# Connective TISSUE MECHANICS

08/14/2006

## Tissue-level biomechanics

Allan Grodzinsky

Biomechanics of tissues

**Mechanics**
- I. (linear) elastic behavior
- II. viscoelastic
- III. poroelastic
- IV. electromechanical and physicochemical properties

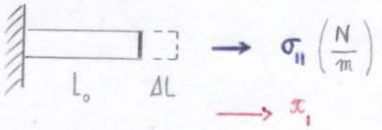
**Bio-** side of the picture
- I. biochemical & molecular biology of ECM molecules
  - A. collagen superfamily
  - B. proteoglycan superfamily
  - C. other glycoproteins
- II. Nanomolecular structures ↔ tissu
- III. Mechanobiology

- loading of joints (hard & soft tissue) → pathology
- examples of connective tissues : • ordinary connective tissues
  - irregular : loose (epithelial membrane, nerves...), dense (skin dermis...), adipose
  - regular : tendons, ligaments, cornea, fascia
  - • specialized (dense) connective tissues
  - skeletal : bone, cartilage, joints
  - hemopoietic : blood, lymph, marrow

what are the biomolecular mechanical properties of these nonhomogeneous tissues ?

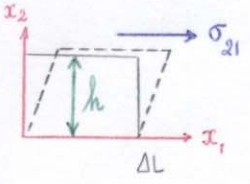
equilibrium E (Young moduli) : from 1kPa (collagen) to 1 GPa (bone)

- compression (confined or unconfined), tension and shear experiments




tension

$$\sigma_{11} = E\,\varepsilon_{11}$$

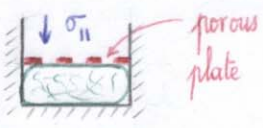



shear

$$\sigma_{21} = 2G\,\varepsilon_{21}$$

with $\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$

$$\sigma_{shear} = G\,\frac{\Delta L}{h} = G\,\frac{\partial u_1}{\partial x_2}$$




confined compression

$$\sigma_{11} = H\,\varepsilon_{11} = (2G + \lambda)\,\varepsilon_{11}$$

Empirical evidence : <u>generalized Hooke's law</u> $\sigma_{ij}^{TOT} = 2G\,\varepsilon_{ij} + \lambda\,\delta_{ij}\,\varepsilon_{kk} - \delta_{ij}P$

to measure Young's modulus E, shear modulus G, bulk modulus K, Poisson's ratio $\nu$ ...

| Categorize tissues : | YES | NO | |
|---|---|---|---|
| linear ? | | | T: tendon |
| homogeneous ? | | T, C, B | C: cartilage |
| isotropic ? | | T, C, B | B: bone |
| time independent ? | | T | |

- biochemistry and molecular biology of the <u>ECM : extracellular matrix</u>

tissue biomechanical properties depend on composition and structure of the ECM.

- <u>collagen</u> fibrils resist tension and shear
  structure : from primary ( amino acid sequence ) to secondary ( triple helix ) to quaternary ( staggered fibers of bundled $\alpha$- chains )
  intra- cellular synthesis and extra- cellular assembly into fibrils
  collagen superfamily : fibrillar, beaded, sheeted collagens, (→ type XXVI
- <u>proteoglycans</u> : core protein with attached GAG chains ( glycosaminoglycans )
  cell surface : syndecan, glypican families
  ECM: leucine- rich repeat, aggrecan, collagen families
  GAG chains of hyaluronic acid, chondroitin sulfate, keratan sulfate, ...
  ADAMTS family of proteoglycan - clipping enzymes

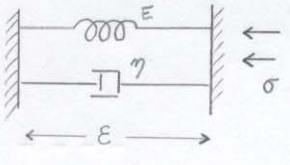
the ECM is synthesized and secreted by cells ( 90 min from transcription to release ).
normal degradation and cleavage take care of molecule turnover.

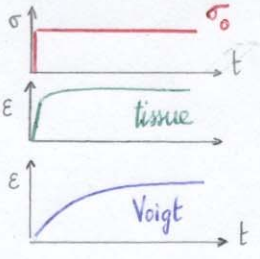
- osteoarthritis : who are the responsible agents ? what biomarkers could help early detection ? how can the process be reversed ?

- <u>Viscoelasticity</u> ( time - dependent behavior )

during a compressive creep experiment, does fluid flow or intrinsic mechanics dominate the tissue collapse ?

<u>Creep : Voigt model</u>

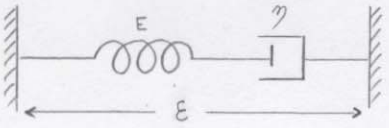


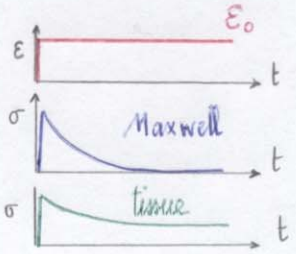




$$\varepsilon = \frac{\sigma_0}{E}\left\{1 - \exp\left(-\frac{t}{\tau}\right)\right\}$$ Voigt

tissue is a bit different

## Stress relaxation : Maxwell model




$\sigma(t) = E\varepsilon_0 \, e^{-t/\tau}$ Maxwell

tissue is a bit different

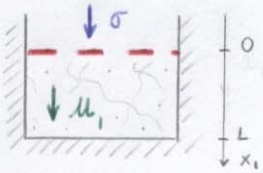
In articular cartilage : ( J. Jurvelin )

axial tension , collagen (viscoelasticity)
axial compression, fluid pressurization (poroelasticity)
} are responsible for stress relaxation.

3-element solid to better approximate data ? E' storage modulus, E'' loss modulus } $E(\omega) = E' + i\,E''$

- Poroelasticity

in confined compression, { apply displacement $\varepsilon = \varepsilon_0 \cos(\omega t)$ ; measure stress $\sigma = \sigma_0 \cos(\omega t + \delta)$



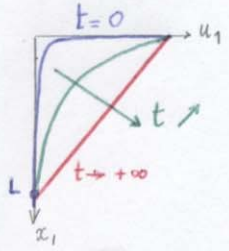

$$\frac{\partial u_1}{\partial t} = Hk \frac{\partial^2 u_1}{\partial x_1^2} \quad (1)$$ ( one-dimensional diffusion equation )

k : fluid permeability ; fluid
H : elastic modulus ; solid
} $Hk \equiv \mathcal{D}$ diffusivity

kinetics $\tau \propto \frac{L^2}{Hk}$

initial conditions and boundaries { $u_1 = 0$ at $x_1 = L$ ; $u_1 = u_0$ at $x_1 = 0$ ; $u_1 = 0$ at $t < 0$

↓ solve (1)




$$\begin{cases} u_1(x_1, t) = u_0\left(1 - \frac{x_1}{L}\right) - \sum_n A_n \sin\left(\frac{n\pi x_1}{L}\right) \exp\left(-\frac{t}{\tau_n}\right) \\ \tau_n = \frac{L^2}{n^2 \pi^2 Hk} \end{cases}$$

k from Darcy's law : velocity ∝ pressure drop : $\underline{U} = -k \nabla p$

poroelasticity explicitely accounts for fluid flow
viscoelasticity implicitly incorporates fluid effects through dashpots

- electromechanics : streaming potential (electrical) documents / is surrogate for fluid flow (mechanical) !