18 – remodeling
fiber reorientation

18 - remodeling

day	date		topic
tue	jan	08	motivation - everything grows!
thu	jan	10	basics maths - notation and tensors
tue	jan	15	basic kinematics - large deformation and growth
thu	jan	17	kinematics - growing hearts
tue	jan	22	guest lecture - growing surfaces
thu	jan	24	kinematics - growing leaflets
tue	jan	29	basic balance equations - closed and open systems
thu	jan	31	basic constitutive equations - growing muscle
tue	feb	05	basic constitutive equations - growing tumors
thu	feb	07	volume growth - finite elements for growth - theory
tue	feb	12	volume growth - finite elements for growth - matlab
thu	feb	14	volume growth - growing skin
tue	feb	19	basic constitutive equations - growing bones
thu	feb	21	density growth - finite elements for growth
tue	feb	26	density growth - growing bones
thu	feb	28	everything grows! - midterm summary
tue	mar	05	midterm
thu	mar	07	remodeling - remodeling arteries and tendons
tue	mar	12	class project - discussion, presentation, evaluation
thu	mar	14	class project - discussion, presentation, evaluation
thu	mar	14	written part of final projects due

everything grows! - midterm summary

me 337 - grading

- 30 % homework - 3 homework assignments, 10% each
- 30 % midterm - closed book, closed notes, one single page cheat sheet
- 20 % final project oral presentations - graded by the class
- 20 % final project essay - graded by instructor

almost done…

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**: yanli
- **bone adaptation in birds**: david

tue 03/12 and/or thu 03/14

almost done…

ME 337 – Mechanics of Growth

Final Project Presentations

Instructions for Judges
according to ASME / SBC conference review guidelines

The presentation format includes the **structure of the presentaiton and its composition**. In general, a presentation should be structured to include an introduction, method, analysis, results, a conclusion, and references. The introduction should define the problem, scope of the study, and a brief background of previous work. The method section also should be brief to leave the majority of the report body for results and discussion. The final paragraph should be a brief paragraph on inference or conclusions reached.

Technical merit should be judged on the completeness of what is reported. For scientific studies, the result should support the conclusions presented. The key is validation of the express conclusion with results and data. Unsubstantiated conclusions or results should receive minimum points. However, not all papers represent basic research. Some papers present the design of a hardware system or a new software development. Both require the development of tests and measurement procedures to validate the product.

After the scoring is complete, please indicate a final grade. Please provide a comment in the designated area that describes why you think this presentation suitable/not suitable. These comments will be collected and provide to the students for feedback.

almost done…

ME 337 – Mechanics of Growth

Is not necessary for the judge to be an expert in the field represented by the paper to evaluate its technical merit using these criteria. Subjective rating of the paper's scientific contribution is not encouraged unless there is evidence that the conclusions are incorrect. A judge should feel free to consult colleagues who are experts in the field, if you are unsure about the correctness of the conclusions. Since presentations can vary from hardware designs to software technique, or simulations and modeling to basic research, each reviewer will have to use his/her own best judgment about the technical merit of the work that is presented.

Scoring & Evaluation System:

Please use the same scoring system as for the General Abstracts for each of the evaluation categories.

Score – Provide a ranking according to

Excellent	=	100
Very Good	=	90
Good	=	80
Marginal	=	60
Poor	=	50

Evaluation Categories

1. Structure of presentation
2. Technical merit
3. Style of presentation

groups & dates…

Keep in mind the judges cannot be perfect, but will try to be consistent in scoring. There are multiple judges for

almost done…

growth, remodeling and morphogenesis

remodeling [riˈmad. l.ɪŋ] 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.

taber 'biomechanics of growth, remodeling and morphogenesis' [1995]

motivation – remodeling

adaptation of microstructural direction

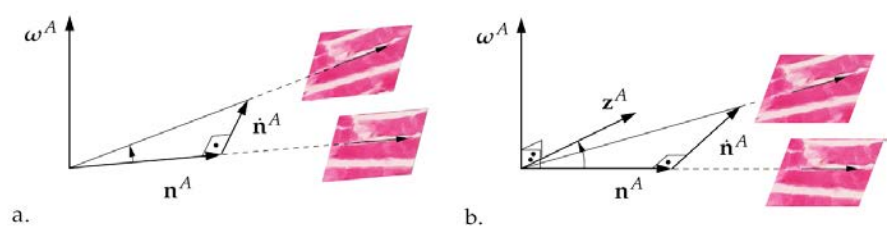
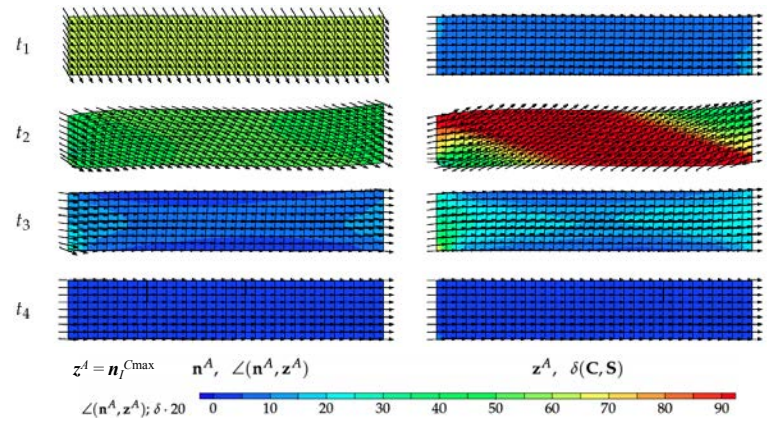


figure 5.1. the characteristic direction $\boldsymbol{n}^A$ rotates such that, in the equilibrium state, it is aligned with the target direction $\boldsymbol{z}^A$. to avoid drilling rotation, the angular velocity $\boldsymbol{\omega}^A$ must be perpendicular to the plane spanned by the vectors $\boldsymbol{n}^A$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

himpel [2007], himpel, menzel, kuhl & steinmann [2008]

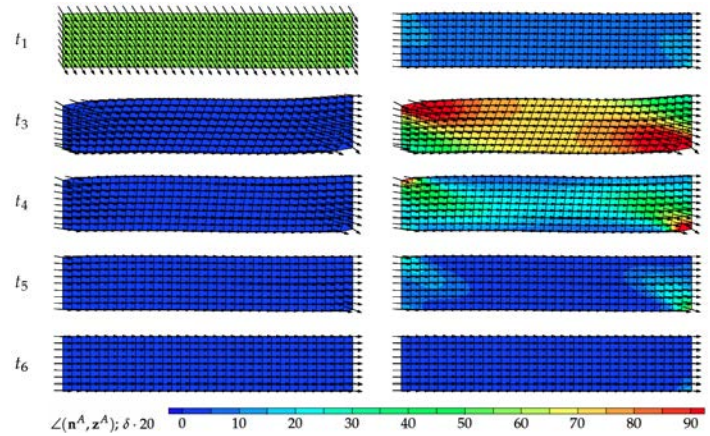
mathematical modeling of fiber reorientation

strain-driven adaptation of microstructural direction



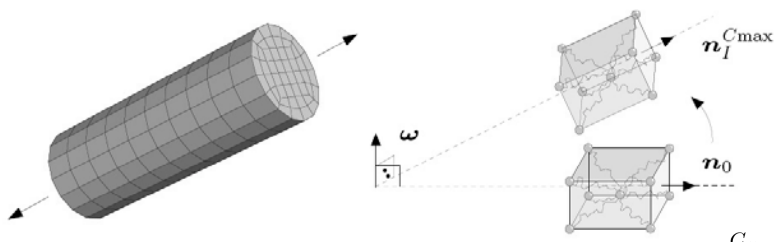
himpel [2007], himpel, menzel, kuhl & steinmann [2008]

stress-driven adaptation of microstructural direction



himpel [2007], himpel, menzel, kuhl & steinmann [2008]

model I: re-orientaiton of microstructural direction



- gradual alignment of fiber direction $\boldsymbol{n}_0$ with max principal strain $\boldsymbol{n}_I^{C\max}$

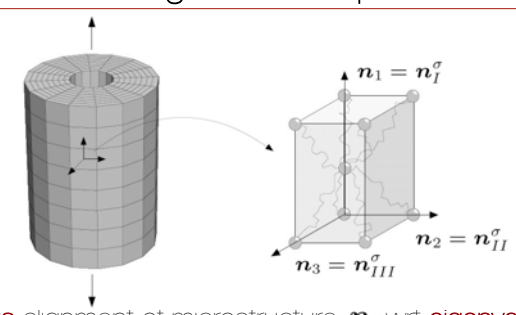
$$\boldsymbol{n}_0 \rightarrow \boldsymbol{n}_I^{C\max} \qquad \boldsymbol{C} = \lambda_I^C\, \boldsymbol{n}_I^C \otimes \boldsymbol{n}_I^C$$

- exponential update/euler-rodrigues for direction of transverse isotropy $\boldsymbol{n}_0$

$$\boldsymbol{n}_0^{k+1} = \exp(-\Delta t\ \overset{3}{\boldsymbol{e}} \cdot \boldsymbol{\omega}) \cdot \boldsymbol{n}_0^k \qquad \boldsymbol{\omega} = [\, \boldsymbol{n}_0^k \times \boldsymbol{n}_I^{C\max} \,] \,/\, \kappa_\omega$$

fyrhie & carter [1986], cowin [1989], [1994], vianello [1996], sgarra & vianello [1997], menzel [2004], driessen [2006], kuhl, menzel & garikipati [2006]

model II: re-sizing of anisotropic unit cells

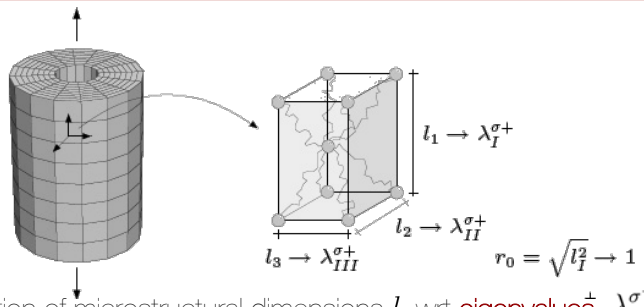


- instantaneous alignment of microstructure $\boldsymbol{n}_I$ wrt eigenvectors $\boldsymbol{n}_I^\sigma$

$$\boldsymbol{n}_I \doteq \boldsymbol{n}_I^\sigma \qquad \boldsymbol{\sigma} = \lambda_I^\sigma\, \boldsymbol{n}_I^\sigma \otimes \boldsymbol{n}_I^\sigma$$

„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



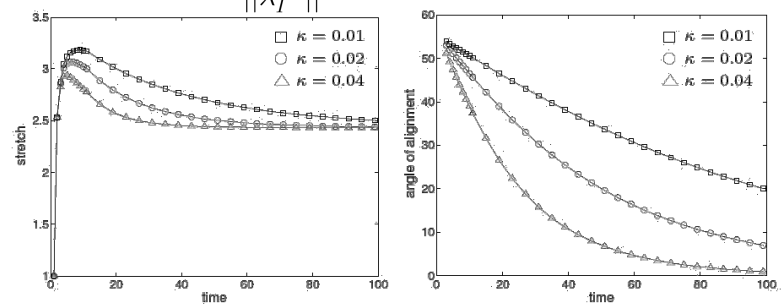
- gradual adaptation of microstructural dimensions l_I wrt eigenvalues $\lambda_I^{\sigma+}$

$$l_I \to \begin{cases} \lambda_I^{\sigma+}/||\lambda_I^{\sigma+}|| & \text{if} \quad \lambda_I^{\sigma} > 0 \\ 0 & \text{if} \quad \lambda_I^{\sigma} \leq 0 \end{cases} \qquad \boldsymbol{\sigma} = \lambda_I^{\sigma}\, \boldsymbol{n}_I^{\sigma} \otimes \boldsymbol{n}_I^{\sigma}$$

„the collagen fibers are located between the directions of the maximum principal stresses." hariton, de botton, gasser & holzapfel [2006]

model II: re-sizing of anisotropic unit cells

$$l_I = [\,\frac{\lambda_I^{\sigma+}}{||\lambda_I^{\sigma+}||} - l_I^0\,]\,[\,1 - \exp(-\boldsymbol{\kappa}\, t)\,] + l_I^0$$



stress driven adaptation of microstructure

micromechanically motivated parameter κ

anisotropy of bone mineral density

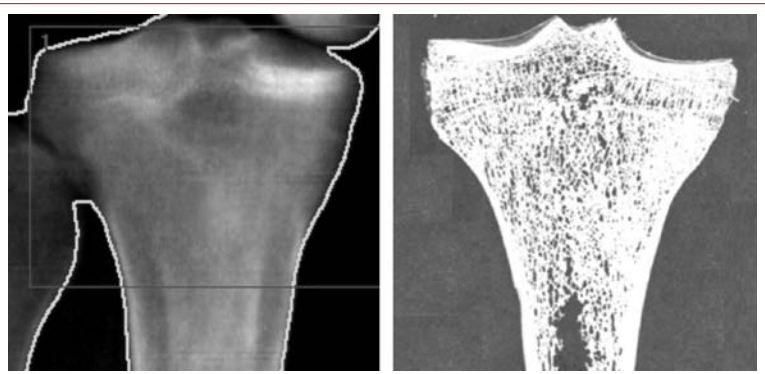


figure 1. healthy proxima tibia. isometric desity distribution, left, visualized through DEXA scan, which displays the characteristic heterogeneous density distriubtion with a dense region in the medial plateau, a lower density region in the lateral plateau, and the lowest density in the central region, pang et al. [2012]. anisotropic density distriubtion, right, visualized through a thin section. Trabeculae are aligned with axis of maximum principal loading, wolff [1870].

anisotropy of bone mineral density

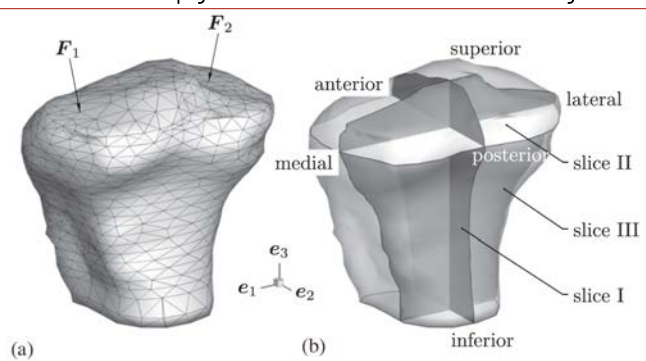
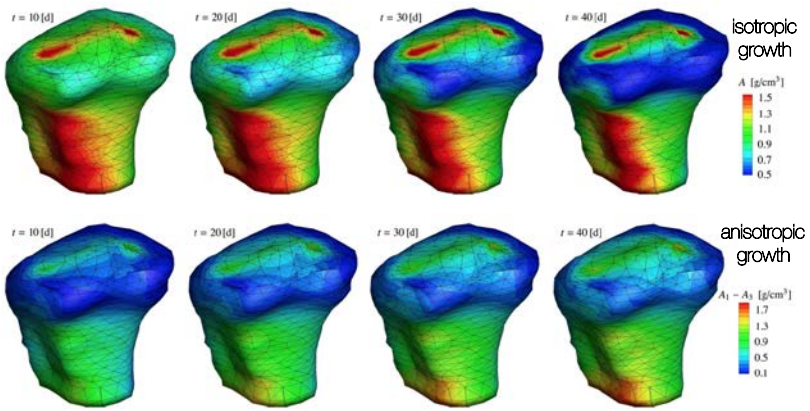


Fig. 6. Geometry of the upper part of the proximal tibia. (a) Finite element mesh with applied concentrated forces F_1, F_2 and (b) location of slices I (sagittal slice), II (axial slice) and III (coronal slice) used in Figs. 9–13.

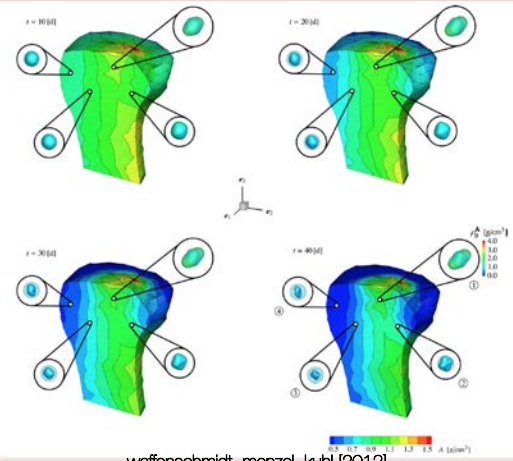
waffenschmidt, menzel, kuhl [2012]

anisotropy of bone mineral density



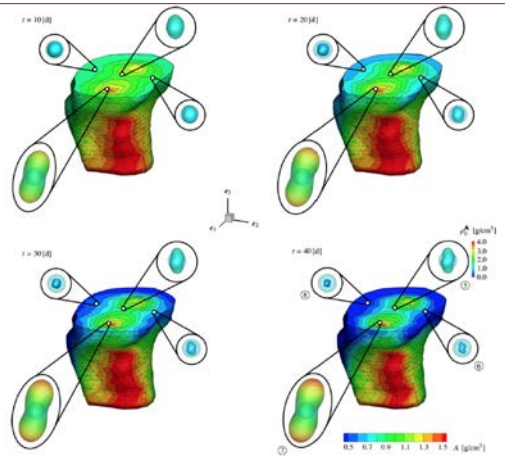
waffenschmidt, menzel, kuhl [2012]

anisotropy of bone mineral density



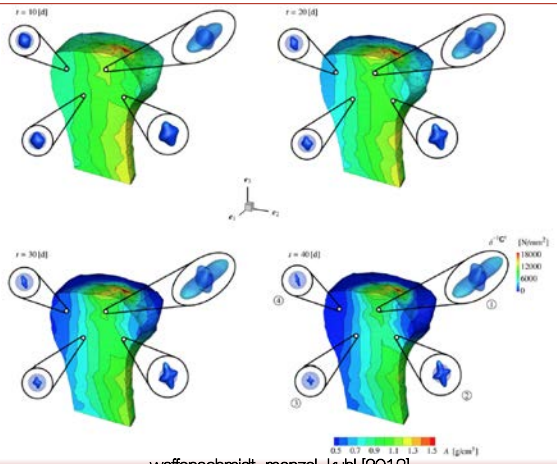
waffenschmidt, menzel, kuhl [2012]

anisotropy of bone mineral density



waffenschmidt, menzel, kuhl [2012]

anisotropy of bone mineral density



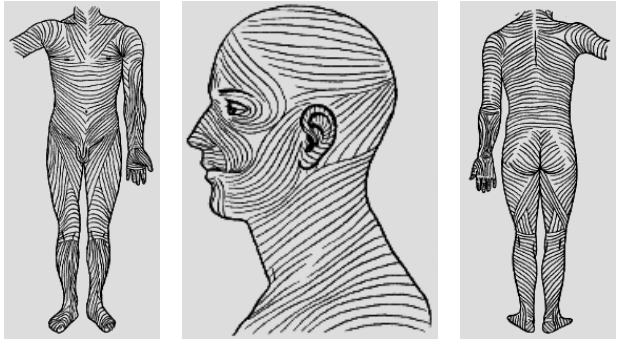
waffenschmidt, menzel, kuhl [2012]

remodeling in skin - langer's lines

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.

WIKIPEDIA
The Free Encyclopedia

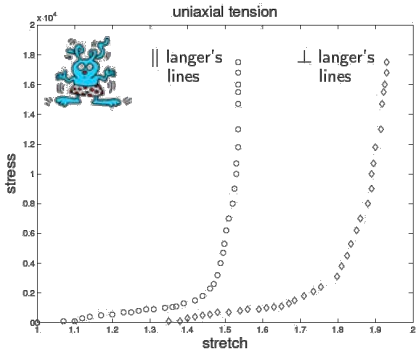
langer's lines - anisotropy of human skin



lines of tension - orientation of collagen fiber bundles

carl ritter von langer [1819-1887]

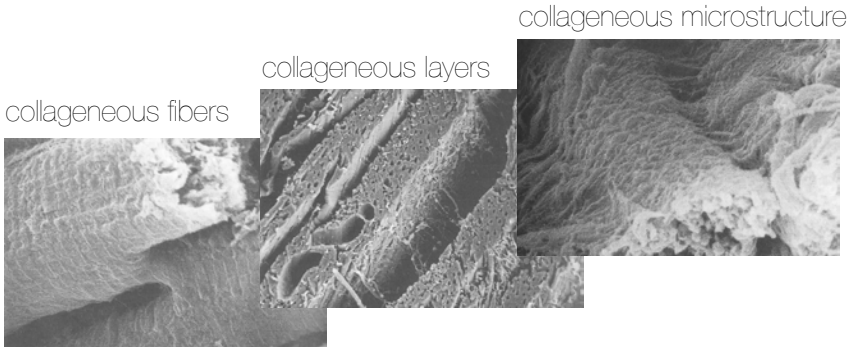
langer's lines - anisotropy of rabbit skin



stiffer || to langer's lines - stress locking @crit stretch

lanir & fung [1974]

collagen fibers - anisotropy of human tissue



directional strengthening due to collagen fibers

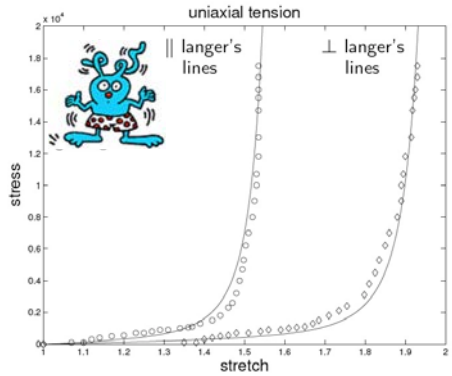
humphrey [2002]

collagen fibers - anisotropy of human tissue

directional strengthening due to collagen fibers

viidik [1973]

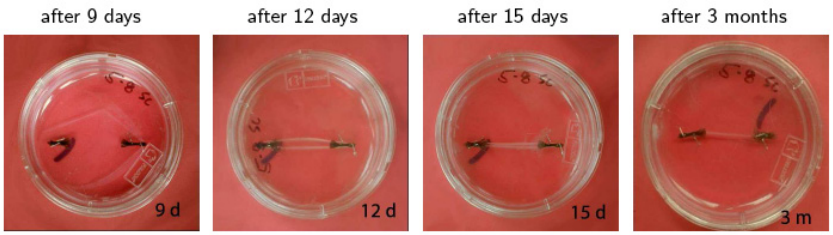
experiment vs simulation - rabbit skin



stiffer || to langer's lines - stress locking @crit stretch

lanir & fung [1974], kuhl, garikipati, arruda & grosh [2005]

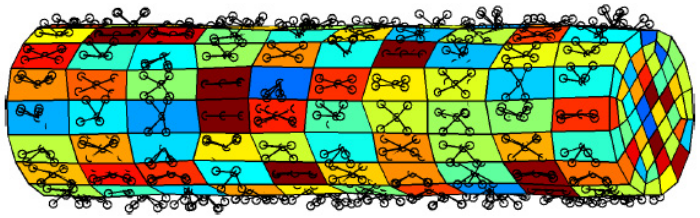
remodeling of collagen fibers - living tendon



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

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

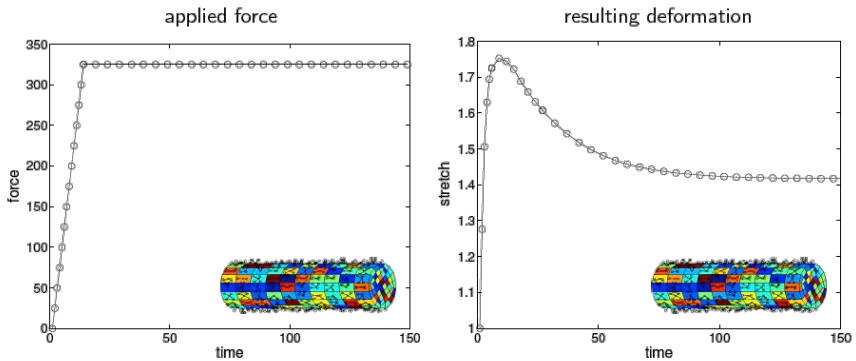
remodeling of collagen fibers - living tendon



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

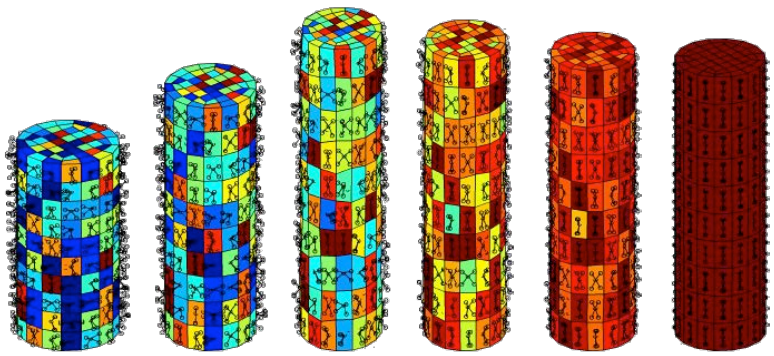
kuhl, garikipati, arruda & grosh [2005]

remodeling of collagen fibers - living tendon



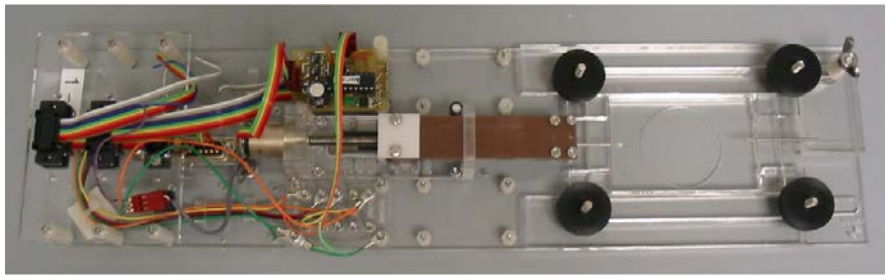
characteristic locking, remodeling & stiffening

remodeling of collagen fibers - living tendon



gradual fiber alignment with max principal stress

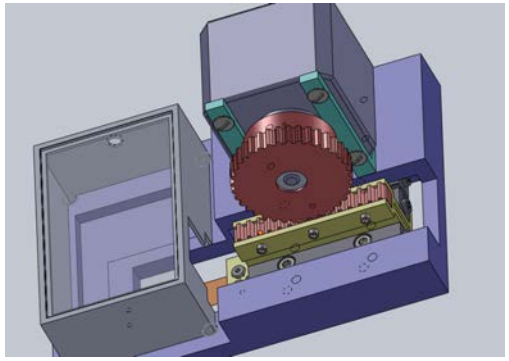
remodeling of collagen fibers - living tendon



tissue stretcher - cyclic loading
mechanically stimulated reorientation of collagen fibers

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

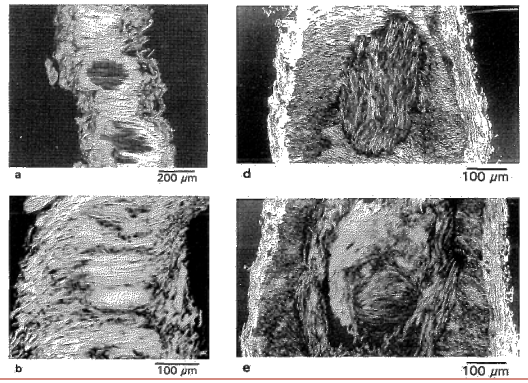
alignment of cells - iPSC-derived heart muscle cells



mechanically stimulated stem cell differentiation

courtesy of oscar abilez, bioengineering, stanford university

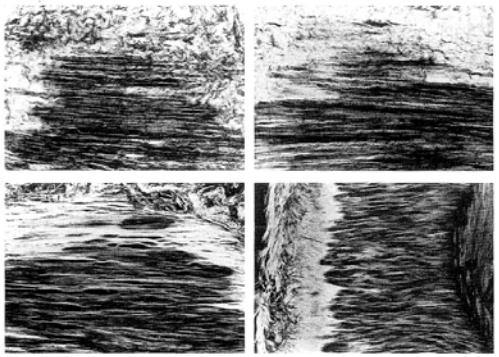
tangentially sectioned brain arteries



circularly polarized light micrographs

finlay [1995]

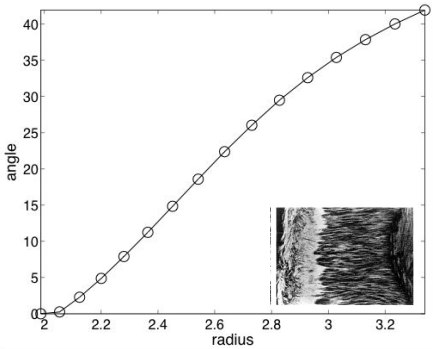
tangentially sectioned brain arteries

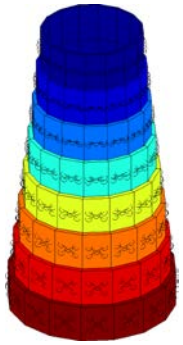


circularly polarized light micrographs

finlay [1995]

remodeling of collagen fibers

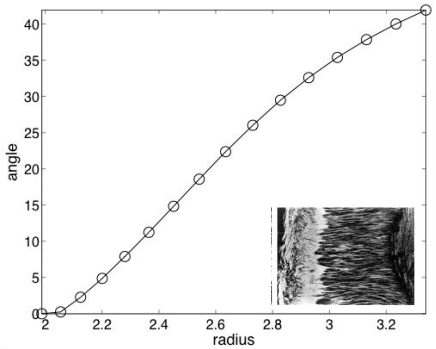


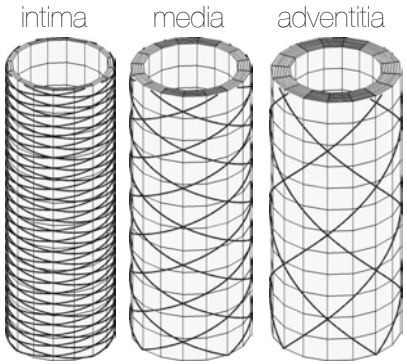


stress driven functional adaptation

kuhl & holzapfel [2007]

remodeling of collagen fibers

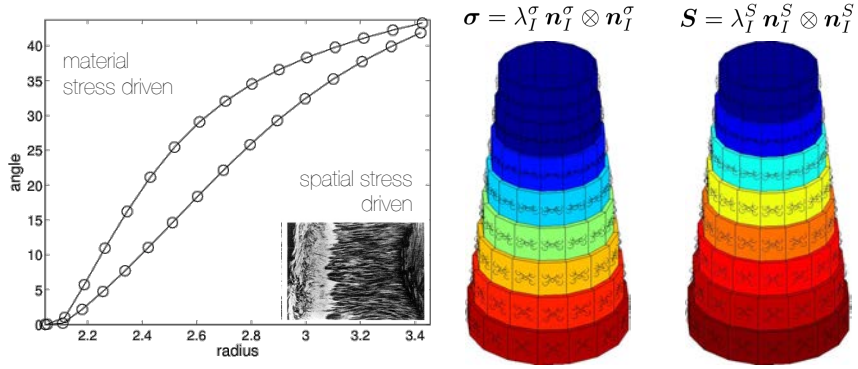




stress driven functional adaptation

kuhl & holzapfel [2007]

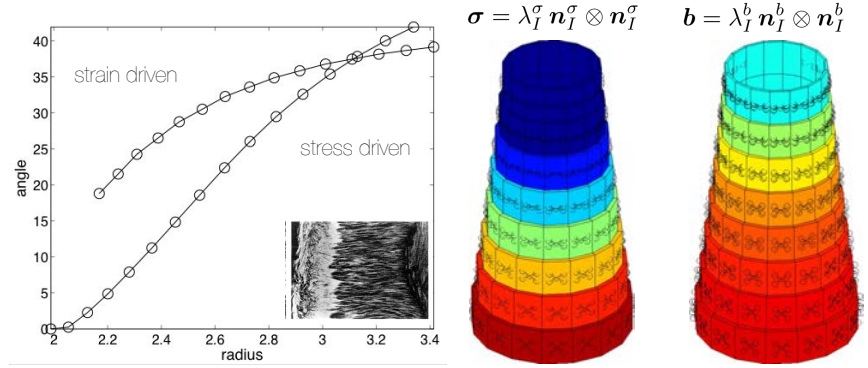
sensitivity wrt driving force - spatial vs material stress



true spatial driving force more reasonable

kuhl & holzapfel [2007]

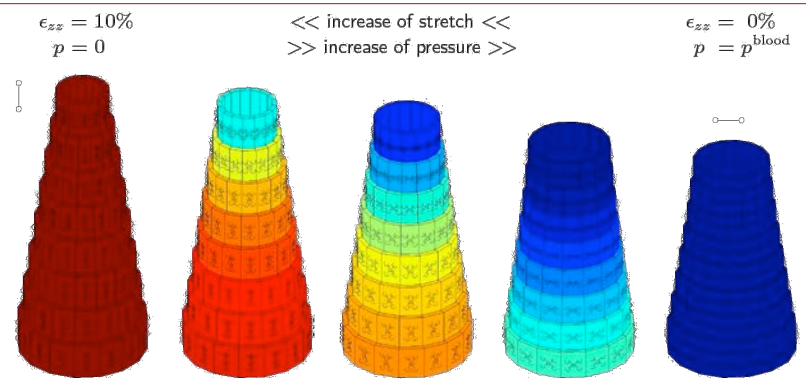
sensitivity wrt driving force - stress vs strain



eigenvectors coincide but eigenvalues differ significantly

kuhl & holzapfel [2007]

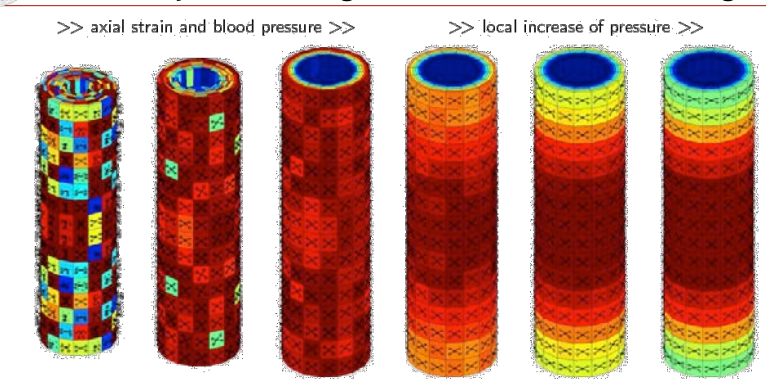
sensitivity wrt pressure to stretch ratio



collagen fiber angle governed by pressure2stretch ratio

kuhl & holzapfel [2007]

sensitivity wrt changes in mechanical loading



fiber reorientation in response to changes in loading

kuhl & holzapfel [2007]

collagen fiber orientation in the aortic valve leaflet

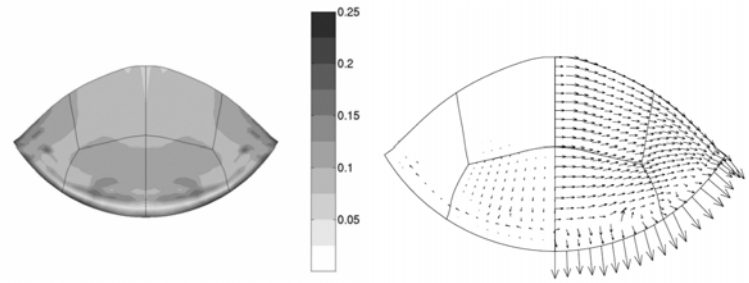
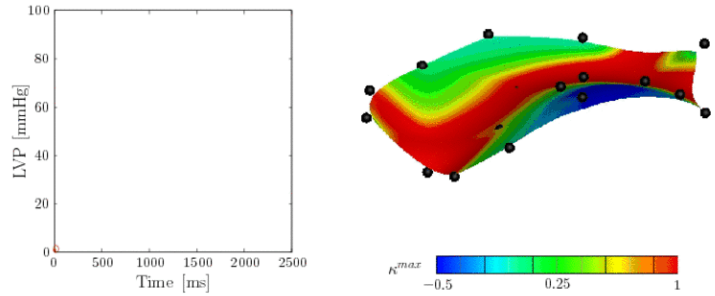


figure 2.6. computationally predicted fiber orientations. mean value of the final total volume fraction on the aortic and ventricular side (left) and final fiber orientation on the aortic sdie of the leaflet (right).

are collagen fibers aligned w/maximum principal strains?

driessen [2006]

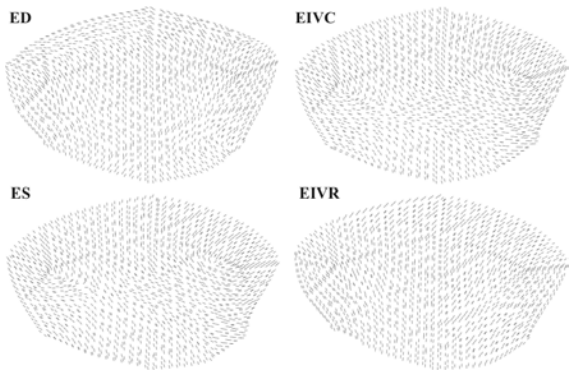
collagen fiber orientation in the mitral valve leaflet



are collagen fibers aligned w/maximum principal strains?

shultz, rausch, kuhl [2010]

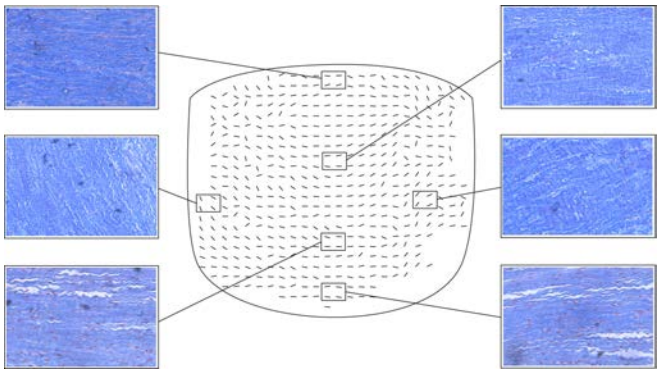
collagen fiber orientation in the mitral valve leaflet



are collagen fibers aligned w/maximum principal strains?

shultz, rausch, kuhl [2010]

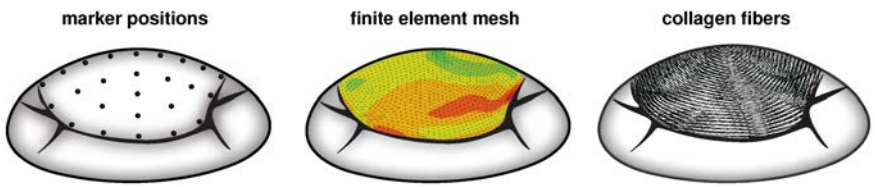
collagen fiber orientation in the mitral valve leaflet



are collagen fibers aligned w/maximum principal strains?

shultz, rausch, kuhl [2010]

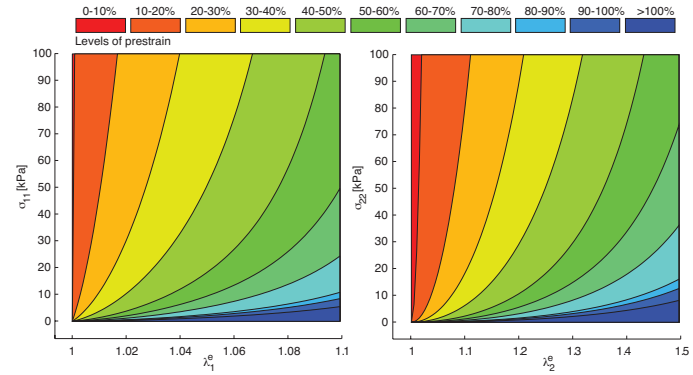
collagen fiber orientation in the mitral valve leaflet



are collagen fibers aligned w/maximum principal strains?

rausch & kuhl [2013]

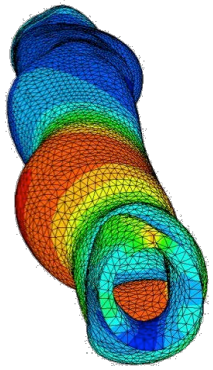
collagen fiber orientation in the mitral valve leaflet



leaflets are stiffer || to fiber direction – λ_1 smaller than λ_2

rausch & kuhl [2013]

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