18 – remodeling
fiber reorientation

18 – remodeling

final projects - me337 2013

- cerebral aneurysm growth: sheila, andrew
- muscle growth: katrina, jaqi
- brain tumor growth: cesare, zhuozhi
- adaptation of the brain: ronaldo, maria, lyndia
- growth of the developing brain: maria
- airway wall remodeling: mona
- corneal growth / keratoconus: yenli
- bone adaptation in birds: david

almost done…

almost done…
Almost done…

Growth, remodeling and morphogenesis

Remodeling involves changes in material properties. These changes, which often are adaptive, may be brought about by alterations in modulus, internal structure, strength, or density. For example, bones, and heart muscle may change their internal structures through reorientation of trabeculae and muscle fibers, respectively.

Mathematical modeling of fiber reorientation

Figure 5.1, the characteristic direction $n^A$ rotates such that, in the equilibrium state, it is aligned with the target direction $z^A$. To avoid drilling rotation, the angular velocity $\omega^A$ must be perpendicular to the plane spanned by the vectors $n^A$ and $z^A$. The change in direction $D_t n^A$ can then be expressed as $D_t n^A = \omega^A \times n^A$; the target direction $z^A$ could, for example, be the maximum principal strain $n^A_{\text{max}}$ or the maximum principal stress $n^A_{\text{max}}$.  

Himpel [2007], Himpel, Menzel, Kuhl & Steinmann [2008]
mathematical modeling of fiber reorientation

model I: re-orientation of microstructural direction

- gradual alignment of fiber direction $n_0$ with max principal strain $n_F^{\text{Cmax}}$

$$n_0 \rightarrow n_F^{\text{Cmax}}$$

- exponential update/euler-rodrigues for direction of transverse isotropy $n_0$

$$n_0^{k+1} = \exp(-\Delta t \, \overset{\wedge}{e} \cdot \omega) \cdot n_0^k \quad \omega = [n_0^k \times n_F^{\text{Cmax}}] / \kappa_0$$


model II: re-sizing of anisotropic unit cells

- instantaneous alignment of microstructure $n_F$ wrt eigenvectors $n_F^\sigma$

$$n_F = n_F^\sigma$$

$$\sigma = \lambda_F n_F^\sigma \otimes n_F^\sigma$$

"the unit cell used in each of the network models is taken to deform in principal stretch space," boyce & arruda [2000]
**model II: re-sizing of anisotropic unit cells**

- gradual adaptation of microstructural dimensions $l_I$ wrt eigenvalues $\lambda^+$

  
  $$l_I \rightarrow \frac{\lambda^+}{||\lambda^+||} \quad \text{if} \quad \lambda^+ > 0$$
  $$0 \quad \text{if} \quad \lambda^+ \leq 0$$

  $$\sigma = \lambda^+ n^+ \otimes n^+$$

  "The collagen fibers are located between the directions of the maximum principal stresses," Hariton, de Botton, Gasser & Holzapfel [2006]

**mathematical modeling of fiber reorientation**

**anisotropy of bone mineral density**

*Figure 1.* Healthy proximal tibia. Isometric density distribution, left, visualized through DEXA scan, which displays the characteristic heterogeneous density distribution with a dense region in the medial plateau, a lower density region in the lateral plateau, and the lowest density in the central region. Pang et al. [2012]. Anisotropic density distribution, right, visualized through a thin section. Trabeculae are aligned with axes of maximum principal loading, Wolff [1870].

**example – trabeculae in bone**

**model II: re-sizing of anisotropic unit cells**

$$l_I = \left[ \frac{\lambda^+}{||\lambda^+||} - l_I^0 \right] \left[ 1 - \exp(-\kappa t) \right] + l_I^0$$

**stress driven adaptation of microstructure**

- micromechanically motivated parameter $\kappa$

**mathematical modeling of fiber reorientation**

**anisotropy of bone mineral density**

*Fig. 6.* Geometry of the upper part of the proximal tibia. (a) Finite element mesh with applied concentrated forces $F_1$, $F_2$ and (b) location of slices I (sagittal slice), II (axial slice) and III (coronal slice) used in Figs. 9–13. Waffenschmidt, Menzel, Küh [2012].

**example – trabeculae in bone**
Langer's lines, sometimes called cleavage lines, are topological lines drawn on a map of the human body. They are defined by the direction in which the human skin would split when struck with a spike. Langer's lines correspond to the natural orientation of collagen fibers in the dermis and epidermis. Knowing the direction of langer's lines within a specific area of the skin is important for surgical procedures, particularly cosmetic surgery involving the skin. If a surgeon has a choice about where and in what direction to place an incision, he may choose to cut in the direction of langer's lines. Incisions made parallel to langer's lines may heal better and produce less scarring than those cut across.
collagen fibers - anisotropy of human tissue

directional strengthening due to collagen fibers

example – collagen fibers in skin

experiment vs simulation - rabbit skin

stiffer \parallel \text{to Langer's lines} - stress locking \text{at} \text{crit stretch}

remodeling of collagen fibers - living tendon

example – tissue engineering

remodeling of collagen fibers - living tendon

example – tissue engineering

- ex vivo engineered tendon shows characteristics of embryonic tendon
- remodeling of collagen fibers upon mechanical loading
- long term goal mechanically stimulated tissue engineering

calve, dennis, kocnik, baar, grosh & arruda [2004]

finite element simulation of functional adaptation in tendons
- wormlike chain model with initial random anisotropy
- analysis of fiber reorientation in uniaxial tension

kuhl, garikipati, arruda & grosh [2005]
remodeling of collagen fibers - living tendon

characteristic locking, remodeling & stiffening

example - tissue engineering

remodeling of collagen fibers - living tendon

tissue stretcher - cyclic loading
mechanically stimulated reorientation of collagen fibers

courtesy of sarah calve & ellen arruda, mechanical engineering, university of michigan

example - tissue engineering

remodeling of collagen fibers - living tendon

gradual fiber alignment with max principal stress

example - tissue engineering

alignment of cells - iPSC-derived heart muscle cells

mechanically stimulated stem cell differentiation

courtesy of oscar ablez, bioengineering, stanford university

example - stem cell differentiation
Example – collagen fibers in arteries

Remodeling of collagen fibers

Stress driven functional adaptation

Kuhl & Holzapfel (2007)

Intima – Media – Adventitia
sensitivity wrt driving force - spatial vs material stress

\[ \sigma = \lambda^S_i n_i^Q \otimes n_i^Q \quad S = \lambda^S_i n_i^S \otimes n_i^S \]

true spatial driving force more reasonable

Kuhl & Holzapfel [2007]

example – collagen fibers in arteries

sensitivity wrt driving force - stress vs strain

\[ \sigma = \lambda^S_i n_i^Q \otimes n_i^Q \quad b = \lambda^S_i n_i^b \otimes n_i^b \]

eigenvectors coincide but eigenvalues differ significantly

Kuhl & Holzapfel [2007]

example – collagen fibers in arteries

sensitivity wrt pressure to stretch ratio

\[ \varepsilon_{zz} = 10\% \quad p = 0 \]

<< increase of stretch <<<

>> increase of pressure >>>

\[ \varepsilon_{zz} = 0\% \quad p = p_{blood} \]

collagen fiber angle governed by pressure%stretch ratio

Kuhl & Holzapfel [2007]

example – collagen fibers in arteries

sensitivity wrt changes in mechanical loading

>> axial strain and blood pressure >>

>> local increase of pressure >>>

fiber reorientation in response to changes in loading

Kuhl & Holzapfel [2007]

example – collagen fibers in arteries
Collagen fiber orientation in the aortic valve leaflet

Are collagen fibers aligned with maximum principal strains?

Driessen [2006]

Example – collagen fibers in mitral leaflets

Collagen fiber orientation in the mitral valve leaflet

Are collagen fibers aligned with maximum principal strains?

Shultz, Rausch, Kuhl [2010]

Example – collagen fibers in mitral leaflets
collagen fiber orientation in the mitral valve leaflet

are collagen fibers aligned w/maximum principal strains?

rausch & kuhl [2013]

example – collagen fibers in mitral leaflets

leaflets are stiffer || to fiber direction – $\lambda_1$ smaller than $\lambda_2$

rausch & kuhl [2013]

example – collagen fibers in mitral leaflets

challenges – understanding mechanotransduction

• how do tissues sense mechanical stimuli?
  receptors on cell surface • cytoskeleton

• how are signals transmitted?
  focal adhesion • role of biochemistry • ion channels

• how does remodeling take place?
  collagen synthesis / turnover • gene expression

mechanics of the cell

remodeling