03 - kinematic equations - large deformations and growth

day	date		topic
tue	jan	10	motivation - everything grows!
thu	jan	12	basics maths - notation and tensors
tue	jan	17	basic kinematics - large deformation and growth
thu	jan	19	kinematics - growing hearts
tue	jan	24	guest lecture - growing skin
thu	jan	26	guest lecture - growing leaflets
tue	jan	31	basic balance equations - closed and open systems
thu	feb	02	basic constitutive equations - growing tumors
tue	feb	07	volume growth - finite elements for growth
thu	feb	09	volume growth - growing arteries
tue	feb	14	volume growth - growing skin
thu	feb	16	volume growth - growing hearts
tue	feb	21	basic constitutive equations - growing bones
thu	feb	23	density growth - finite elements for growth
tue	feb	28	density growth - growing bones
thu	mar	01	everything grows! - midterm summary
tue	mar	06	midterm
thu	mar	08	remodeling - remodeling arteries and tendons
tue	mar	13	class project - discussion, presentation, evaluation
thu	mar	15	class project - discussion, presentation, evaluation
thu	mar	15	written part of final projects due

problem 4 - design your own project

Now, it's time to design your own class project. At this point, you don't have to commit to a particular type of growth. This is more meant for you to brainstorm and think of some form of *mechanically driven growth* that you are really excited about. We will carefully read your ideas and give you feedback and literature hints. Describe

- the type of tissue (hard, soft)
- the type of growth (density, surface, volume)
- the level at which you would like to study growth (cellular, tissue, organ)
- the mechanical driving force for growth (strain, stretch, stress, pressure, shear, force)
- the type of adaptation (disease specific, treatment specific, training, ...)
- the way in which you want to study growth (review, analytical, computational, ...)

Write a short summary about what you would like to study, and, if you decide to do this in a group, with whom you would like to work.

final projects - me337 2010

- mechanically driven growth of skin: chris, adrian, xuefeng
- muscle growth: brandon, robyn, esteban, ivan, jenny
- cardiac growth review: manuel
- cardiac growth in response to training: holly, tyler
- cardiac growth in response to heart attack:amit
- cardiac or arterial growth: andrew
- cardiac growth in response to medical devices: kyla, andrew
- bone growth in response to medical devices: chinedu
- impact of obesity on osteoarthritis: abhishek, chris
- tumor growth: apoorva
- facial volume aging: jonathan
- idiopathic scoliosis or rhubarb growth: anusuya
- driving forces for different types of growth: james

growth, remodeling and morphogenesis

growth [groʊθ] which is defined as added mass, can occur through cell division (hyperplasia), cell enlargement (hypertrophy), secretion of extracellular matrix, or accretion @ external or internal surfaces. negative growth (atrophy) can occur through cell death, cell shrinkage, or resorption. in most cases, hyperplasia and hypertrophy are mutually exclusive processes. depending on the age of the organism and the type of tissue, one of these two growth processes dominates.

taber „biomechanics of growth, remodeling and morphogenesis" [1995]

growth, remodeling and morphogenesis

remodeling [riˈmɑd. 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.

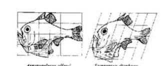
taber „biomechanics of growth, remodeling and morphogenesis" [1995]

growth, remodeling and morphogenesis

morphogenesis [mɔːr.foˈdʒen.ə.sɪs] is the generation of animal form. usually, the term refers to embryonic development, but wound healing and organ regeneration are also morphogenetic events. morphogenesis contains a complex series of stages, each of which depends on the previous stage. during these stages, genetric and environmental factors guide the spatial-temporal motions and differentiation (specification) of cells. a flaw in any one stage may lead to structural defects.

taber „biomechanics of growth, remodeling and morphogenesis" [1995]

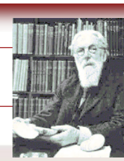
growth, remodeling and morphogenesis

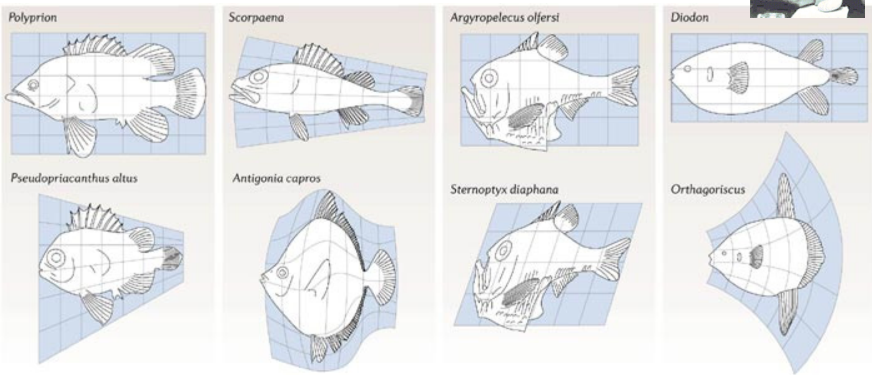


mathematical descriptions of growth [groʊθ] in plants and animals have been published since the 1940s. most of these analyses are purely **kinematic** and many borrow from the methods of continuum mechanics to describe growth rates and velocity fields. during the last quarter century, **mechanical** theories of growth have been formulated.

taber „biomechanics of growth, remodeling and morphogenesis" [1995]

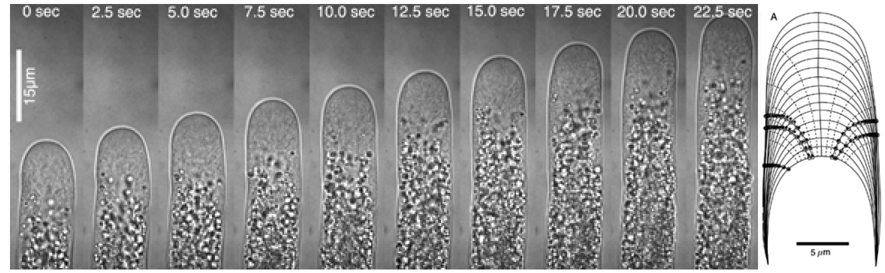
scaling growth





sir d'arcy thompson "on growth and form" [1917]

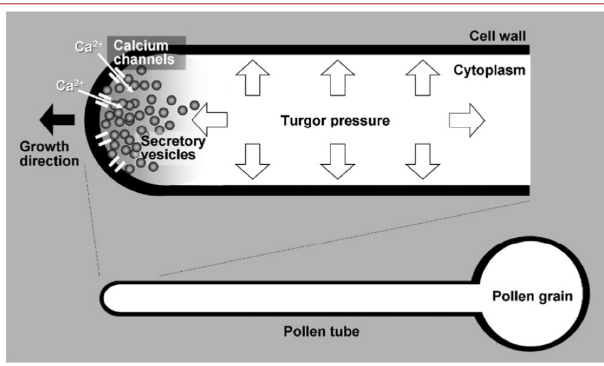
tip growth



time lapse sequence of a growing lily pollen tube. note that the morphology of the tube is drawn by the expanding tip and does not change behind it. tip growth is a common mode of cell morphogenesis observed in root hairs, fungal hyphae, pollen tubes, and many unicellular algae. these organisms have cell walls with distinct polymer compositions and structures.

dumais, long, shaw (2004)

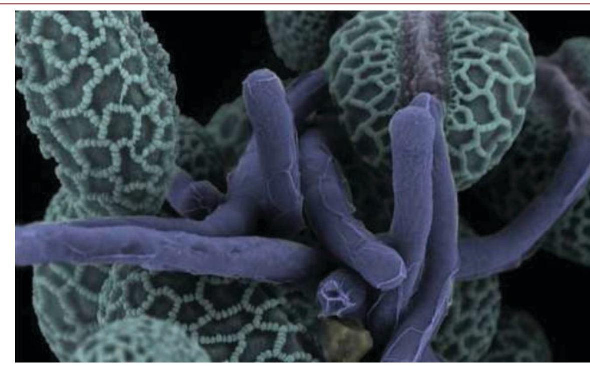
tip growth

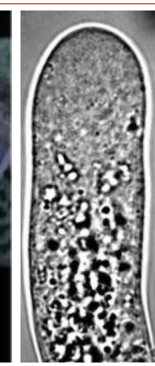


unlike diffusely growing cells that expand over their entire surface or large portions of it, cell wall expansion in pollen tubes is confined to the apex of the cell. this highly polarized mechanism is called tip growth. pollen tubes have the function to rapidly grow and deliver the sperm cells from the pollen grain to the ovule.

kroeger, geitmann, grant [2008]

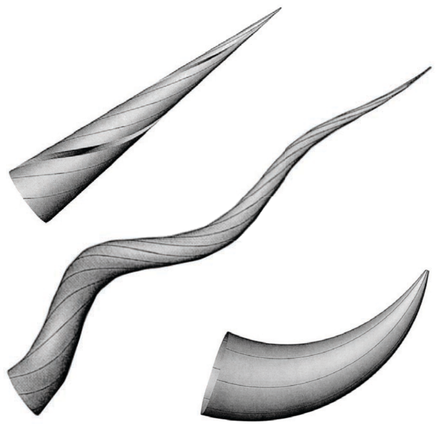
tip growth





scanning electron microscope of growing lily pollen grains germinated in vitro. the spherical objects are the pollen grains, the cylindrical objects are the pollen tubes, or cellular protuberances growing from the grains (left). brightfield microscopy of the apical region of a lily pollen tube. the outermost end of the tube is filled mainly with delivery vesicles.

kroeger & geitmann [2012]



skalak, farrow, hoger [1997]

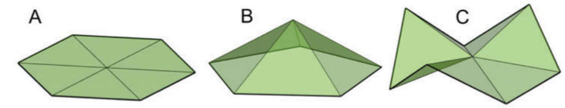


Fig. 1. Illustration of Gauss's Theorema Egregium. Change of metric in a regular hexagon (A), induced by the removal of a triangle, produces a cup-like shape (positive Gaussian curvature) (B). Conversely, insertion of a triangle produces a saddle shape (negative curvature) (C).

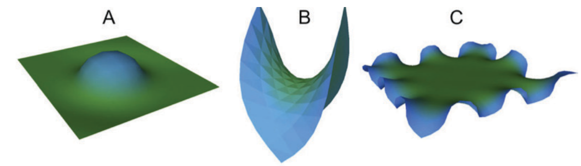


Fig. 3. Snapshots from an interactive program illustrating relations between growth, metric, and form (Matthews, 2002). The simulation begins with a relaxed square shape. Deposition of a growth-inducing morphogen (blue) in the central parts of the surface causes the formation of a cup-like shape (A). Deposition of the morphogen at the margin, with the concentrations slowly decreasing towards the centre, induces a saddle shape (B). Deposition of the morphogen along the margin, with the concentration quickly decreasing towards the centre, results in a wavy border (C).

prusinkiewicz & de reuille "constraints of space in plant development" [2010]

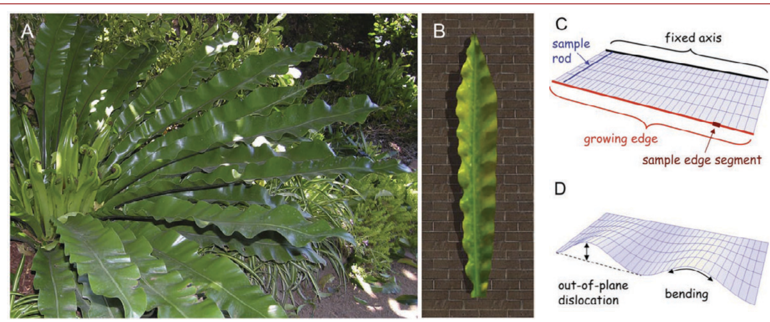


Fig. 4. Simulation study of wavy leaves. A photograph (A) and a simulation model (B) of *Asplenium australasicum* leaves showing simple waves along the margin. The model was constructed by joining surface models representing the left and right parts of the blade along the midrib. Each surface was represented as a sequence of rods spanning the area between a fixed axis and a growing edge (C). An increase in the growing edge length causes buckling, which is controlled by the relative strength of springs that counter out-of-plane dislocation and springs that counter bending of the growing edge (D). Simulations show that increasing the strength of the former type of springs compared to the latter type decreases the wavelength and amplitude of the waves

prusinkiewicz & de reuille "constraints of space in plant development" [2010]

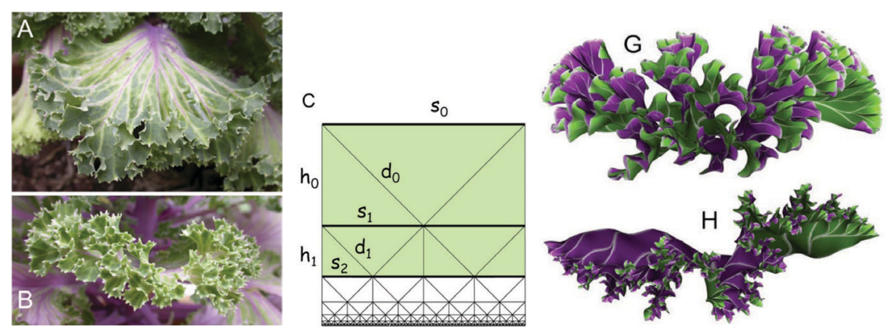
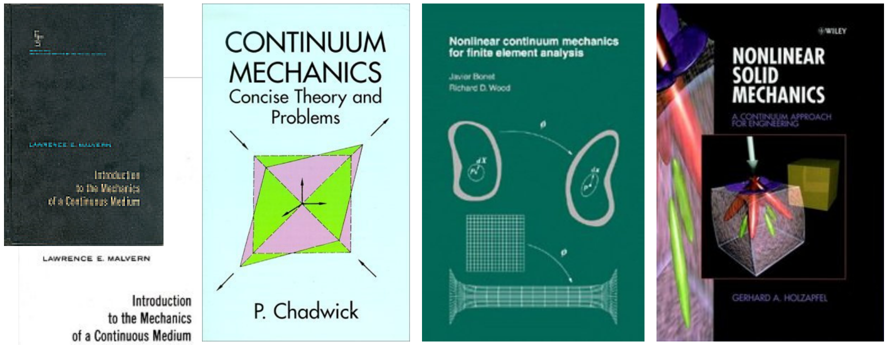


Fig. 5. Simulation study of surfaces with a fractal cascade of waves at the margin. (A) A kale (a variety of *Brassica oleracea*) leaf showing a superposition of waves with a decreasing amplitude and wavelength towards the leaf margin. (B) The fractal character of the leaf margin. (C) A computational representation of a leaf. The surface is divided into rows of geometrically similar rectangles, each row with twice the number of rectangles as its predecessor. The first two rows are highlighted in green. Each rectangle is further subdivided into three triangles. Proportions are controlled by the scaling ratio r, initially set to $\frac{1}{2}$, such that $s_{i+1}=h_i=rs_i$ and $d_i=r\sqrt{2}s_i$ for i=0,1,2,....

prusinkiewicz & de reuille "constraints of space in plant development" [2010]

suggested reading



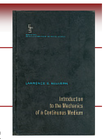
malvern le: introduction to the mechanics of a continuous medium, prentice hall, 1969
chadwick p: continuum mechanics - concise theory and problems, dover reprint, 1976
bonet j, wood rd: nonlinear continuum mechanics for fe analysis, cambridge university press, 1997
holzapfel ga: nonlinear solid mechanics, a continuum approach for engineering, john wiley & sons, 2000

continuum mechanics

continuum mechanics [kən'tɪn.ju.əm mə'kæn.ɪks] is a branch of physics (specifically mechanics) that deals with continuous matter. the fact that matter is made of atoms and that it commonly has some sort of heterogeneous microstructure is ignored in the simplifying approximation that physical quantities, such as energy and momentum, can be handled in the infinitesimal limit. differential equations can thus be employed in solving problems in continuum mechanics.

WIKIPEDIA The Free Encyclopedia

continuum mechanics

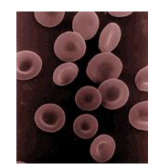


continuum mechanics [kən'tɪn.ju.əm mə'kæn.ɪks] is the branch of mechanics concerned with the stress in solids, liquids and gases and the deformation or flow of these materials. the adjective continuous refers to the simplifying concept underlying the analysis: we disregard the molecular structure of matter and picture it as being without gaps or empty spaces. we suppose that all the mathematical functions entering the theory are continuous functions. this hypothetical continuous material we call a continuum.

malvern „introduction to the mechanics of a continuous medium" [1969]

continuum mechanics

continuum hypothesis [kən'tɪn.ju.əm haɪ'pɑːθ.ə.sɪs] we assume that the characteristic length scale of the microstructure is much smaller than the characteristic length scale of the overall problem, such that the properties at each point can be understood as averages over a characteristic length scale



$$l^{\text{micro}} \ll l^{\text{averg}} \ll l^{\text{conti}}$$

example: biomechanics

$$l^{\text{micro}} = l^{\text{cells}} \approx 10\mu\text{m}$$
$$l^{\text{conti}} = l^{\text{tissue}} \approx 10\text{cm}$$

the continuum hypothesis can be applied when analyzing tissues

the potato  equations

- kinematic equations - what's strain? $\epsilon = \frac{\Delta l}{l}$
  general equations that characterize the deformation of a physical body without studying its physical cause
- balance equations - what's stress? $\sigma = \frac{F}{A}$
  general equations that characterize the cause of motion of any body
- constitutive equations - how are they related? $\sigma = E\,\epsilon$
  material specific equations that complement the set of governing equations

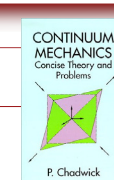
the potato  equations

- kinematic equations - why not $\epsilon = \frac{\Delta l}{l}$?
  inhomogeneous deformation » non-constant
  finite deformation » non-linear $\quad \boldsymbol{F} = \nabla_X \boldsymbol{\varphi}$
  inelastic deformation » growth tensor $\quad \boldsymbol{F} = \boldsymbol{F}_{\mathrm{e}} \cdot \boldsymbol{F}_{\mathrm{g}}$
- balance equations - why not $\sigma = \frac{F}{A}$? $\quad \mathrm{Div}(\boldsymbol{P}) + \rho\,\boldsymbol{b}_0 = \boldsymbol{0}$
  equilibrium in deformed configuration » multiple stress measures
- constitutive equations - why not $\sigma = E\,\epsilon$?
  finite deformation » non-linear $\quad \boldsymbol{P} = \boldsymbol{P}(\boldsymbol{F})$
  inelastic deformation » internal variables $\quad \boldsymbol{P} = \boldsymbol{P}(\rho, \boldsymbol{F}, \boldsymbol{F}_{\mathrm{g}})$

kinematic equations

kinematic equations [kɪnəˈmætɪk ɪˈkweɪ.ʒəns] describe the motion of objects without the consideration of the masses or forces that bring about the motion. the basis of kinematics is the choice of coordinates. the 1st and 2nd time derivatives of the position coordinates give the velocities and accelerations. the difference in placement between the beginning and the final state of two points in a body expresses the numerical value of strain. strain expresses itself as a change in size and/or shape.

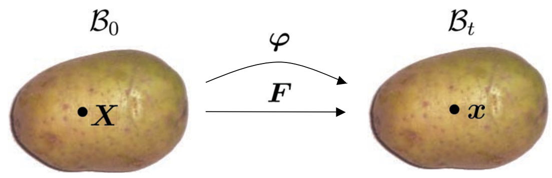
kinematic equations



kinematics [kɪnəˈmætɪks] is the study of motion per se, regardless of the forces causing it. the primitive concepts concerned are position, time and body, the latter abstracting into mathematical terms intuitive ideas about aggregations of matter capable of motion and deformation.

Chadwick „Continuum mechanics" [1976]

potato - kinematics



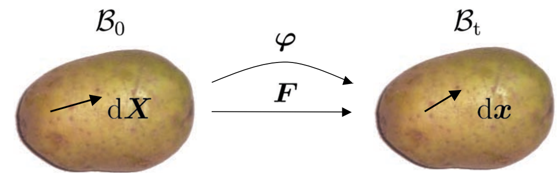
- nonlinear deformation map $\boldsymbol{\varphi}$

  $\boldsymbol{x} = \boldsymbol{\varphi}(\boldsymbol{X}, t)$ with $\boldsymbol{\varphi} : \mathcal{B}_0 \times \mathbb{R} \to \mathcal{B}_t$

- spatial derivative of $\boldsymbol{\varphi}$ - deformation gradient

  $\mathrm{d}\boldsymbol{x} = \boldsymbol{F} \cdot \mathrm{d}\boldsymbol{X}$ with $\boldsymbol{F} : T\mathcal{B}_0 \to T\mathcal{B}_t$ $\quad \boldsymbol{F} = \left.\frac{\partial \boldsymbol{\varphi}}{\partial \boldsymbol{X}}\right|_{t \text{ fixed}}$

potato - kinematics



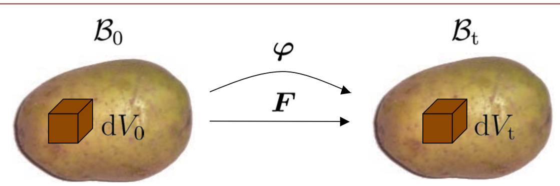
- transformation of line elements - deformation gradient F_{ij}

  $\mathrm{d}x_i = F_{ij}\,\mathrm{d}X_j$ with $F_{ij} : T\mathcal{B}_0 \to T\mathcal{B}_t$ $\quad F_{ij} = \left.\frac{\partial \varphi_i}{\partial X_j}\right|_{t \text{ fixed}}$

- uniaxial tension (incompressible), simple shear, rotation

$$F_{ij}^{\mathrm{uni}} = \begin{bmatrix} \alpha & 0 & 0 \\ 0 & \alpha^{-\frac{1}{2}} & 0 \\ 0 & 0 & \alpha^{-\frac{1}{2}} \end{bmatrix} \quad F_{ij}^{\mathrm{shr}} = \begin{bmatrix} 1 & \gamma & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad F_{ij}^{\mathrm{rot}} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

potato - kinematics



- transformation of volume elements - determinant of $\boldsymbol{F}$

$$\mathrm{d}V_0 = \mathrm{d}\boldsymbol{X}_1 \cdot [\mathrm{d}\boldsymbol{X}_2 \times \mathrm{d}\boldsymbol{X}_3] \qquad \mathrm{d}V_t = \mathrm{d}\boldsymbol{x}_1 \cdot [\mathrm{d}\boldsymbol{x}_2 \times \mathrm{d}\boldsymbol{x}_3]$$

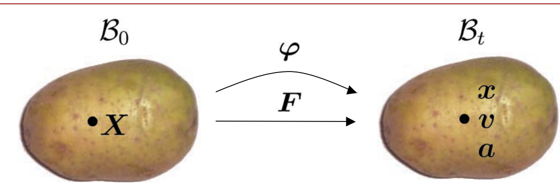
$$= \det([\mathrm{d}\boldsymbol{x}_1, \mathrm{d}\boldsymbol{x}_2, \mathrm{d}\boldsymbol{x}_3])$$

$$= \det([\mathrm{d}\boldsymbol{X}_1, \mathrm{d}\boldsymbol{X}_2, \mathrm{d}\boldsymbol{X}_3]) \qquad = \det(\boldsymbol{F})\,\det([\mathrm{d}\boldsymbol{X}_1, \mathrm{d}\boldsymbol{X}_2, \mathrm{d}\boldsymbol{X}_3])$$

- changes in volume - determinant of deformation tensor J

$$\mathrm{d}V_t = J\,\mathrm{d}V_0 \qquad J = \det(\boldsymbol{F})$$

potato - kinematics



- temporal derivative of $\boldsymbol{\varphi}$ - velocity (material time derivative)

  $\boldsymbol{v} = \mathrm{D}_t\boldsymbol{\varphi} = \left.\frac{\partial \boldsymbol{\varphi}}{\partial t}\right|_{X \text{ fixed}}$ with $\boldsymbol{v} : \mathcal{B}_0 \times \mathbb{R} \to \mathbb{R}^3$

- temporal derivative of $\boldsymbol{v}$ - acceleration

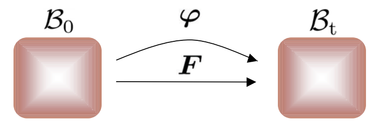
  $\boldsymbol{a} = \mathrm{D}_t\boldsymbol{v} = \left.\frac{\partial \boldsymbol{v}}{\partial t}\right|_{X \text{ fixed}} = \left.\frac{\partial^2 \boldsymbol{\varphi}}{\partial t^2}\right|_{X \text{ fixed}}$ with $\boldsymbol{a} : \mathcal{B}_0 \times \mathbb{R} \to \mathbb{R}^3$

volume growth

volume growth ['val.juːm groʊθ] is conceptually comparable to thermal expansion. in linear elastic problems, growth stresses (such as thermal stresses) can be superposed on the mechanical stress field. in the nonlinear problems considered here, another approach must be used. the fundamental idea is to refer the strain measures in the constitutive equations of each material element to its current zero-stress configuration, which changes as the element grows.

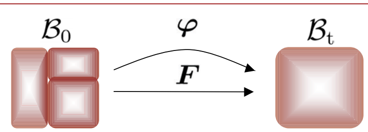
taber " biomechanics of growth, remodeling and morphogenesis" [1995]

kinematics of finite growth



[1] consider an elastic body $\mathcal{B}_0$ at time t_0, unloaded & stressfree

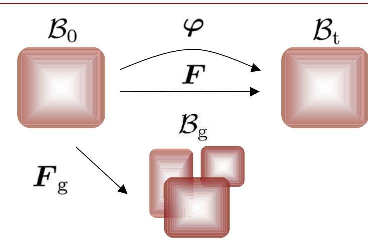
kinematics of finite growth



[1] consider an elastic body $\mathcal{B}_0$ at time t_0, unloaded & stressfree

[2] imagine the body is cut into infinitesimal elements each of which is allowed to undergo volumetric growth

kinematics of finite growth

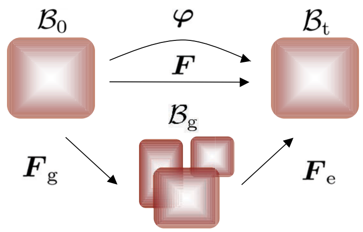


[1] consider an elastic body $\mathcal{B}_0$ at time t_0, unloaded & stressfree

[2] imagine the body is cut into infinitesimal elements each of which is allowed to undergo volumetric growth

[3] after growing the elements, $\mathcal{B}_g$ may be incompatible

kinematics of finite growth



[1] consider an elastic body $\mathcal{B}_0$ at time t_0, unloaded & stressfree

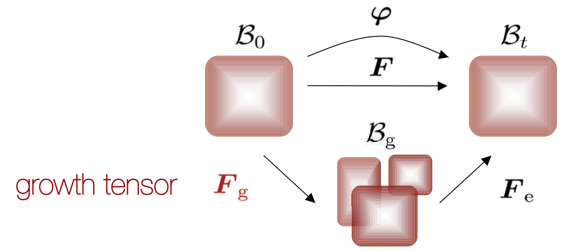
[2] imagine the body is cut into infinitesimal elements each of which is allowed to undergo volumetric growth

[3] after growing the elements, $\mathcal{B}_g$ may be incompatible

[4] loading generates compatible current configuration $\mathcal{B}_t$

kinematics of finite growth

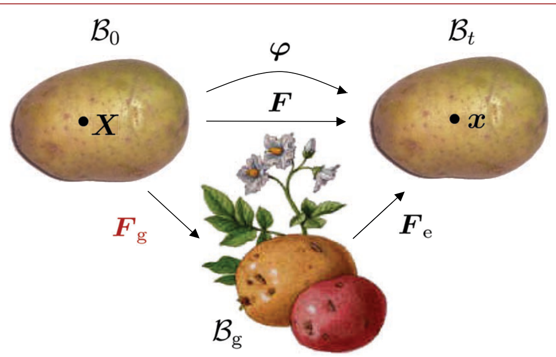
$$\boldsymbol{F} = \boldsymbol{F}_e \cdot \boldsymbol{F}_g$$



multiplicative decomposition

Lee [1969], Simo [1992], Rodriguez, Hoger & Mc Culloch [1994], Epstein & Maugin [2000], Humphrey [2002], Ambrosi & Mollica [2002], Himpel, Kuhl, Menzel & Steinmann [2005]

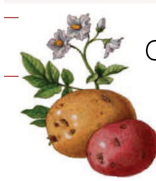
potato - kinematics of finite growth



- incompatible growth configuration $\mathcal{B}_g$ & growth tensor $\boldsymbol{F}_g$

$$\boldsymbol{F} = \boldsymbol{F}_e \cdot \boldsymbol{F}_g$$

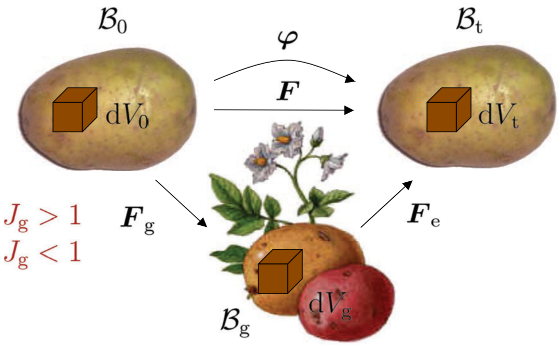
rodriguez, hoger & mc culloch [1994]



concept of incompatible growth configuration

biologically, the notion of **incompatibility** implies that subelements of the grown configuration may overlap or have gaps. the implication of incompatibility is the existence of residual stresses necessary to `squeeze` these grown subelements back together. mathematically, the notion of **incompatibility** implies that unlike the deformation gradient, $\boldsymbol{F} = \left.\frac{\partial \varphi}{\partial \boldsymbol{X}}\right|_{t \text{ fixed}}$ the growth tensor cannot be derived as a gradient of a vector field. incompatible configurations are useful in finite strain inelasticity such as viscoelasticity, thermoelasticity, elastoplasticity and growth.

potato - kinematics of finite growth



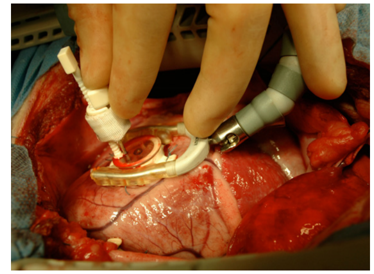
growth $J_g > 1$

resorption $J_g < 1$

- changes in volume - determinant of growth tensor J_g

$$\mathrm{d}V_g = J_g \, \mathrm{d}V_0 \qquad J_g = \det(\boldsymbol{F}_g)$$

kinematics of cardiac growth

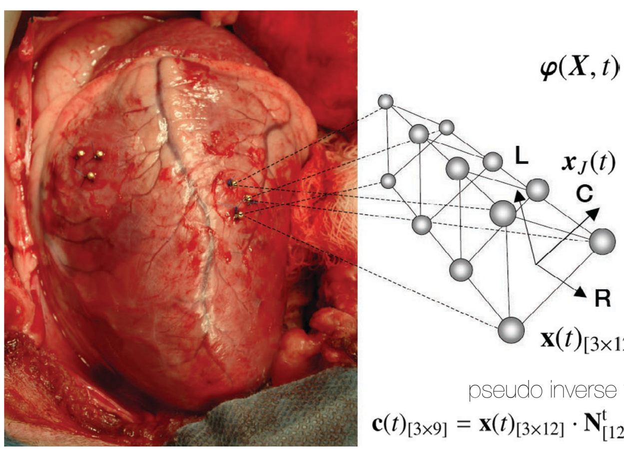


surgically implantation of 4x3 beads across the left ventricular wall

4d coordiantes from in vivo biplane videofluoroscopic marker images

tsamis, cheng, nguyen, langer, miller, kuhl [2012]

kinematics of cardiac growth



deformation

$$\boldsymbol{\varphi}(\boldsymbol{X},t) = \sum_{I=1}^{n_{\mathrm{apx}}} \boldsymbol{c}_I(t)\, N_I(\boldsymbol{X})$$

valid for all data points

$$\boldsymbol{x}_J(t) = \sum_{I=1}^{n_{\mathrm{apx}}} \boldsymbol{c}_I(t)\, N_I(\boldsymbol{X}_J)$$

with coordinates

$$\boldsymbol{x} = [x_c, x_l, x_r]^{\mathrm{t}}$$

system for 12 markers

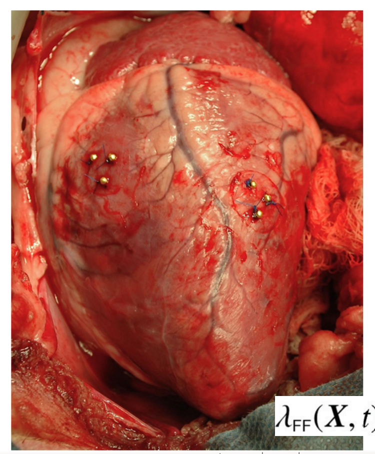
$$\mathbf{x}(t)_{[3\times12]} = \mathbf{c}(t)_{[3\times9]} \cdot \mathbf{N}_{[9\times12]}$$

pseudo inverse to determine coefficients

$$\mathbf{c}(t)_{[3\times9]} = \mathbf{x}(t)_{[3\times12]} \cdot \mathbf{N}^{\mathrm{t}}_{[12\times9]} \cdot [\, \mathbf{N}_{[9\times12]} \cdot \mathbf{N}^{\mathrm{t}}_{[12\times9]}\,]^{-1}$$

tsamis, cheng, nguyen, langer, miller, kuhl [2012]

kinematics of cardiac growth



deformation

$$\boldsymbol{\varphi}(\boldsymbol{X},t) = \sum_{I=1}^{n_{\mathrm{apx}}} \boldsymbol{c}_I(t)\, N_I(\boldsymbol{X})$$

deformation gradient

$$\boldsymbol{F}(\boldsymbol{X},t) = \sum_{I=1}^{n_{\mathrm{apx}}} \boldsymbol{c}_I(t) \otimes \nabla N_I(\boldsymbol{X})$$

spatial gradient

$$\nabla(\circ) = [\partial_c(\circ), \partial_l(\circ), \partial_r(\circ)]^{\mathrm{t}}$$

volume changes

$$J(\boldsymbol{X},t) = \det(\boldsymbol{F}(\boldsymbol{X},t))$$

fiber stretch

$$\lambda_{\mathrm{FF}}(\boldsymbol{X},t) = [\, \boldsymbol{f}(\boldsymbol{X}) \cdot \boldsymbol{F}^{\mathrm{t}}(\boldsymbol{X},t) \cdot \boldsymbol{F}(\boldsymbol{X},t) \cdot \boldsymbol{f}(\boldsymbol{X})\,]^{1/2}$$

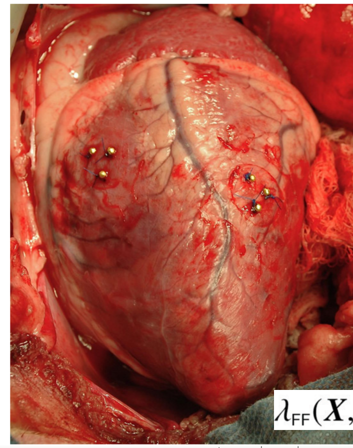
tsamis, cheng, nguyen, langer, miller, kuhl [2012]

kinematics of cardiac growth

	epi 20% depth	p	mid 50% depth	p	endo 80% depth	p
F^g_{CC}	1.00±0.12	0.96	1.03±0.14	0.46	1.02±0.10	0.44
F^g_{CL}	0.04±0.14	0.42	0.01±0.10	0.77	0.01±0.09	0.61
F^g_{CR}	−0.07±0.29	0.46	−0.03±0.16	0.61	0.05±0.14	0.29
F^g_{LC}	−0.02±0.17	0.75	−0.04±0.13	0.33	−0.04±0.11	0.24
F^g_{LL}	1.10±0.15	0.06	1.10±0.13	0.03	1.11±0.11	0.01
F^g_{LR}	0.02±0.16	0.71	0.10±0.20	0.11	0.18±0.34	0.12
F^g_{RC}	−0.01±0.09	0.64	−0.03±0.17	0.54	−0.05±0.19	0.41
F^g_{RL}	0.00±0.05	0.86	−0.00±0.09	0.96	−0.01±0.11	0.67
F^g_{RR}	0.68±0.15	0.00	0.73±0.15	0.00	0.77±0.22	0.01
J^g	0.74±0.19	0.00	0.82±0.19	0.01	0.89±0.21	0.10
λ^g_{FF}	1.03±0.12	0.49	1.04±0.16	0.36	1.08±0.11	0.04

tsamis, cheng, nguyen, langer, miller, kuhl [2012]

kinematics of cardiac growth



deformation

$$\varphi(X,t) = \sum_{I=1}^{n_{apx}} c_I(t)\, N_I(X)$$

green lagrange strains

$$E(X,t) = \frac{1}{2}\,[\, F^t \cdot F - I \,]$$

fiber strain

$$E_{FF}(X,t) = f(X) \cdot E(X,t) \cdot f(X)$$

relation of fiber strain to fiber stretch

$$E_{FF} = 1/2\ [\ \lambda_{FF}^2 - 1\ ]$$

fiber stretch

$$\lambda_{FF}(X,t) = [\, f(X) \cdot F^t(X,t) \cdot F(X,t) \cdot f(X)\,]^{1/2}$$

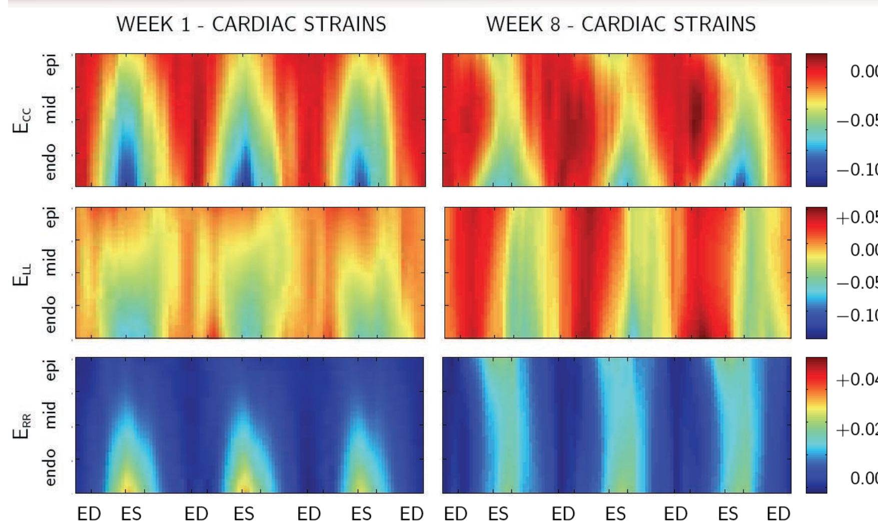
tsamis, cheng, nguyen, langer, miller, kuhl [2012]

kinematics of cardiac growth

- longitudinal growth by more than 10%
- radial thinning by more than 20%
- fiber lengthening by more than 5%
- volume decrease by more than 15%

	epi 20% depth	p	mid 50% depth	p	endo 80% depth	p
E^g_{CC}	0.03±0.15	0.56	0.06±0.18	0.27	0.05±0.13	0.20
E^g_{LL}	0.12±0.17	0.04	0.12±0.15	0.03	0.13±0.12	0.00
E^g_{RR}	−0.21±0.12	0.00	−0.19±0.09	0.00	−0.10±0.15	0.05
E^g_{CL}	0.01±0.15	0.79	−0.01±0.09	0.63	−0.01±0.06	0.46
E^g_{LR}	0.00±0.08	0.86	0.06±0.11	0.10	0.11±0.19	0.10
E^g_{CR}	−0.04±0.17	0.51	−0.03±0.11	0.39	0.00±0.10	0.88
E^g_{FF}	0.03±0.13	0.42	0.06±0.18	0.31	0.09±0.12	0.03

tsamis, cheng, nguyen, langer, miller, kuhl [2012]



tsamis, cheng, nguyen, langer, miller, kuhl [2012]