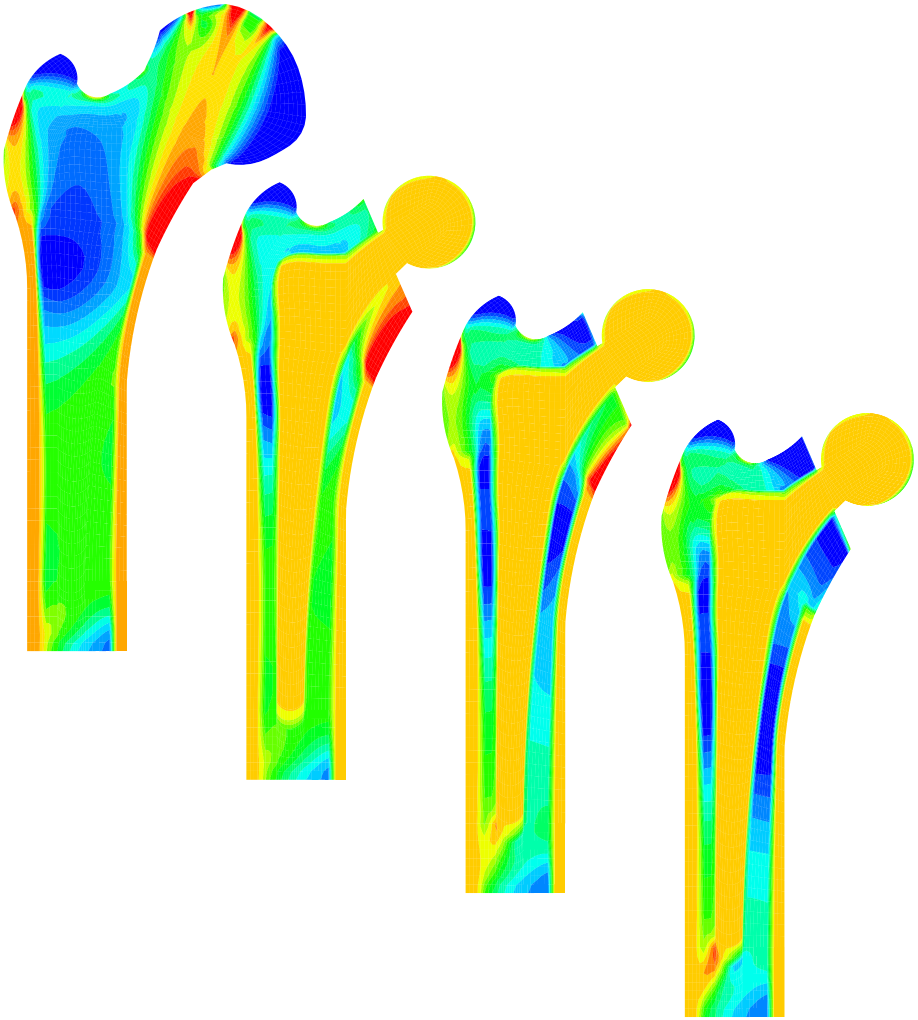
continuum biomechanics

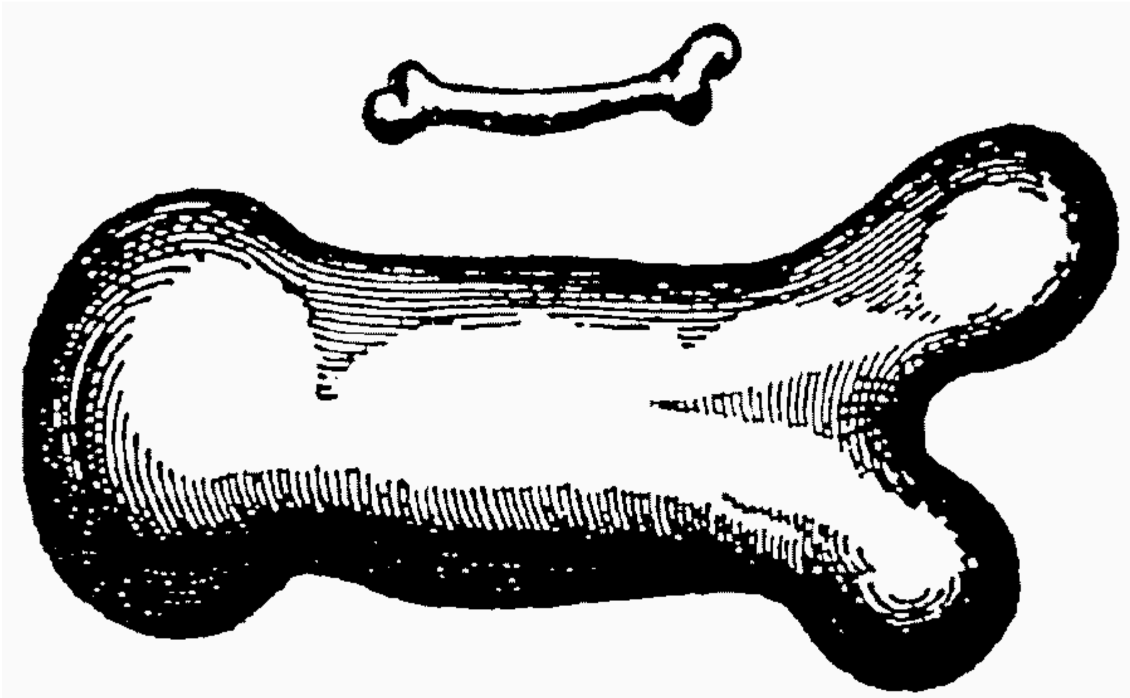
– pantha psiloni –



ellen kuhl
assistant professor of biomechanics
faculty of mechanical engineering
tu kaiserslautern - germany

- **motivation**
  history of biomechanics
- **density growth**
  adaptation in bone
  wound healing
- **volume growth**
  adaptation in arteries
  tube in tension
- **remodelling**
  simulation of skin
  tissue engineering
- **outlook**

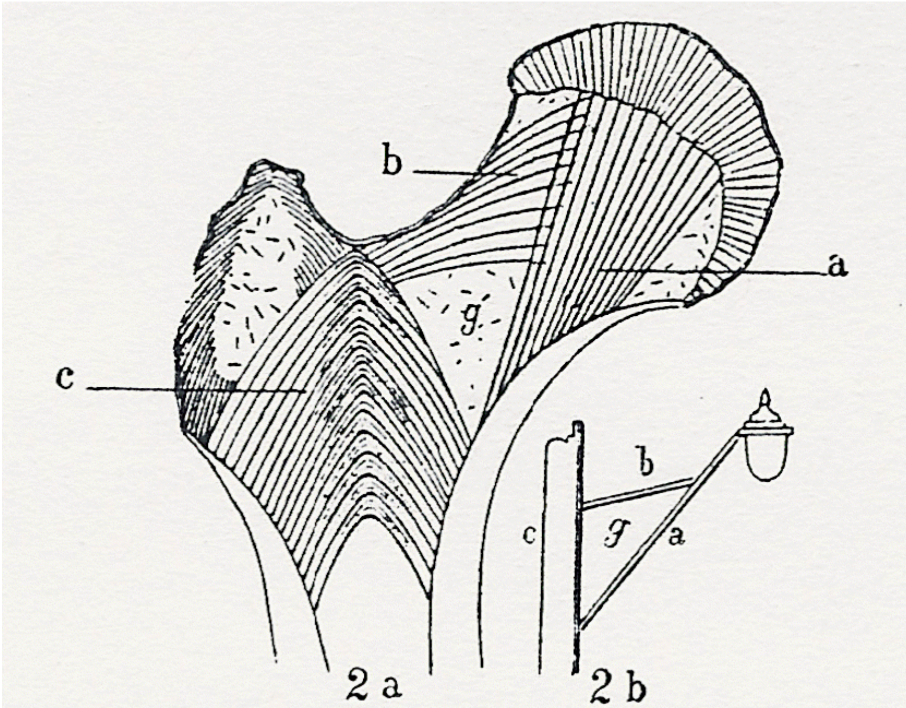
discorsi e dimostrazioni matematiche



"...dal che e manifesto, che chi volesse mantener in un vastissimo gigante le proporzioni, che hanno le membra in un huomo ordinario, bisognerebbe o trouar materia molto piu dura, e resistente per formarne l'ossa o vero ammettere, che **la robustezza sua fusse a proporzione assai piu fiacca, che negli huomini de statura mediocre**; altrimente crescendogli a smisurata altezza si vedrebbono dal proprio peso opprimere, e cadere..." GALILEI [1638]

biomechanics in the 17th century

law of bone remodelling

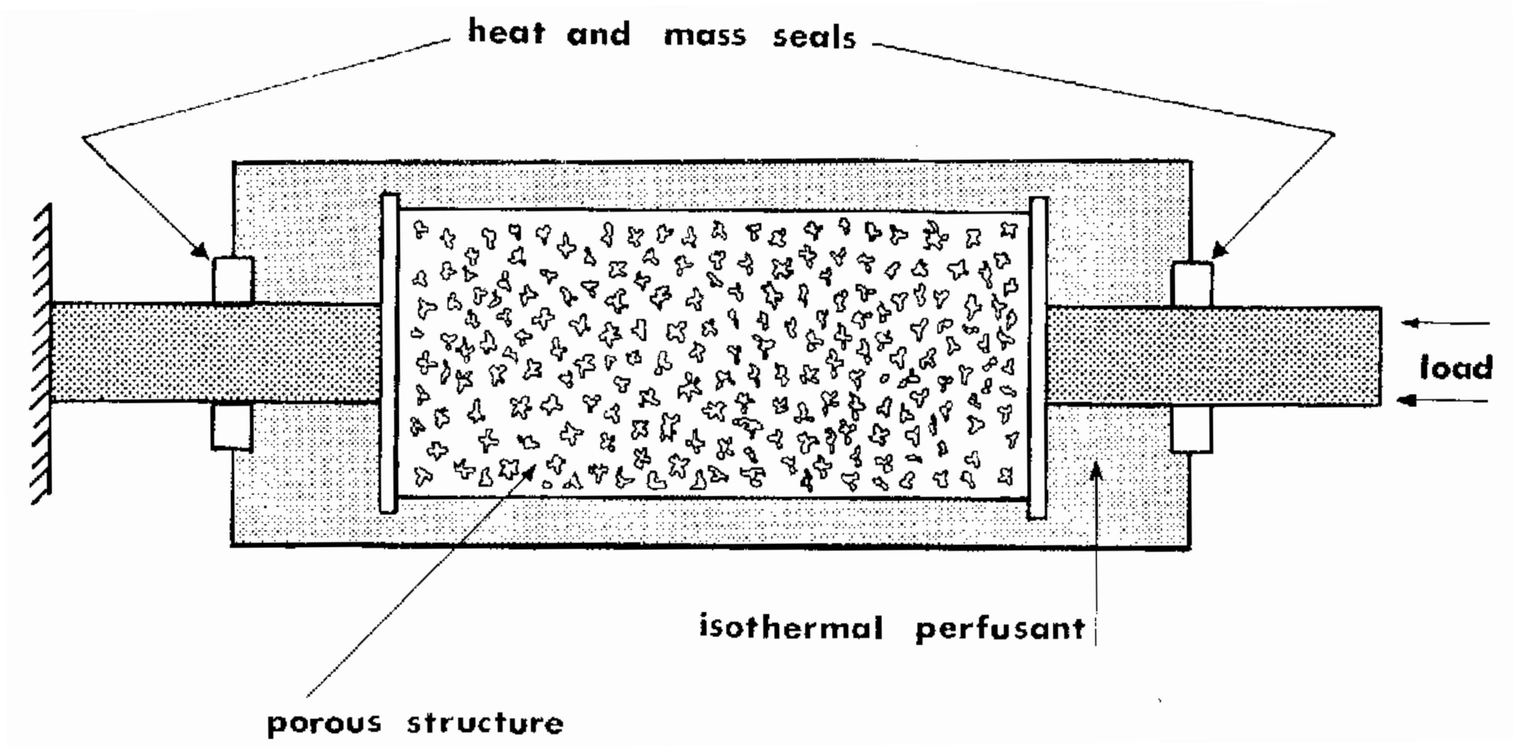


WARD [1832]

"...es ist demnach unter dem gesetze der transformation der knochen dasjenige gesetz zu verstehen, nach welchem im gefolge primärer abänderungen der form und inanspruchnahme bestimmte **umwandlungen der inneren architectur** und **umwandlungen der äusseren form** sich vollziehen..."

WOLFF [1892]

theory of adaptive elasticity



" ...the system of only the porous structure without its entrained perfusant is **open with respect to momentum transfer as well as mass, energy, and entropy transfer**. we shall write balance and constitutive equations for only the bone matrix..." COWIN & HEGEDUS [1976]

density growth

example – rocket propulsion

- balance of mass

$$d_t\, \mathfrak{m} = \mathfrak{R} \qquad \text{with ejection} \qquad \mathfrak{R} \le 0$$

- balance of momentum – volume specific

$$d_t\, [\mathfrak{m}\, \mathfrak{v}] = \mathfrak{f} + \mathfrak{v}\, \mathfrak{R}$$

- balance of momentum – mass specific

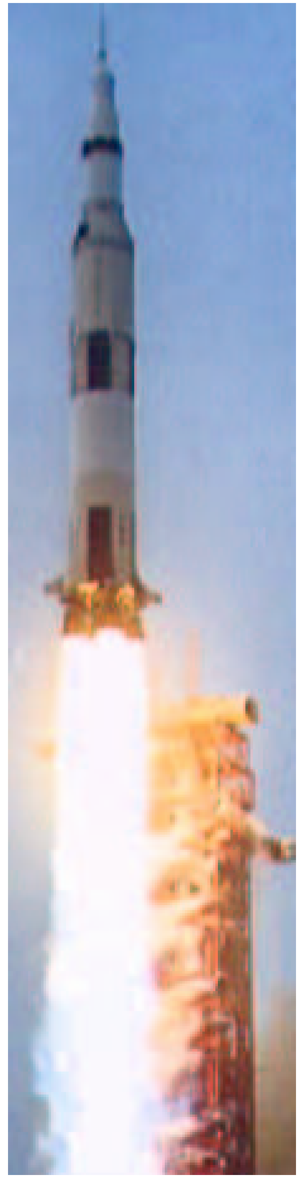
$$\mathfrak{m}\, d_t \mathfrak{v} = \mathfrak{f} \qquad \text{with} \qquad \mathfrak{f} := \mathfrak{f}^{\text{closed}} + \mathfrak{f}^{\text{open}}$$

- balance of momentum of rocket & ejection

$$D_t\, [\mathfrak{m}\, \mathfrak{v}] - \bar{\mathfrak{v}}\, \mathfrak{R} = \mathfrak{f}^{\text{closed}}$$

- propulsive force

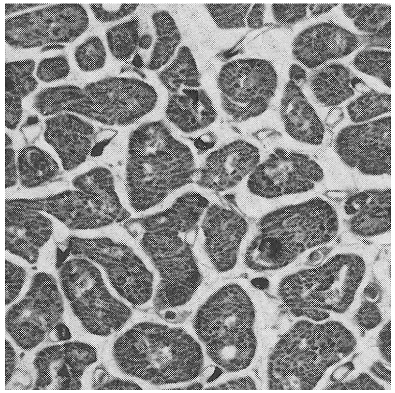
$$\bar{\mathfrak{f}}^{\text{open}} = [\, \bar{\mathfrak{v}} - \mathfrak{v}\,]\, \mathfrak{R}$$

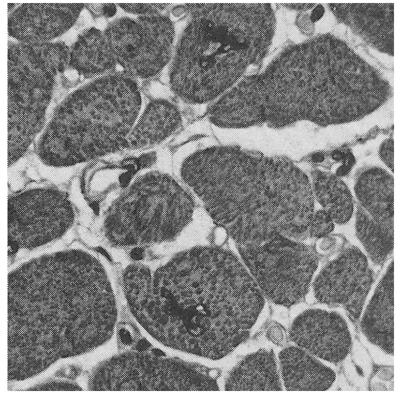


• open system thermodynamics – balance of mass

$$\mathrm{d}_t\ \rho_0 = \mathrm{Div}\ (\boldsymbol{R}) + \mathcal{R}_0$$

FUNG [1990]





MASS FLUX $\boldsymbol{R}$

- migration (cell movement)

MASS SOURCE $\mathcal{R}_0$

- proliferation (cell growth)
- hyperplasia (cell division)
- hypertrophie (cell enlargement)

'biological equilibrium'

COWIN & HEGEDUS [1976], BEAUPRÉ, ORR & CARTER [1990], WEINANS, HUISKES & GROETENBOER [1992], HARRIGAN & HAMILTON [1992], NACKENHORST [1997], HUISKES [2000], EPSTEIN & MAUGIN [2000], CARTER & BEAUPRÉ [2001], KUHL & STEINMANN [2002]

density growth - balance equations

open system thermodynamics – balance of momentum

- volume specific version

$$\mathrm{d}_t(\rho_0\, \boldsymbol{v}) = \mathrm{Div}\,(\,\boldsymbol{\Pi}^{\mathrm{t}} + \boldsymbol{v} \otimes \boldsymbol{R}\,) + [\,\boldsymbol{b}_0 + \boldsymbol{v}\,\mathcal{R}_0 - \nabla_X \boldsymbol{v} \cdot \boldsymbol{R}\,]$$

subtraction of balance of mass weighted by $\boldsymbol{v}$

$$\boldsymbol{v}\,\mathrm{d}_t\rho_0 = \mathrm{Div}\,(\,\boldsymbol{v} \otimes \boldsymbol{R}\,) + \boldsymbol{v}\,\mathcal{R}_0 - \nabla_X \boldsymbol{v} \cdot \boldsymbol{R}$$

- mass specific version

$$\rho_0\,\mathrm{d}_t\boldsymbol{v} = \mathrm{Div}\,(\boldsymbol{\Pi}^{\mathrm{t}}) + \boldsymbol{b}_0$$

'mechanical equilibrium'

open system thermodynamics – dissipation inequality

- free energy

$$\psi = \psi(\boldsymbol{F}, \rho_0, \ldots)$$

- definition of stress $\boldsymbol{\Pi}^{\mathrm{t}}$

$$\boldsymbol{\Pi}^{\mathrm{t}} = \rho_0 \, \partial_{\boldsymbol{F}} \psi$$

- reduced dissipation inequality

$$\mathcal{D}_0^{\mathrm{red}} = -\rho_0 \, \mathrm{d}_{\rho_0} \psi [\mathrm{Div}\,(\boldsymbol{R}) + \mathcal{R}_0] + \theta [\mathrm{Div}\,(\boldsymbol{S}) + \mathcal{S}_0] + \ldots \geq 0$$

- thermodynamic restrictions

$$\boldsymbol{R} \leq \frac{\theta}{\rho_0 \, \mathrm{d}_{\rho_0} \psi} \boldsymbol{S} \qquad \mathcal{R}_0 \leq \frac{\theta}{\rho_0 \, \mathrm{d}_{\rho_0} \psi} \mathcal{S}_0$$

"...a living organism can only keep alive by continually **drawing from its environment negative entropy**. it feeds upon negative entropy to compensate the entropy increase it produces by living..." SCHRÖDINGER [1944]

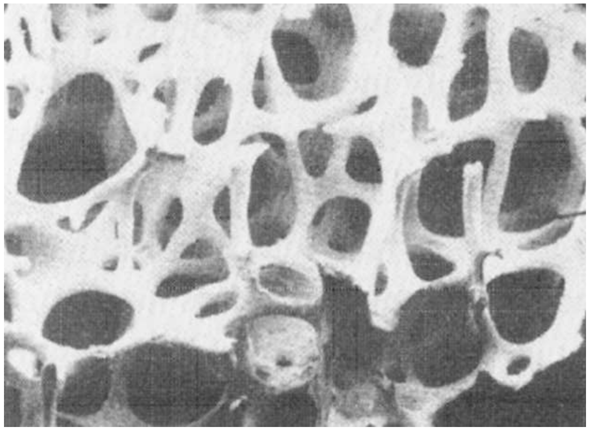
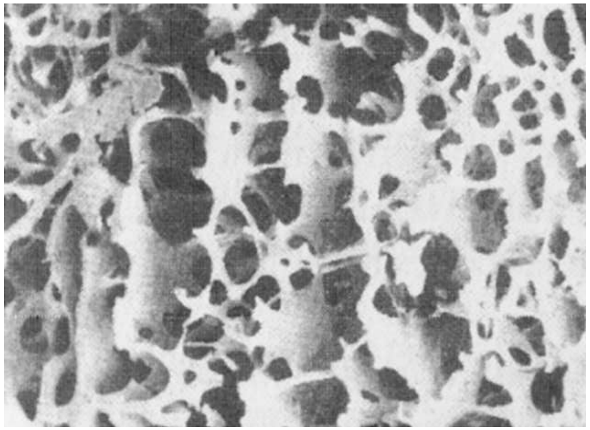
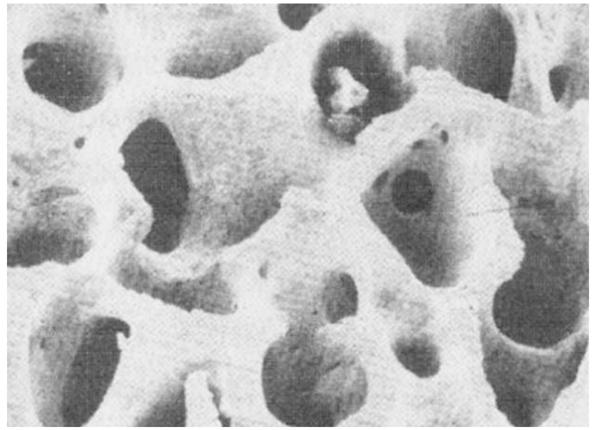
theory of open systems	theory of porous media
• constituents are **spatially seperated**	• local **superposition** of constituents
• overall behavior primarily determined by **one single constituent**	• consideration of mixture of **multiple constituents**
• **exchange** of mass, momentum, energy and entropy **with environment**	• **exchange** of mass, momentum, energy and entropy **amongst constituents**

Biot [1941], [1955], de Groot [1951], Truesdell & Toupin [1960], Bowen [1976], Cowin & Hegedus [1976], Ehlers & Markert [1998], Epstein & Maugin [2000], de Boer [2000], Ehlers [2002], Humphrey & Rajagopal [2002], Kuhl & Steinmann [2002], [2003]

comparison – open systems vs. porous media

density growth at constant volume

- free energy $\psi_0 = \left[\frac{\rho_0}{\rho_0^*}\right]^n \psi^{\text{neo}}$
- stress $\boldsymbol{\Pi}^{\text{t}} = \left[\frac{\rho_0}{\rho_0^*}\right]^n \boldsymbol{\Pi}^{\text{tneo}}$
- mass flux $\boldsymbol{R} = R_0 \nabla \rho_0$
- mass source $\mathcal{R}_0 = \left[\frac{\rho_0}{\rho_0^*}\right]^{-m} \psi_0 - \psi_0^*$

constitutive coupling of growth and deformation

Harrigan & Hamilton [1992], Weinans et al. [1992], Jacobs et al. [1995]

density growth – constitutive equations

biomechanics		damage mechanics	
• **living** tissues		• **engineering** materials	
• **density**	ρ_0	• **damage variable**	$d = 1 - \rho_0 \,/\, \rho_0^*$
• free energy	$\psi = [\,\rho_0 \,/\, \rho_0^*\,]^n \, \psi^{\mathrm{neo}}$	• free energy	$\psi = [\,1 - d\,]\, \psi^{\mathrm{neo}}$
• **increase** in stiffness	$\mathrm{d}_t \rho_0 > 0$	• **decrease** in stiffness	$\mathrm{d}_t d > 0$
• external entropy supply	$\mathcal{S}_0 \geq 0,\ \boldsymbol{S} \geq \boldsymbol{0}$	• no external entropy supply	$\mathcal{S}_0 = 0,\ \boldsymbol{S} = \boldsymbol{0}$

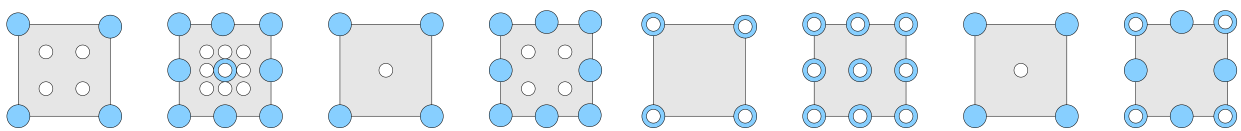
Kachanov [1958], Chaboche [1982], Lemaître [1984], [1992], Lemaître & Chaboche [1985], Simo & Ju [1987], Krajcinovic & Lemaître [1987], Ju [1990], Krajcinovic [1996]

comparison – biomechanics vs. damage mechanics

continuous initial boundary value problem

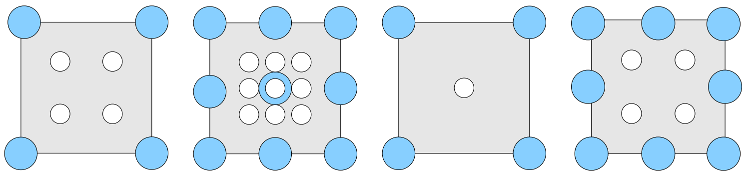
$$\mathrm{d}_t \rho_0 - \mathrm{Div}\,(\boldsymbol{R}) \; - \mathcal{R}_0 = 0$$
$$\rho_0 \, \mathrm{d}_t \boldsymbol{v} \; - \mathrm{Div}\,(\boldsymbol{\Pi}^{\mathrm{t}}) - \boldsymbol{b}_0 \; = \boldsymbol{0}$$

- temporal discretization — **implicit EULER backward scheme**
  semi-discrete boundary value problem
- spatial discretization — **finite element method**
  discrete boundary value problem
- consistent linearization — **GATEAUX derivative**
  linearized discrete boundary value problem
- solution — **incremental iterative NEWTON–RAPHSON scheme**
  integration point based vs. node point based approach



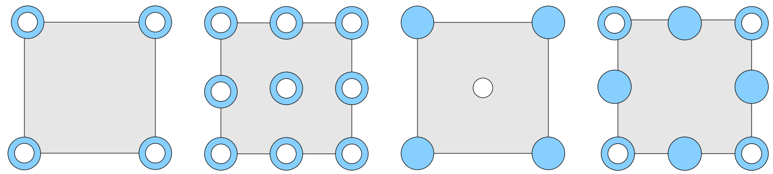
density growth - numerics

integration point based



- $\mathcal{C}^{-1}$–**continuous** density interpolation designed for discontinuous problems
- number of global dofs unaffected
- **additional local newton iteration**
- convergence upon mesh refinement
- restricted to **flux-free** formulations

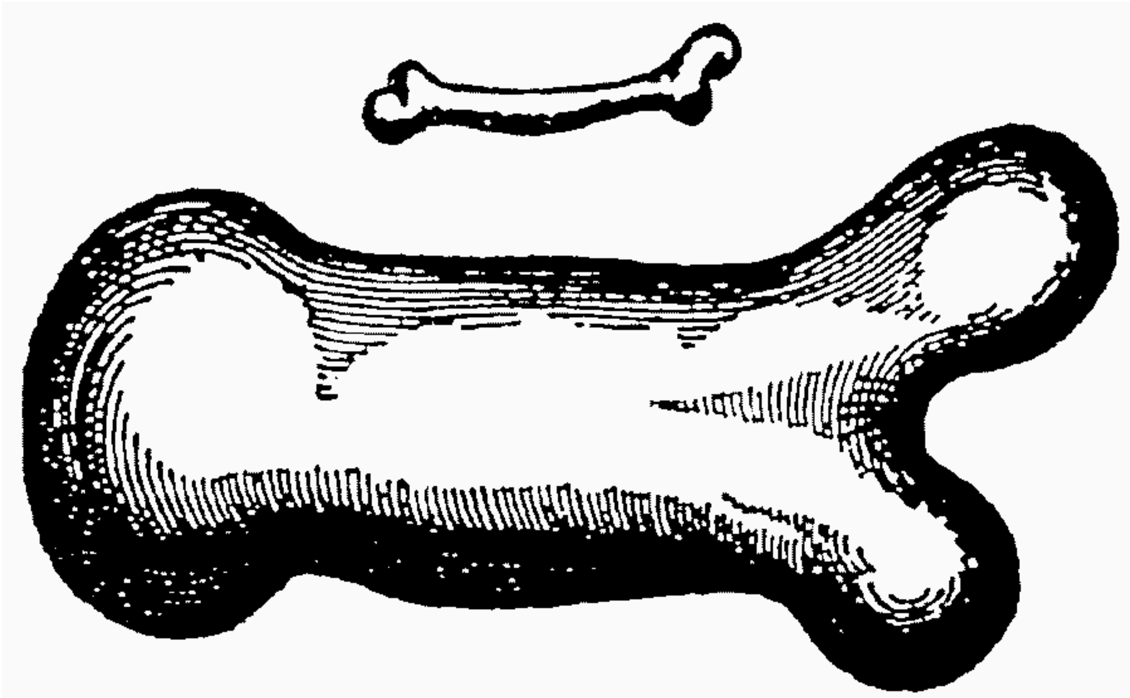
node point based



- $\mathcal{C}^{0}$–**continuous** density interpolation designed for continuous problems
- **additional global dofs**
- no local newton iteration
- convergence upon mesh refinement
- mandatory in case of **mass flux** $\boldsymbol{R} \propto \nabla \rho_0$

comparison – integration vs. node point based

discorsi e dimostrazioni matematiche



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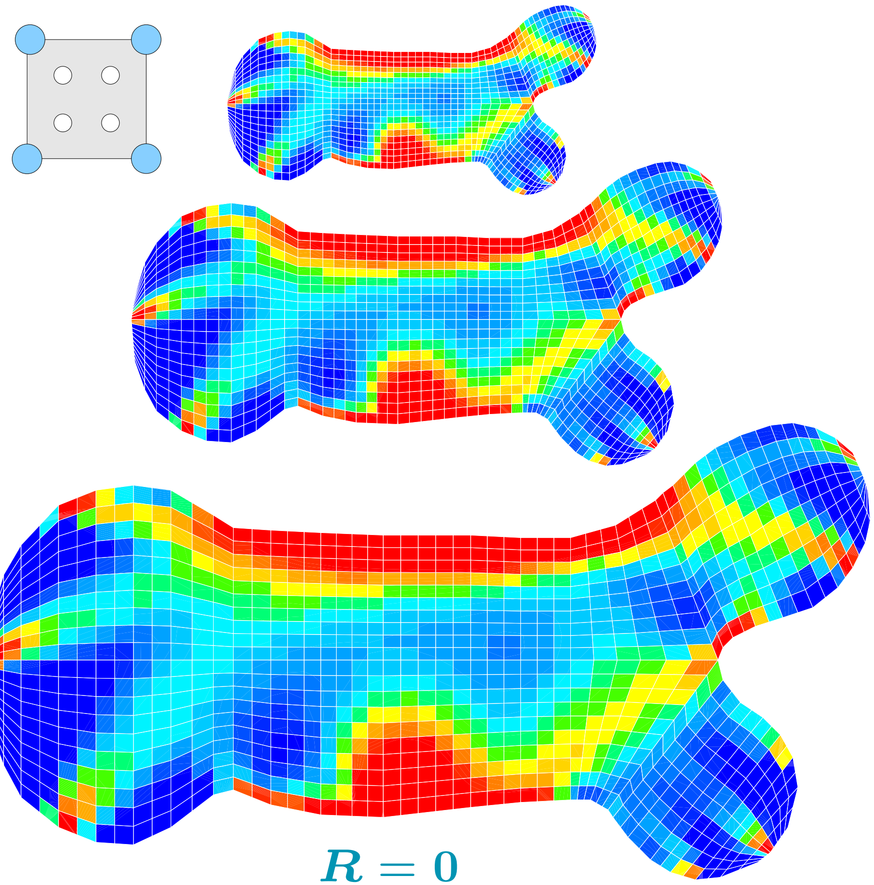
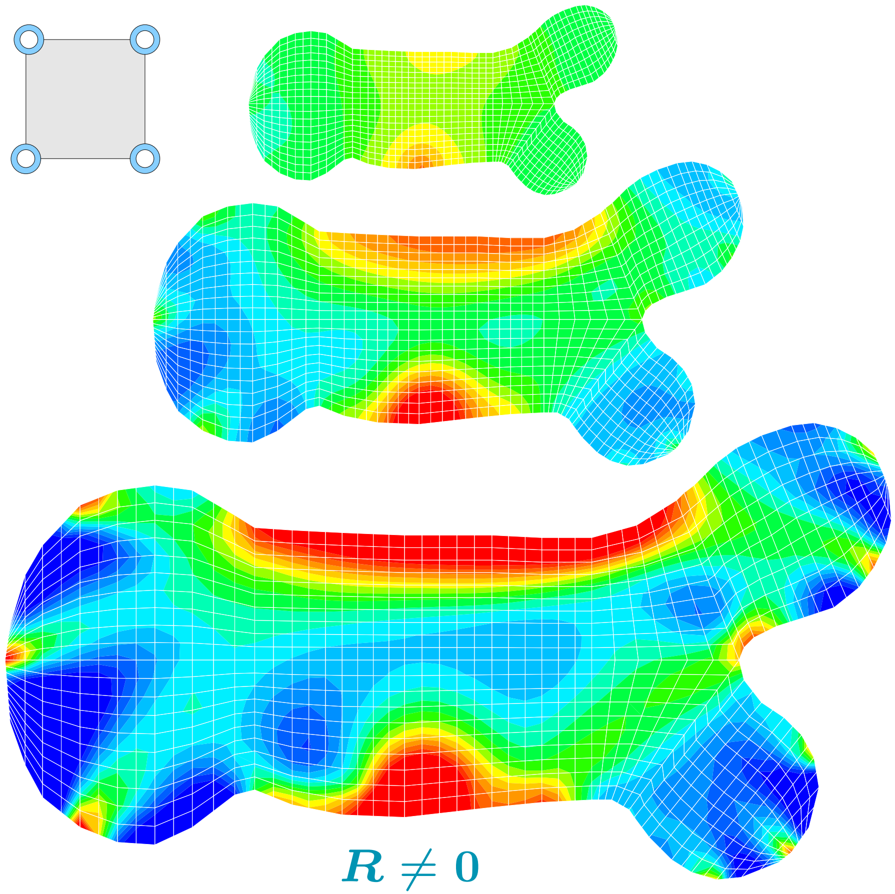
example – size effect in bone

integration point based vs. node point based

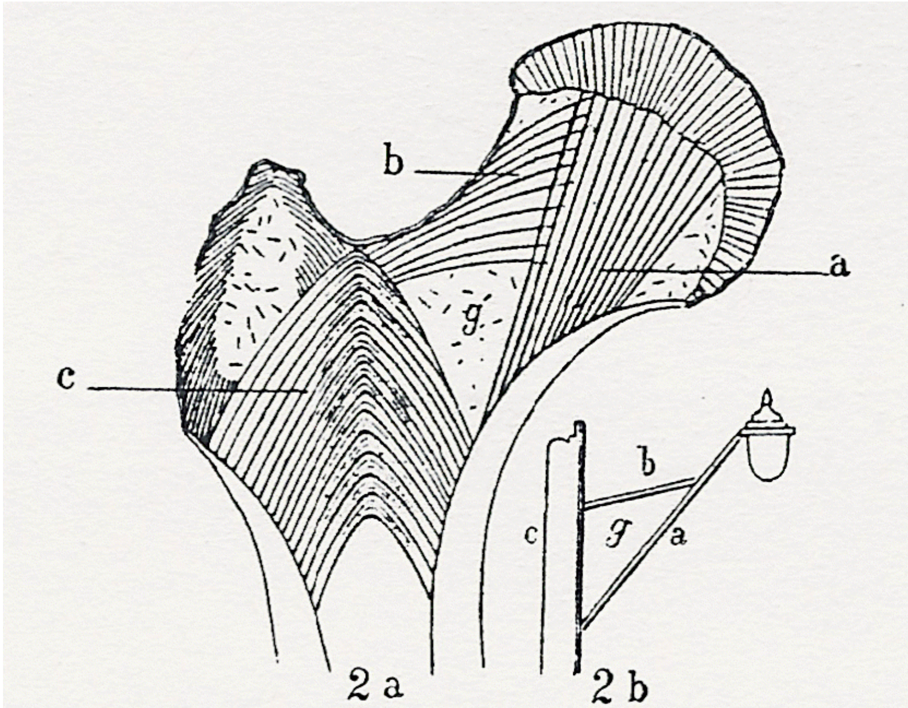




incorporation of **mass flux** enables simulation of **galileo's size effect**

example - size effect in bone

law of bone remodelling



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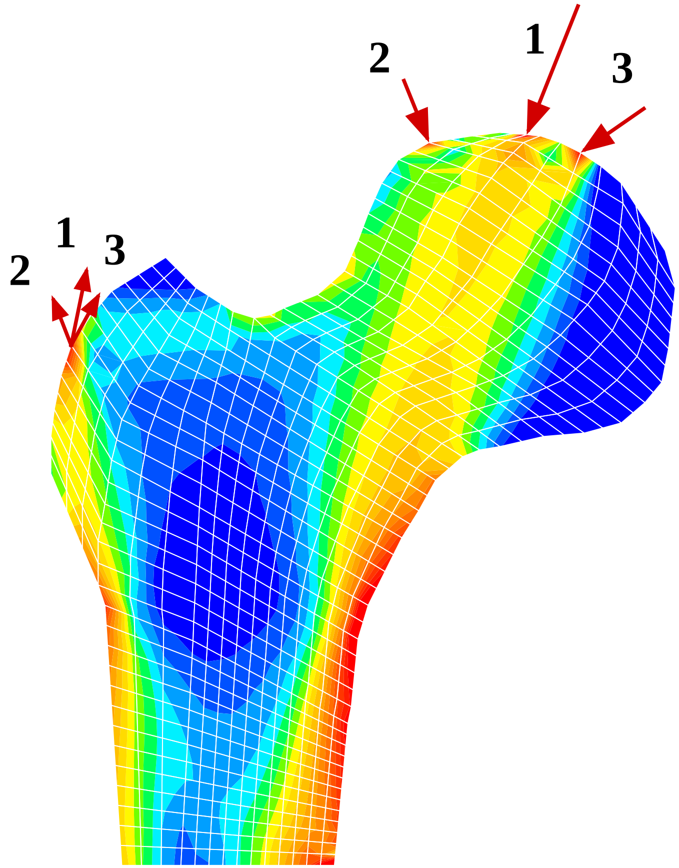
example – adaptation in bone

experimental observation vs. numercial simulation

WOLFF [1892]



- **dense system of compressive trabeculae** carrying stress into calcar region
- **secondary arcuate system** form medial joint surface to lateral metaphyseal region
- **ward's triangle** low–density region contrasting **dense cortical shaft**

example – adaptation in bone

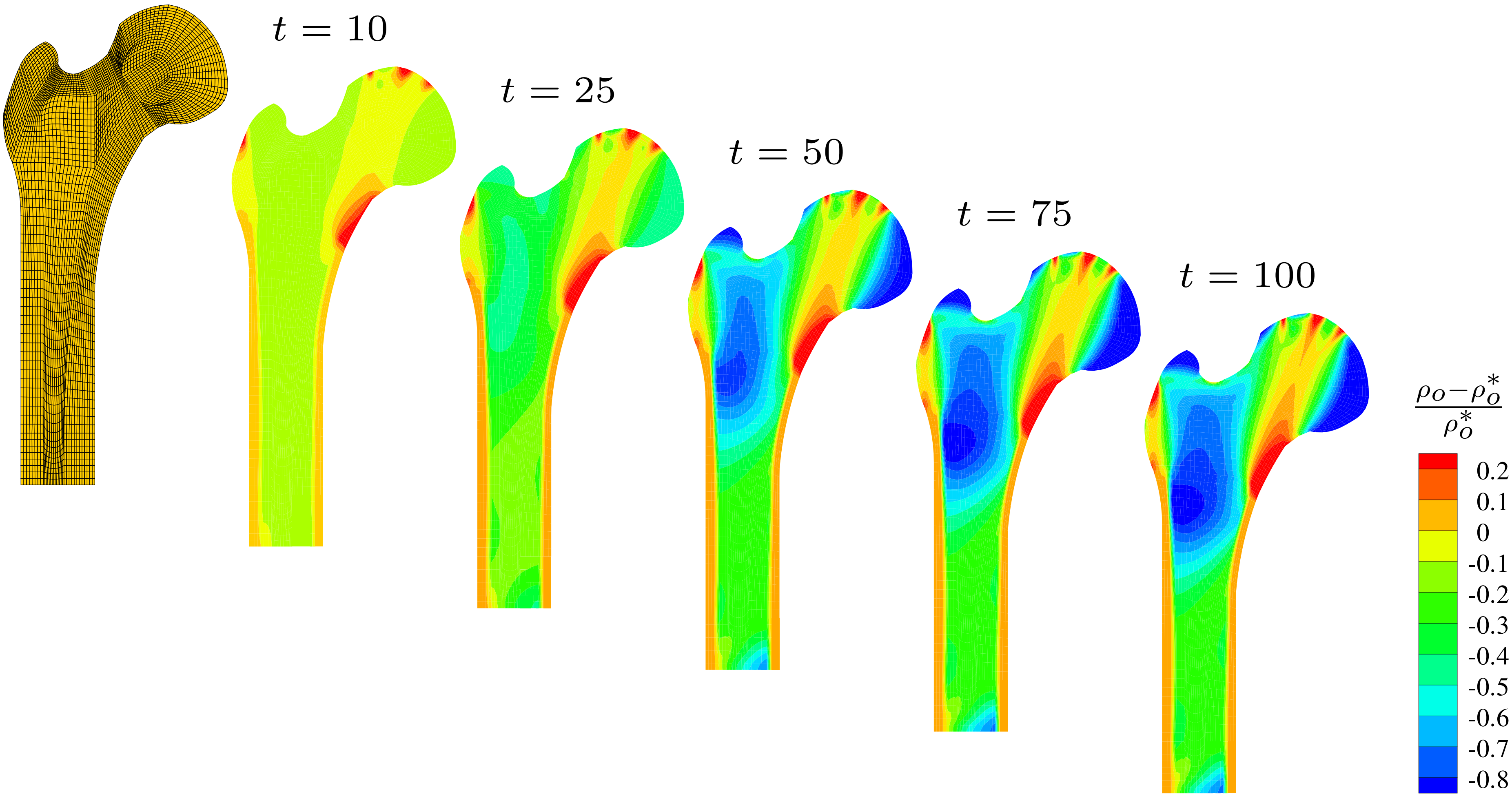
total hip replacement vs. hip resurfacing

- about 1 000 000 artificial hip replacements per year
- **aseptic loosening** caused by **adaptive bone remodelling**
- goal: prediction of **redistribution of bone density**

KUHL & BALLE [2004]

example – hip replacement

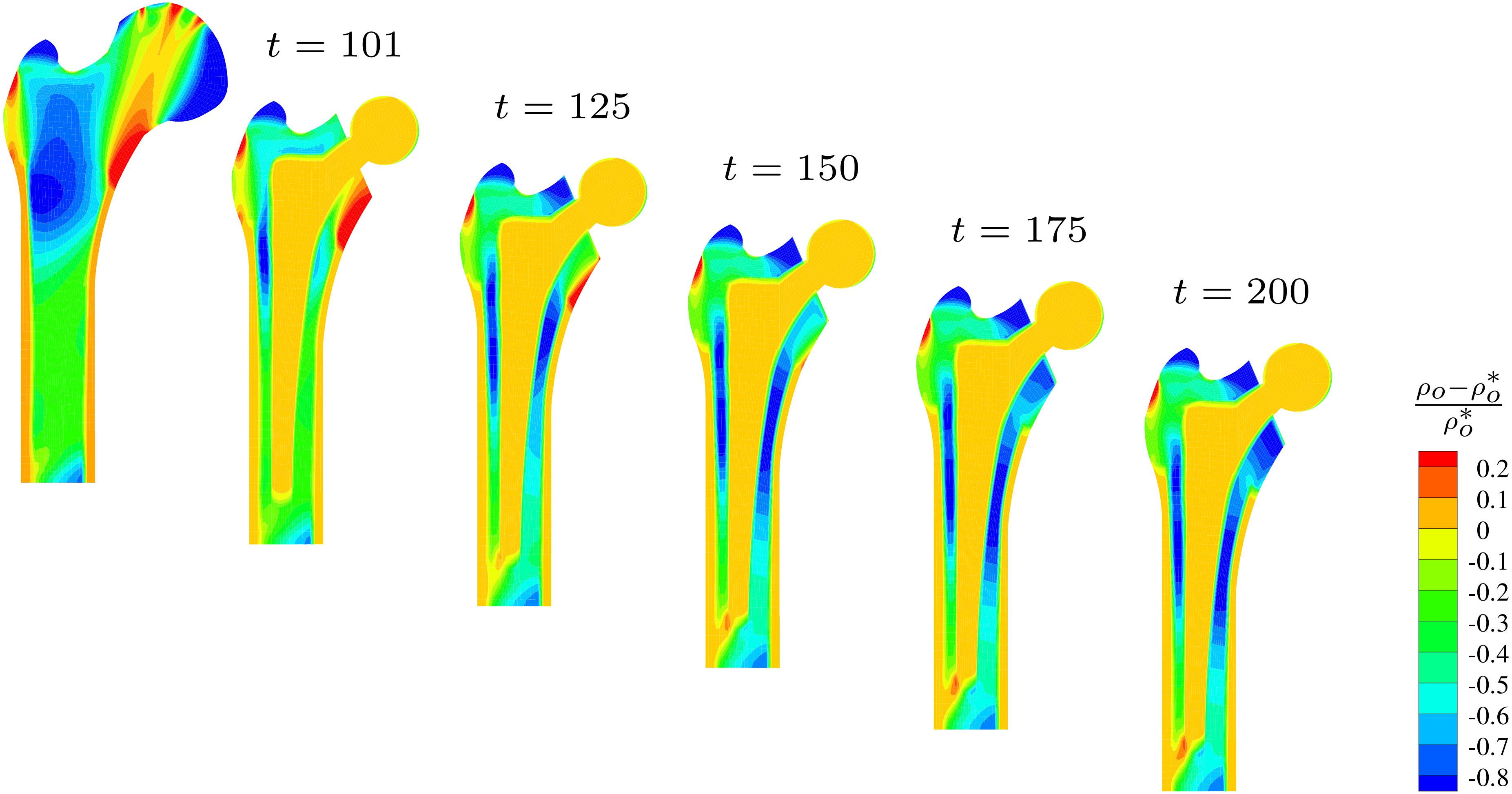
• density evolution – before implantation



ward's triangle – tensile & compressive trabeculae - dense cortical shaft

example – hip replacement

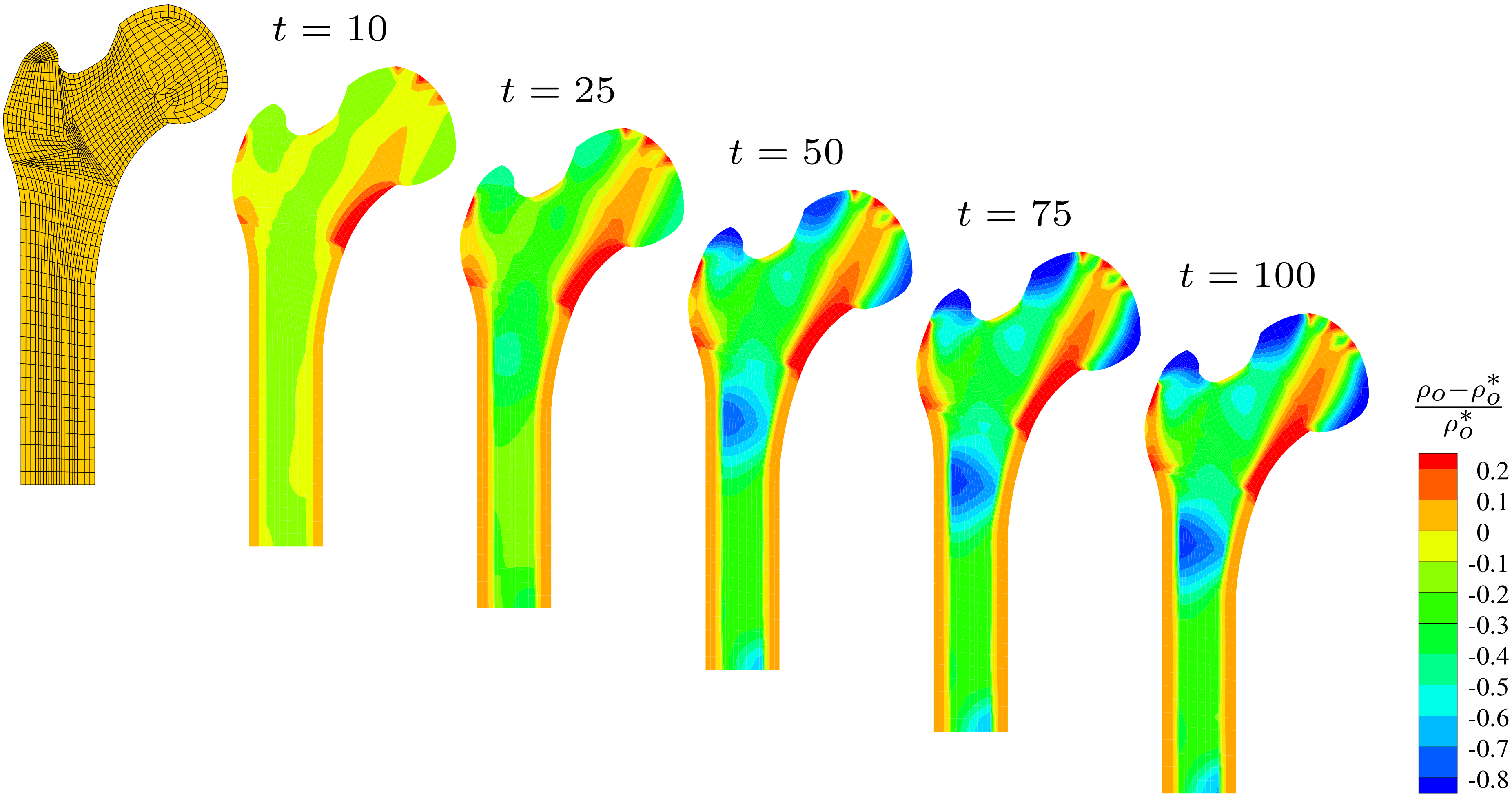
• density evolution – conventional total hip replacement



stiff prosthesis – stress shielding – bone resorption – implant loosening

example – hip replacement

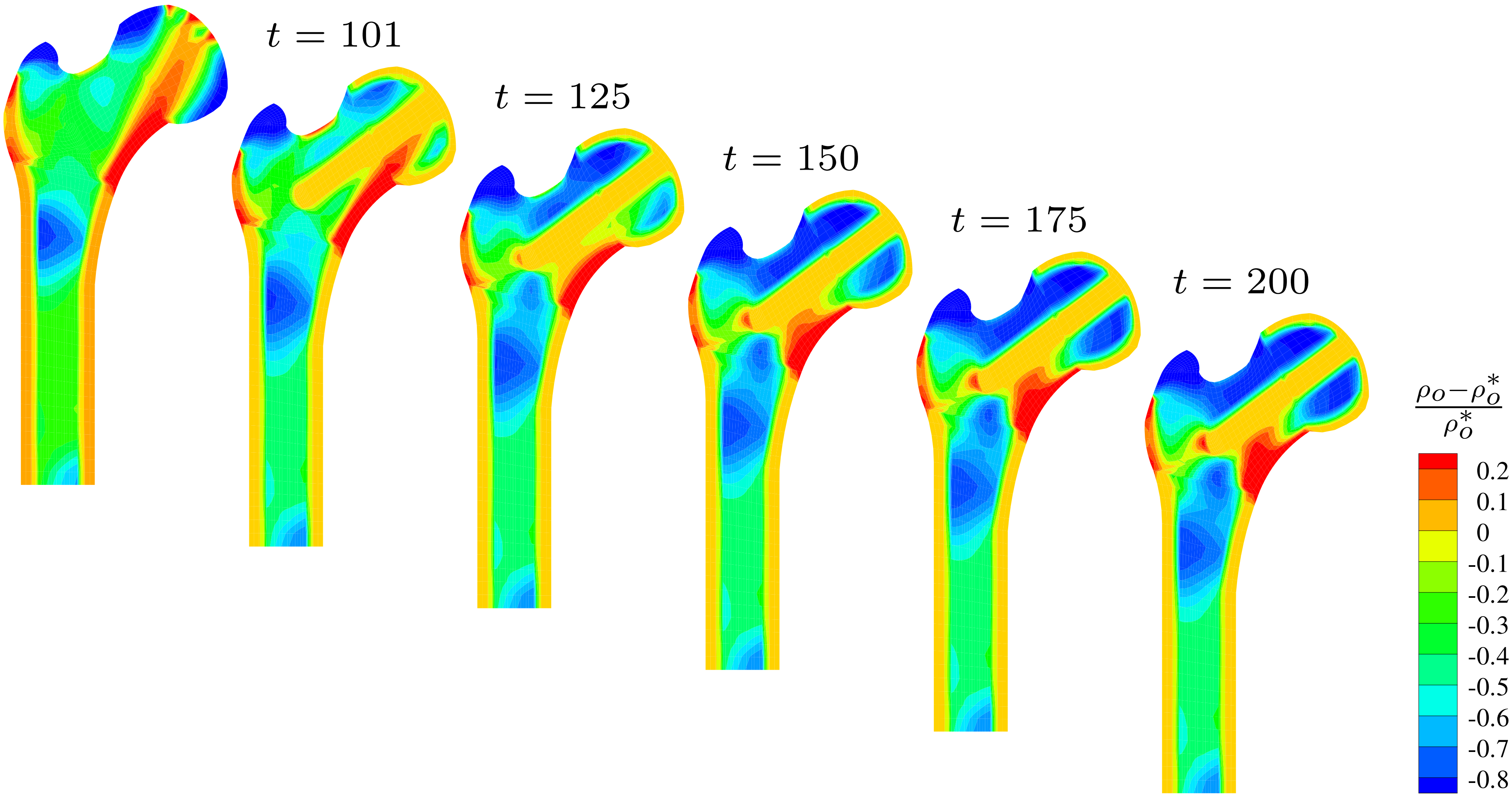
• density evolution – before implantation



ward's triangle – tensile & compressive trabeculae - dense cortical shaft

example – hip replacement

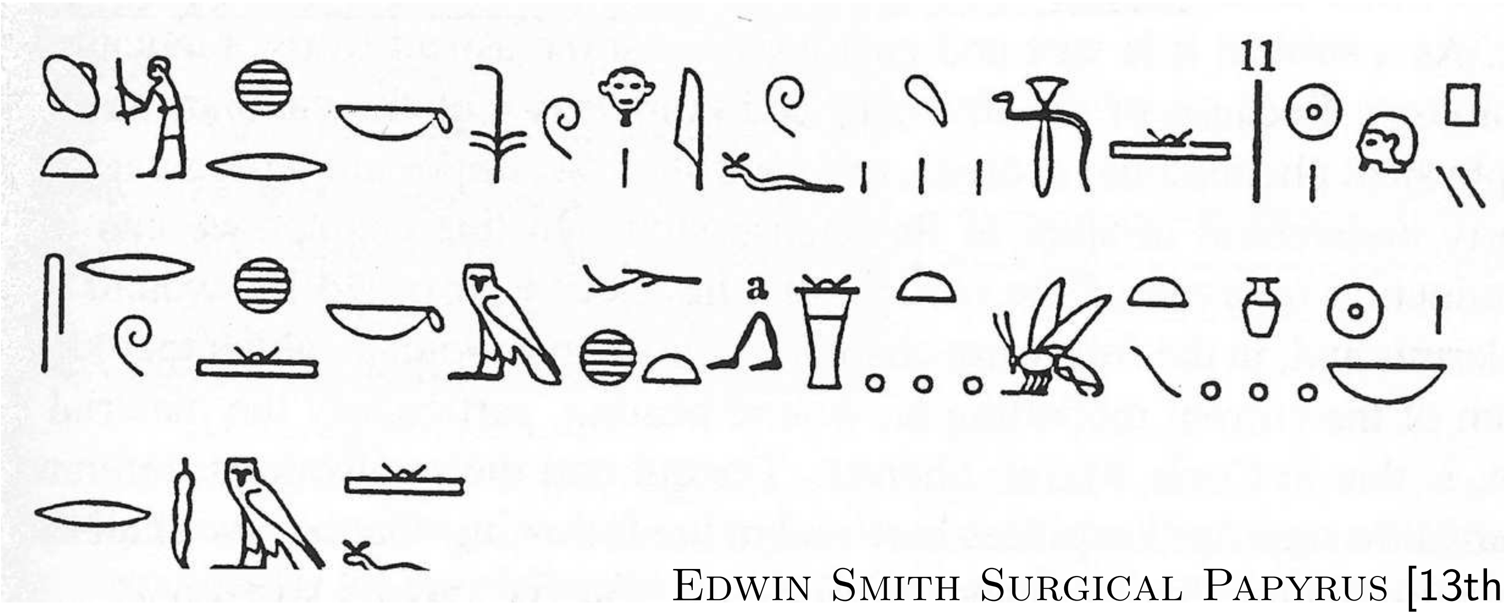
• density evolution – new birmingham hip resurfacing



improved ingrowth - anatomic loading situation preserved - less resorption

example – hip replacement

wound treatment in egypt 2500 bc

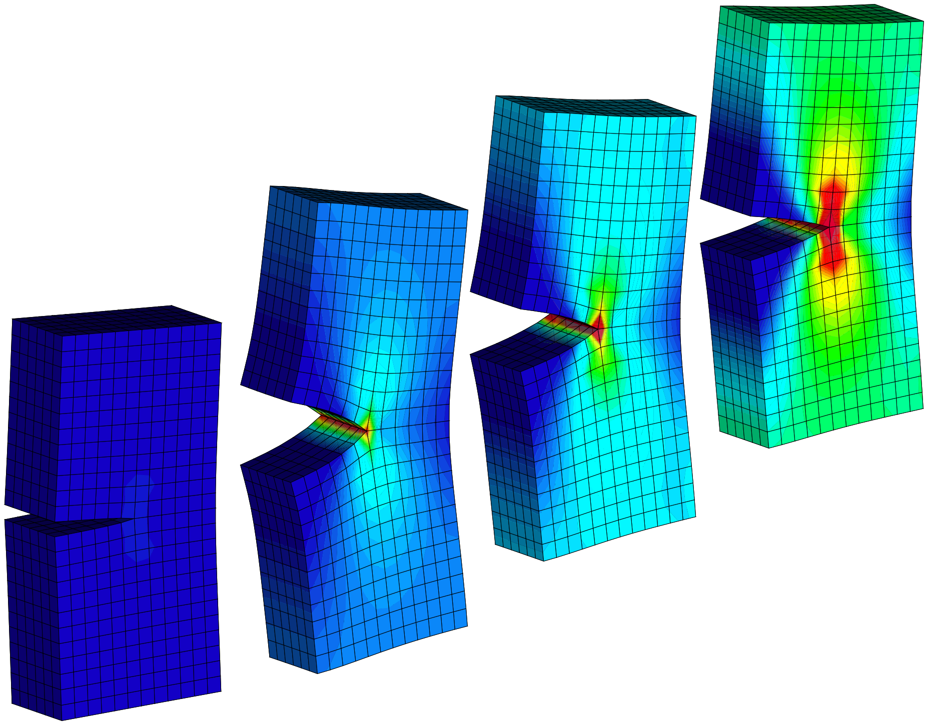


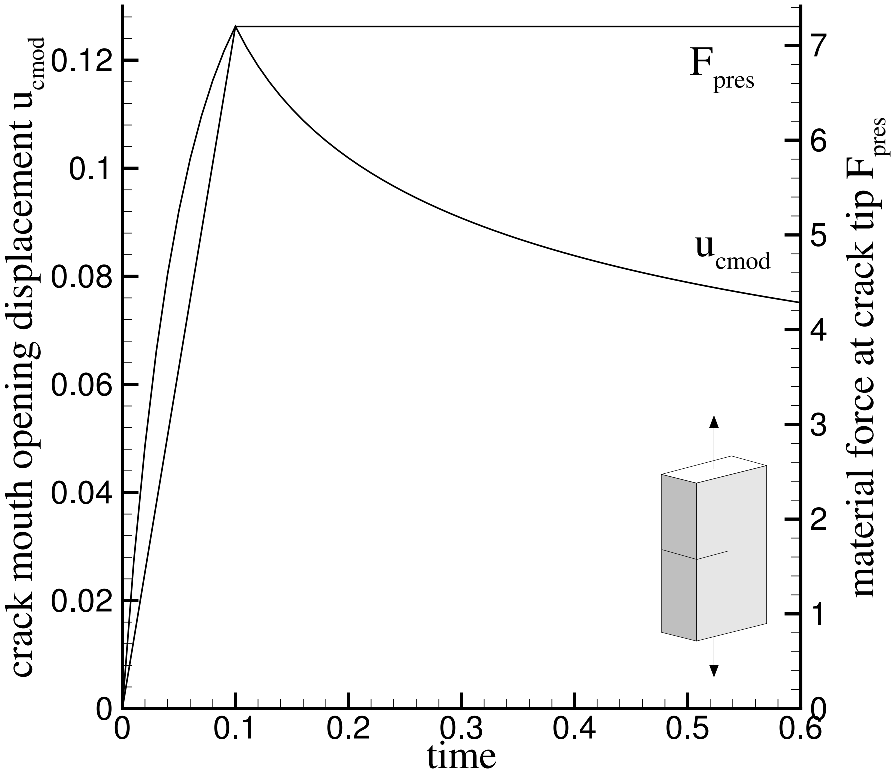
Edwin Smith Surgical Papyrus [13th Dynasty]

"...thou shouldst bind it with fresh meet the first day, and thou shouldst treat afterword with grease and honey every day until he recovers..."

example – wound healing

• self healing of notch under tension

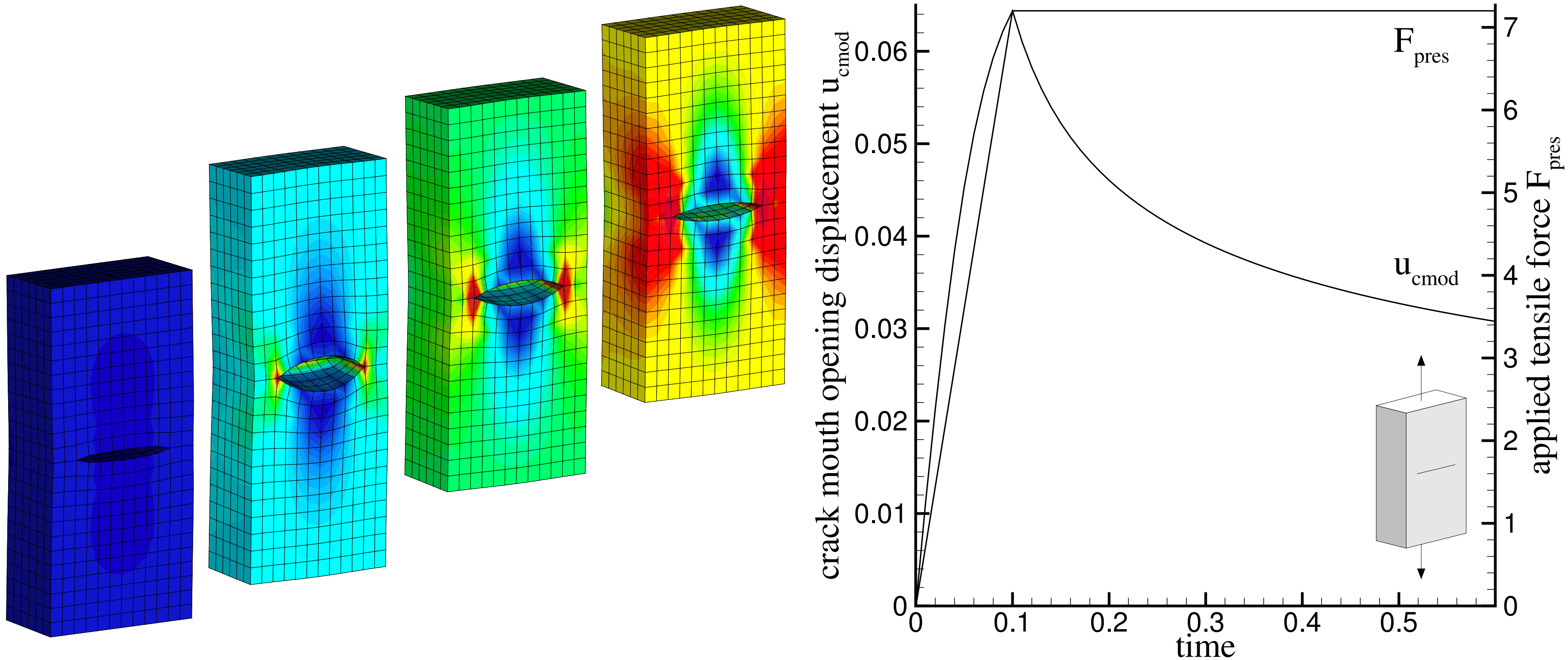




• **cell migration** & **cell growth** stimulated by surface traction at wound boundary
• remarkable **reduction of overall deformation** accompanied by **wound closure**

example – wound healing

• **self healing of surface cut under tension**



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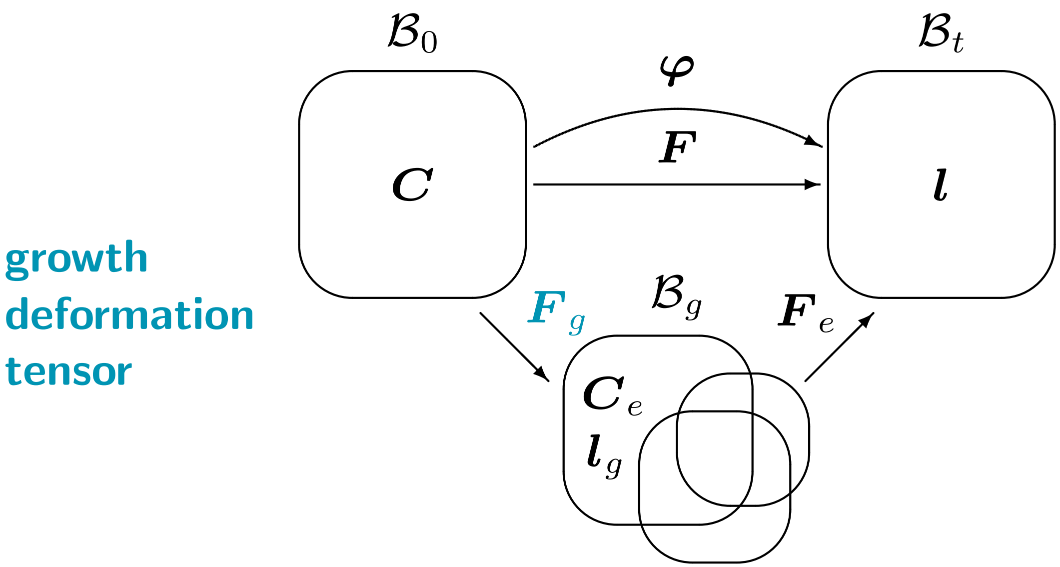
example – wound healing

volume growth

multiplicative decomposition

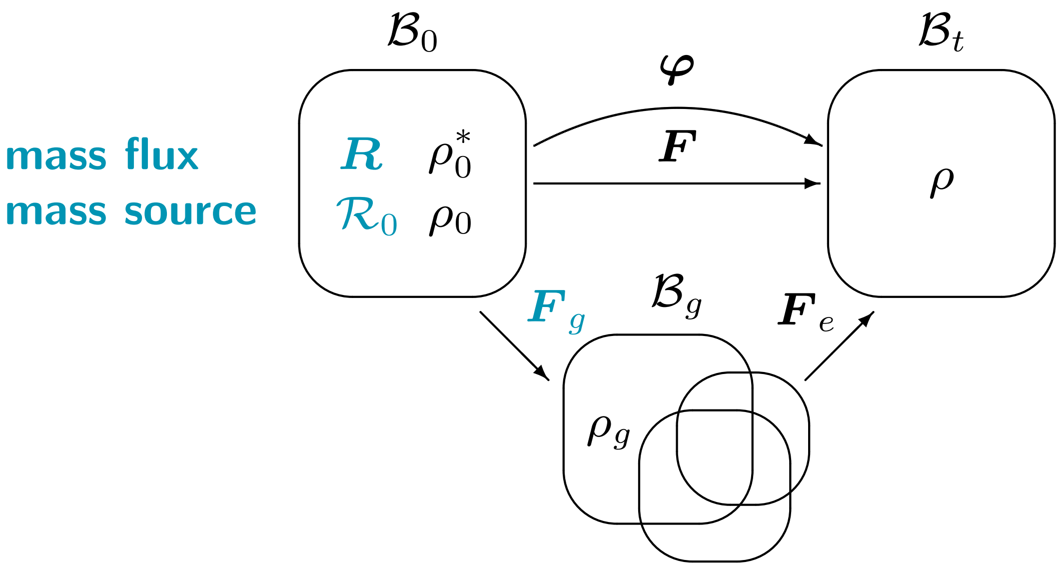


- deformation gradient $\boldsymbol{F} = \nabla\boldsymbol{\varphi} = \boldsymbol{F}_e \cdot \boldsymbol{F}_g$
- elastic right cauchy green tensor $\boldsymbol{C}_e = \boldsymbol{F}_e^{\mathrm{t}} \cdot \boldsymbol{F}_e$
- growth velocity gradient $\boldsymbol{l}_g = \mathrm{d}_t \boldsymbol{F}_g^{\mathrm{t}} \cdot \boldsymbol{F}_g^{-1}$

Lee [1969], Rodriguez, Hoger & McCulloch [1994], Epstein & Maugin [2000], Chen & Hoger [2000], Ambrosi & Mollica [2002], Humphrey [2002], Imatani & Maugin [2002], Lubarda [2004], Garikipati, Arruda, Grosh, Narayanan & Calvé [2004]

growth – kinematics

change in mass

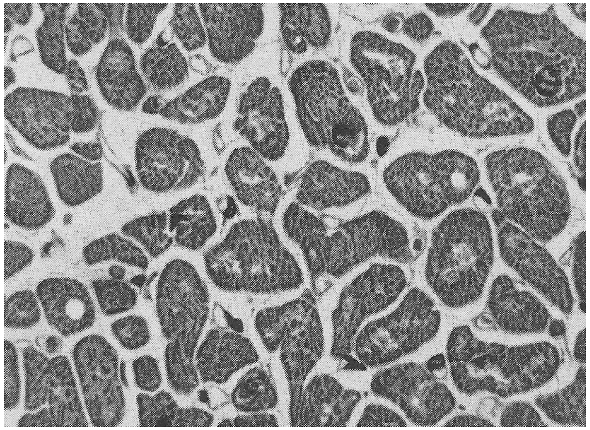
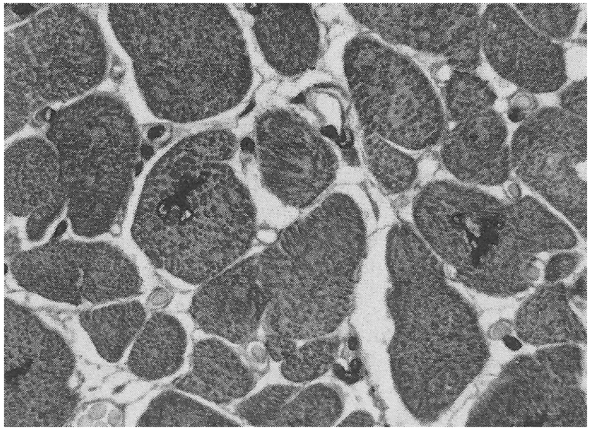
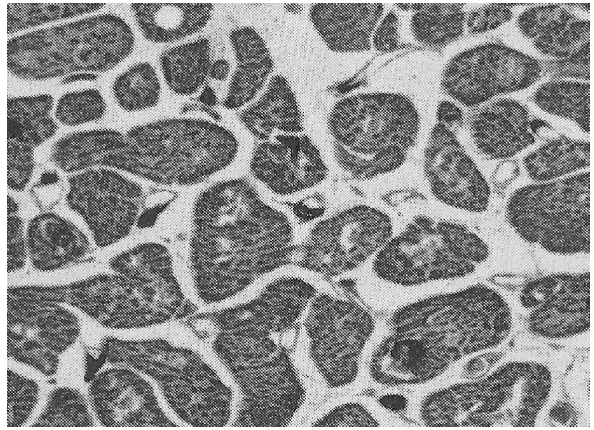


- change in **density** $\rho_0 = \rho_0^* + \int_0^t \mathrm{Div}(\boldsymbol{R}) + \mathcal{R}_0 \,\mathrm{d}\tau$
- change in **volume** $\mathrm{d}V_g = \det(\boldsymbol{F}_g)\,\mathrm{d}V_0$

LUBARDA & HOGER [2002], HIMPEL, KUHL, MENZEL & STEINMANN [2005]

volume growth at constant density

- free energy $\psi_0 = \psi_0^{\text{neo}}(\boldsymbol{F}_e)$
- stress $\boldsymbol{\Pi}_e^{\text{t}} = \boldsymbol{\Pi}_e^{\text{tneo}}(\boldsymbol{F}_e)$
- growth deformation tensor $\boldsymbol{F}_g = \vartheta\,\boldsymbol{I} \qquad \mathrm{d}_t\vartheta = k_\vartheta(\vartheta)\ \mathrm{tr}(\boldsymbol{C}_e \cdot \boldsymbol{S}_e)$
- mass source $\mathcal{R}_0 = 3\ \rho_0^*\,\vartheta^2\,\mathrm{d}_t\vartheta$

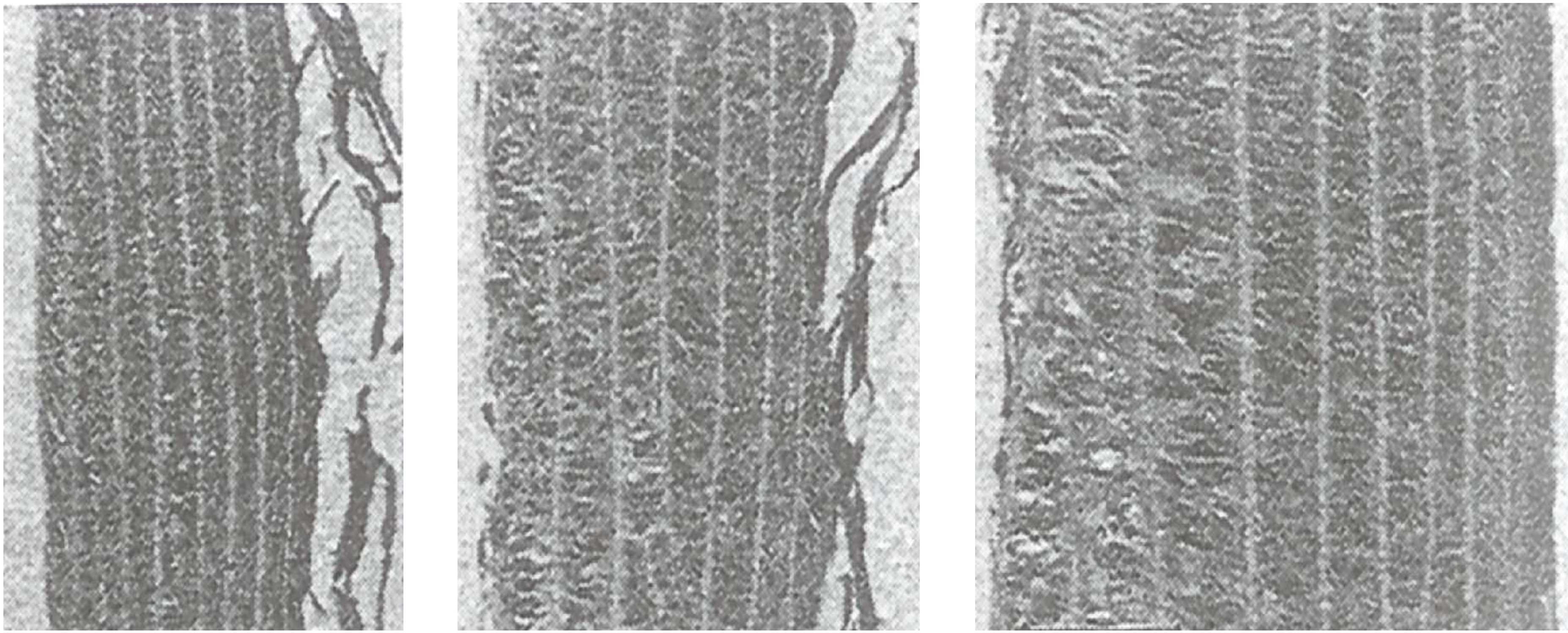
kinematic coupling of growth and deformation

Rodriguez, Hoger & McCulloch [1994], Epstein & Maugin [2000], Humphrey [2002]

volume growth – constitutive equations

density preserving volume growth of the aortic wall

normotensitive hypertensitive severely hypertensitive

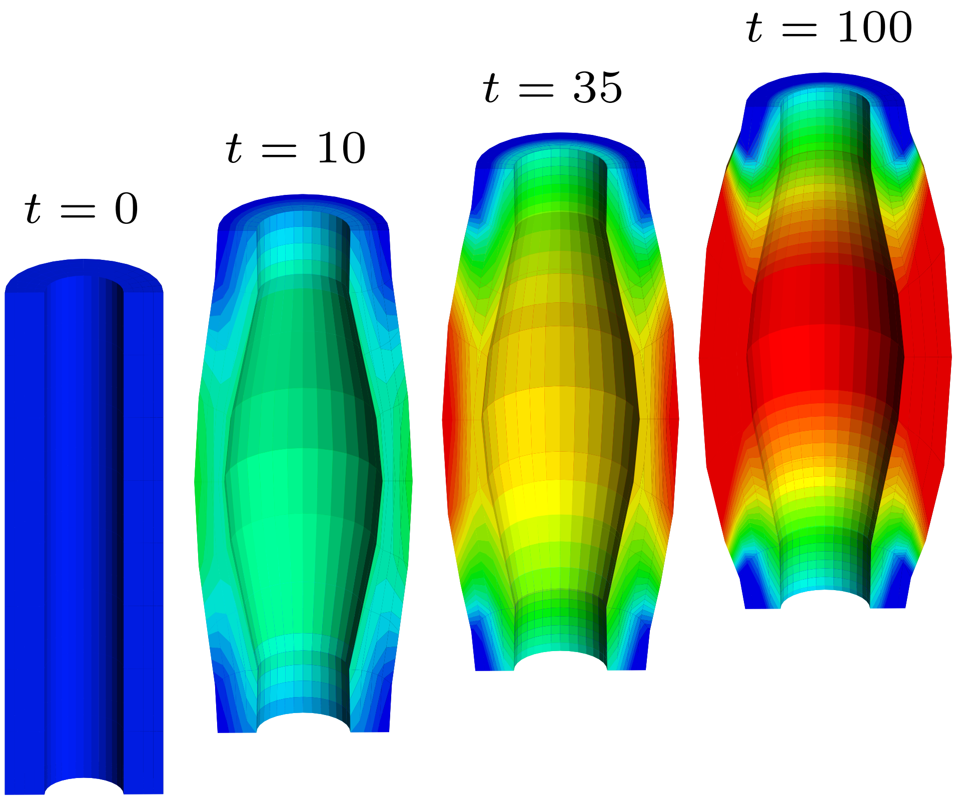


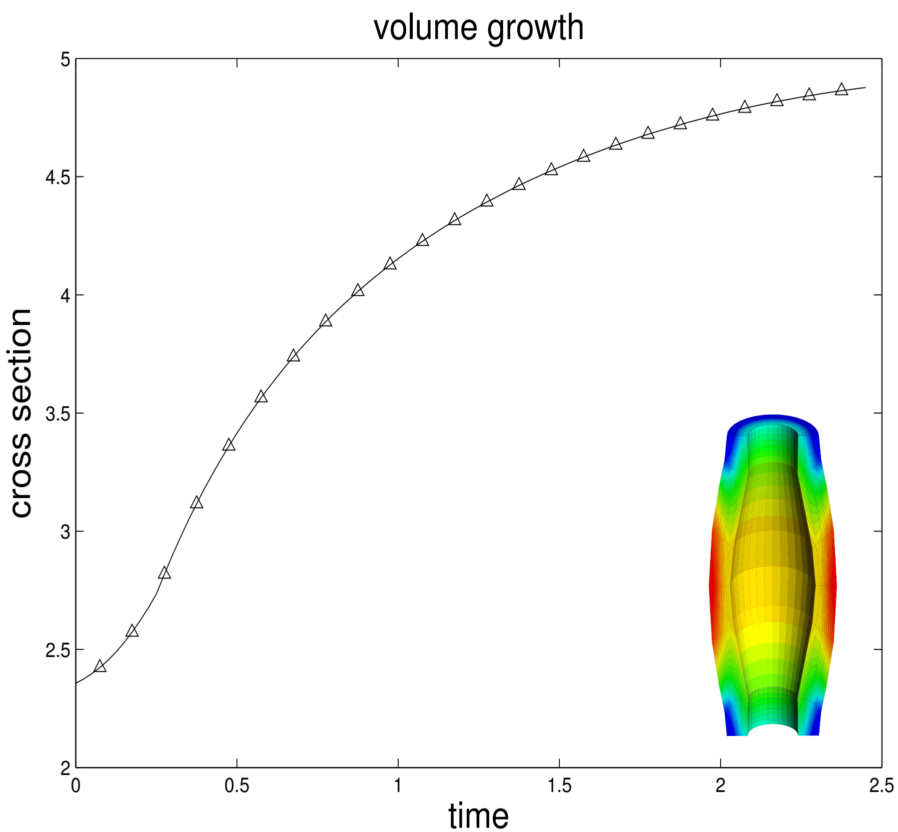
overall wall thickening via thickening of individual musculoelastic fascicles

MATSUMOTO & HAYASHI [1996], HUMPHREY [2002]

example – adaptation in aorthic wall

• volume evolution – qualitative simulation of stent implantation

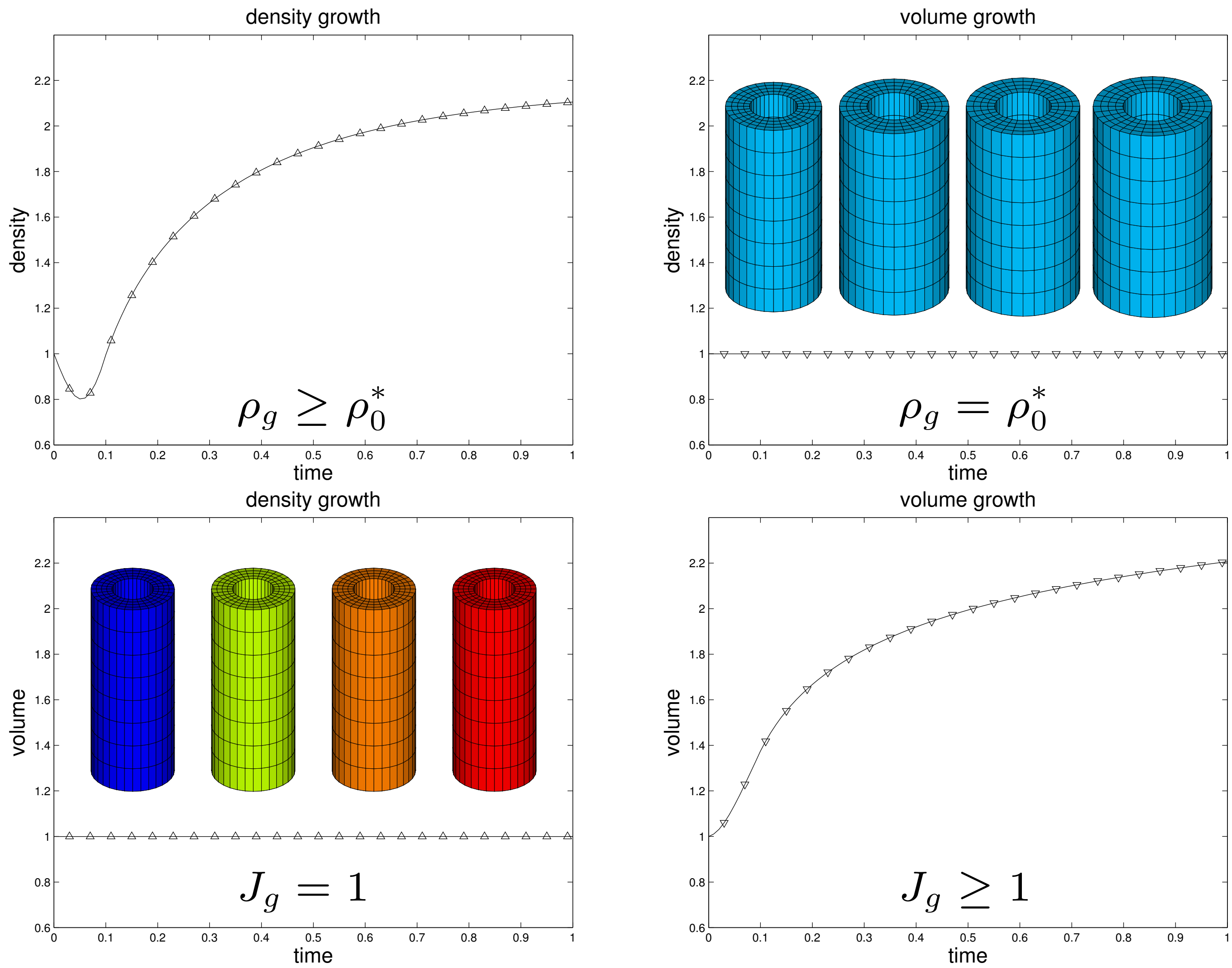




deformation induced volume growth at constant density

example – adaptation in aorthic wall

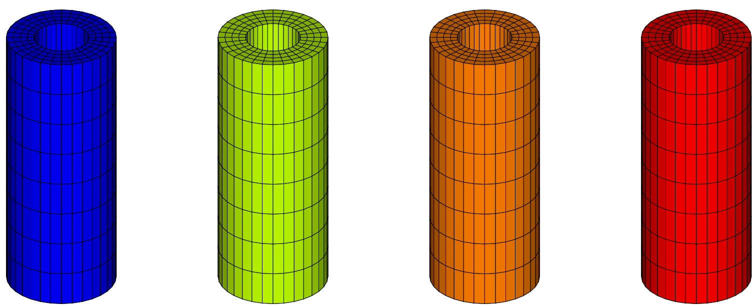
isotropic density growth vs. isotropic volume growth



comparison – density vs. volume growth

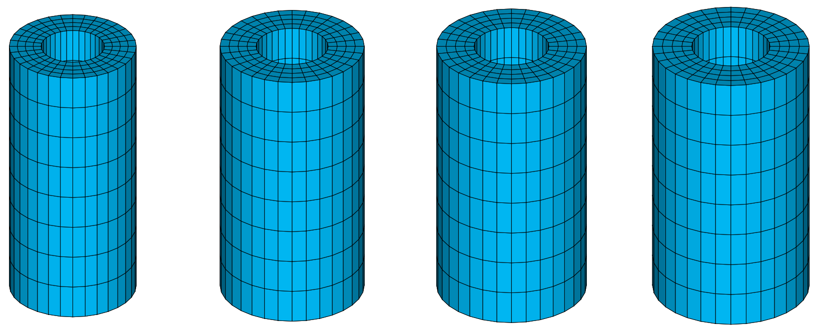
isotropic density growth

- growth in density at **constant volume**
  $\rho_g \geq \rho_0^*$ and $J_g = 1$
- $\boldsymbol{F}_g = \boldsymbol{I}$, choose $\mathrm{d}_t \rho_0 = \mathcal{R}_0$
- **constitutive coupling**
  $\psi = \psi\,(\boldsymbol{F}, \rho_0)$
- characteristic for growth of **hard tissues**
- Cowin & Hegedus [1976]



isotropic volume growth

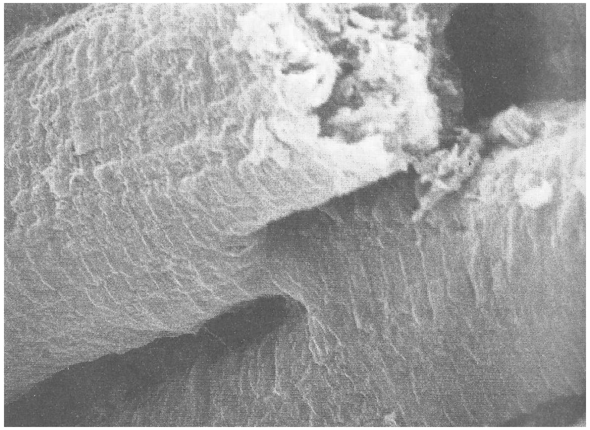
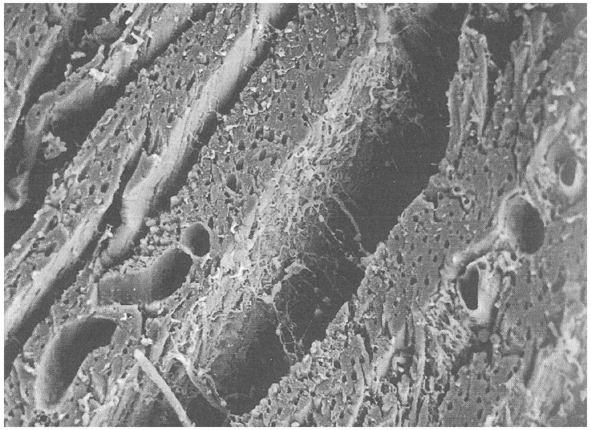
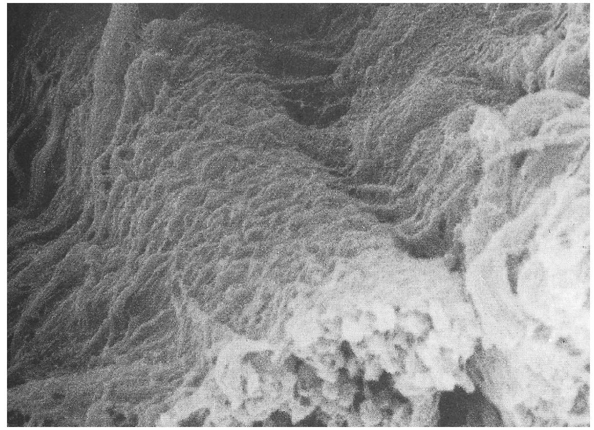
- growth in volume at **constant density**
  $\rho_g = \rho_0^*$ and $J_g \geq 1$
- $\mathcal{R}_0 = \rho_0 \, \mathrm{d}_t \boldsymbol{F}_g : \boldsymbol{F}_g^{-1}$, choose $\mathrm{d}_t \boldsymbol{F}_g$
- **kinematic coupling**
  $\boldsymbol{F}_e = \boldsymbol{F} \cdot \boldsymbol{F}_g^{-1}$
- characteristic for growth of **soft tissues**
- Rodriguez,Hoger,McCulloch[1994]



comparison – density vs. volume growth

fiber growth at constant density

- free energy $\psi_0 = \psi_0^{\text{iso}}(\boldsymbol{F}_e) + \frac{1}{2}\,\alpha\,[\, I_4 - 1\,]^2$
- stress $\boldsymbol{\Pi}_e^{\text{t}} = \boldsymbol{\Pi}_e^{\text{tiso}}(\boldsymbol{F}_e) + \alpha\,\boldsymbol{F}_e\cdot\boldsymbol{n}_0 \otimes \boldsymbol{n}_0$
- growth deformation tensor $\boldsymbol{F}_g = \vartheta\,\boldsymbol{I} + [\,\eta - \vartheta\,]\,\boldsymbol{n}_0 \otimes \boldsymbol{n}_0 \qquad \boldsymbol{F}_g \cdot \boldsymbol{n}_0 = \eta\,\boldsymbol{n}_0$
- mass source $\mathcal{R}_0 = \rho_0^*\,[\,\eta\,\vartheta\,\mathrm{d}_t\vartheta + \vartheta^2\,\mathrm{d}_t\eta\,]$

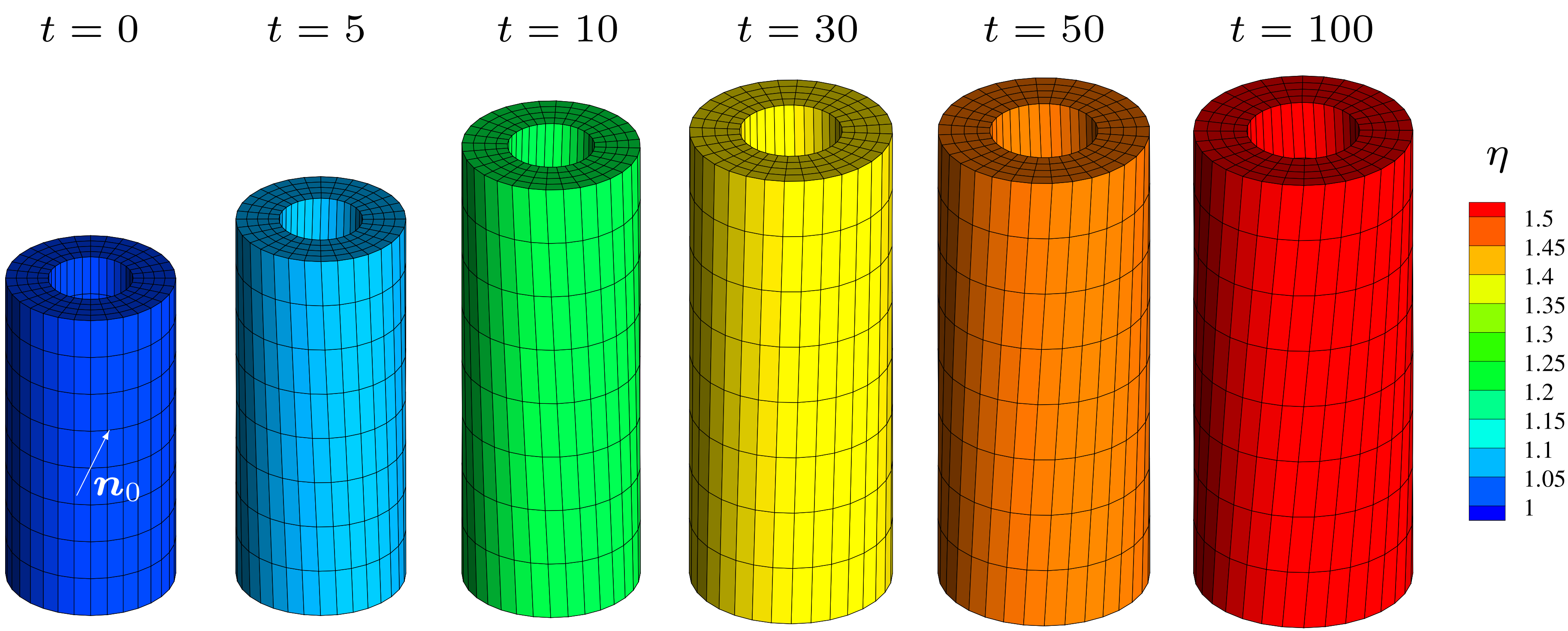




kinematic coupling of growth and deformation

Lubarda & Hoger [2002], Himpel, Kuhl, Menzel & Steinmann [2005]

fiber growth – constitutive equations

• anisotropic growth in cylindrical tube



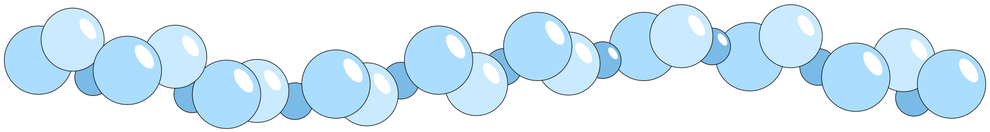
deformation induced fiber and volume growth at constant density

example – tube in tension

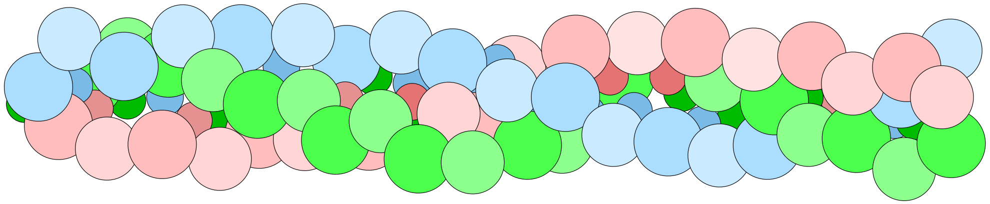
remodelling

collagen chains as major protein of extracellular matrix

glycin hydroxyprolin prolin amino acids



about 1000 amino acids
form a collagen α chain

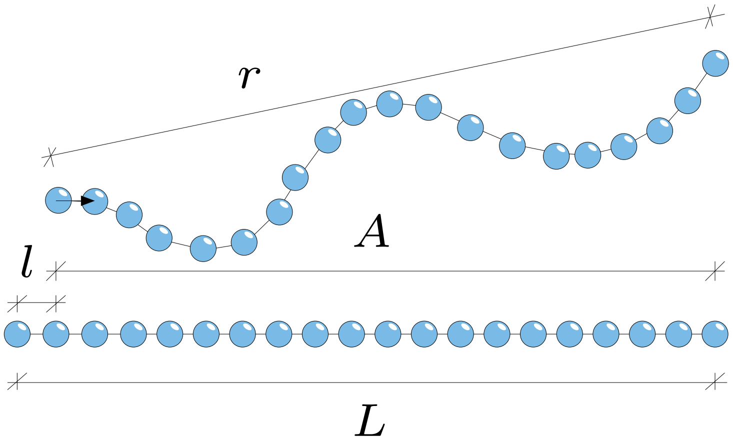


three α chains
form collagen triple helix
1.5 nm diameter

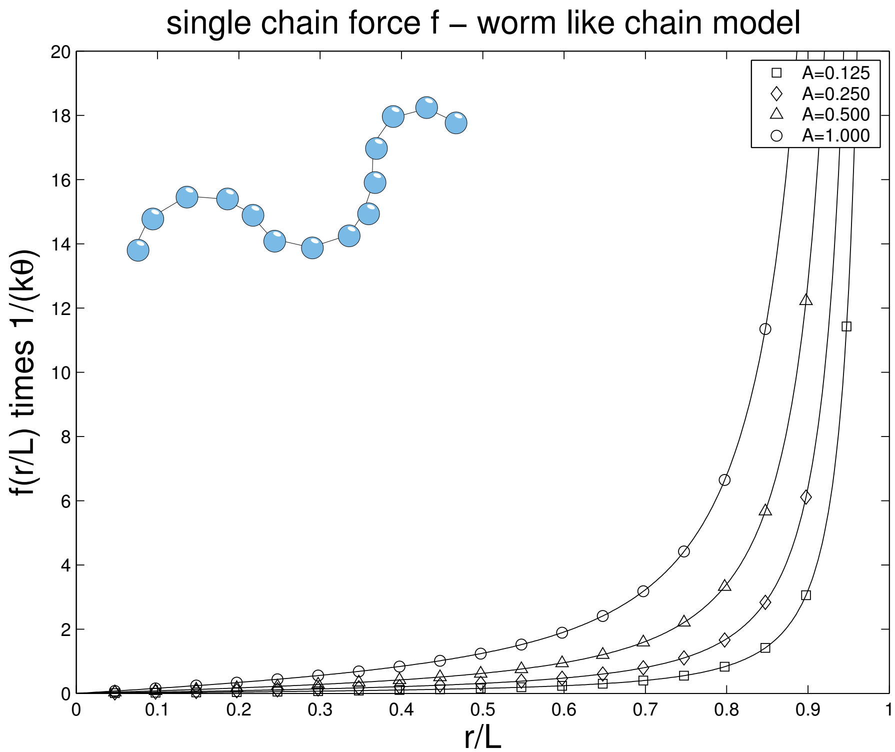
collagen fibrils
form a collagen fiber
10-300 nm diameter

transverse isotropy – collagen fibers provide directional strengthening

microscale – statistical mechanics of long chain molecules



$$\psi^{\text{chn}} = \theta \, \frac{k\, \boldsymbol{L}}{4\boldsymbol{A}} \left[2\frac{r^2}{\boldsymbol{L}^2} + \frac{1}{[1 - r/\boldsymbol{L}]} - \frac{r}{\boldsymbol{L}} \right]$$

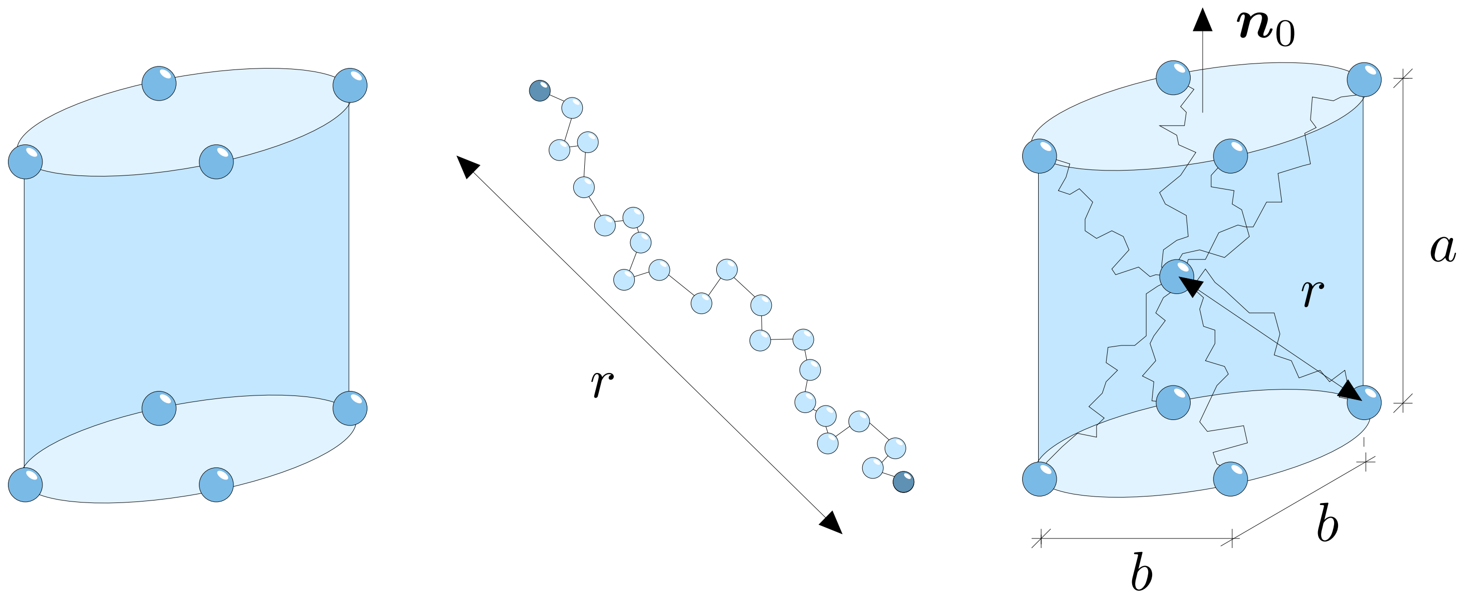


- **wormlike chain model** for biomaterials, e.g. dna or collagen fibers
- characteristic **locking behavior** towards full elongation as $r \longrightarrow L$

Kuhn [1934], [1936], Kuhn & Grün [1942], Porod [1949], Kratky & Porod [1949], Flory [1969], Treloar [1975], Bustamante, Smith, Marko & Siggia [1994], Boyce [1996]

macroscale – transversely isotropic chain network

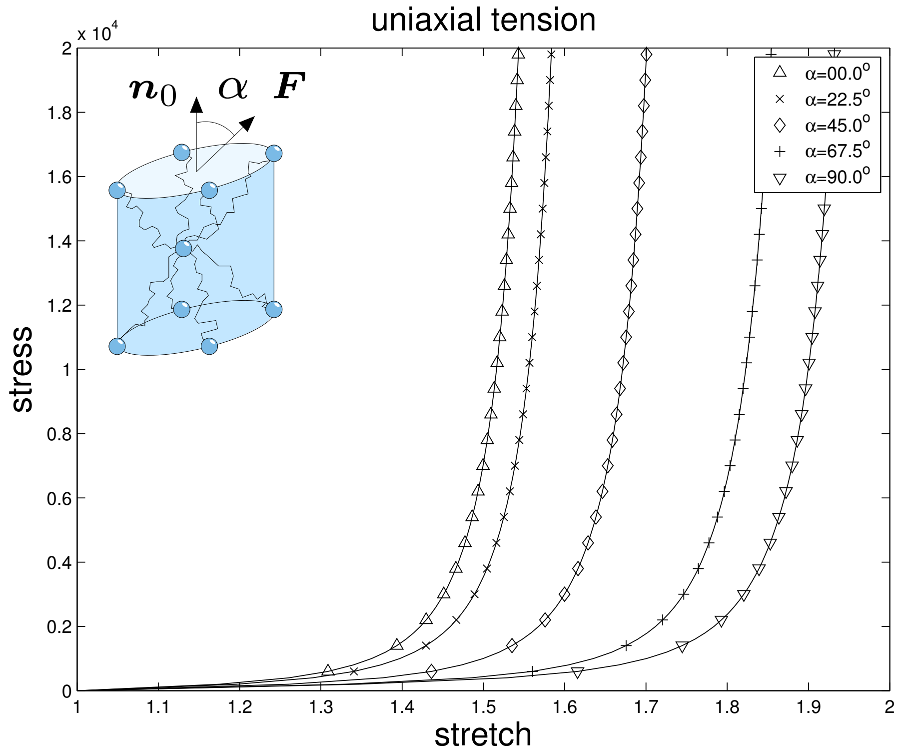
cell matrix | eight single chains | eight-chain model



ψ^{blk} | $\psi^{\text{chn}} + \psi^{\text{rep}}$ | $\psi^{\text{chn}} + \psi^{\text{rep}} + \psi^{\text{bulk}}$

KUHL, GARIKIPATI, ARRUDA & GROSH [2005]

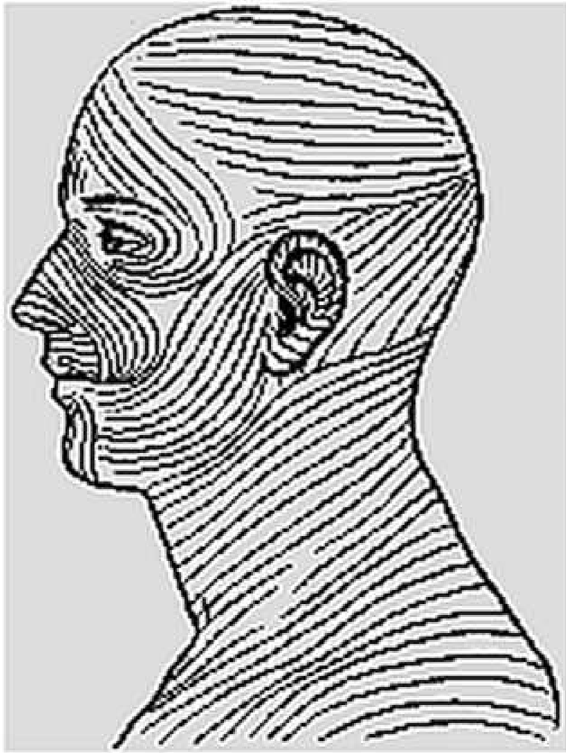
macroscale – transversely isotropic chain network

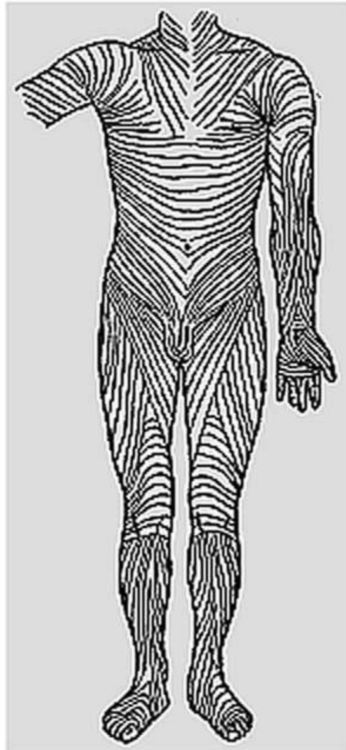


- **increasing stiffness for decreasing fiber load angle**

example – influence of fiber load angle

langer's lines on skin



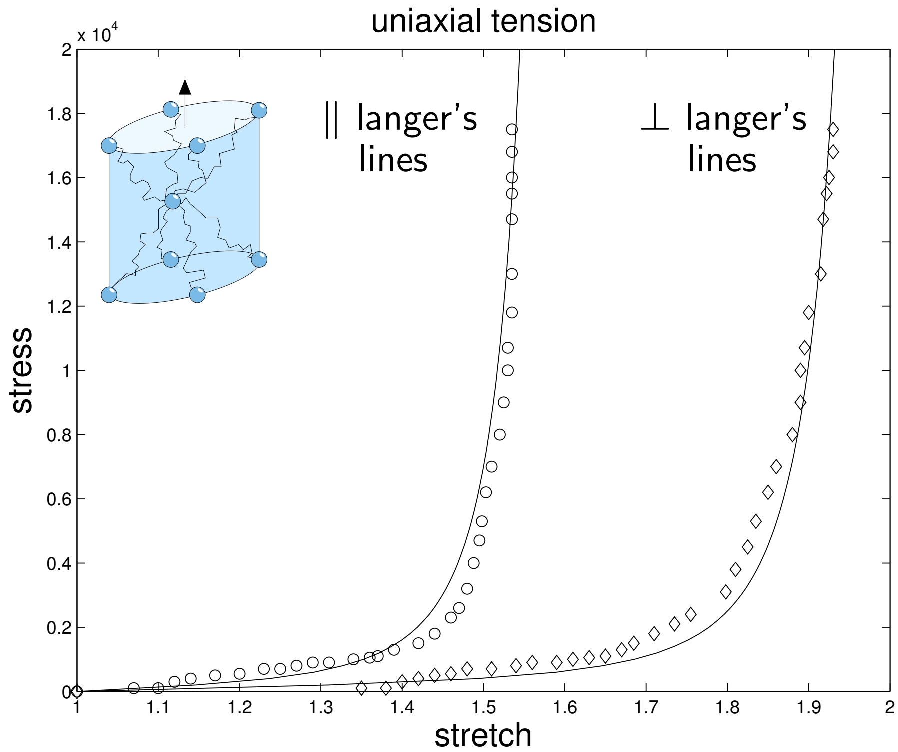


- **lines of tension** or cleavage within skin
- orientation of **collagen fiber bundles** $\parallel$ to langer's lines
- surgery – incisions $\parallel$ to langer's lines heal with finer scar

Carl Ritter von Langer [1819-1887]

example – langer's lines in skin

uniaxial tests on rabbit skin – experiment vs. simulation

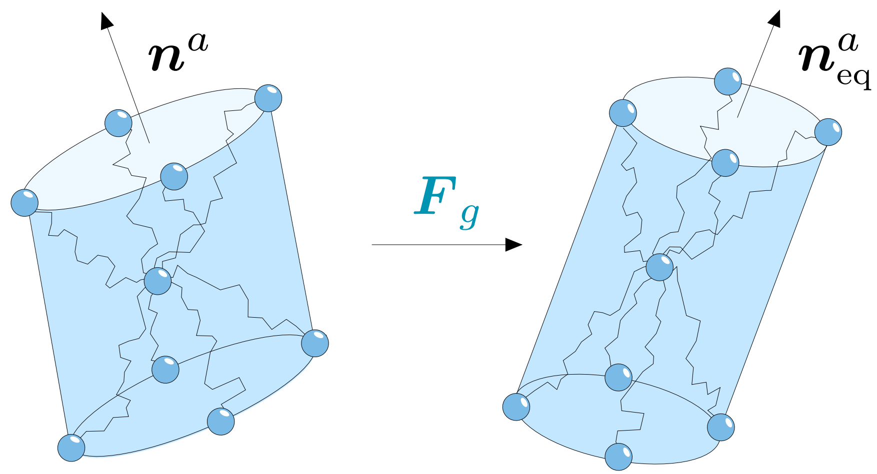


- **stiffer along langer's lines**, characteristic **locking behavior**
- **good agreement** of eight-chain-model and experimental results

Lanir & Fung [1974], Kuhl, Garikipati, Arruda & Grosh [2005]

example – langer's lines in skin

functional adaptation of collagen fibers



- general idea: introduction of fiber direction $\boldsymbol{n}^a$ as internal variable

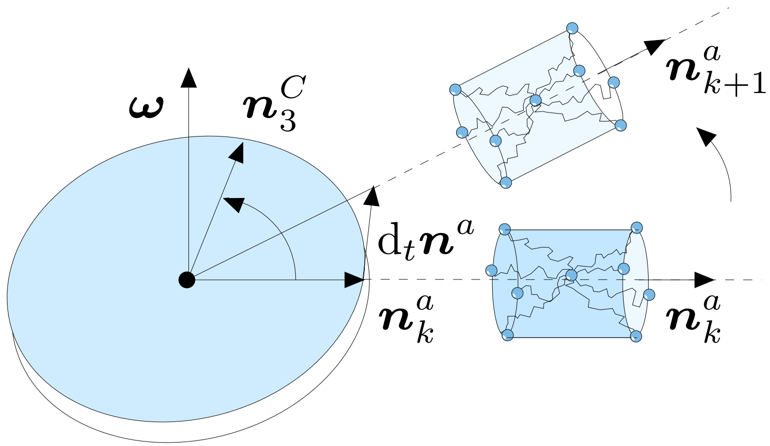
$$\psi = \psi(\boldsymbol{F}, \boldsymbol{n}^a, ...)$$

- reorientation with respect to stimulus $\boldsymbol{n}^a_{\text{eq}}$, e.g. strain or stress based

$$\mathrm{d}_t \boldsymbol{n}^a = \frac{1}{\tau_\omega}[\, \boldsymbol{n}^a - \boldsymbol{n}^a_{\text{eq}} \,]$$

Fyrhie & Carter [1986], Cowin [1989], Pedersen [1989], Vianello [1996], Sgarra & Vianello [1997], Driessen, Peters, Huyghe, Bouten & Baaijens [2003], Menzel [2004]

functional adaptation of collagen fibers



- gradual alignment of fiber direction $\boldsymbol{n}^a$ with principal strain direction $\boldsymbol{n}_3^C$

$$\boldsymbol{C} = \sum_{I=1}^{3} \lambda_I^C \, \boldsymbol{n}_I^C \otimes \boldsymbol{n}_I^C$$

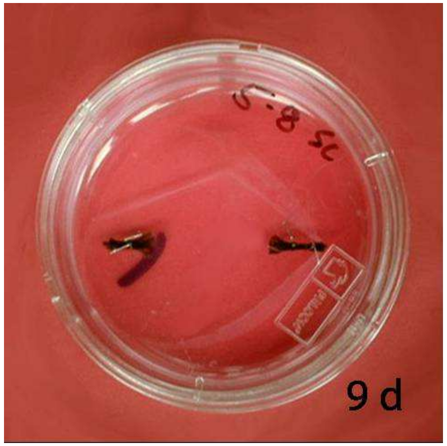
- evolution of fiber direction $\boldsymbol{n}^a$ with rotation vector $\boldsymbol{\omega}$ orthogonal to $\boldsymbol{n}^a$ and $\boldsymbol{n}_3^C$

$$\mathrm{d}_t \boldsymbol{n}_a = \frac{1}{\tau_\omega} \left[\boldsymbol{n}_3^C - [\, \boldsymbol{n}_3^C \cdot \boldsymbol{n}^a \,] \, \boldsymbol{n}^a \right]$$

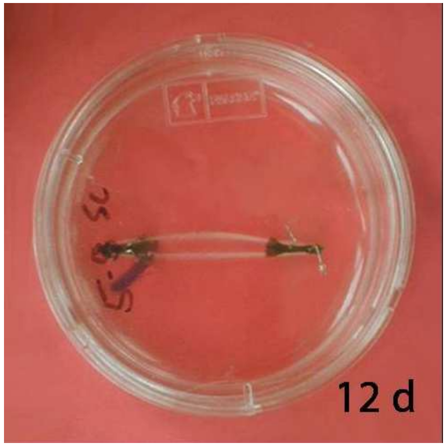
one single material parameter τ_ω, remodelling time, can be measured optically

fiber reorientation in living tendon – experiment

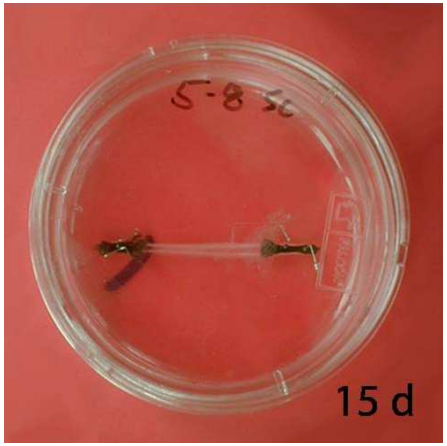
after 9 days



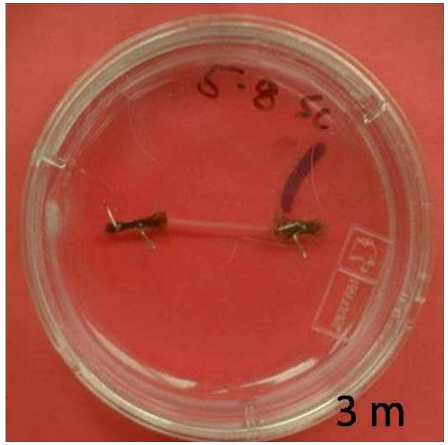
after 12 days



after 15 days



after 3 months



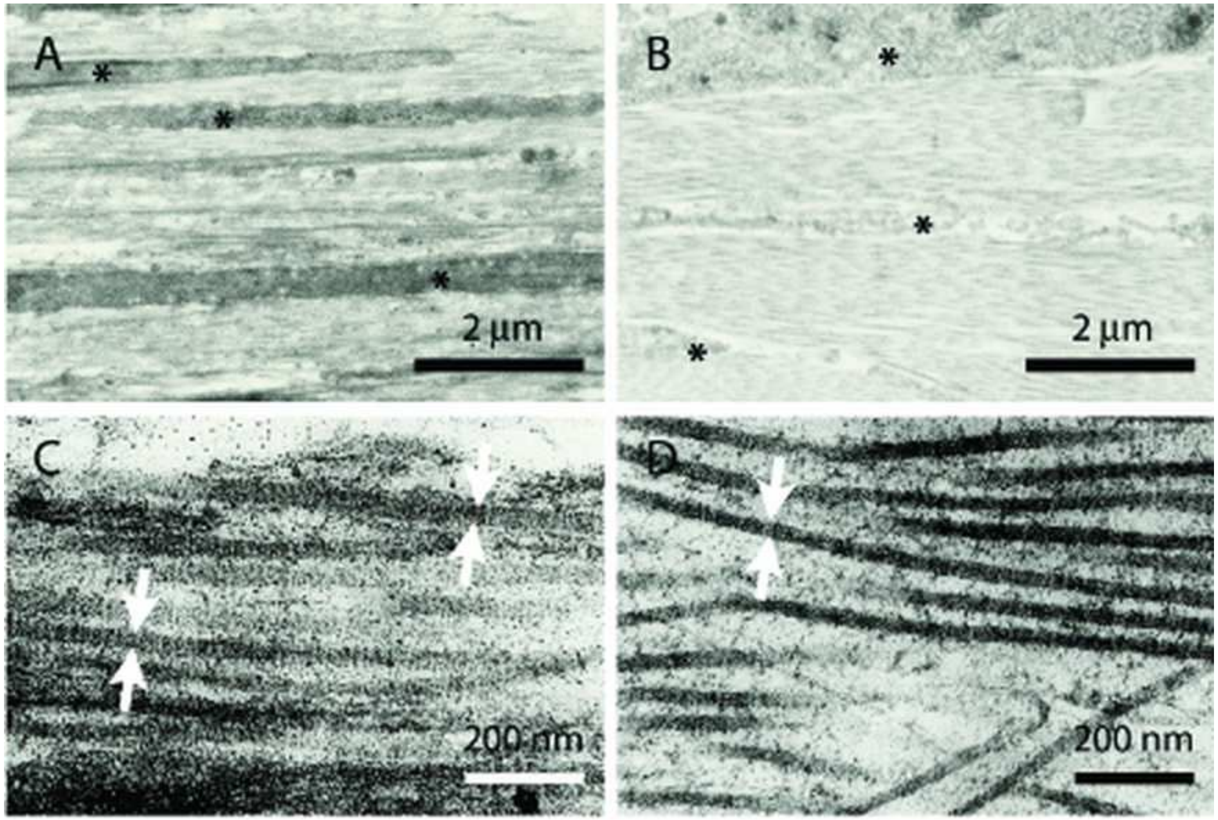
- ex vivo engineered tendon showing **characteristics of embryonic tendon**
- **remodelling of collagen fibers** upon mechanical loading
- long term goal – **mechanically stimulated tissue engineering**

Calve, Dennis, Kosnik, Baar, Grosh & Arruda [2004]

example – tissue engineering

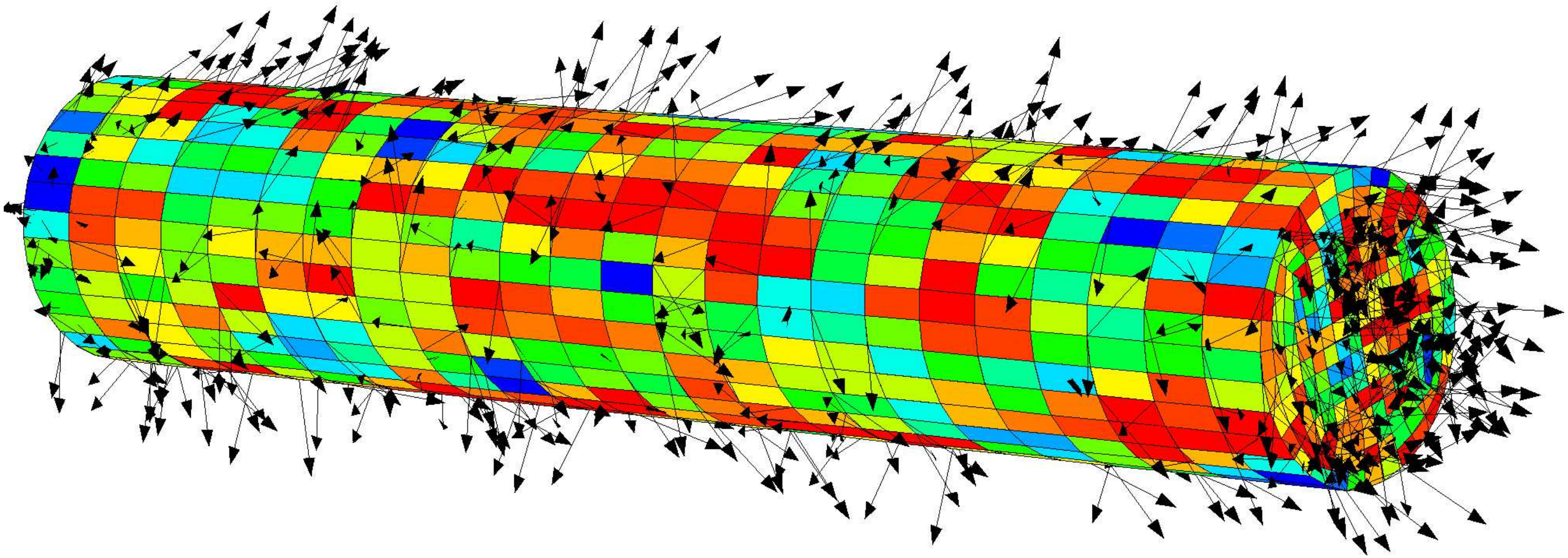
fiber reorientation in living tendon – experiment

ex vivo grown tendon embryonic tendon



- **absence of collageneous scaffold** in ex vivo grown
- **typical characteristics of embryonic tendon**

fiber reorientation in living tendon – simulation

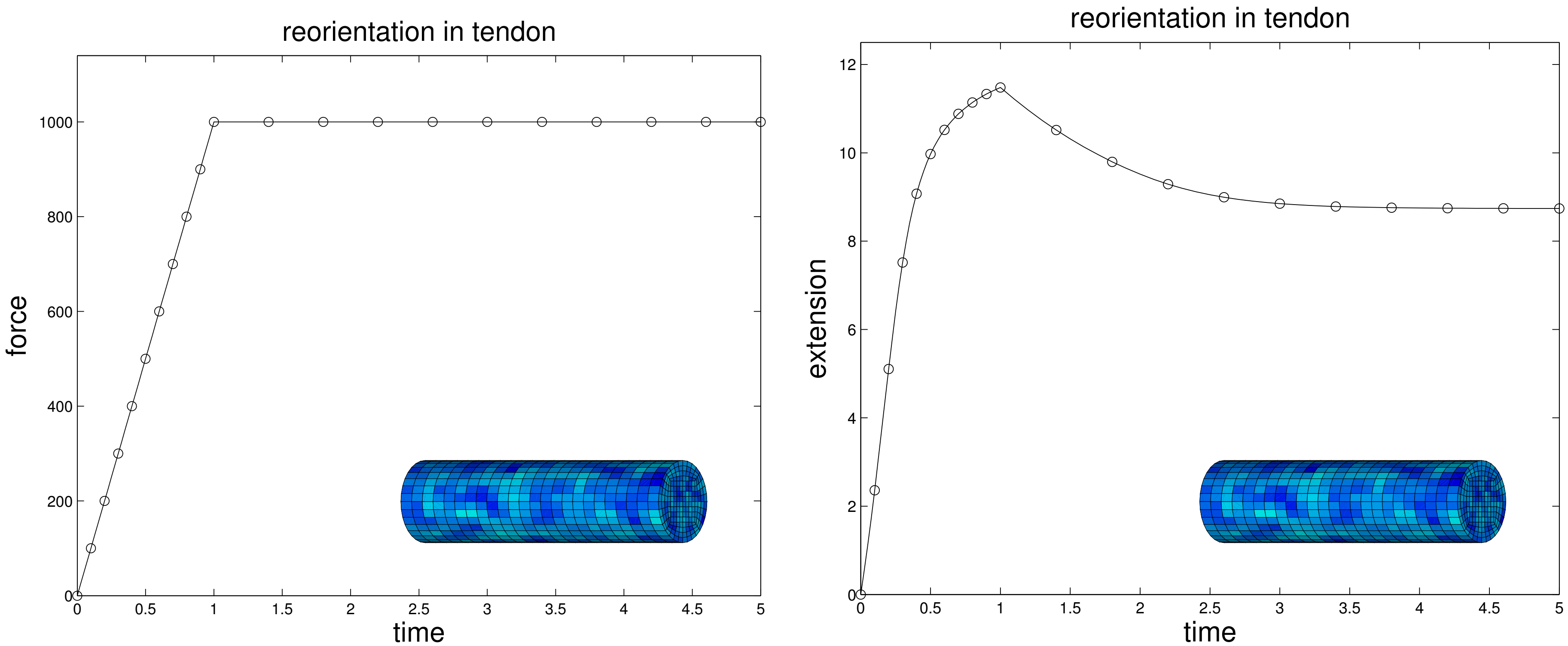


- finite element simulation of **functional adaptation in tendons**
- transversely isotropic **wormlike chain model**, **initially random** fiber orientation
- analysis of **fiber reorientation in uniaxial tension**

Kuhl, Garikipati, Arruda & Grosh [2004]

example – tissue engineering

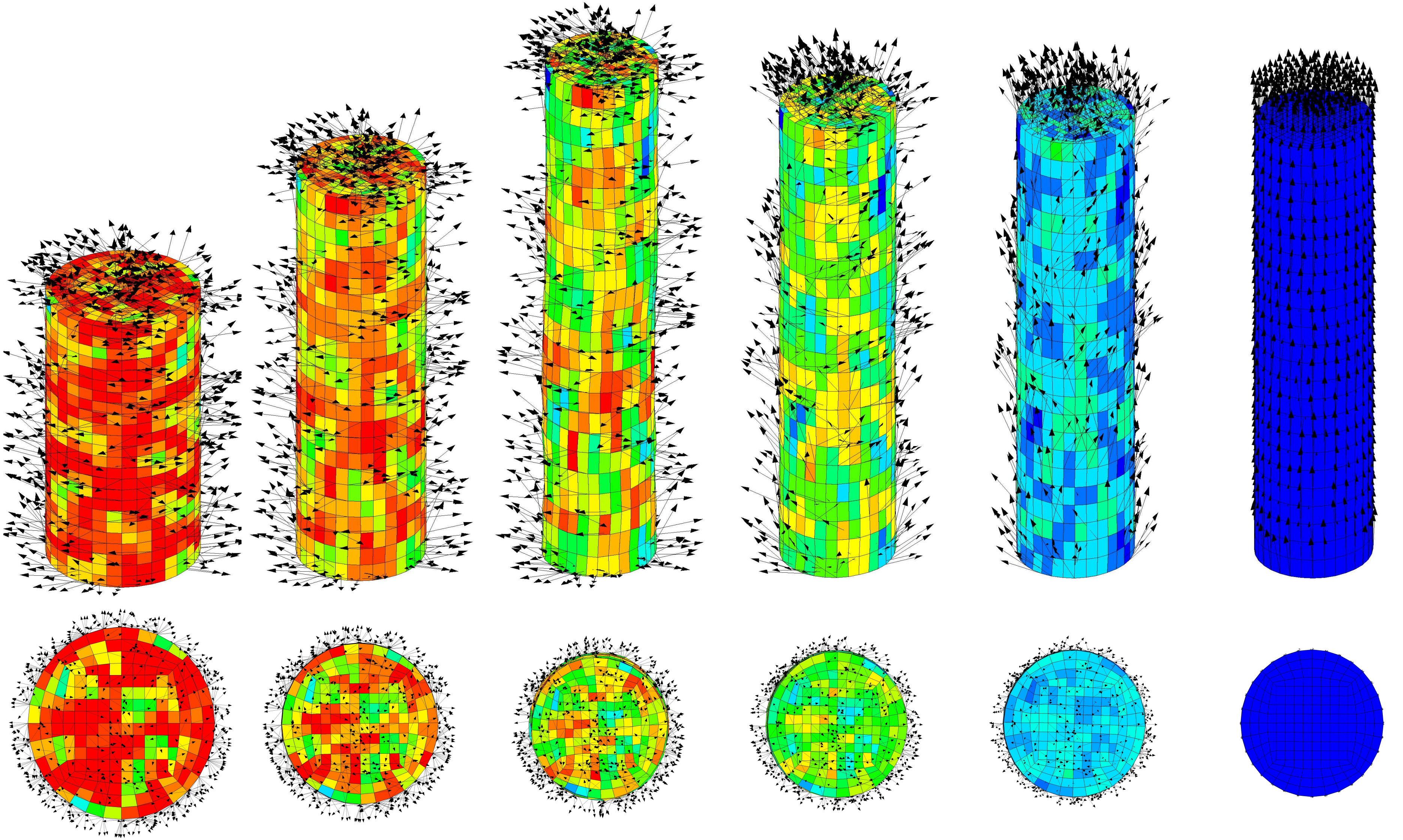
fiber reorientation in living tendon – simulation



- characteristic **locking behavior** upon loading
- **remodelling** and **stiffening** – **biological equilibrium**

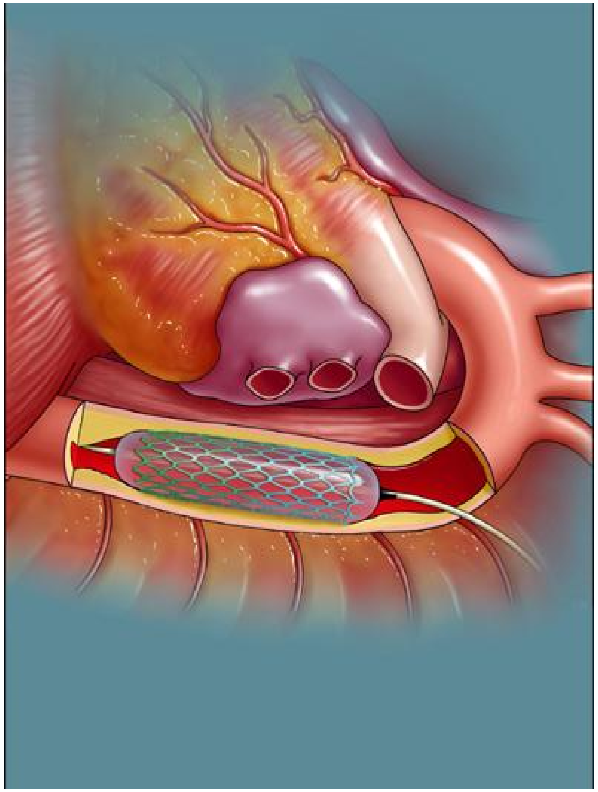
example – tissue engineering

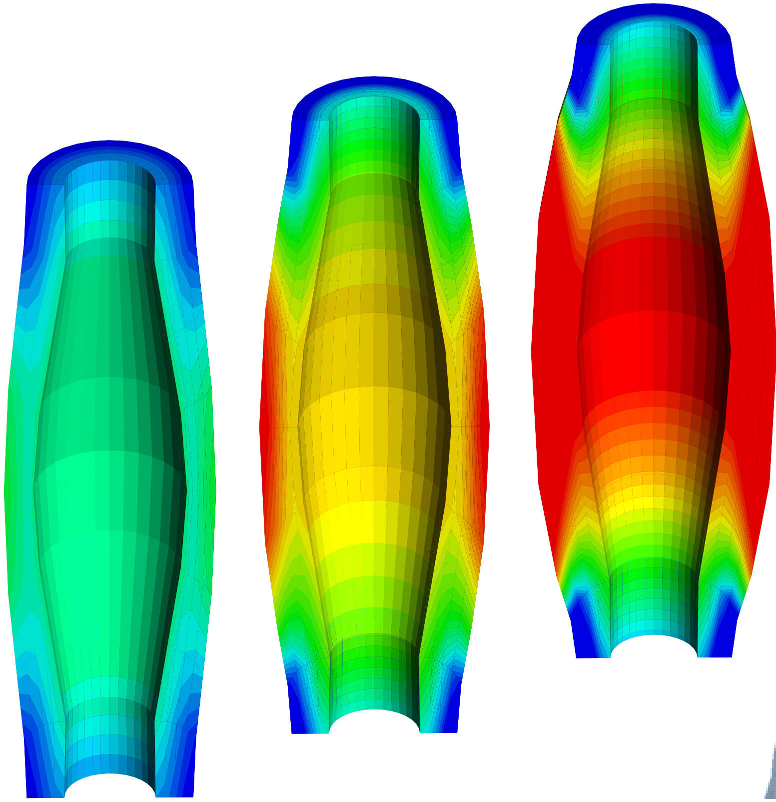
• fiber reorientation in living tendon – simulation

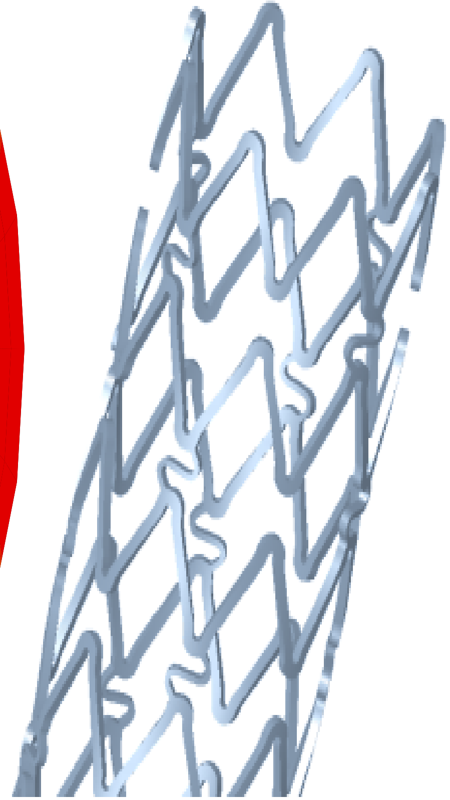


example – tissue engineering

simulation of stent implantation







improved long term reliability

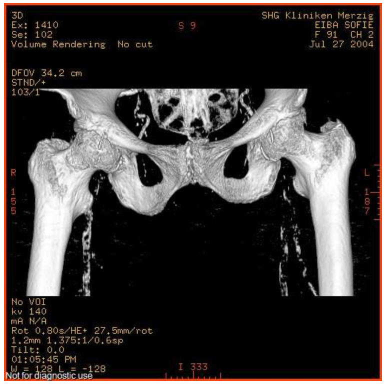
currently working on this project ramona maas & grieta himpel

Technische Universität Kaiserslautern

visions – optimization of medical implants

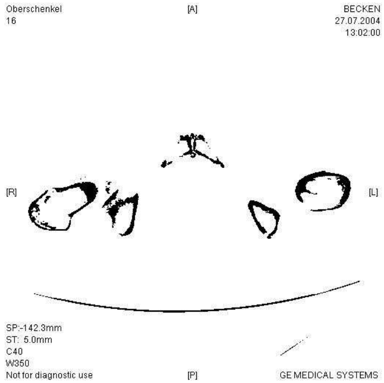
generation of patient specific model

ct of overall hip

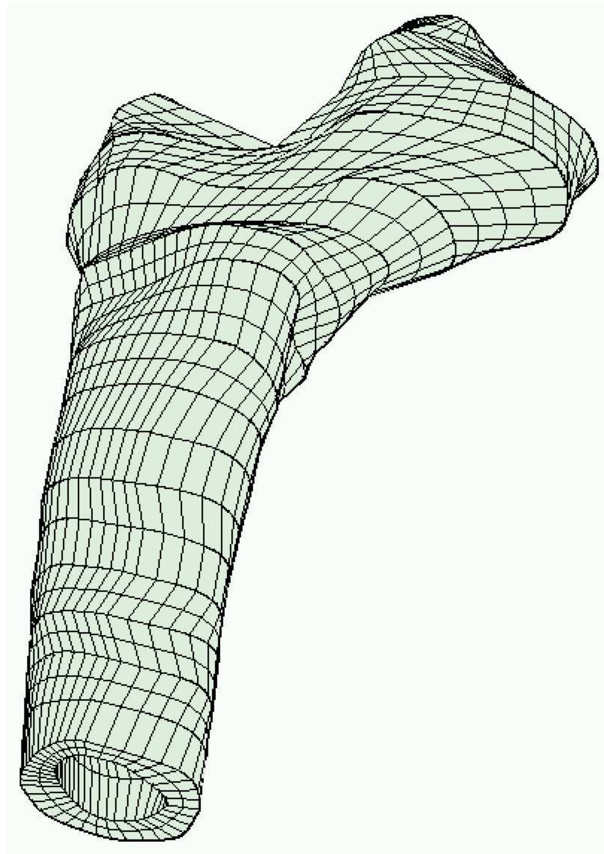


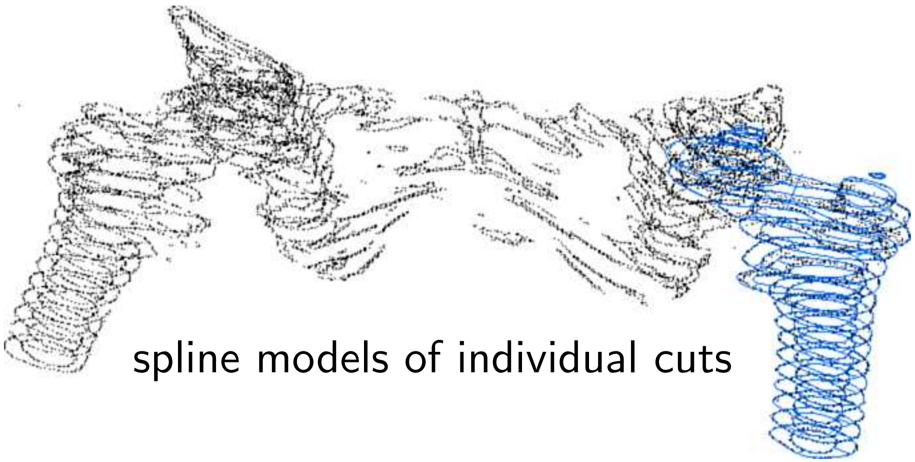
representative cut

binary data model



solid model of proxima femur





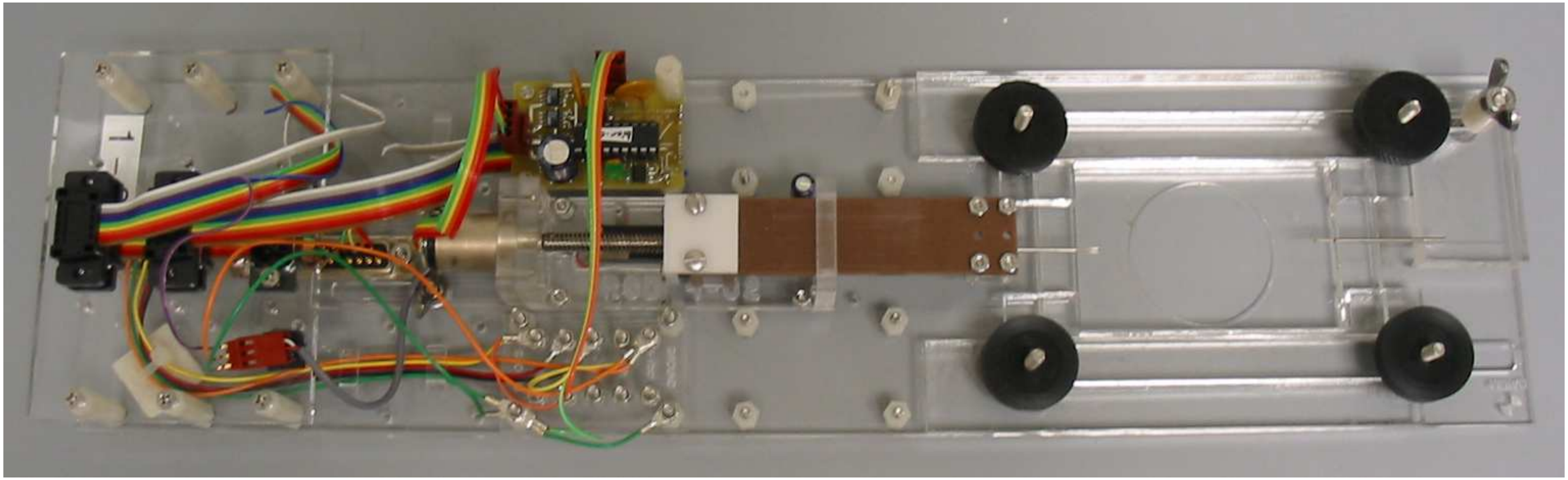
spline models of individual cuts

computer tomography of human femur

in cooperation with Klinik Merzig [2004]

visions – patient specific medical treatment

optimal stimulation of growth and remodelling

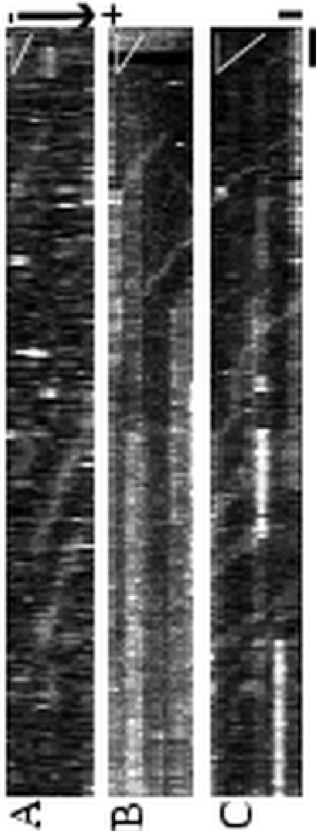


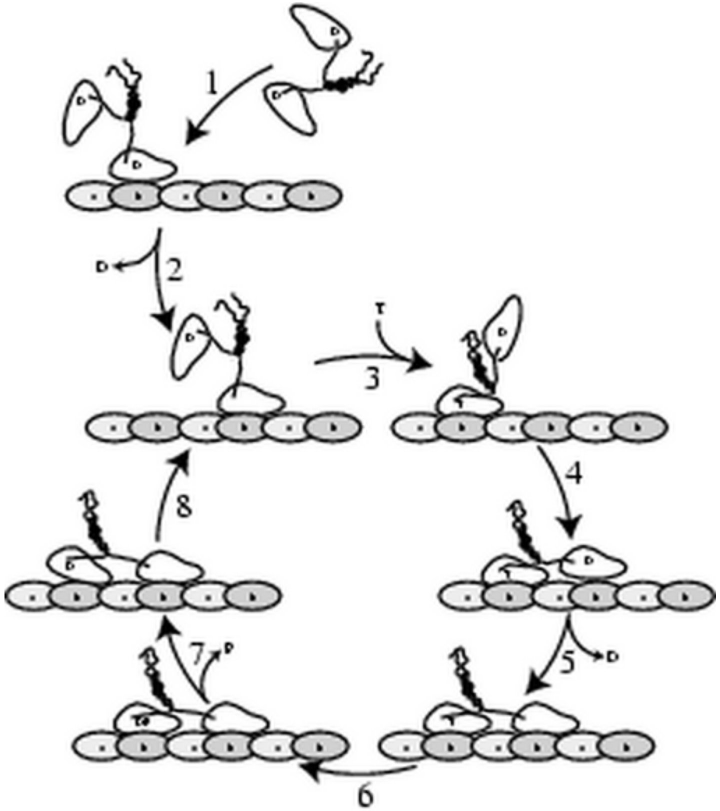
- analysis of **influence of** constant or cyclic **mechanical loading**
- long term goal – **mechanically stimulated tissue engineering**

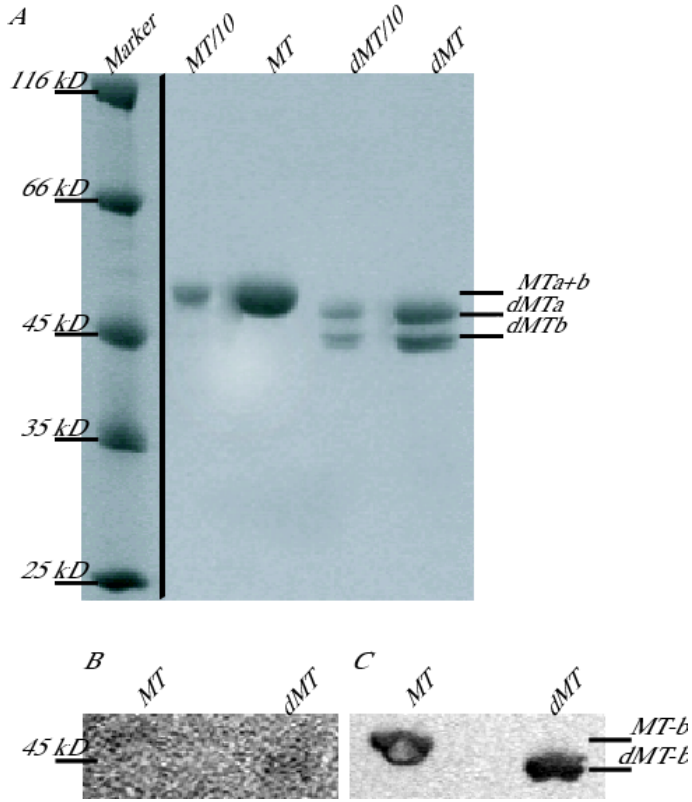
in cooperation with krishna garikipati & ellen m. arruda [2004]

visions – tissue engineering

simulation of kinesin moving along microtubules





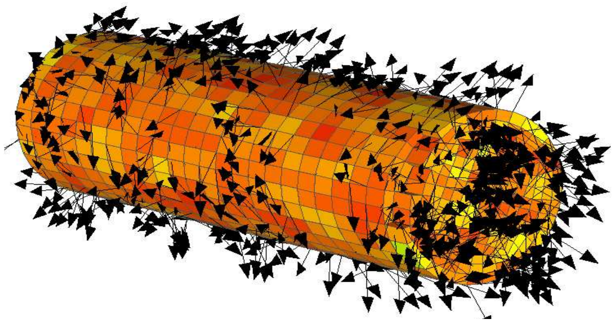


influence of mass changes & electrostatic interaction on processivity

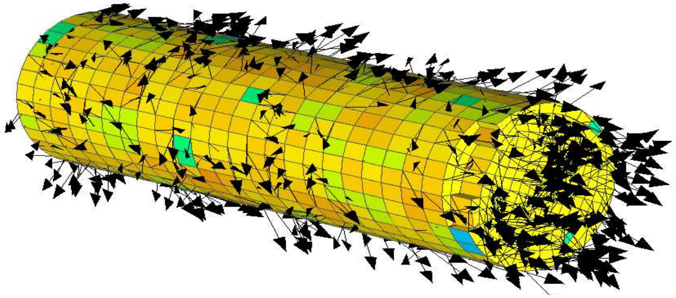
joint work with stefan lakämper vrije Universiteit amsterdam

visions – improved understanding of molecular motors

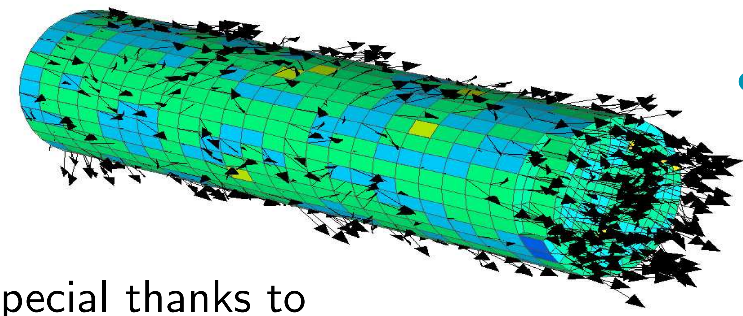
... everything grows ...



- **isotropic density growth**
  changes in density at constant volume
  example: artificial hip replacement



- **isotropic volume growth**
  changes in volume at constant density
  example: stent implantation



- **anisotropic fiber growth**
  changes in fiber volume at constant orientation
  example: blood vessel

- **anisotropic fiber remodelling**
  changes in fiber orientation at constant volume
  example: tissue engineering of functional tendon

with special thanks to
Ellen Arruda, Frank Balle, Sarah Calvé, Grieta Himpel, Krishna Garikipati, Karl Grosh, Stefan Lakämper, Andreas Menzel, Paul Steinmann