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Connective Tissue Mechanics notes

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Connective TISSUE MECHANICS

08/14/2006

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Tissue-level biomechanics

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 ↔ tissue
- III. Mechano-biology

- 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

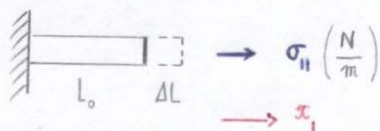
skeletal : bone, cartilage, joints

hemopoietic : blood, lymph, marrow

what are the biomolecular mechanical properties of these nonhomogeneous tissues?

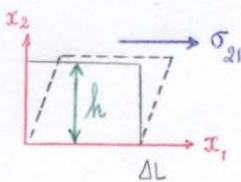
equilibrium E (Young moduli) : from 1kPa (collagen) to 1 GPa (bone)

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



tension

$$\sigma_{11} = E \epsilon_{11}$$



shear

$$\sigma_{21} = 2G \epsilon_{21}$$

$$\sigma_{\text{shear}} = G \frac{\Delta L}{h}$$

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



confined compression

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

Empirical evidence : generalized Hooke's law
 to measure Young's modulus E , shear modulus G ,
 Poisson's ratio ν ...

$$\sigma_{ij}^{TOT} = 2G \epsilon_{ij} + \lambda \delta_{ij} \epsilon_{kk} - \delta_{ij} P$$

Categorize tissues :

- linear ?
- homogeneous ?
- isotropic ?
- time independent ?

YES

NO

T, C, B

T, C, B

T

T: tendon
 C: cartilage
 B: bone

- Biochemistry and molecular biology of the ECM : extracellular matrix

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

- collagen fibrils resist tension and shear

structure : from primary (amino acid sequence) to secondary (triple helix) to quaternary (staggered fibers of bundled α -chains)
 intra-cellular synthesis and extra-cellular assembly into fibrils

collagen superfamily : fibrillar, beaded, sheeted collagens, (+ type XXV)

- proteoglycans : 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).

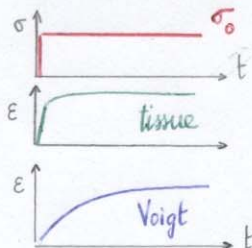
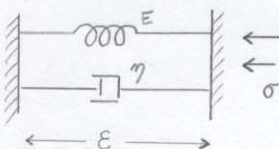
normal degradation and cleavage take care of molecule turnover.

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

- Viscoelasticity (time-dependent behavior)

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

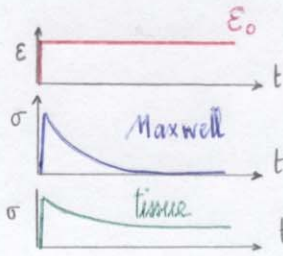
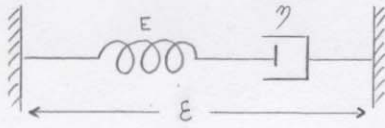
Creep : Voigt model



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

tissue is a bit different

Stress relaxation: Maxwell model



$\sigma(t) = E \epsilon_0 e^{-t/\tau}$ Maxwell

time is a bit different

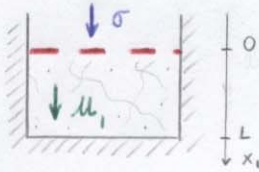
In articular cartilage: (J. Jurvelin)

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

3-element solid to better approximate data? $\left. \begin{matrix} E' \text{ storage modulus} \\ E'' \text{ loss modulus} \end{matrix} \right\} E(\omega) = E' + i E''$

- Poroelasticity

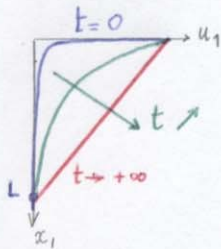
in confined compression, $\left\{ \begin{matrix} \text{apply displacement } \epsilon = \epsilon_0 \cos(\omega t) \\ \text{measure stress } \sigma = \sigma_0 \cos(\omega t + \delta) \end{matrix} \right.$



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

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

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



initial conditions and boundaries $\left\{ \begin{matrix} u_1 = 0 \text{ at } x_1 = L \\ u_1 = u_0 \text{ at } x_1 = 0 \\ u_1 = 0 \text{ at } t < 0 \end{matrix} \right.$
 ↓ solve (1)

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

k from Darcy's law: velocity \propto pressure drop : $\underline{U} = -k \nabla p$
 poroelasticity explicitly accounts for fluid flow
 viscoelasticity implicitly incorporates fluid effects through dashpots

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