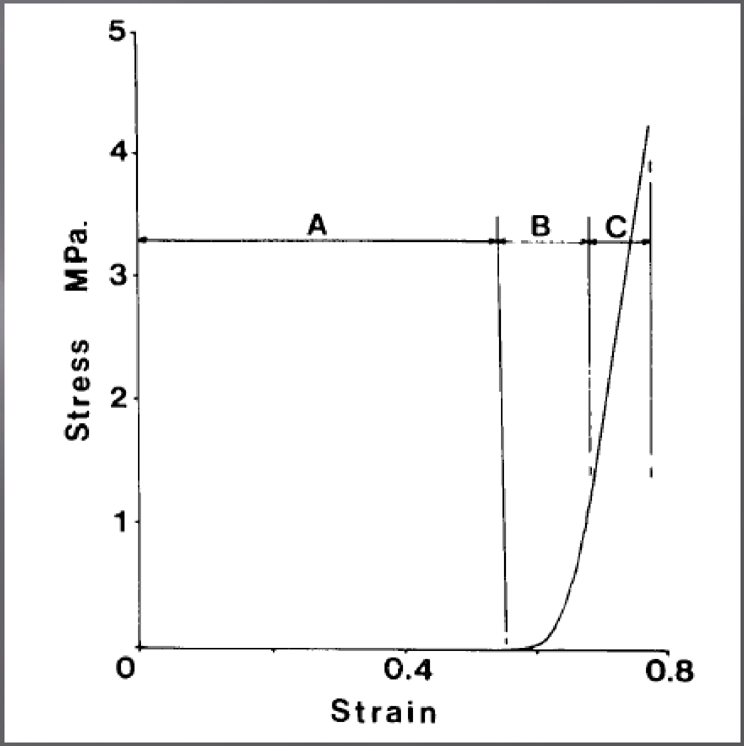
- Upon stretching, collagen fibers straightens and realign parallel to one another

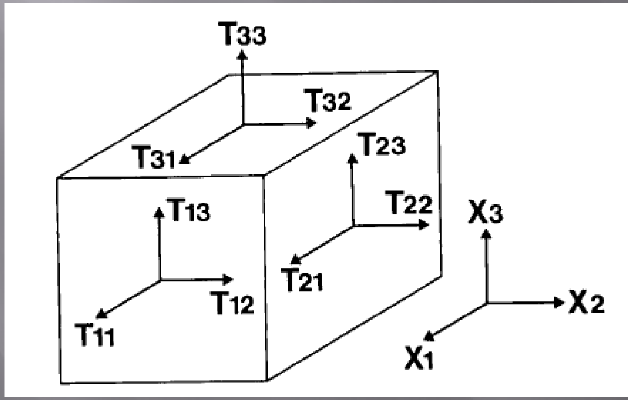


- Skin has non-linear viscoelastic properties
- Skin exhibit hysteresis loop effect with energy loss when deformation occurs
- Creep is a skin mechanical failure- the result of water molecules displacement from collagen fibers network

Finite element modeling of skin deformation







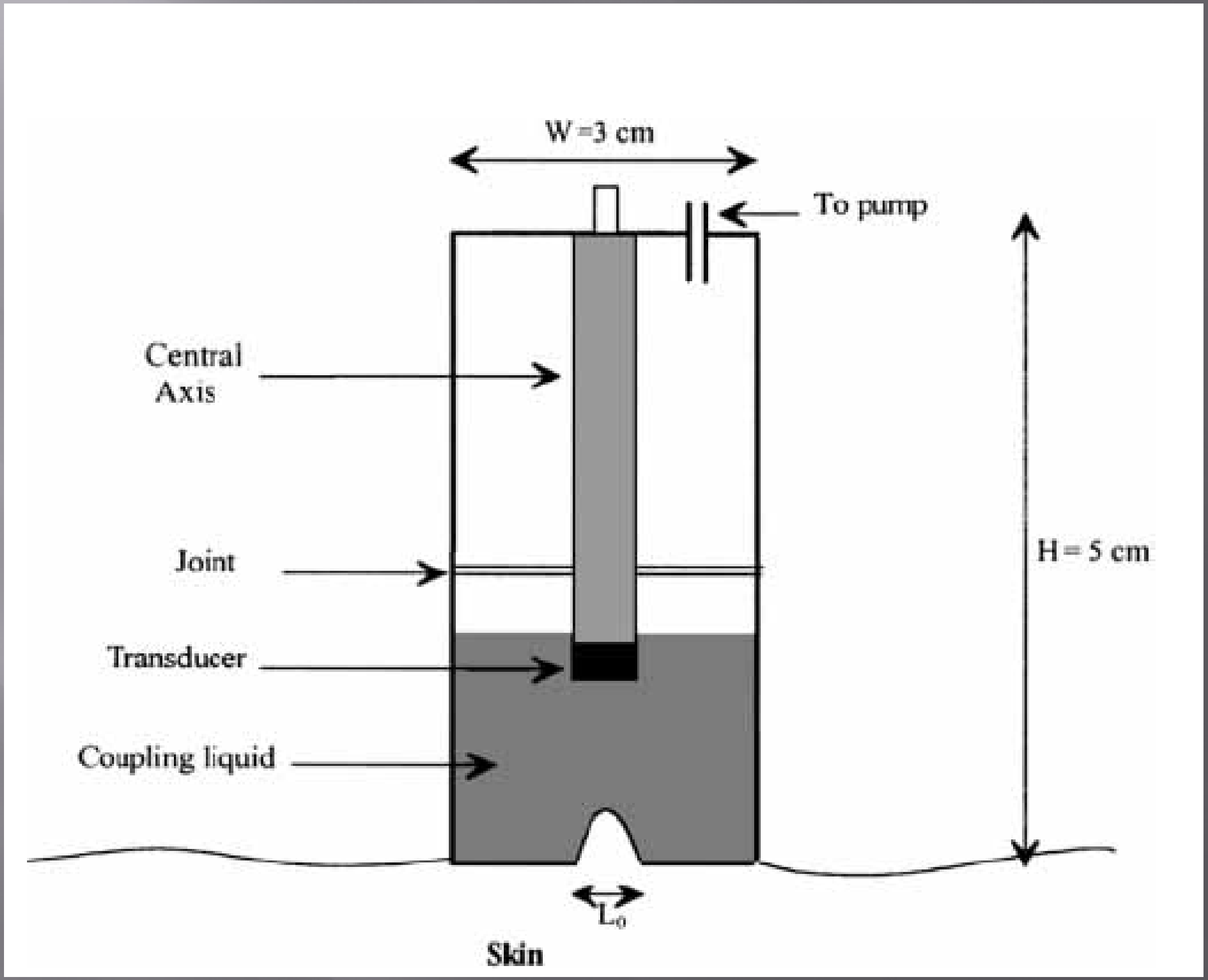
Bischoff, Jeffrey, “Finite element modeling of human skin using isotropic, nonlinear elastic constitutive model”, Journal of Biomechanics

Mechanical properties of skin

- Measuring devices
  - suction system
  - torsion device

Agache P, “ Mechanical properties and Young’s modulus of human skin in vivo”, Arch Dermatol Res 1980: 269: 221-232

Suction device setup

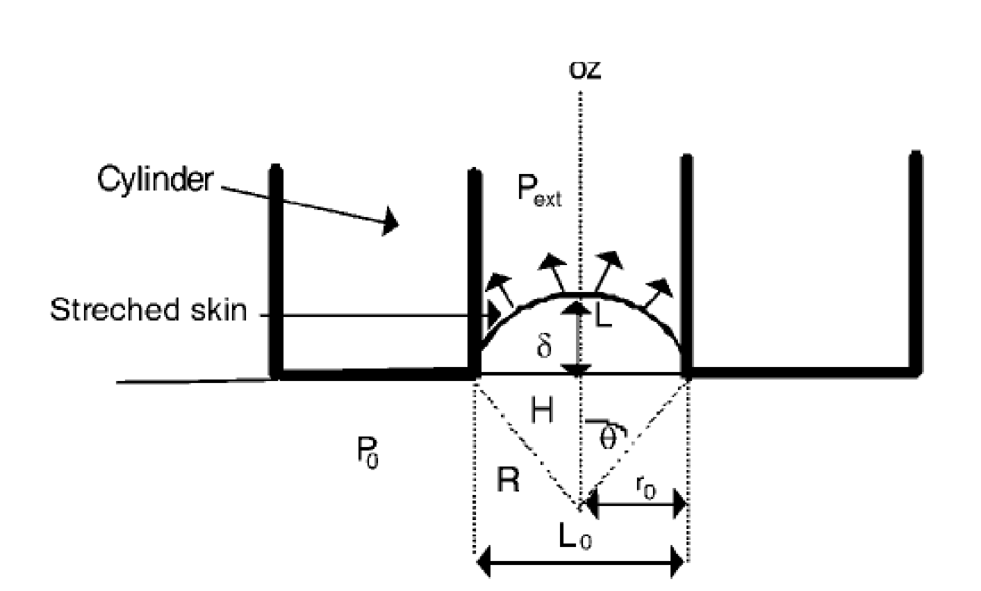


Diridollou S., “In vivo model of the mechanical properties of the human skin under suction”, Skin research and technology (2000) , Vol 6: 214-221

Law of Laplace

- Assumptions: skin is an isotropic elastic membrane and the geometry of deformation is a portion of a sphere

$$\sigma = \frac{\Delta P r_0}{2t}$$



σ – circumferential stress

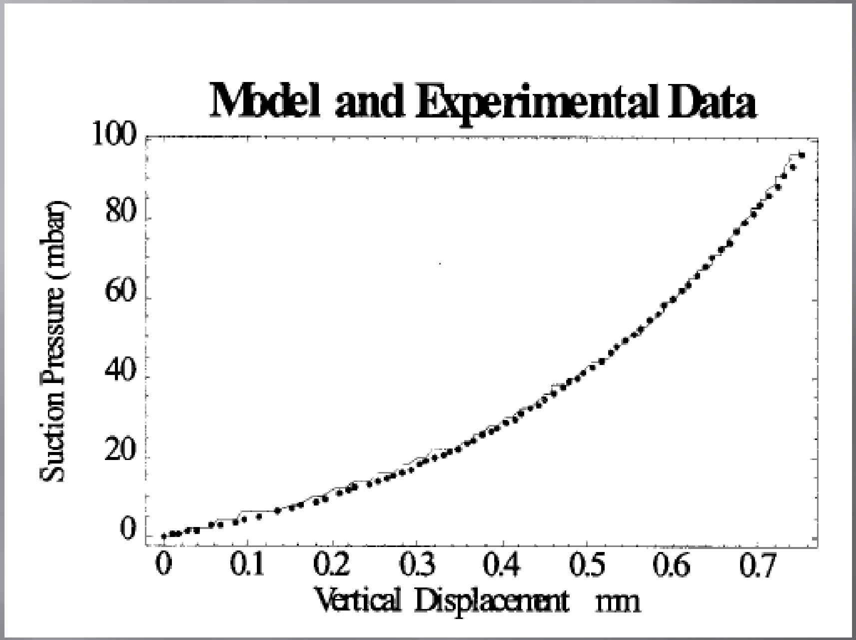
$\Delta P = (P_{ext} - P_0)$

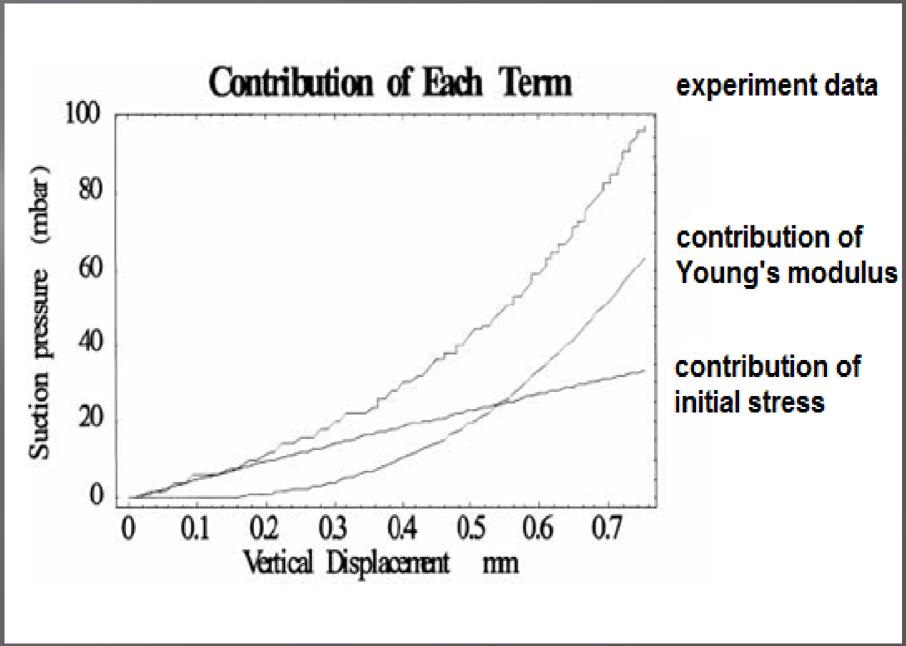
r_0 = inner radius of the sphere

t - thickness of the skin

Diridollou S., "In vivo model of the mechanical properties of the human skin under suction", Skin research and technology (2000) , Vol 6: 214-221

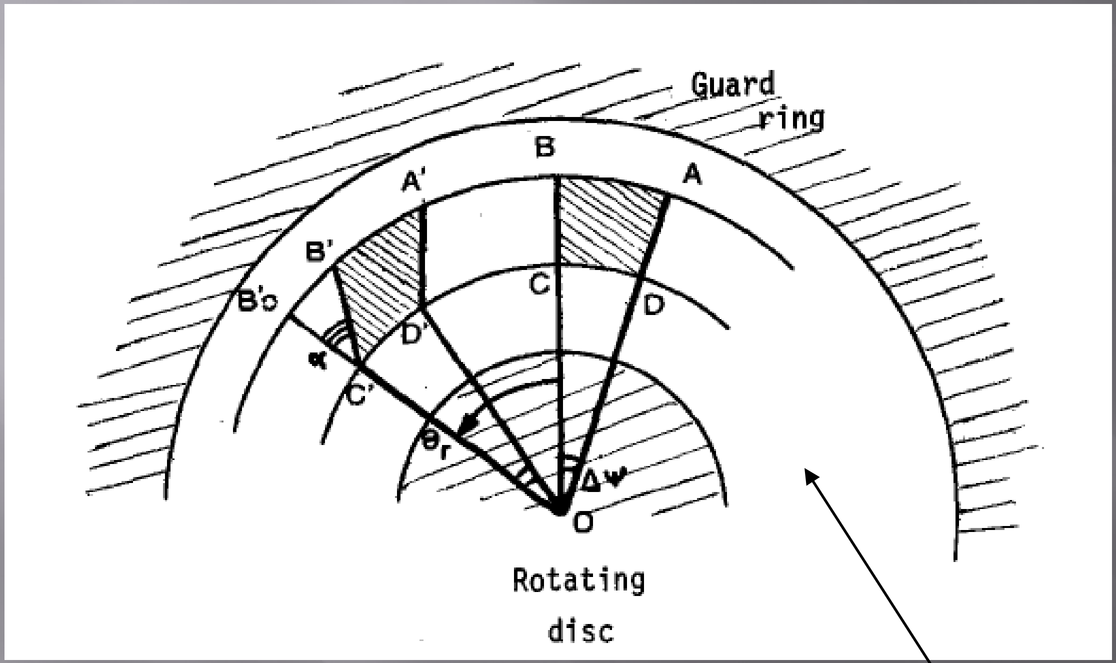
Suction pressure vs. vertical displacement





Diridollou S., “In vivo model of the mechanical properties of the human skin under suction”, Skin research and technology (2000) , Vol 6: 214-221

Torque application: elasticity measurement



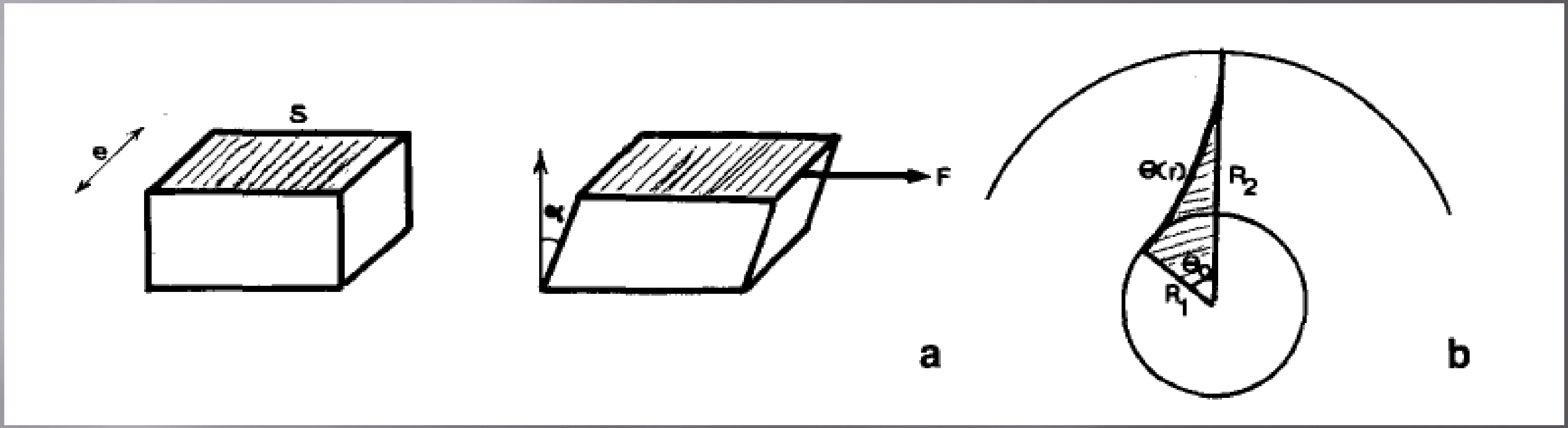
Skin

1. Fixture on skin
2. Twist of 2-6 degrees
3. Measure radial displacement
4. Applied load is approximately

   28.6 $*10^{-3}$ N

Agache, P.G, "Mechanical Properties and Young's Modulus of Human Skin in Vivo", Journal of Dermatological Research

Volumetric deformation



Agache, P.G, “Mechanical Properties and Young’s Modulus of Human Skin in Vivo”, Journal of Dermatological Research

Burn patients

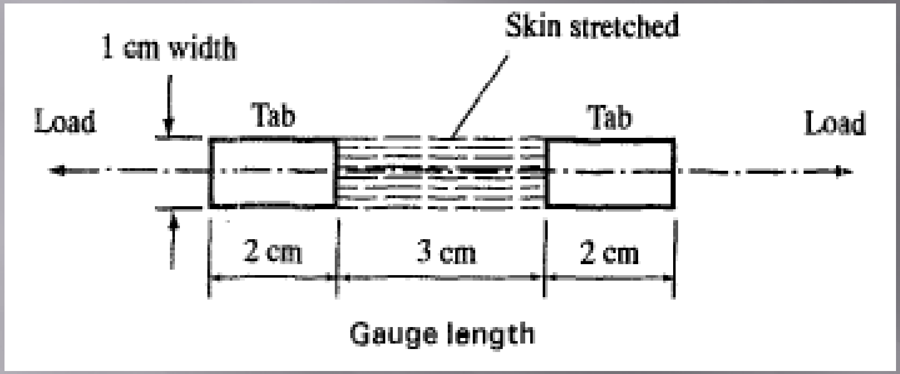
- First-degree of burns: damage on epidermis layer
- Second-degree of burns: papillary dermis layer (hypertrophic scarring)
- Third-degree of burns: reticular dermis layer
- Forth-degree of burns: subcutaneous layer (needs skin graft)

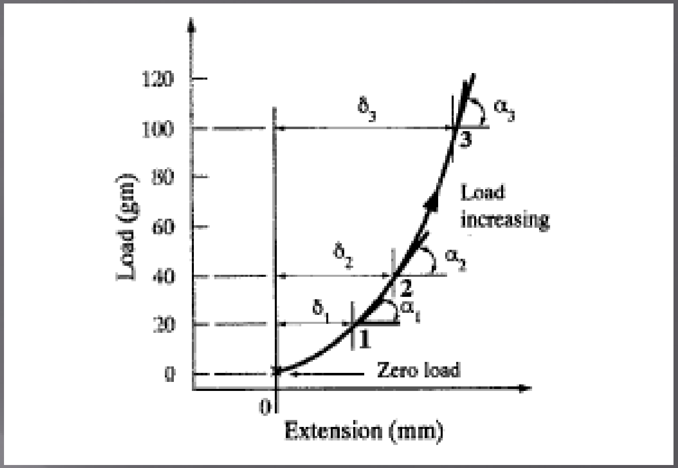
Hypertrophic scars

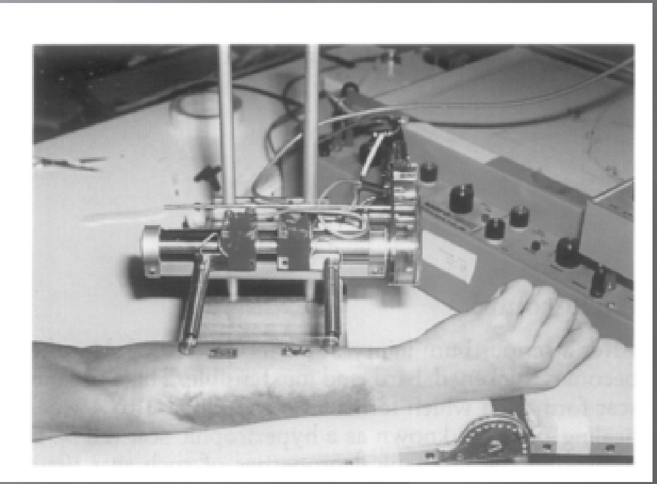
- Scars tissue are usually thickened and inextensible
- Pressure therapy to progressively softening and thinning of the scar tissue
- Applied pressure ranges from 10 mmHg to 35 mmHg
- Stimulate and remodel the scar tissue

Clark, J. A, “Mechanical properties of normal skin and hypertrophic scars”, Burns 1996: Vol. 22: p443-446

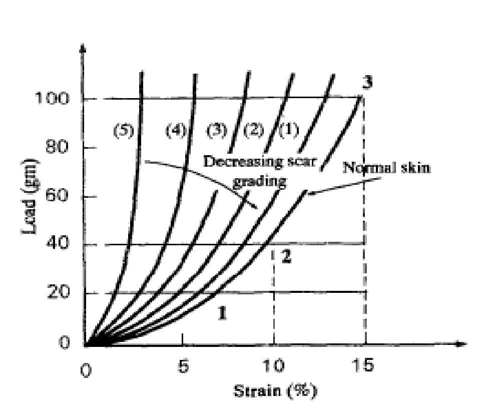
Pressurized hypertrophic scars





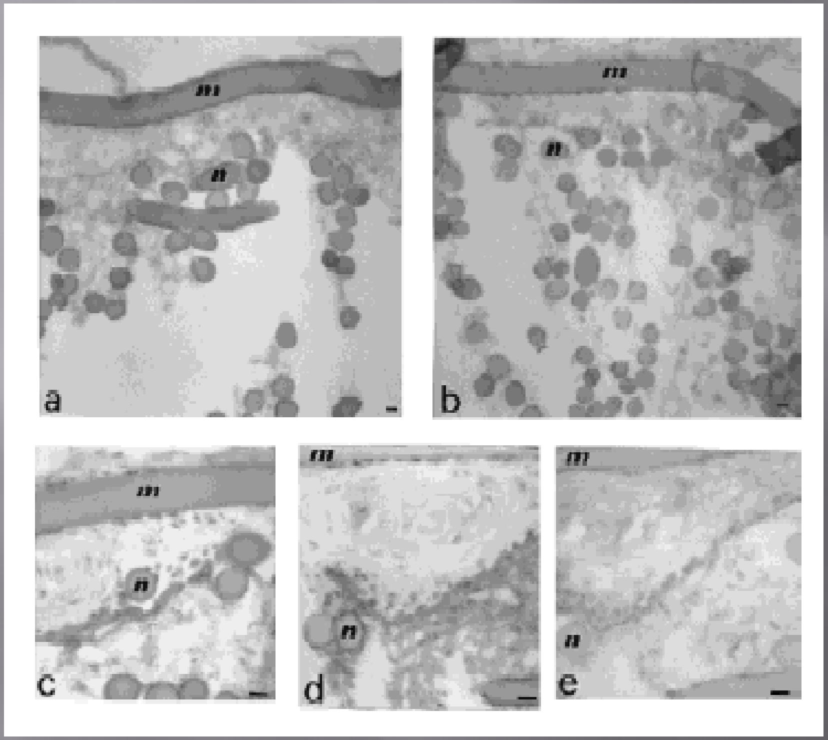


Uniaxial loading device



Clark, J. A, "Mechanical properties of normal skin and hypertrophic scars", Burns 1996: Vol. 22: p443-446

In vitro engineering of human skin-like tissue



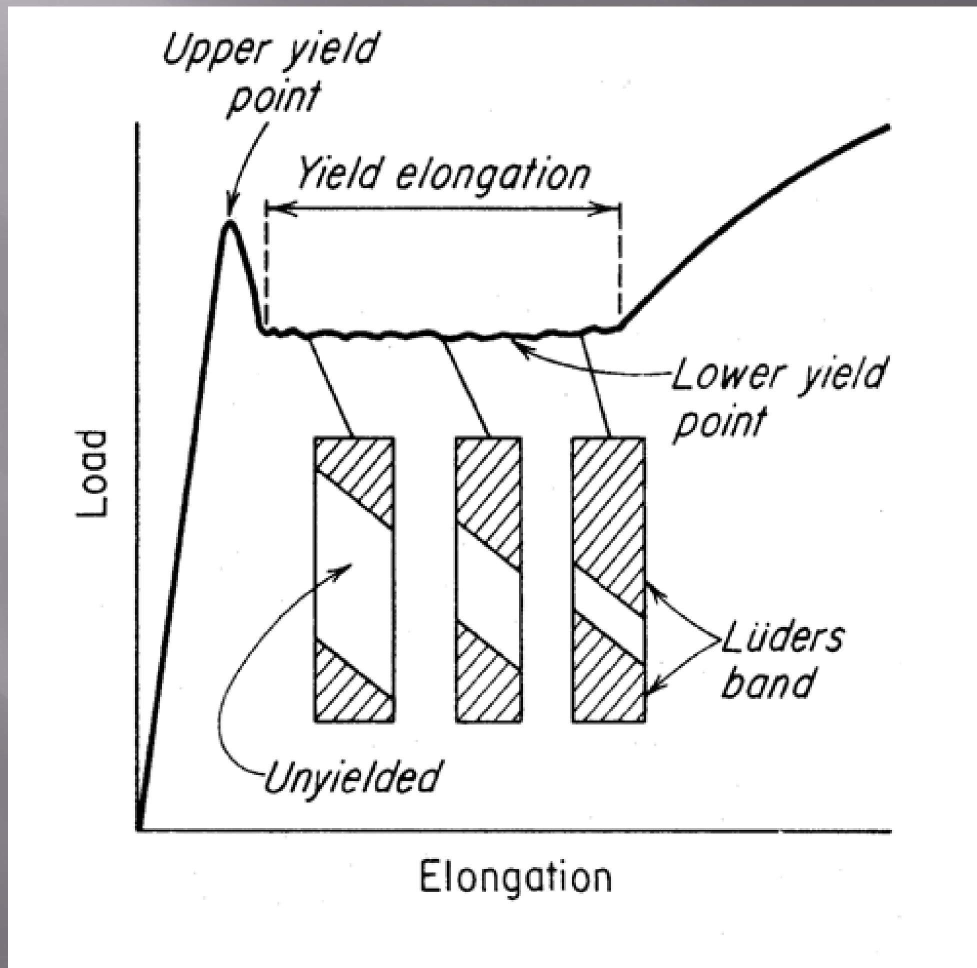
Scaffold's biomaterial: hyaluronan with benzyl ester

cells: Fibroblast-keratinocytes were obtained from epidermis by trypsin digestion.

Results: fibroblasts seeded inside the three dimensional structure, they are able to adhere, proliferate, and secrete main ECM ingredients. They observed basement membrane between epithelial and dermal layer.

Zacchi, Valentina, " In vitro engineering of human skin-like tissue", J Biomed Mater Res. 1998 May; 40(2): pp.187-94

Lüders band in Striae distensae

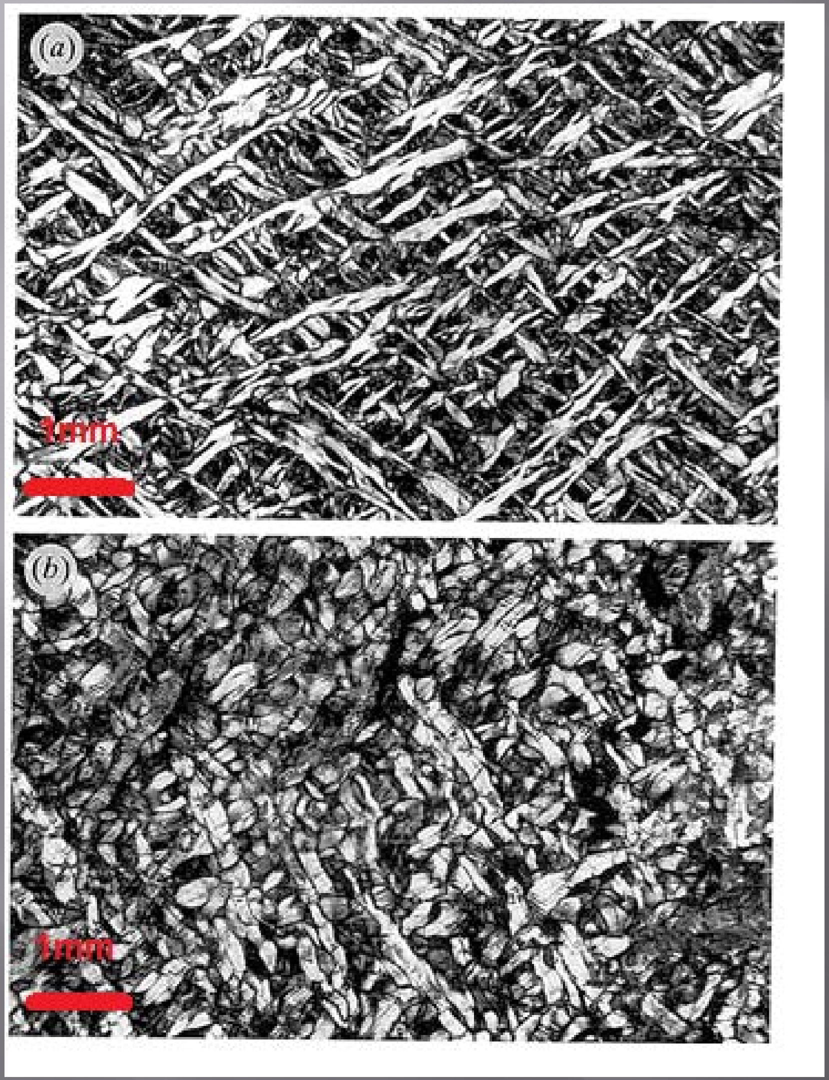


Studies of rhinoceros skin

- Collagenous dermis- thick and protective
- showing off: a dense and highly ordered three dimensional array of straight and highly crosslinked collagen fibers
- High impact resistance
- Steep stress-strain curve
- High elastic young's modulus of 240MPa
- Tensile strength of 30MPa
- High breaking energy: $3MJm^{-3}$
- Work of fracture: $78kJm^{-2}$
- As a biological material, material properties is in between a cat and a human tendon

http://school.digitalbrain.com/school/web/rhino.jpg
Shadwick, Robert. " The structure and mechanical design of rhinoceros dermal armour", Phil. Trans. R. Soc. Lond. B (1992): 337, pp. 419-428

Skin histology of rhino



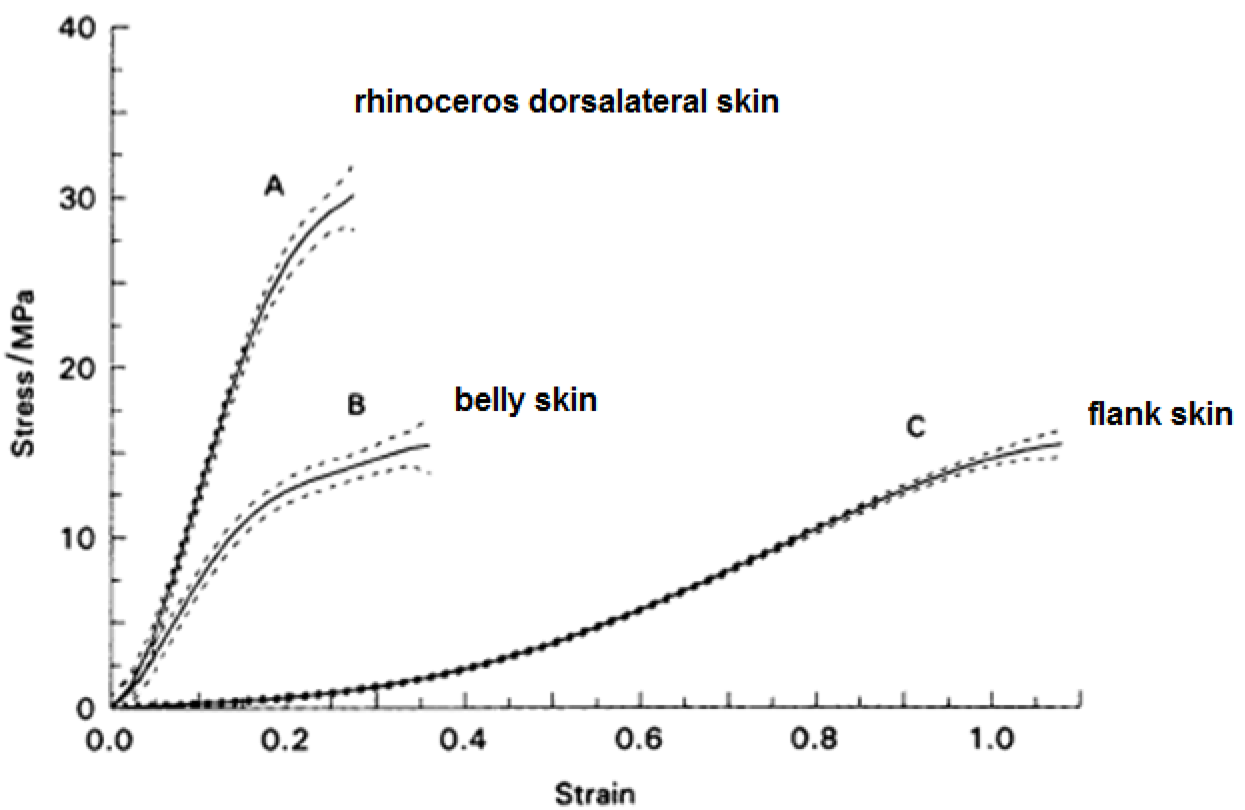
- Polarized light micrographs of transverse sections of white rhinoceros skin showing collagen fibers in the deep dermis (a) the flank (b) the belly

- Highly crosslinked of fiber network for flank region skin

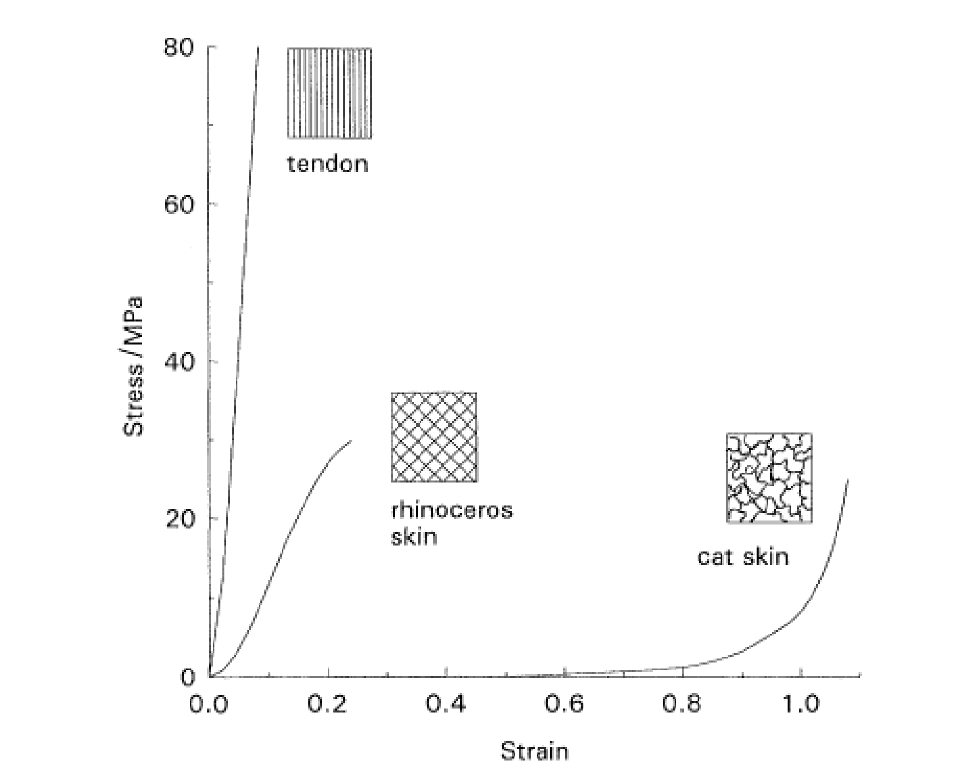
- Fibers are relatively straight and averages around 90 μm in diameter

Shadwick, Robert. " The structure and mechanical design of rhinoceros dermal armour", Phil. Trans. R. Soc. Lond. B (1992): 337, pp. 419-428

Stress–strain curves of mechanical tests



Tensile properties according to arrangement of collagen fibers



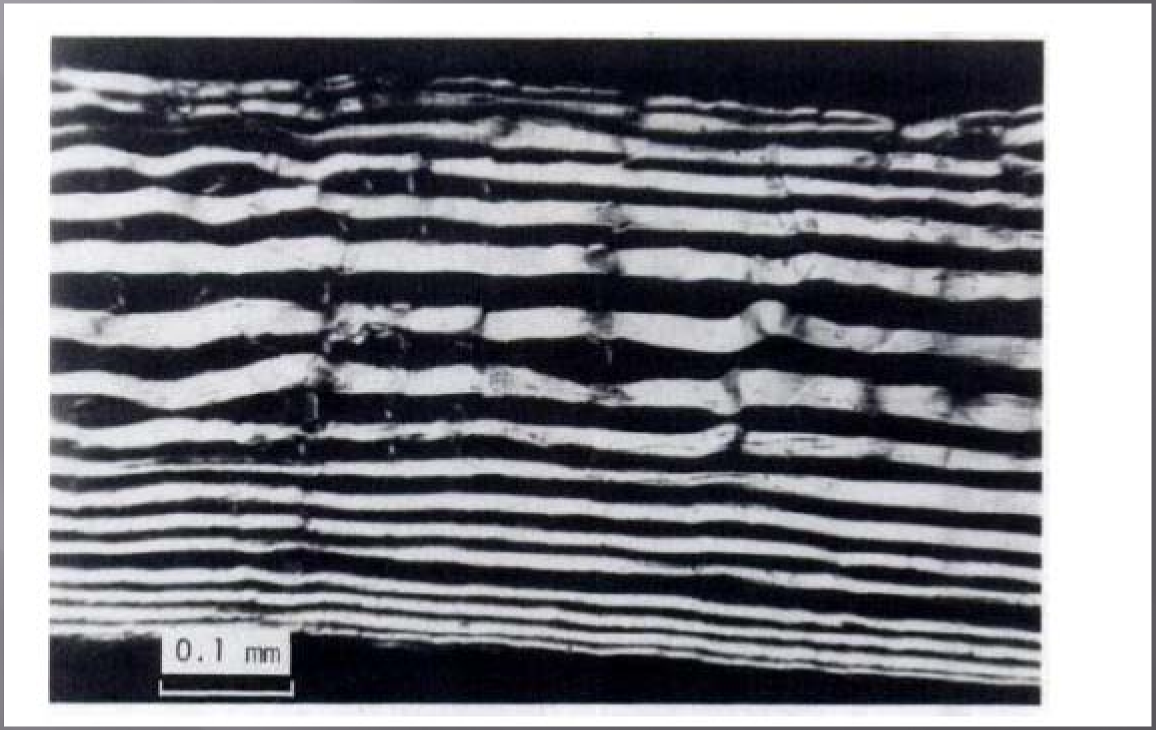
Shadwick, Robert," The structure and mechanical design of rhinoceros dermal armour", Phil. Trans. R. Soc. Land. Vol. B (1992)

Mechanics of eel skin

- Skin can adjust to environment for protection
- Secret mucus to assist in harsh weather
- Used as door hinges (in Scandivia)
- Changes its shape to be flexible for necessary locomotion
- A system of collagen fibers in skin allow for shape changes

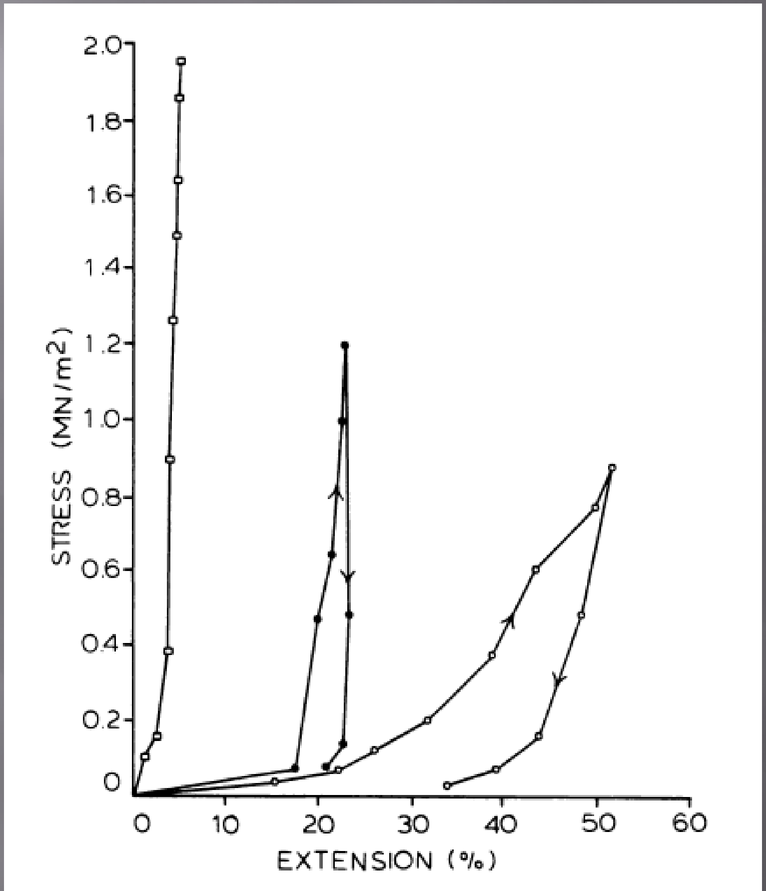
Herbrank, M. R., “ Mechanical properties and locomotor functions of eel skin”, the Biological Bulletin 1980 (158): 58-68

Micrograph image of eel skin



Herbrank, M. R., “ Mechanical properties and locomotor functions of eel skin”, the Biological Bulletin 1980 (158): 58-68

Stress-strain curves for eel skin



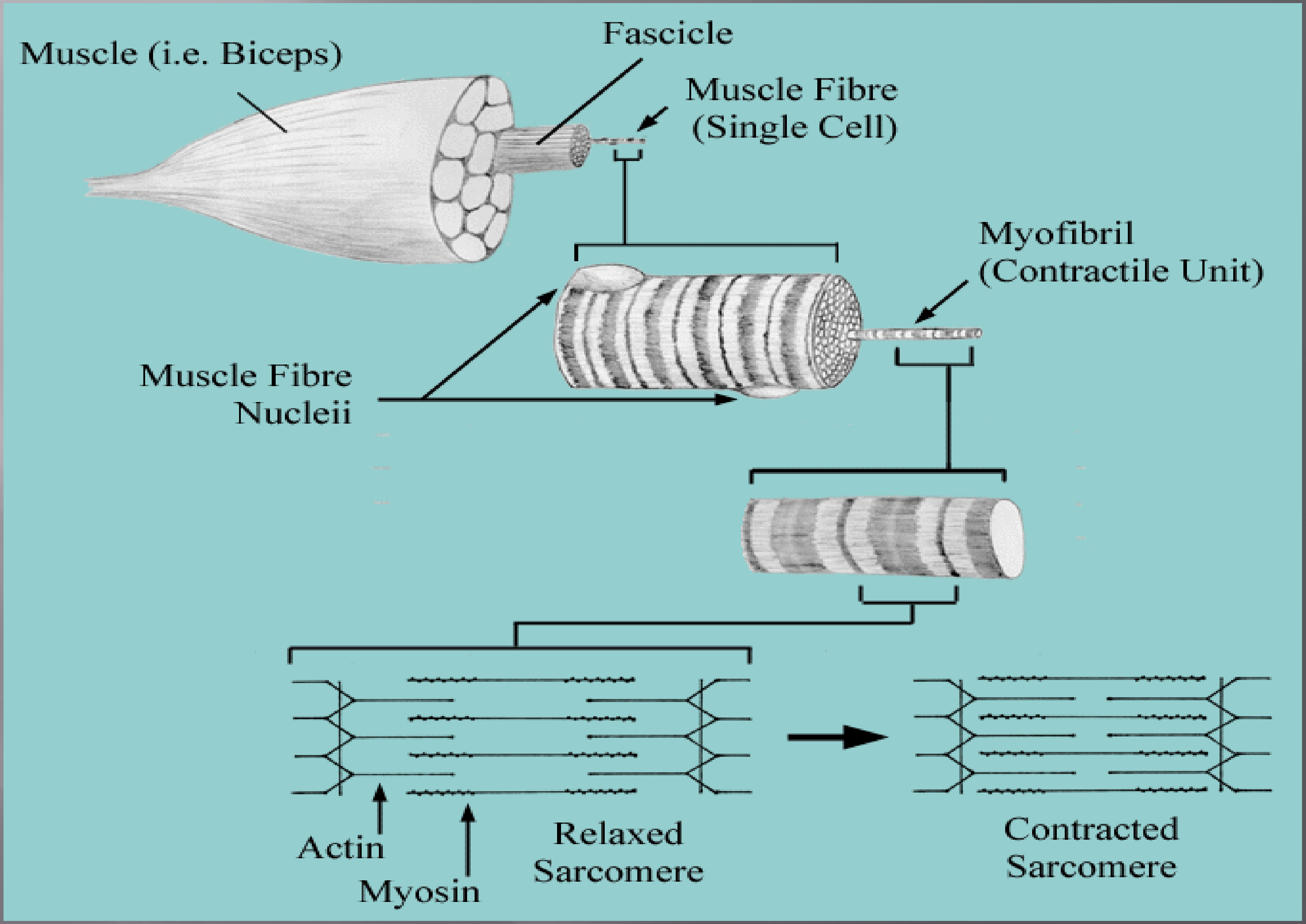
Herbrank, M. R., “ Mechanical properties and locomotor functions of eel skin”, the Biological Bulletin 1980 (158): 58-68

Muscle Tissue

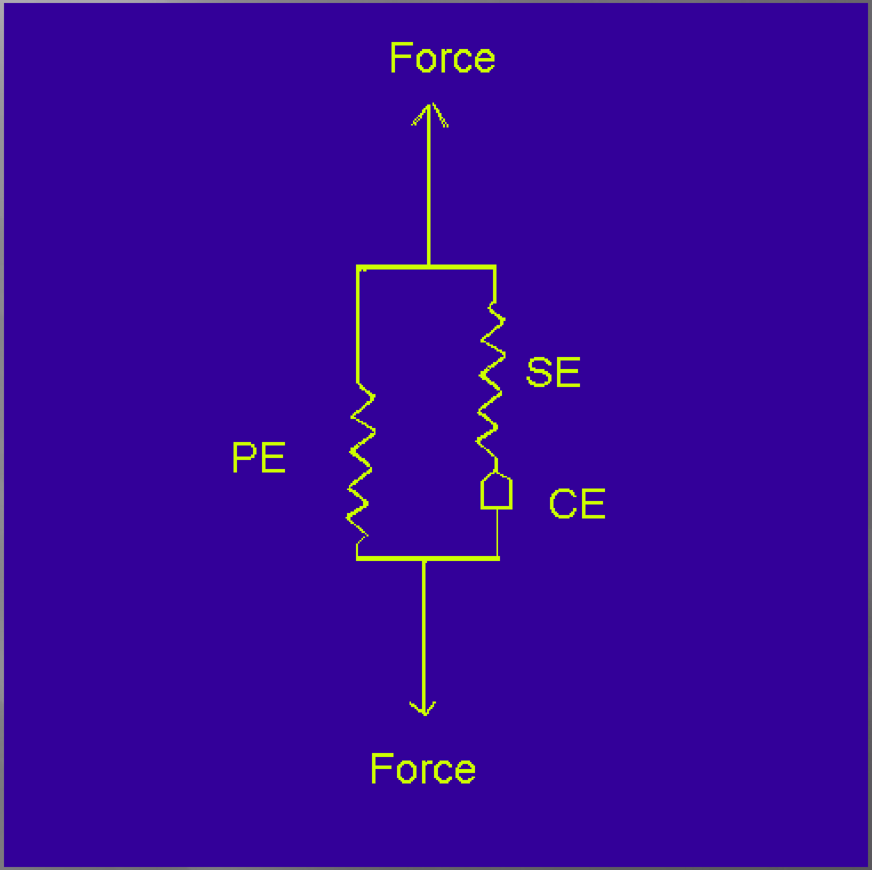
- Purpose: movement of the body and for deformation /undeformation of internal organs

	Skeletal	Cardiac	Smooth
Muscle cell	Large, elongated cell, 10-100 µm in diameter, up to 100 µm in length	Short, narrow cell, 10-15 µm in diameter, 80-100 µm in length	Short, elongated cell, 0.2-2 µm in diameter, 20-200 µm in length
Location	Muscle of skeleton (e.g. tongue, esophagus, diaphragm)	Heart, vena cava, pulmonary veins	Vessels, organs
Fiber	Single skeletal muscle cell	Linear, branched arrangement	Single smooth muscle cell
Types of contraction	"All or none"	"All or none"	Slow, partial, rhythmic

Skeletal muscle tissue

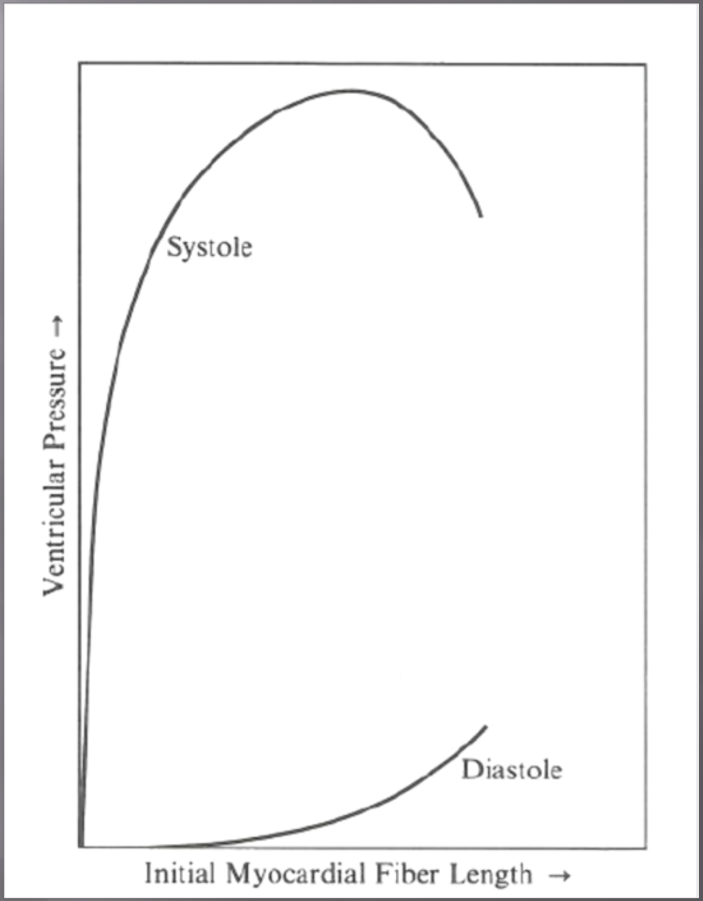


Hill's functional model of the muscle



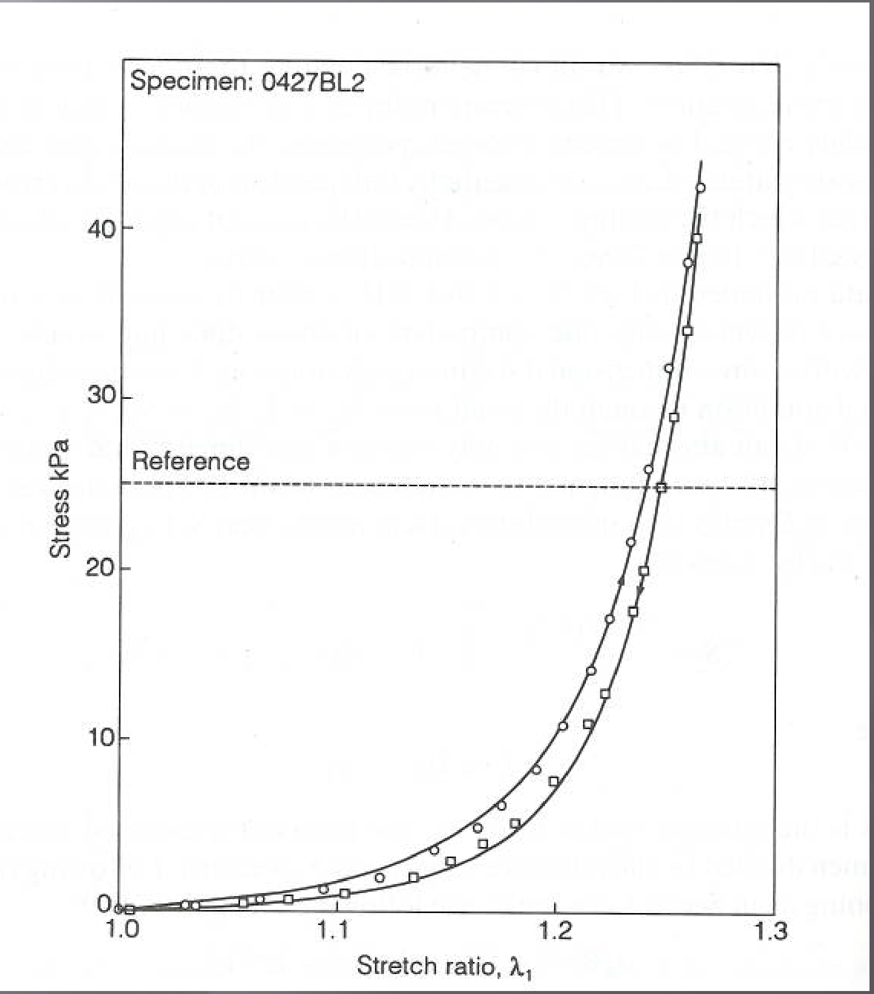
http://www.sghurol.demon.co.uk/urod/ce.gif

Cardiac Mechanics



Fung, Y.C, “ Biomechanics: mechanical properties of living tissue” 2nd ed. Springer(1993)

Mechanical properties of blood vesssel



Fung, Y.C, " Biomechanics: mechanical properties of living tissue" 2nd ed. Springer(1993)

Conclusion

- Skin is multilayered and has different mechanical properties in each layer
- Collagen fibers and elastic fibers arrangement give out different material properties
- Applying mechanical stimuli to skin changes material properties
- Skin tissue engineering can be done
- Animals have their unique properties of different kind of skin tissue
  - Rhinoceros has a strong impact resistance skin
  - Eel has an flexible skin which can change due to environment

Acknowledgements

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- Dr. Po-Yu Chen
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Thank you for your attention!