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 m² 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

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

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

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

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 $\sim 1000$ MPa
- $UTS \sim 50-100$ MPa

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

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/Elasint

Viscoelasticity

- Skin exhibit both viscous and elastic characteristics when undergoing deformation

http://en.wikipedia.org/wiki/Viscoelasticity
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>
<thead>
<tr>
<th>Sample</th>
<th>Slopes (MPa)</th>
<th>Fibril length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial elastic</td>
<td>Final elastic</td>
</tr>
<tr>
<td>Human skin</td>
<td>0.10</td>
<td>18.8</td>
</tr>
<tr>
<td>AlloDerm®</td>
<td>0.10</td>
<td>18.4</td>
</tr>
<tr>
<td>Processed dermis</td>
<td>0.10</td>
<td>17.6</td>
</tr>
</tbody>
</table>

* 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
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

Law of Laplace

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

\[ \sigma = \frac{\Delta P r_0}{2t} \]

- \(\sigma\) – circumferential stress
- \(\Delta P = (P_{ext} - P_0)\)
- \(r_0\) = inner radius of the sphere
- \(t\) - thickness of the skin

Suction pressure vs. vertical displacement

Torque application: elasticity measurement

1. Fixture on skin
2. Twist of 2-6 degrees
3. Measure radial displacement
4. Applied load is approximately 28.6 *10^{-3} N

Volumetric deformation

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)
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.

Pressurized hypertrophic scars

Uniaxial loading device

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.

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
• 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

Stress–strain curves of mechanical tests

- rhinoceros dorsalateral skin
- belly skin
- flank skin
Tensile properties according to arrangement of collagen fibers

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

Micrograph image of eel skin

Stress–strain curves for eel skin

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

<table>
<thead>
<tr>
<th></th>
<th>Skeletal</th>
<th>Cardiac</th>
<th>Smooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle cell</td>
<td>Large, elongated cell, 10-100 μm in diameter, up to 100 μm in length</td>
<td>Short, narrow cell, 10-15 μm in diameter, 80-100 μm in length</td>
<td>Short, elongated cell, 0.2-2 μm in diameter, 20-200 μm in length</td>
</tr>
<tr>
<td>Location</td>
<td>Muscle of skeleton (e.g. tongue, esophagus, diaphragm)</td>
<td>Heart, vena cava, pulmonary veins</td>
<td>Vessels, organs</td>
</tr>
<tr>
<td>Fiber</td>
<td>Single skeletal muscle cell</td>
<td>Linear, branched arrangement</td>
<td>Single smooth muscle cell</td>
</tr>
<tr>
<td>Types of contraction</td>
<td>“All or none”</td>
<td>“All or none”</td>
<td>Slow, partial, rhythmic</td>
</tr>
</tbody>
</table>
Hill’s functional model of the muscle

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

Mechanical properties of blood vessel

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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Thank you for your attention!