Connective Tissue Mechanics notes

Connective TISSUE MECHANICS

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Tissue-level biomechanics

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Biomechanics of tissues

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

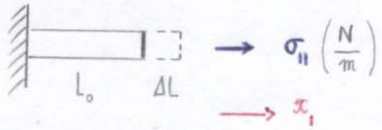
Bio-side of the picture
I. biochemical & molecular biology of ECM molecules
A. collagen superfamily
B. proteoglycan superfamily
C. other glycoproteins
II. Nanomolecular structures ↔ tissu
III. Mechanobiology

- 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

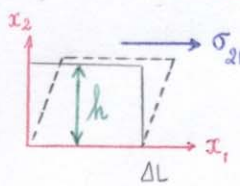
what are the biomolecular mechanical properties of these nonhomogeneous tissues?
equilibrium E (Young moduli) : from 1kPa (collagen) to 1 GPa (bone)

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



tension

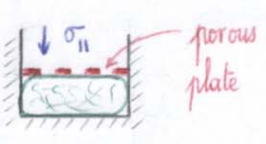
$\sigma_{11} = E\,\varepsilon_{11}$



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 : generalized Hooke's law $\sigma_{ij}^{TOT} = 2G\,\varepsilon_{ij} + \lambda\,\delta_{ij}\,\varepsilon_{kk} - \delta_{ij}\,p$
to measure Young's modulus E, shear modulus G, bulk modulus K, Poisson's ratio ν ...

Categorize tissues :

	YES	NO
linear ?		
homogeneous ?		T, C, B
isotropic ?		T, C, B
time independent ?		T

T: tendon
C: cartilage
B: bone

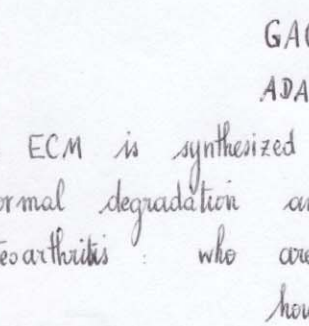
- biochemistry and molecular biology of the ECM : extracellular matrix
tissue biomechanical properties depend on composition and structure of the ECM.
  - collagen fibrils resist tension and shear
    structure : from primary (amino acid sequence) to secondary (triple helix) to quaternary (staggered fibers of bundled α- chains)
    intra-cellular synthesis and extra-cellular assembly into fibrils
    collagen superfamily : fibrillar, beaded, sheeted collagens, (→ type XXVI
  - 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

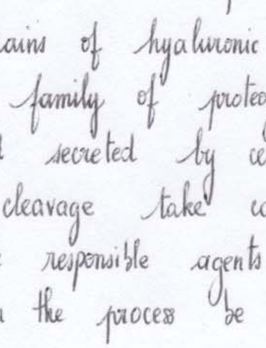
the ECM is synthesized and secreted by cells (90 min from transcription to release).
normal degradation and cleavage take care of molecule turnover.

- 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



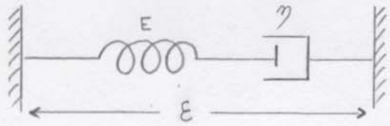


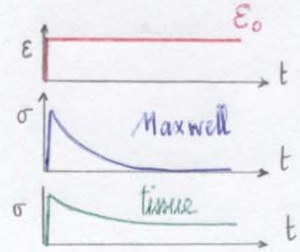
$$\varepsilon = \frac{\sigma_0}{E}\left\{1 - \exp\left(-\frac{t}{\tau}\right)\right\} \quad \text{Voigt}$$

tissue is a bit different

Tissue mechanics - 3.

Stress relaxation : Maxwell model





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

tissue is a bit different

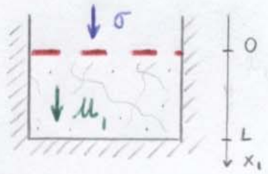
In articular cartilage : (J. Jurvelin)

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 $\sigma = \sigma_0 \cos(\omega t + \delta)$ }



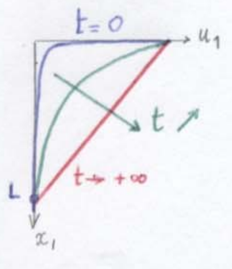
$$\frac{\partial u_1}{\partial t} = Hk \frac{\partial^2 u_1}{\partial x_1^2} \quad (1)$$ (one - dimensional diffusion equation)

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

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

initial conditions and boundaries
↓ solve (1)

$$\begin{cases} u_1 = 0 \text{ at } x_1 = L \\ u_1 = u_0 \text{ at } x_1 = 0 \\ u_1 = 0 \text{ at } t < 0 \end{cases}$$



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

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) !