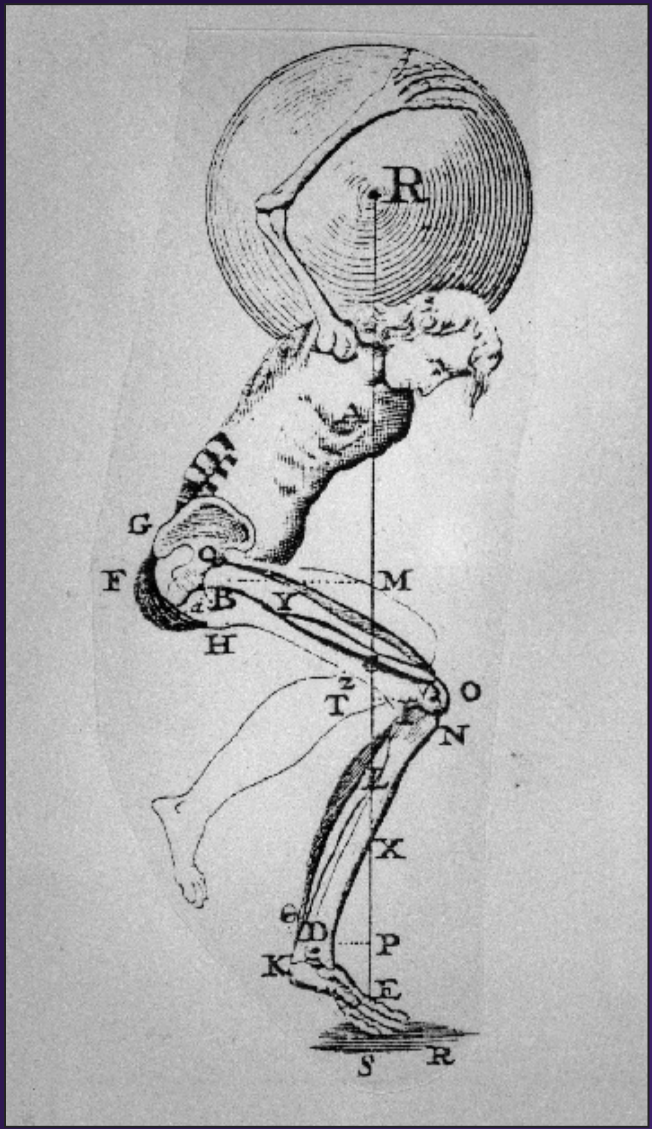


Musculoskeletal Biomechanics

BIOEN 520 | ME 527

Session 2A

Mechanics and Viscoelasticity

Review: Session 1…

- Defined biomechanics
- Looked at benefits of studying biomechanics
- Examined a few important historical figures
- Discussed why it's important to know what others have done in the past
- Examined how to tell if a field is growing
- Reviewed several "hot" research areas
- Discussed anatomical planes, nomenclature and structures (Mini-Lab 1)

"Brain Teaser"…

[Q]: Was Galileo correct? *[He hypothesized that the cross-sectional geometry of long bones would have to increase more quickly than length to support the increased weight of larger animals.]*

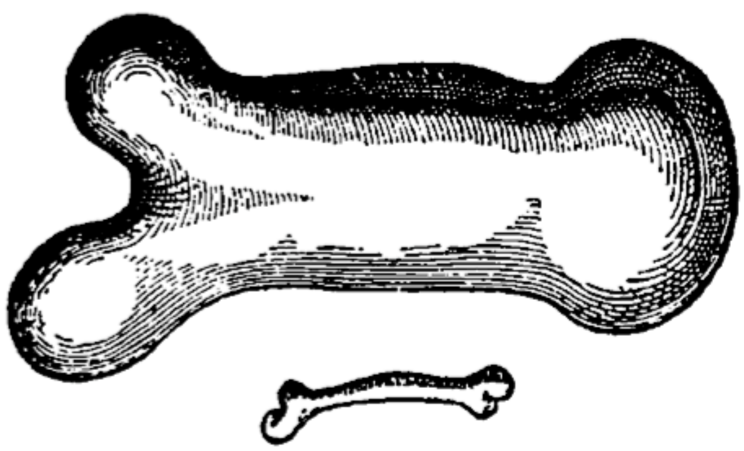


Figure 1.2.3 Galileo's comparison of a normal femur with the femur needed to support an animal three times the size (from Singer, 1959, with permission of Oxford University Press).

“Brain Teaser”...

[Q]: Was Galileo correct?

10 different adult primate femurs

Elephant femur

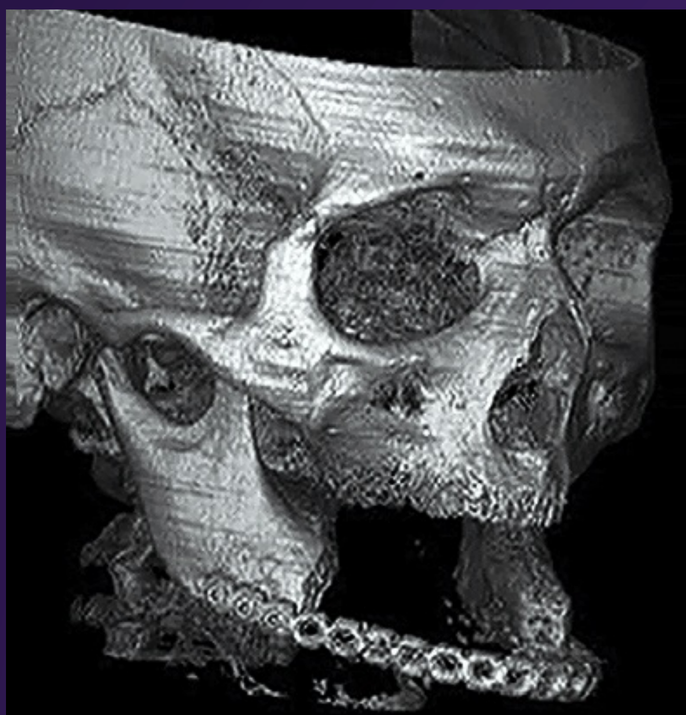
Current Topics…

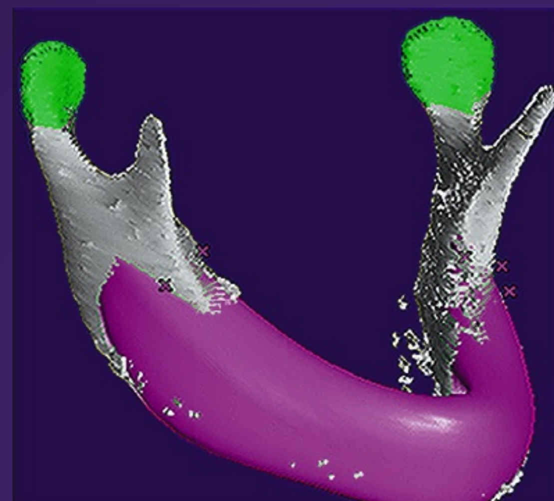
Tissue Engineering Example 1: Human Ear

Xu et al., 2005

Current Topics…

Tissue Engineering Example 2: Human Jaw

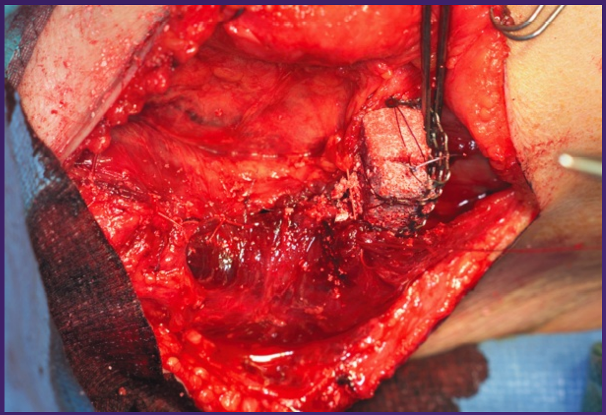


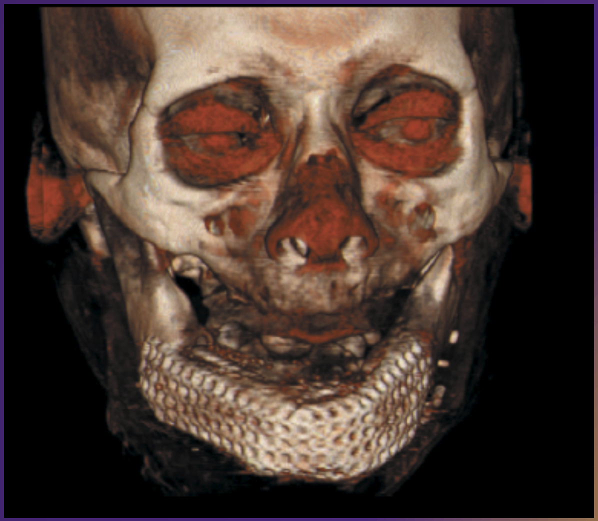


Warnke et al., 2004

Current Topics...

Tissue Engineering Example 2: Human Jaw

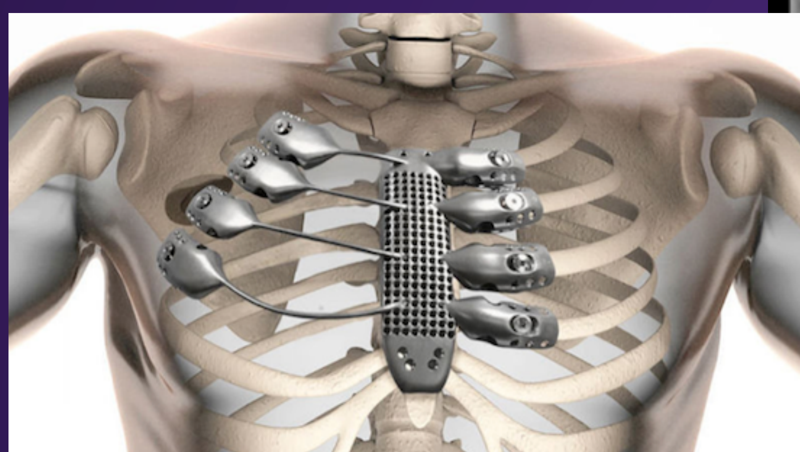


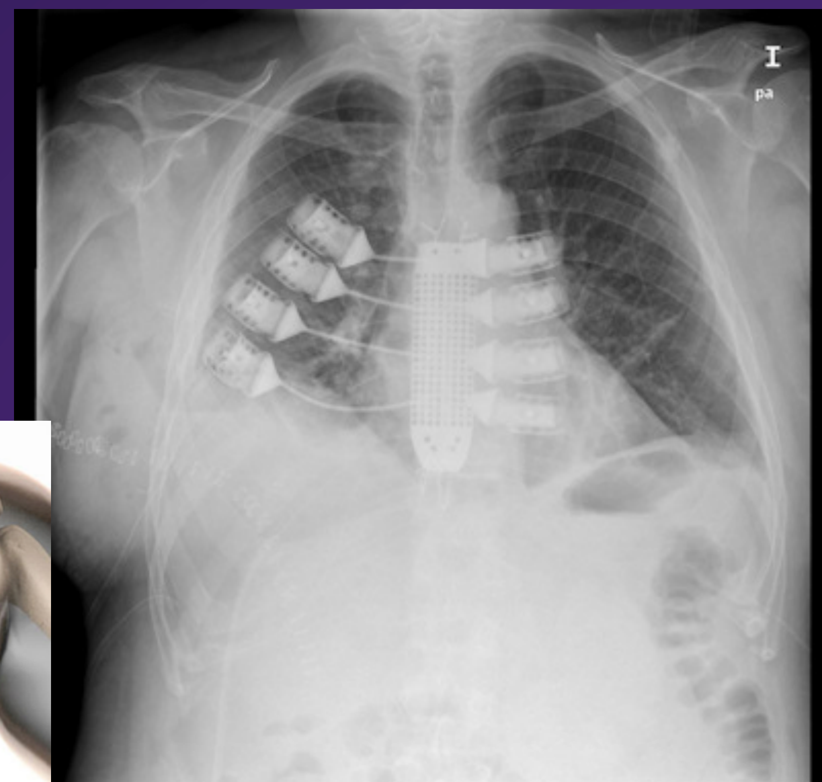


Warnke et al., 2004

Current Topics...

Custom Implants Example 3: *3D Printed Ribcage*





Aranda et al., 2015

Session 2A Discussion Questions...

[Q]: In engineering mechanics, what are the basic concepts and assumptions used in statics, dynamics, and strength of materials?

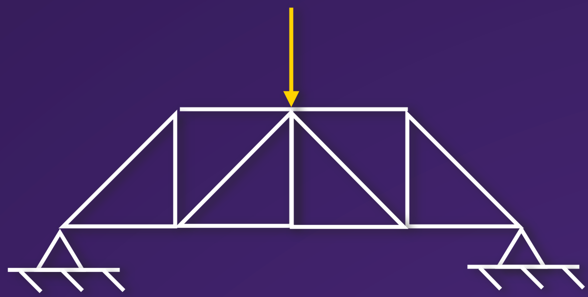
[Q]: What mechanical properties are commonly used to characterize material behavior?

[Q]: What are some fundamental differences between traditional engineering materials and biologic tissues?

[Q]: What is viscoelasticity?

Basic Concepts in Mechanics...

[Q]: What is Statics?

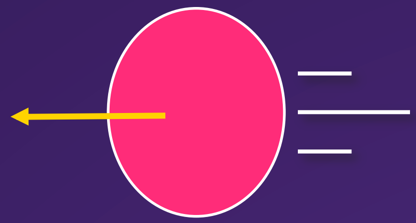


The study of external forces acting on an object in a state of equilibrium...

- *Basic concepts: Forces and moments*
- *Basic assumptions: Rigid-bodies, no motion*
- *Basic tool: Free-body diagram*

Basic Concepts in Mechanics...

[Q]: What is Dynamics?

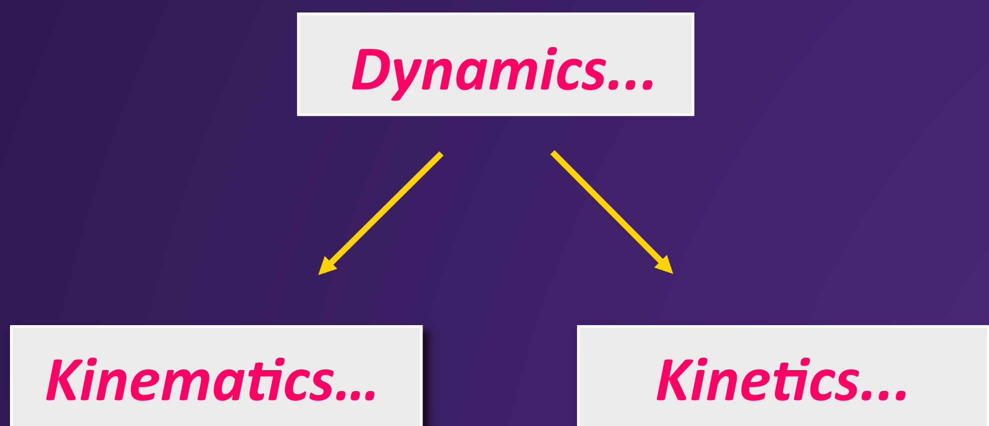


The effect of external forces acting on an object resulting in motion...

- *Basic concepts: Force, mass, and acceleration*
- *Basic assumption: Rigid-body mechanics*
- *Basic tool: Free-body diagram*

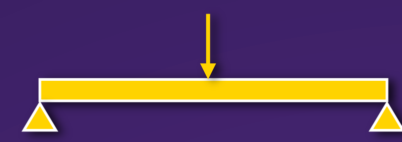
Basic Concepts in Mechanics...

[Q]: What are two sub-fields of dynamics which focus on the study of motion and the forces that produce them?



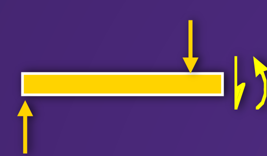
Basic Concepts in Mechanics...

[Q]: What is Strength of Materials?



The effect of external forces acting on an object resulting in deformation...

- *Basic concepts: Stress and strain*
- *Basic assumptions: Solid bodies (homogeneous), small deformations*
- *Basic tool: Method of sections*



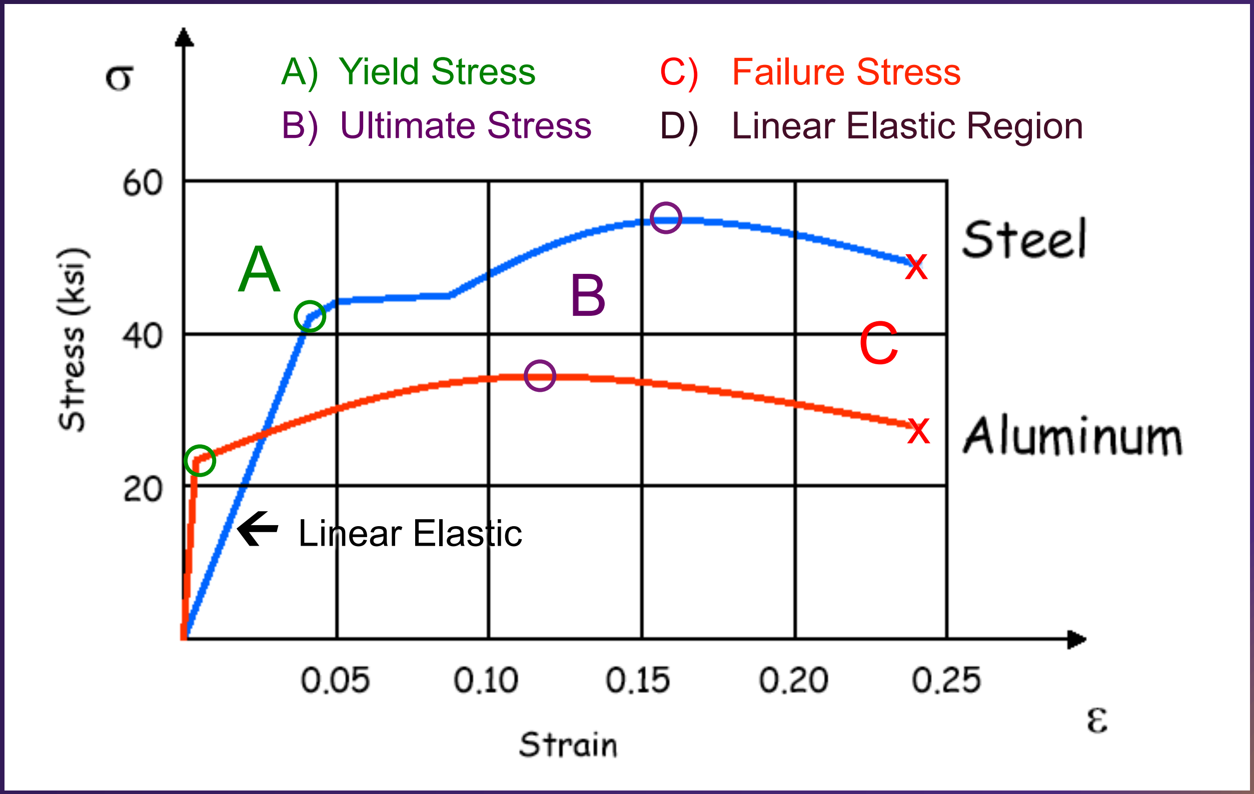
Application to Biological Tissues...

[Q]: Based on load/displacement measurements, what mechanical properties are commonly used to characterize material behavior?

- *Stress-strain*
- *Stiffness / elastic modulus*
- *Yield, ultimate, or failure load/stress*
- *Failure strain*
- *Poisson's ratio*
- *Others (...fatigue strength, toughness, etc.)*

Basic Concepts in Mechanics...

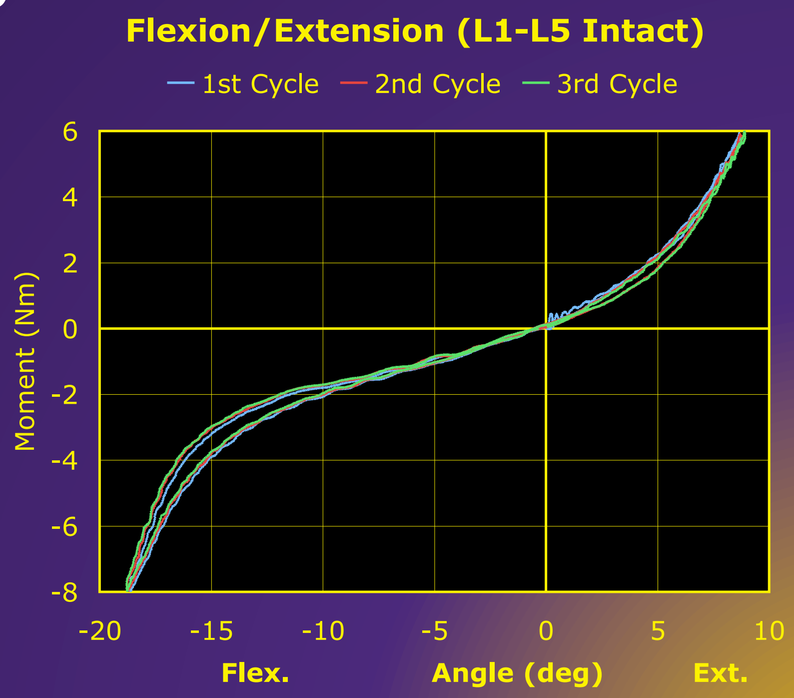
Ex: Stress-Strain Diagram...



Application to Biological Tissues…

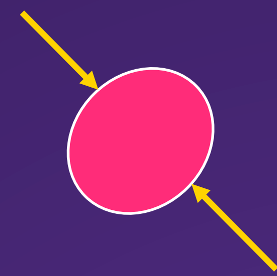
[Q]: What are some fundamental differences between traditional engineering materials and biologic tissues?

- *Non-homogeneous*
- *Large deformations*
- *Non-linear*
- *Hysteresis*
- *Viscoelastic*



Application to Biological Tissues...

[Q]: Can we apply the basic principles of mechanics to biological tissues?
(i.e., Do our assumptions hold?)

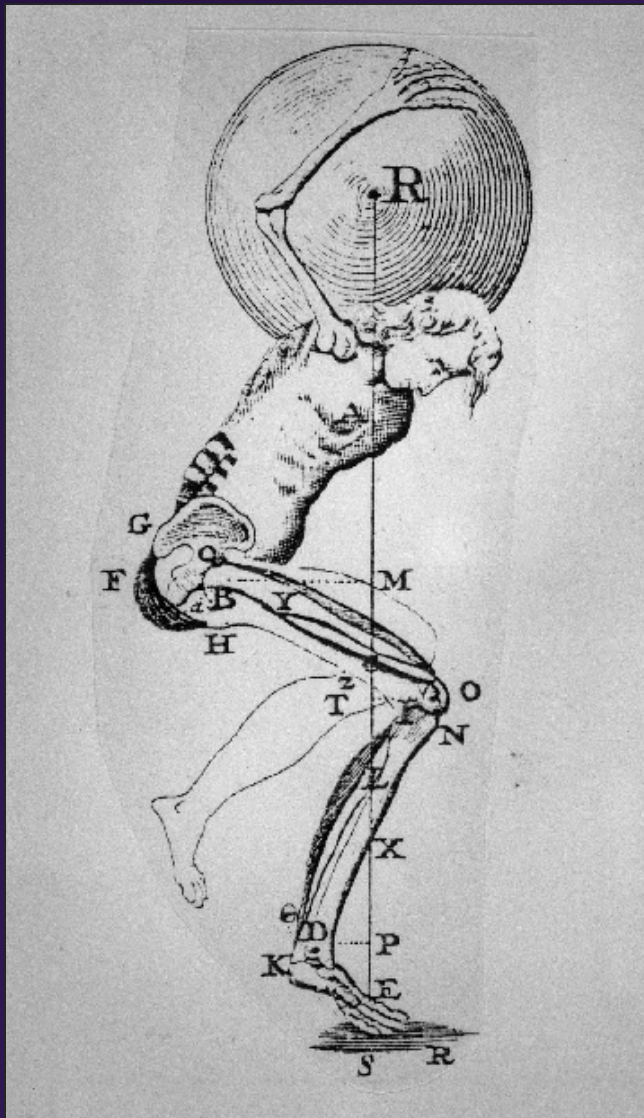


Assumptions:

- *Homogeneous*
- *Small deformations*
- *Linear Elastic*

Reality:

- *Non-homogeneous*
- *Large deformations*
- *Non-linear*
- *Hysteresis*
- *Viscoelastic*



Musculoskeletal Biomechanics

BIOEN 520 | ME 527

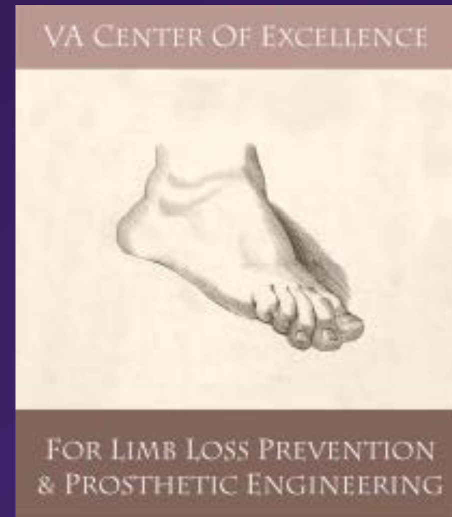
Session 2

Basic Mechanics and Viscoelasticity

Overview

- Introduction
- Follow-up from last class
- Viscoelasticity
- Foot injuries in the news

VA Puget Sound



VA Puget Sound

William R. Ledoux, PhD's Research Interests

VA Center of Excellence for Limb Loss Prevention and Prosthetic Engineering

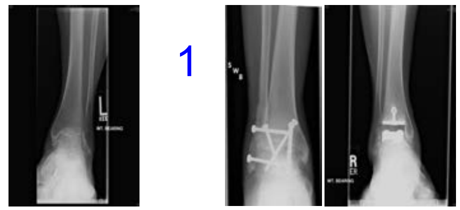
VA Puget Sound Health Care System

University of Washington
Mechanical Engineering and Orthopaedics

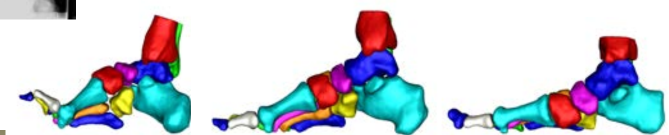
Functional limb loss

Relevant pathologies:

- Ankle OA (arthrodesis vs. arthroplasty) [1]
- Foot type (high arch v. neutral v. flatfoot) [2]



1

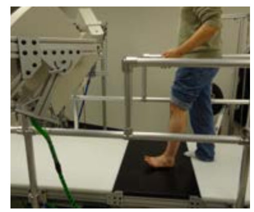


2

Techniques used:

- Robotic gait simulation [A]
- Biplane fluoroscopy [B]

A



B

Anatomical limb loss

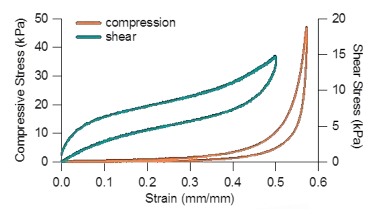
Relevant pathologies:

- Diabetes [3]

3

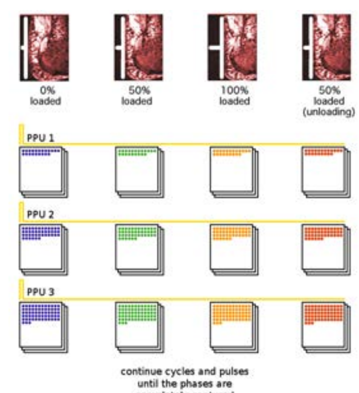
Techniques used:

- Cadaveric tissue testing (diabetic v. non-diabetic) [C]
- Patient-specific computational modeling [D]
- MRI-compatible loading device [E]



C

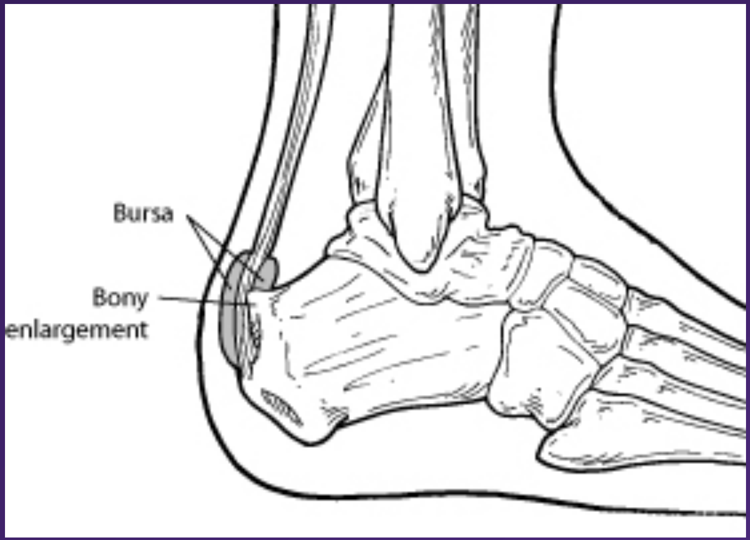
D



E

Follow-ups from last class

- Haglunds deformity
  - Bony enlargement
  - Pain from bursitis
- Foot anatomy
- Dissection video(s)



http://www.foothealthfacts.org/footankleinfo/haglunds-deformity.htm

Foot: motion

sagittal plane

dorsiflexion

neutral

plantar flexion

Foot: motion

frontal plane

Foot: motion

transverse plane

Foot: motion

- Pronation
  - dorsiflexion
  - abduction/external rotation
  - eversion/valgus
  - flat foot
- Supination
  - plantar flexion
  - adduction/internal rotation
  - inversion/varus
  - high arched foot

- issues with pronation and supination:
  - works well for hand, but not for foot due to 90˚ ankle
  - neutral position vs. anatomic position
  - in some texts, refers to pure frontal plane motion
  - in flat foot (hyperpronated foot or pes planus), forefoot actually supinated relative to hindfoot

Foot and ankle anatomical terms

- Discuss the foot with ankle at 90˚ (i.e., neutral position) and not with the ankle plantar flexed (i.e., anatomical position), except if we are taking about the toes.
- Avoid use of pronation/supination (see last slide); instead discuss motion/position in specific cardinal planes.
- Coronal rather than frontal (minor point)

Foot and ankle anatomical terms

- Sagittal plane motion at all joints is referred to as dorsiflexion/plantar flexion.
- Hindfoot (calcaneus to tibia, calcaneus to talus, talus to tibia) ankle at 90˚
  - coronal plane motion = inversion/eversion (and position varus/valgus)
  - transverse plane motion = adduction/abduction or internal/external rotation

Foot and ankle anatomical terms

- Forefoot to hindfoot (first metatarsal to talus) ankle at 90˚
  - coronal plane motion = inversion/eversion (and position varus/valgus)
  - transverse plane motion = adduction/abduction or internal/external rotation
- Hallux to first metatarsal
  - coronal plane motion = inversion/eversion
  - transverse plane motion = varus/valgus
    - hallux valgus = bunion

Foot and ankle anatomical terms

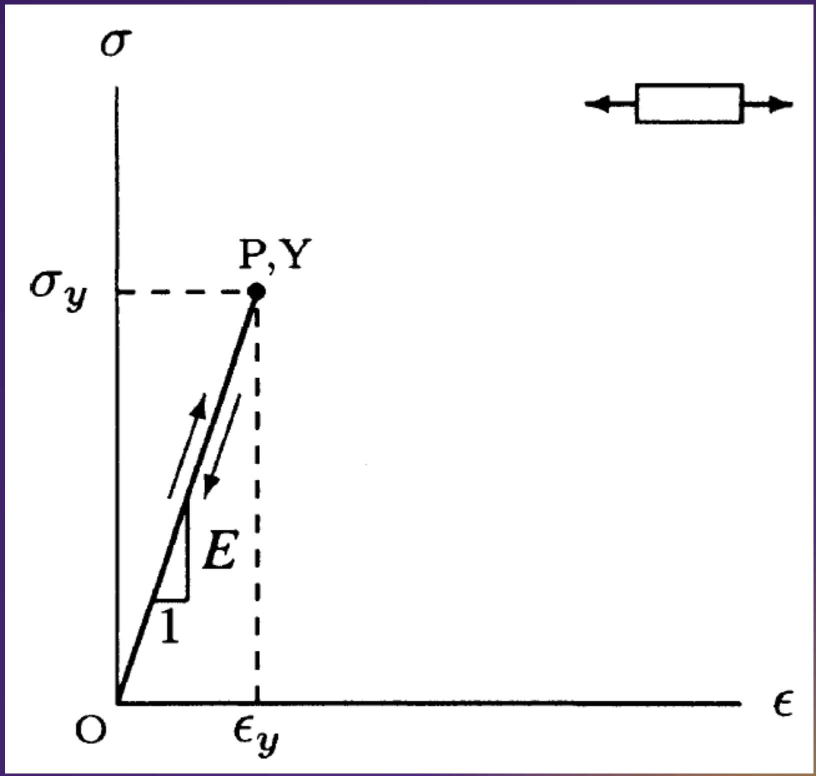
- Use hindfoot not rearfoot
- Use neutrally aligned not rectus
- Can not say “pes planus foot type”, as that literally means “foot flat foot type”. Say “pes planus” or “planus foot type”.

Viscoelasticity

- Define some basic terms: elasticity, plasticity, viscosity, and viscoelasticity
- Review simple, linear viscoelastic models
- Describe the important properties of viscoelastic materials
- Discuss concepts using in house data, as well as text books

Elasticity

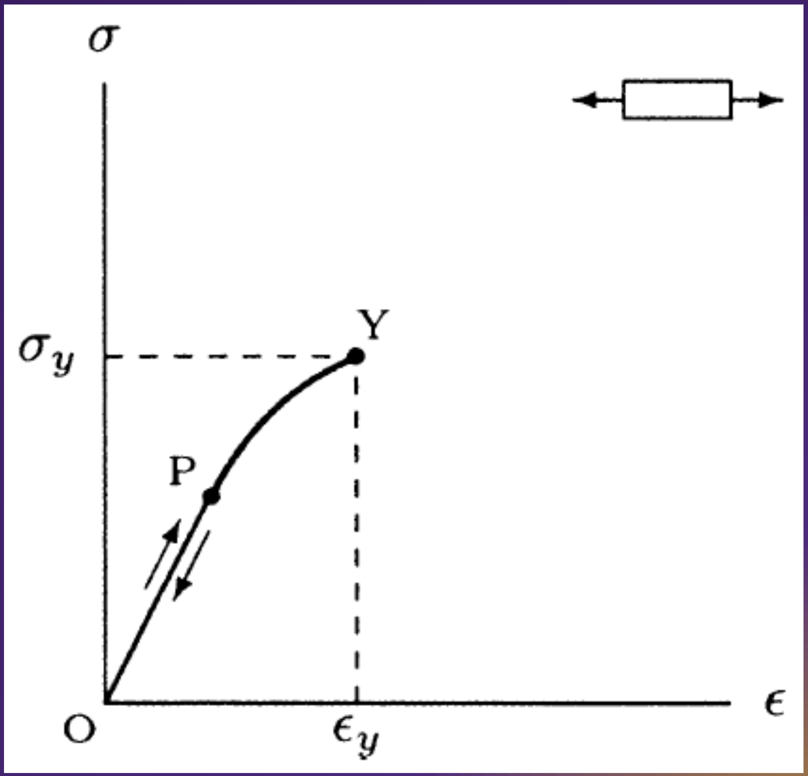
- Ability of a material to resume its original (stress free) size and shape upon removal of applied loads
- Solid property
- Metals under small strain



Ozkaya, et al. 2012

Elasticity

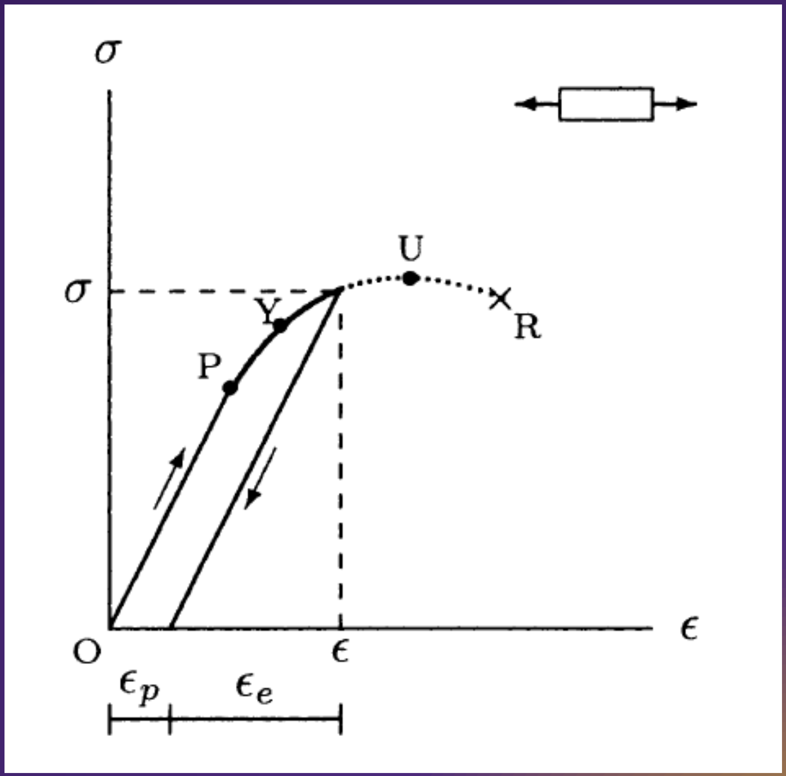
- Linear vs. non-linear
- Hyperelastic material - rubber
- Structural, stiffness N/m
- Material, Young's modulus (E) N/m^2



Ozkaya, et al. 2012

Plasticity

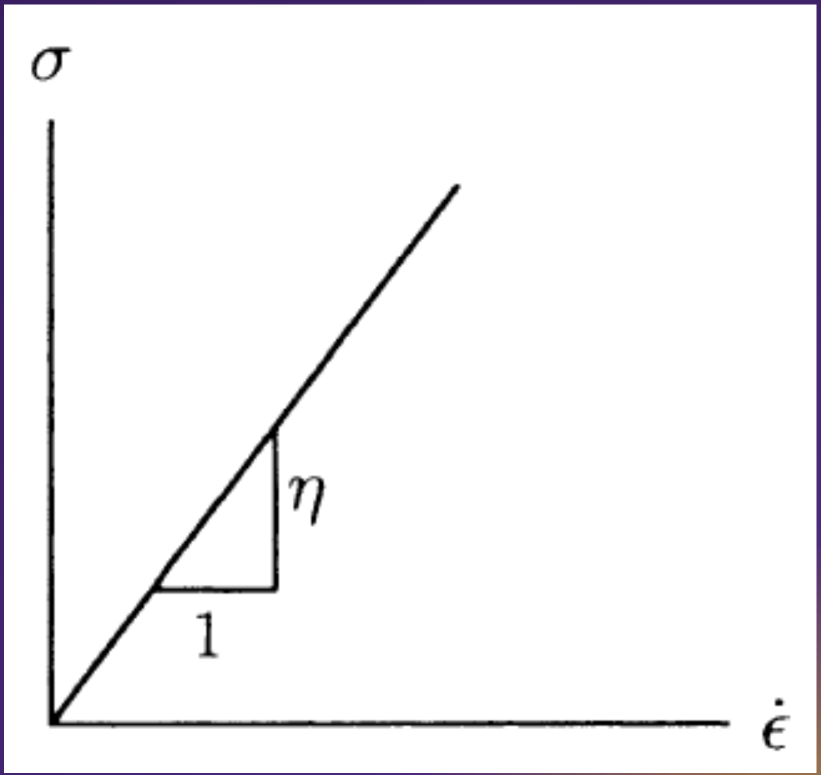
- Propensity of a material to undergo permanent deform-ation under load
- Solid property
- Metals under large strains



Ozkaya, et al. 2012

Viscosity

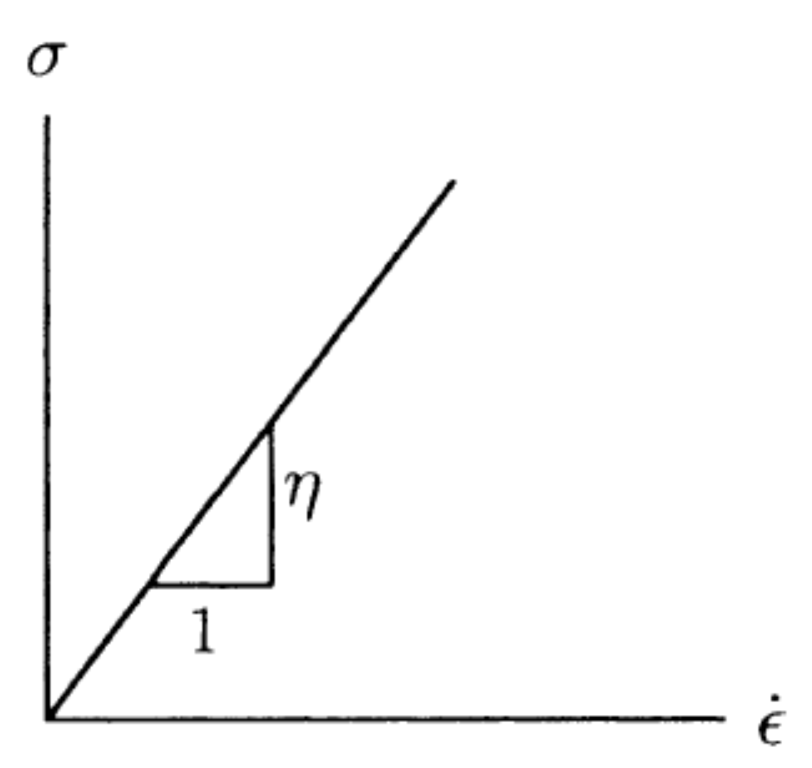
- Resistance of a fluid to a shear motion
- Its internal friction
- Measure of resistance to flow
- Fluid property



Ozkaya, et al. 2012

Viscosity

- η (or c or b or μ) - dynamic viscosity - ratio of shearing stress to rate of deformation
- Ns/m^2 = η (material, coefficient of viscosity) or Ns/m = μ (structural, coefficient of friction)



Ozkaya, et al. 2012

Viscoelasticity

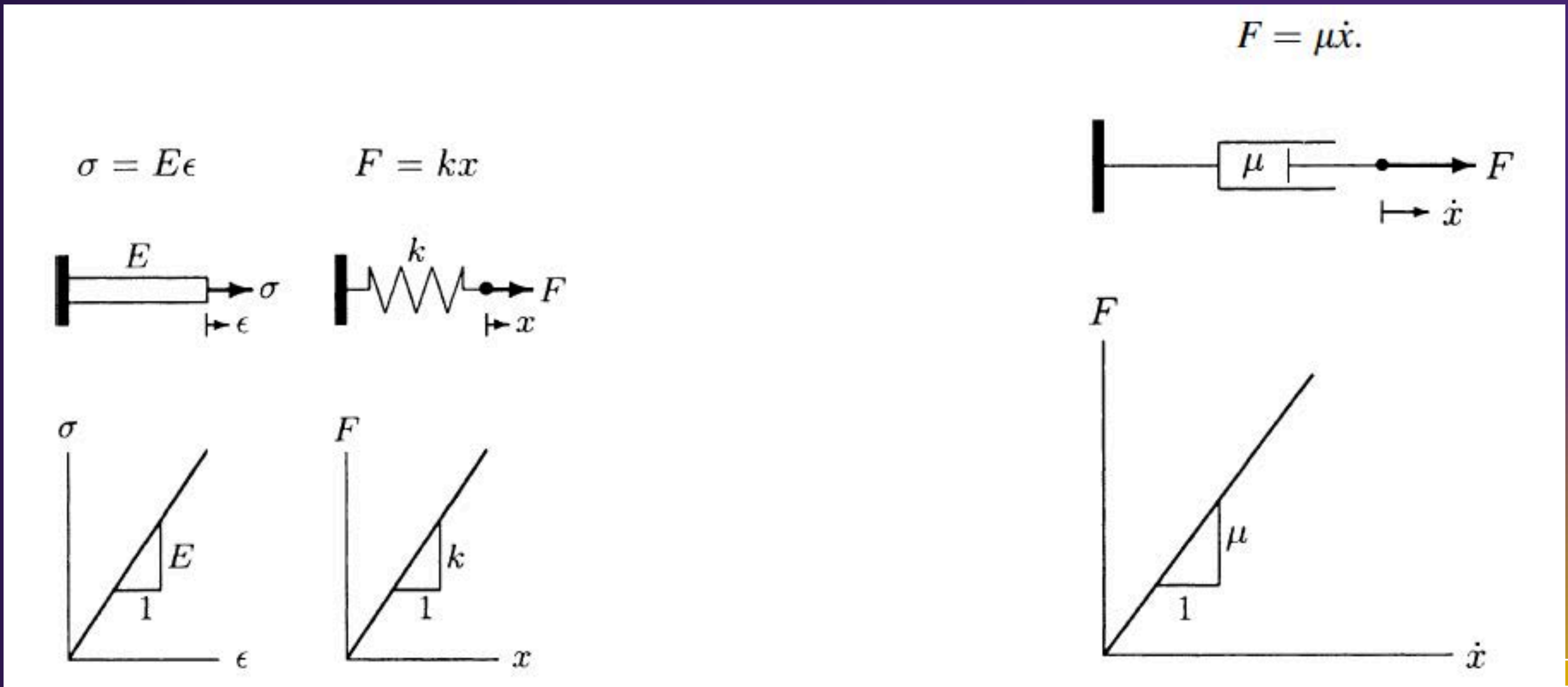
- Solid and liquid properties
- Stress depends on strain (elastic) and strain rate (viscous)
- Deforms when a load is applied, and it recovers, just not instantaneously.

Viscoelasticity

- The effect is due to a molecular rearrangement in the solid induced by stress.
- Once the stress is removed, the molecules slowly recover their former spatial arrangement.
- A property of many polymers, metals at high temperatures, and biological tissues.

Viscoelasticity

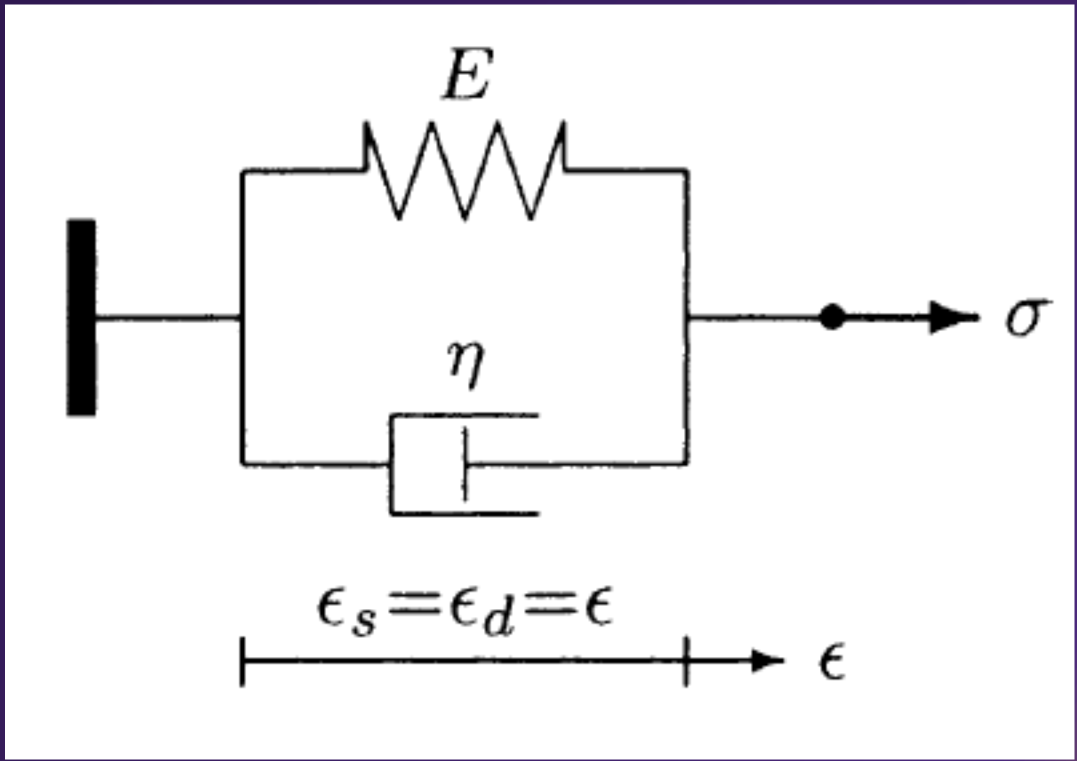
- springs, solids, recovery
- dashpots, fluids, no recovery



Ozkaya, et al. 2012

Viscoelasticity

- Kelvin-Voigt



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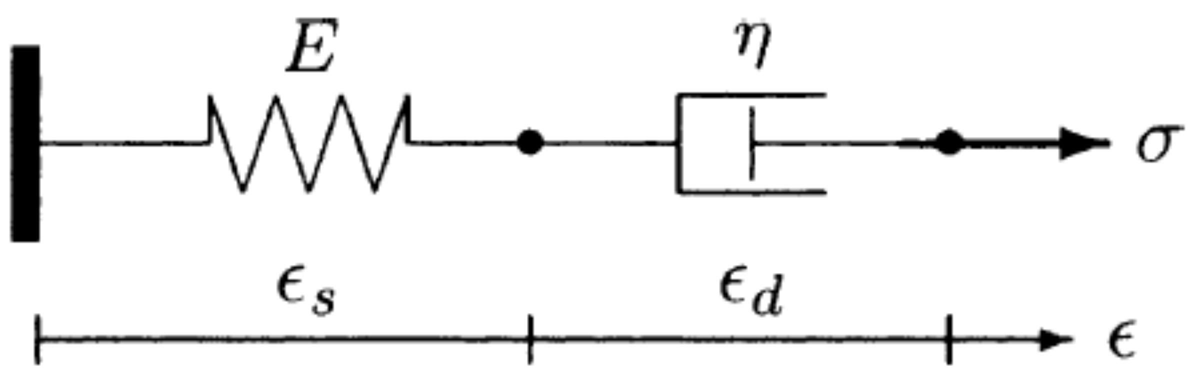
Viscoelasticity

- Maxwell

$$\eta\dot{\sigma} + E\sigma = E\eta\dot{\varepsilon}.$$

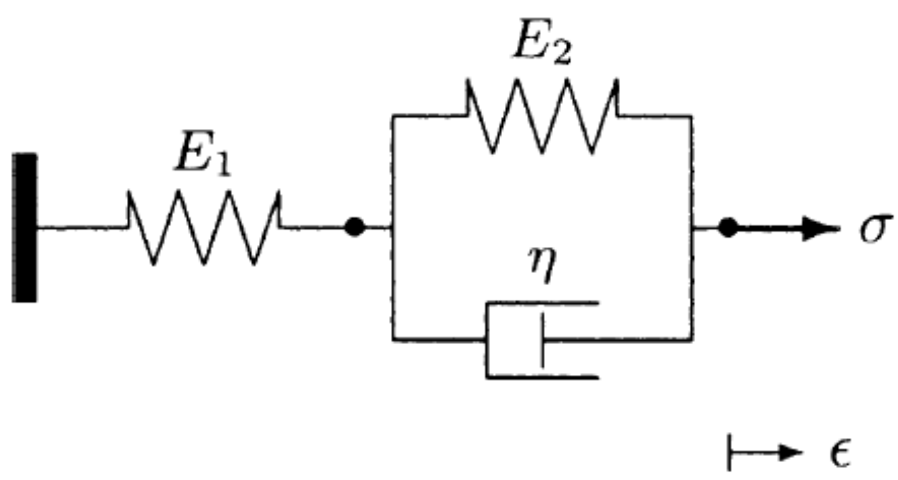


Ozkaya, et al. 2012

Viscoelasticity

- Standard linear solid

$$(E_1 + E_2)\sigma + \eta\dot{\sigma} = (E_1 E_2 \varepsilon + E_1 \eta \dot{\varepsilon}).$$



Ozkaya, et al. 2012

Viscoelasticity

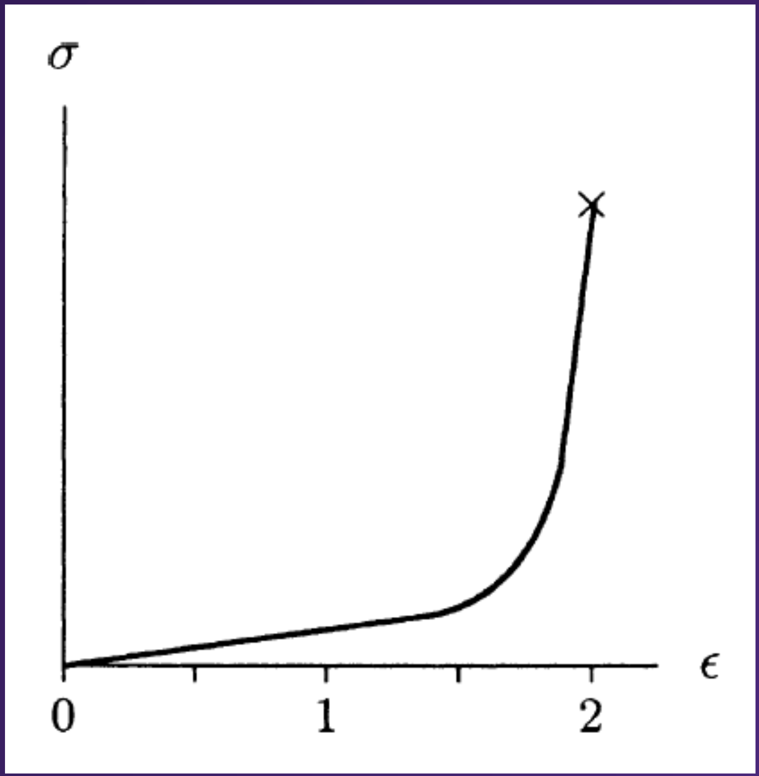
- 6 major properties or attributes
  - nonlinear force v. (large) deformation
  - preconditioning
  - hysteresis
  - strain rate sensitivity
  - stress relaxation
  - creep

Viscoelasticity

- nonlinear force v. (large) deformation
  - also occurs with elastic materials
  - consistently found with viscoelastic materials
  - collagen: crimped fibrils and ground substance
  - elastin: very elastic
  - two mechanisms:
    - collagen uncrimping/elastin stretching (low modulus)
    - collagen and elastin stretching (high modulus > 200% strain)
  - example?
    - heel pad

Viscoelasticity

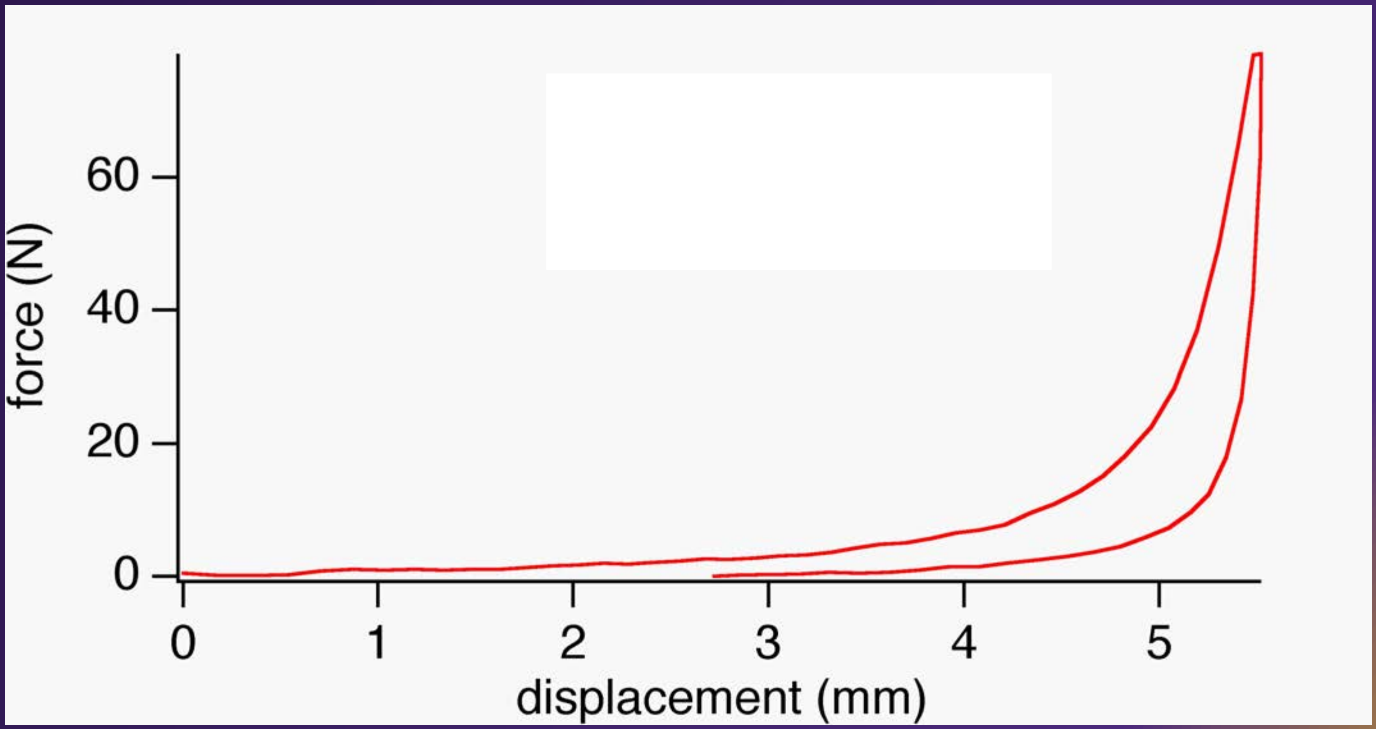
- nonlinear force v. (large) deformation
  - elastin



Ozkaya, et al. 2012

Viscoelasticity

- nonlinear force v. (large) deformation
  - isolated plantar fat from heel



Viscoelasticity

- nonlinear force v. (large) deformation
  - rabbit tendon

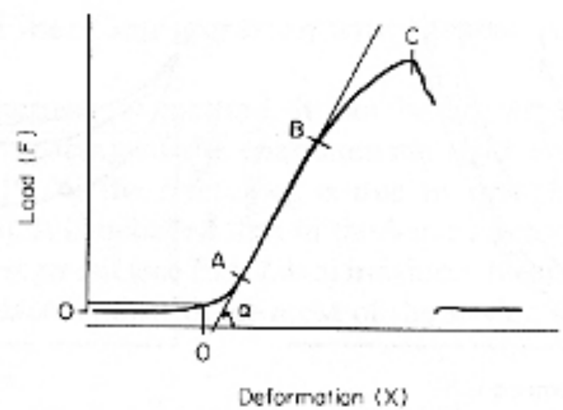


Figure 7.3:7 A typical load-elongation curve for a rabbit limb tendon brought to failure with a constant rate of elongation. The "toe" part is from O to A. The part A–B is almost linear. At point C the maximum load is reached. α is the angle between the linear part of the curve and the deformation axis. The slope, tan α, is taken as the "elastic stiffness," from which the Young's modulus listed in Table 7.2:1 is computed. From Viidik (1973), by permission.

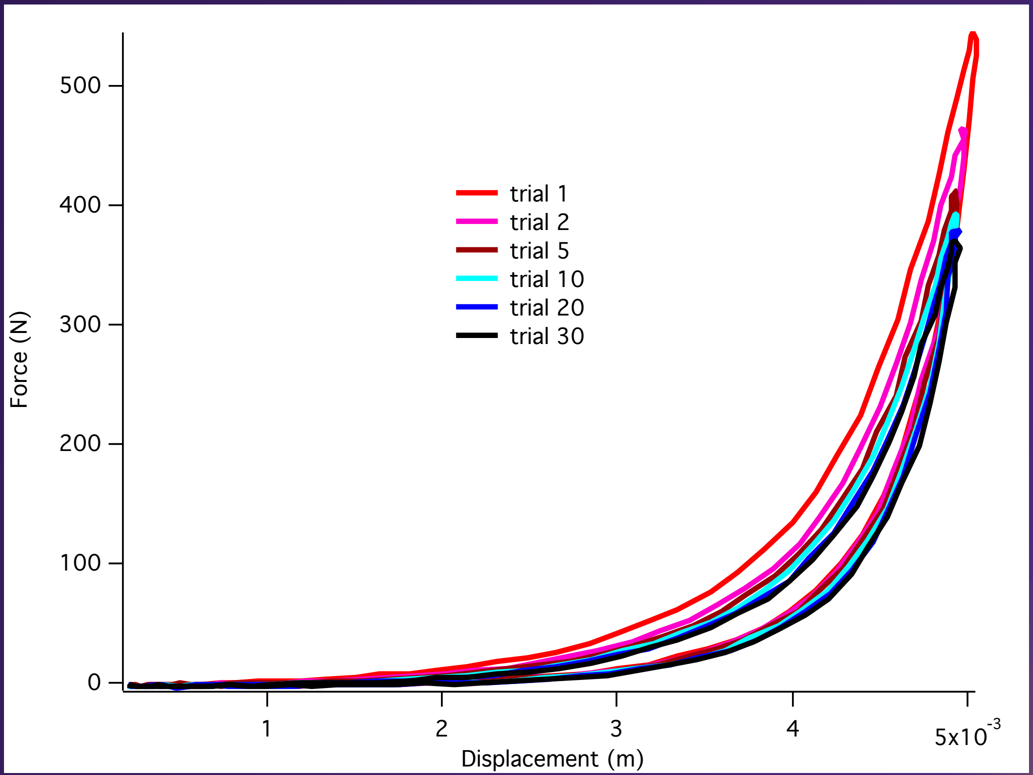
Fung, 1993

Viscoelasticity

- preconditioning
  - force v. deformation cycle changes until steady state is reached
  - internal tissue structure changes
  - implications for materials testing (and examples)?
    - brain
    - artery
    - Achilles tendon
    - liver
    - plantar fat

Viscoelasticity

- preconditioning
  - isolated plantar fat from heel



Viscoelasticity

- preconditioning
  - anterior cruciate ligament

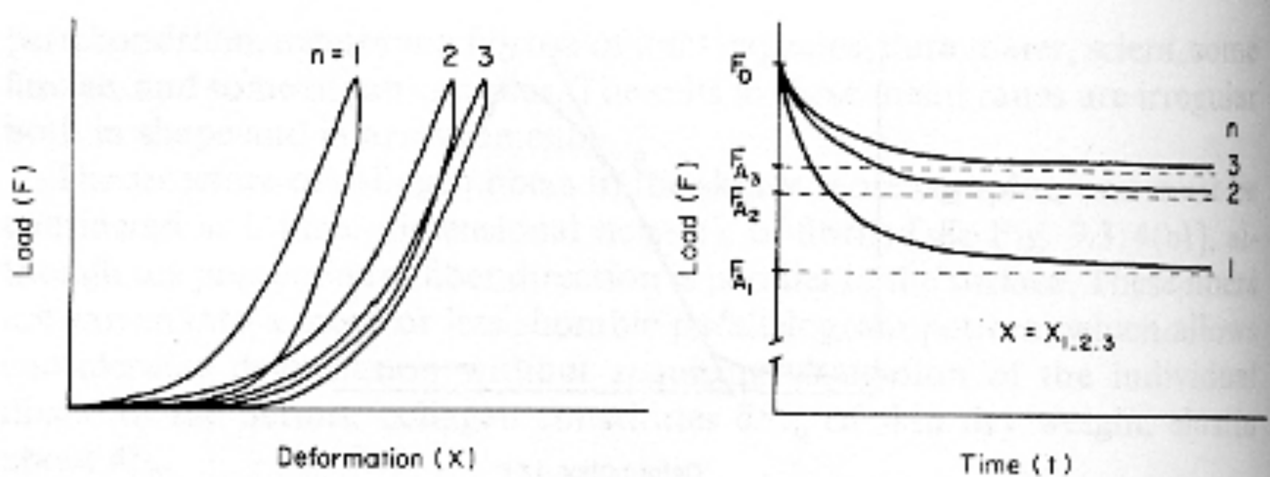


Figure 7.3:9 Preconditioning of an anterior cruciate ligament. The load-elongation and relaxation curves of the first three cycles are shown. From Viidik (1973), by permission.

Fung, 1993

Viscoelasticity

- preconditioning
  - dog carotid artery

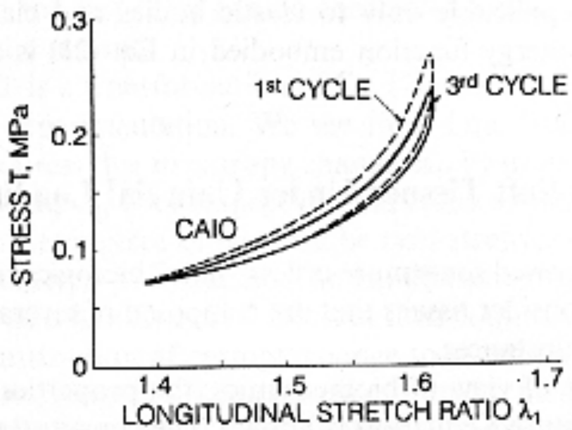


Figure 7.5:1 Preconditioning. Cyclic stress response of a dog's carotid artery, which was maintained in cylindrical configuration (by appropriate inflation or deflation) when stretched longitudinally. λ_1 is the stretch ratio referred to the zero-stress length of the segment; 37°, 0.21 cycles/min. Physiological length $L_p = 4.22$ cm. $L_p/L_0 = 1.67$. Diameter at physiological condition = 0.32 cm. $A_0 = 0.056$ cm^2. Dog wt., 18 kg. From Lee, Frasher, and Fung (1967).

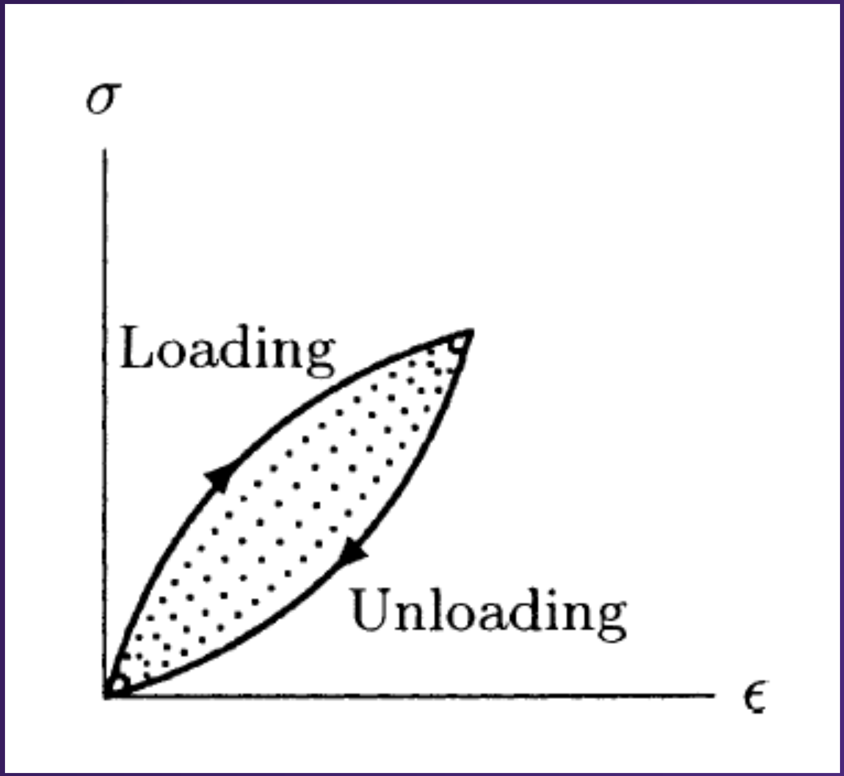
Fung, 1993

Viscoelasticity

- hysteresis
  - a lagging of an effect when forces applied to a body are changed
  - parallels in magnetism, thermoelectricity, etc. during polarity changes
  - energy is “lost”
  - where does it go?
    - dissipated as heat, noise, etc.
  - example?
    - heel pad/footwear

Viscoelasticity

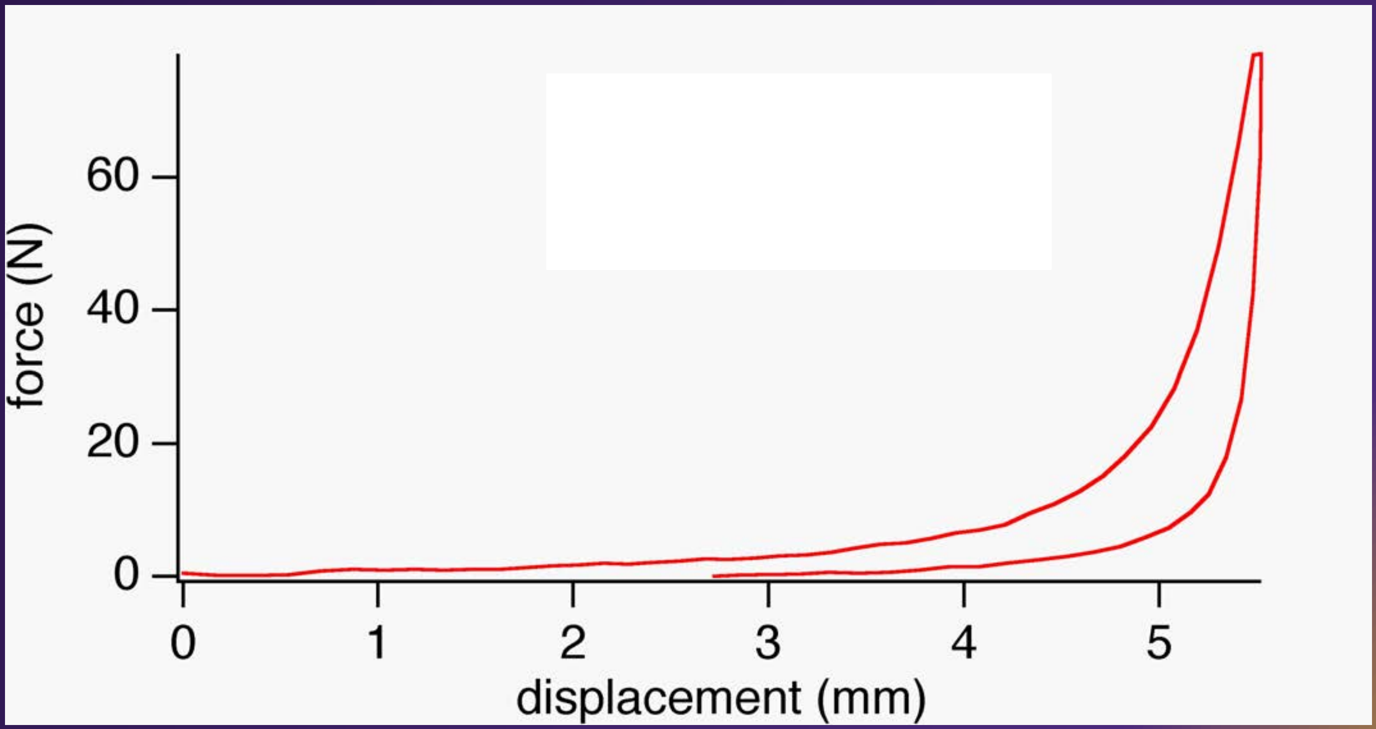
- hysteresis
  - standard linear solid



Ozkaya, et al. 2012

Viscoelasticity

- hysteresis
  - isolated plantar fat from heel



Viscoelasticity

- hysteresis
  - anterior cruciate ligament

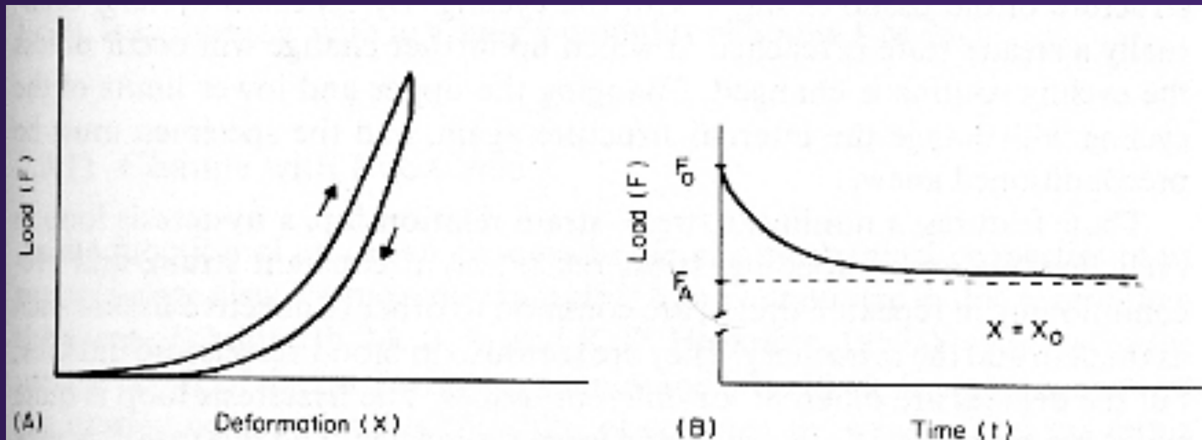


Figure 7.3:8 The load-elongation and relaxation curves of an anterior cruciate ligament specimen. In (A), the specimen was loaded to about one-third of its failure load and then unloaded at the same constant speed. In (B), the specimen was stretched at constant speed until the load reached F_0; then the stretching was stopped and the length was held constant. The load then relaxed. From Viidik (1973), by permission.

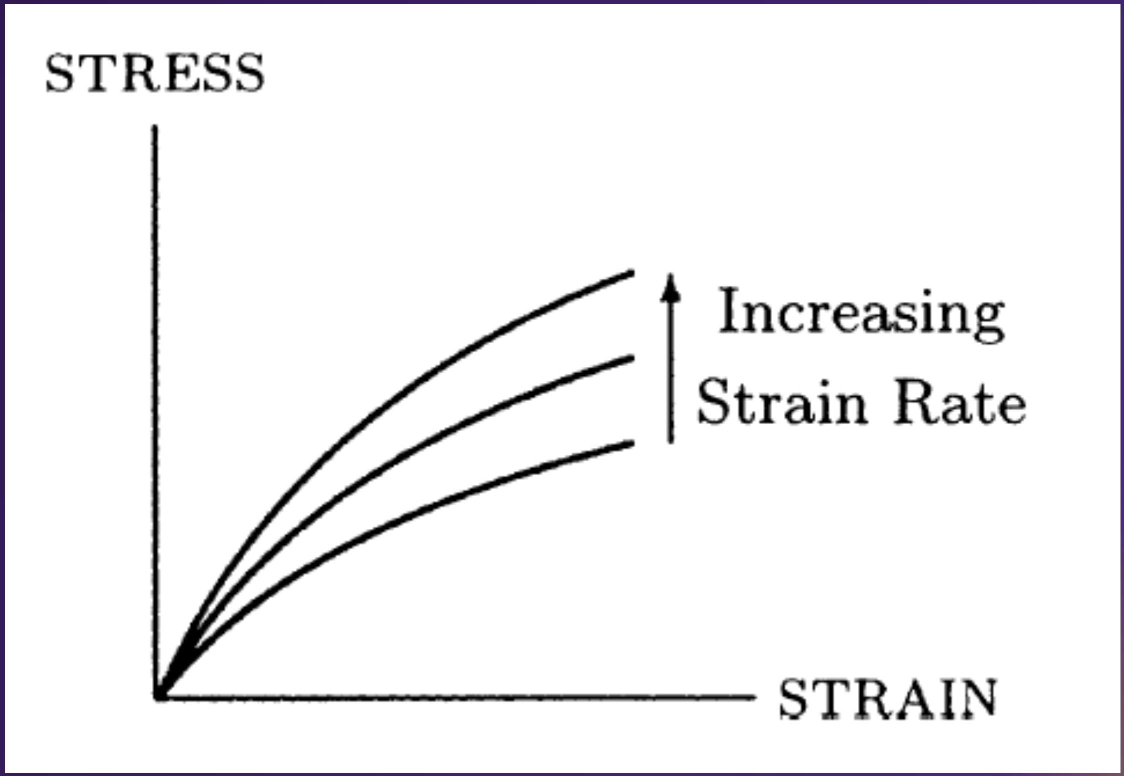
Fung, 1993

Viscoelasticity

- strain rate sensitivity
  - faster you load, stiffer the material gets
  - at slow rates, essentially elastic properties
    - quasi-static
  - soft tissues have wide range of similar frequency responses (stiffness and hysteresis)
  - example?
    - heel pad

Viscoelasticity

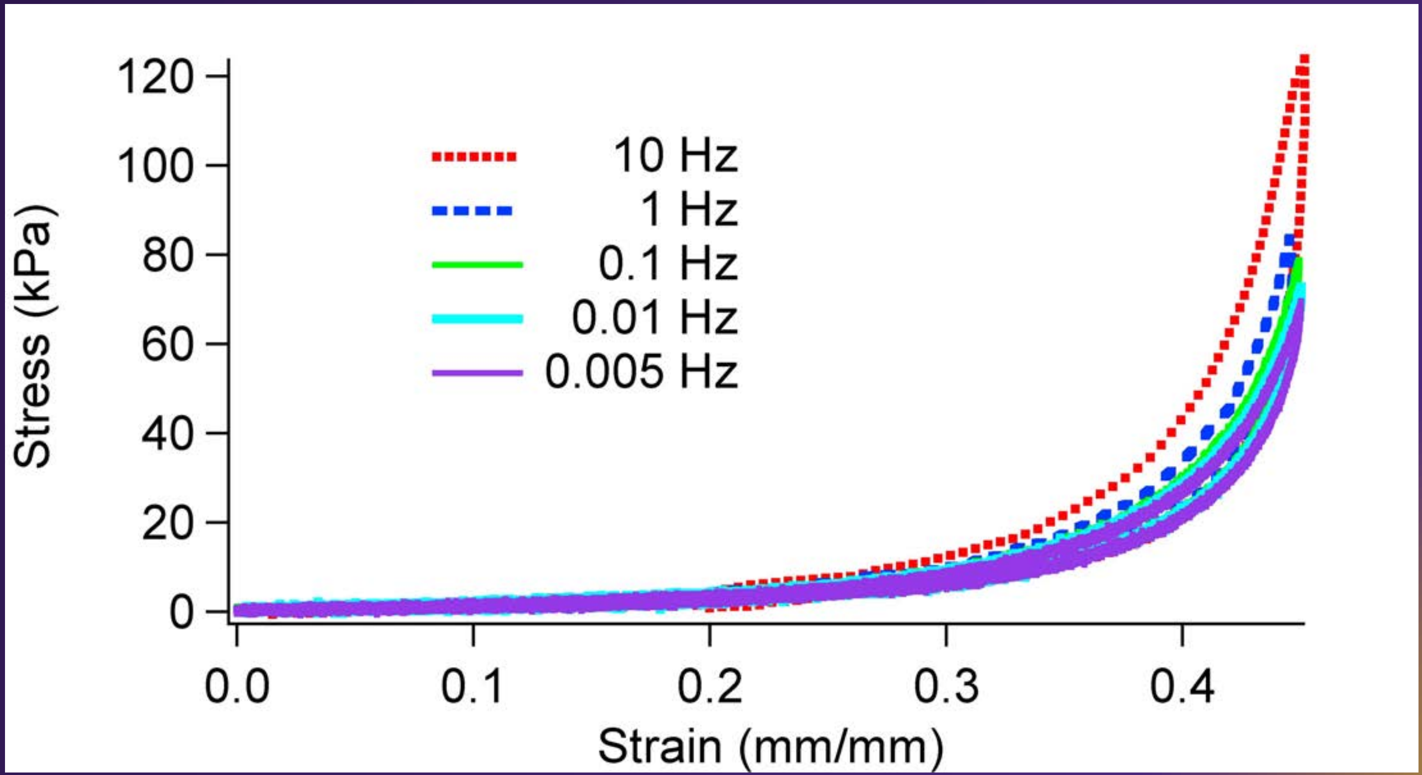
- strain rate sensitivity
  - standard linear solid



Ozkaya, et al. 2012

Viscoelasticity

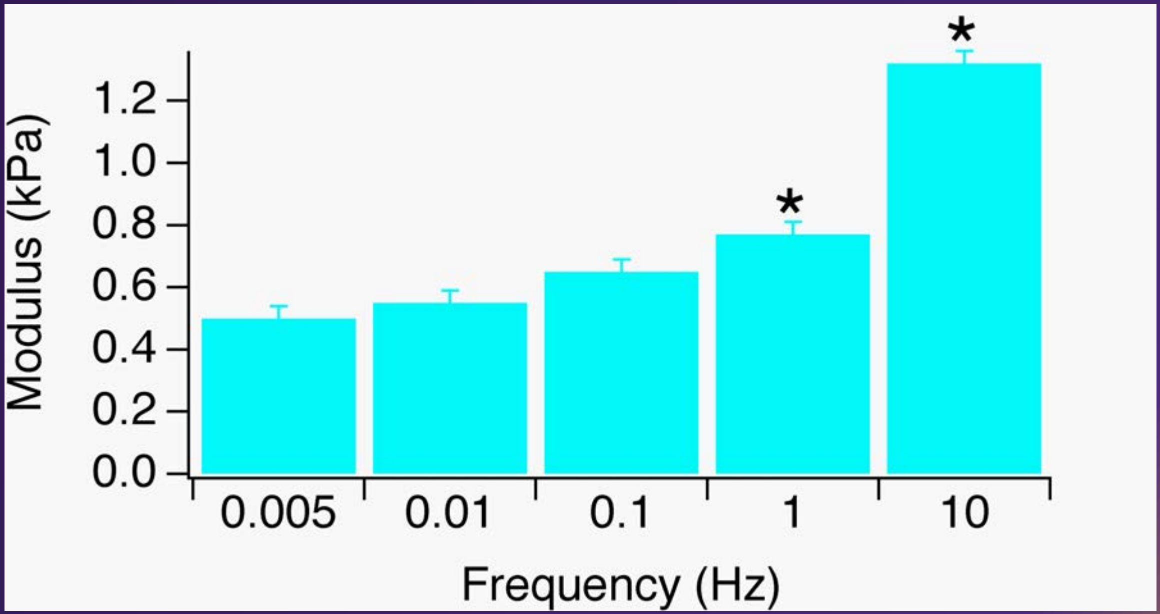
- strain rate sensitivity
  - isolated plantar fat from heel



Pai and Ledoux, 2010

Viscoelasticity

- strain rate sensitivity
  - isolated plantar fat from heel



Pai and Ledoux, 2010

Viscoelasticity

- strain rate sensitivity
  - papillary muscle

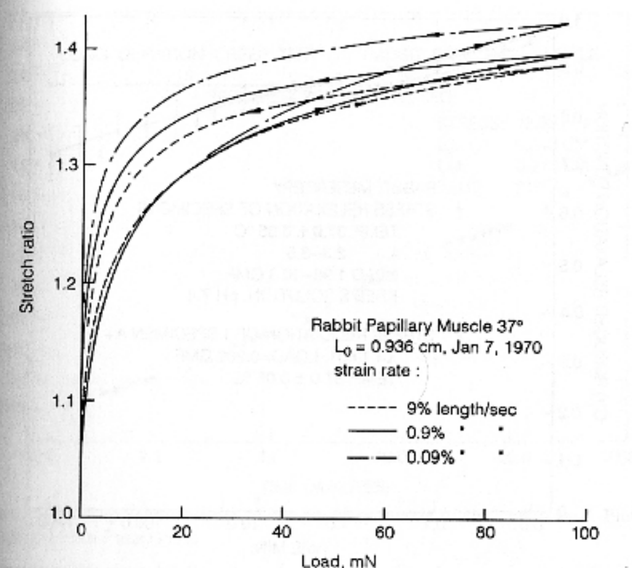


Figure 7.5:2 The length-tension curve of a resting papillary muscle from the right ventricle of the rabbit. Strain rates 0.09% length/sec; 0.9% length/sec; and 9% length/sec. Length at 9 mg force = 0.936 cm. 37°C. $A_0 = 1.287\ mm^2$. From Fung (1972), by courtesy of Dr. John Pinto.

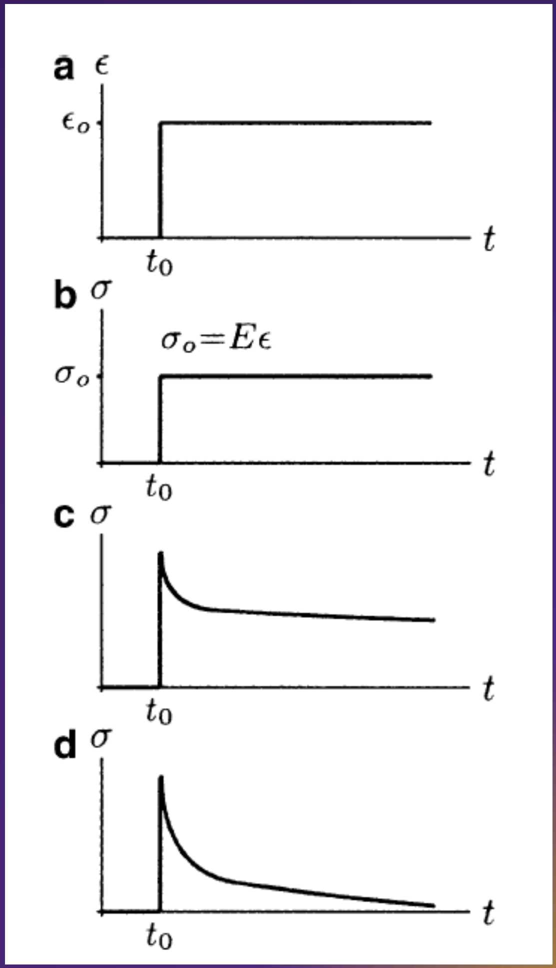
Fung, 1993

Viscoelasticity

- stress relaxation
  - loaded at a constant displacement and force relaxes
  - easier than creep test, but not real world conditions
  - example?
    - isometric stretching

Viscoelasticity

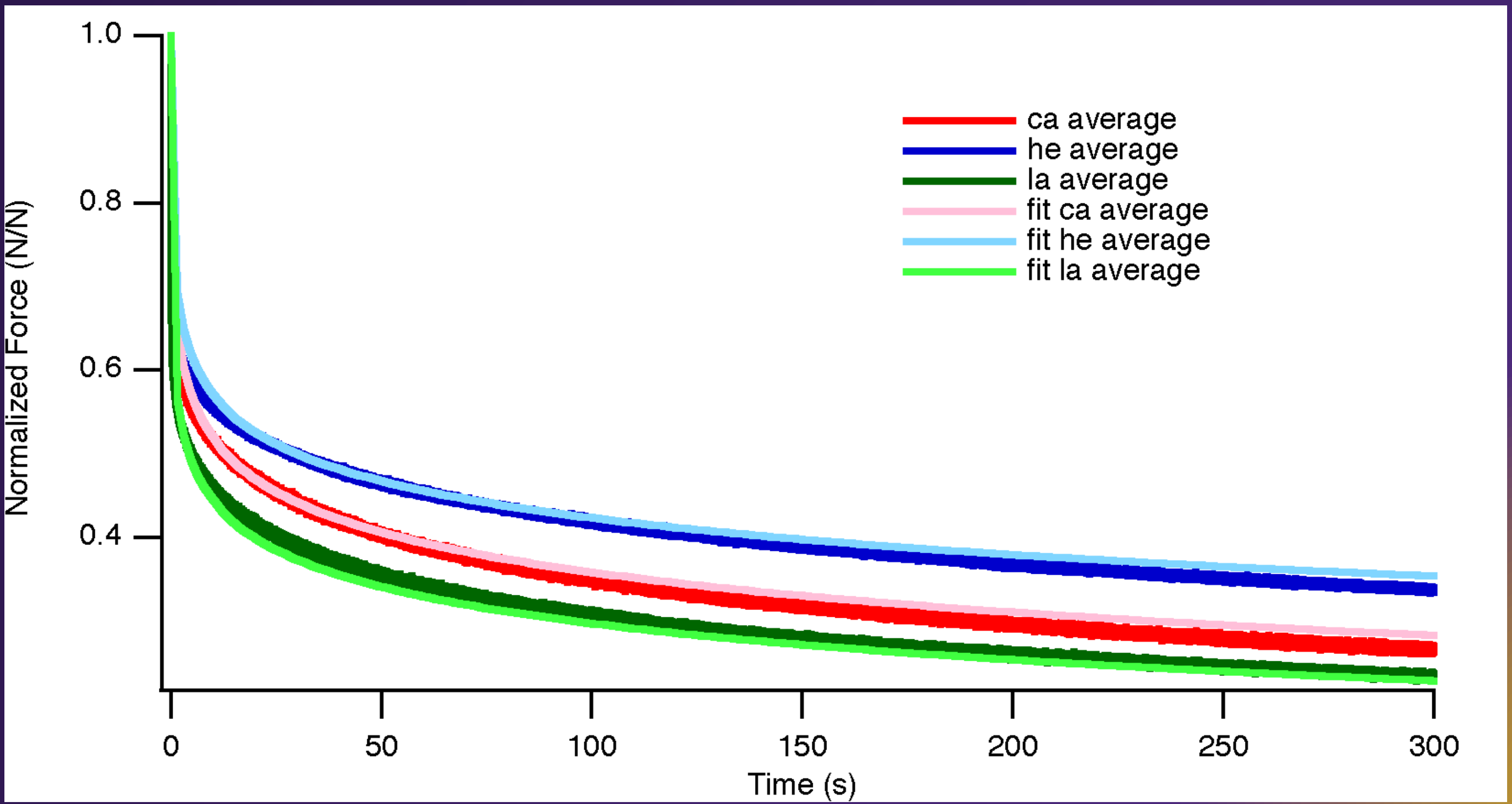
- stress relaxation
  - a) “instantaneous” strain
  - b) elastic response
  - c) viscoelastic response of a solid
  - d) viscoelastic response of a fluid



Ozkaya, et al. 2012

Viscoelasticity

- stress relaxation
  - isolated plantar fat from heel



Viscoelasticity

- stress relaxation
  - anterior cruciate ligament

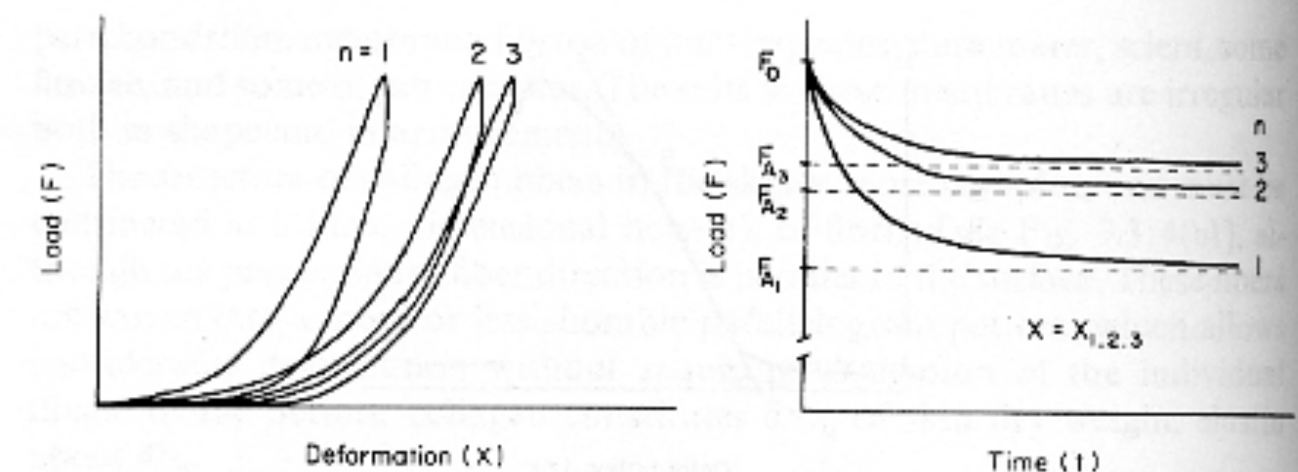


Figure 7.3:9 Preconditioning of an anterior cruciate ligament. The load-elongation and relaxation curves of the first three cycles are shown. From Viidik (1973), by permission.

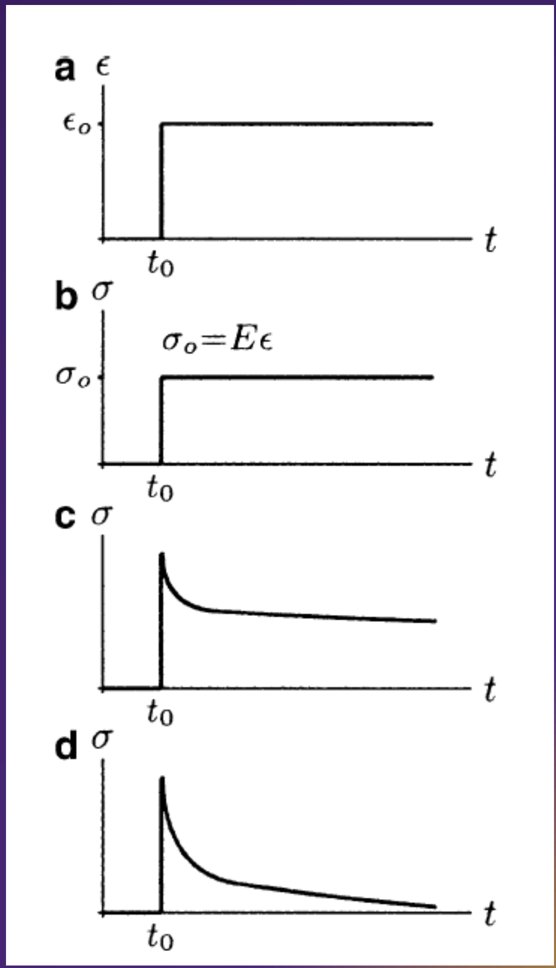
Fung, 1993

Viscoelasticity

- creep
  - loaded at a constant force and displacement changes
  - harder to conduct, but more physiologic
  - example?
    - height through out day

Viscoelasticity

- creep
  - a) step stress
  - b) elastic response
  - c) viscoelastic response of a solid
  - d) viscoelastic response of a fluid



Ozkaya, et al. 2012

Foot injuries in the news

- Headline: Foot fetish: A brief -- and scientific -- review of foot injuries on the eve of the NFL playoffs - The Boston Globe
- Date: Jan 7, 2016
- Several key players, including Tom Brady, have contended with feet and ankle injuries this NFL season.
- http://tinyurl.com/zq92vpm