Course Outline

– Basic biology of bone, Biomechanics of cortical and cancellous bone; Bone anisotropy; Bone as a composite; Bone viscoelasticity

– Bone remodeling process; Adaptive elasticity theory and some modifications; A semi-mechanistic bone remodeling theory and some modifications;....

– Mixture models of bone resorption and a quick review on mixture theory

– Biomechanics of fracture fixation and mechanobiology of bone healing process

– Biomechanics of articular cartilage

– Experimental techniques for bone mechanics & Imaging of bone structure & Orthopedic and dental biomechanics: Bone screws, plates and intramedullary nails
Evaluation

- Assignments 25%
- Mid-term: 2nd session after Nowrouz vacation 20%
- Research project report and presentation 25%
- Final exam 30%
- Bonus questions: Max. 5%

Bone biomechanics, Win/Spr 2019, G. Rouhi
Class presentation

- **1<sup>st</sup> talks**: Monday, 20<sup>th</sup> of Isfand- 5’ talk followed by 2’ question period (3%)

- **2<sup>nd</sup> talks**: last week of the semester- 12’ talk followed by 5’ question period (10%)
  - Grades will be assigned by the class
  - The instructor reserves the right to adjust the grades to achieve a fair distribution of grades
  - A max. of 7 pages report related to your research project and your talk, in a paper format (details will be provided later on)- 12%

- Due date for choosing a topic: Monday, 29<sup>th</sup> of Bahman (*delay penalty will be applied, -10% per day!*)
Potential subjects/titles

- Bone scaffolds
- Bone prostheses and implants
- Orthopaedic screws and bone interaction
- In-vitro measurement of implant stability
- Dental biomechanics: bone-implant interaction
- Bone remodeling theories: known and unknown facts
None
Suggested texts


• Basic Orthopedic Biomechanics and Mechanobiology, V. Mow and R. Huiskes.


Biomechanics

- The field of biomechanics applies principles of mechanics to study the structure and function of biological systems.

- Biomechanics aims to explain the mechanics of life and living. From molecules to organisms, everything must obey the laws of mechanics (Y.C. Fung, 1990).

- Biomechanics has the following salient features:
  - Material constitution
  - The constitutive equations
  - Growth and remodeling of living tissues under stress
  - The existence of residual stress
  - Hierarchy of sizes
Bone biomechanics

Bone microstructure

Osteons (haversian systems)
Inner layer
Periosteum
Compact bone
Cancellous (spongylous) bone
Volkman's canals
Medullary marrow cavity

Endosteum
Trabeculae
Haversian canals
Bone remodeling process

- Bone Remodeling (ARRFQ)

Activation
1-3 weeks

Resorption
1-2 weeks

Deposition

Formation
3-6 months

Reversal
1-2 weeks

Quiescent

Rouhi G, 2004
Historical background and Wolff’s law

Von Meyer (an anatomist, trabecular direction) & Culmann (an engineer, principal stress): Trajectorial theory (1867)
Problem definition

\[ \rho = \rho(t) \]

The bone density evolution law \( \rho = \rho(t) \)

Anisotropy evolution law \( K(t) \)
Historical background and Wolff’s law

- Wolff (1870): Bone structure could adapt in response to change in mechanical environment & maximum mechanical efficiency with the minimum mass

- Wolff’s law:
  “Every change in the form and function of a bone is followed by certain definite changes in their internal architecture, and equally definite secondary alterations in their external conformation, in accordance with mathematical laws.”

Ruimerman et al., J Biomech., 38(931-941), 2005
Mechanical stimuli to initiate remodeling

- Strain (Cowin and Hegedus, 1976)

- Stress (Wolff, 1982; Kummer, 1972)

- Strain energy (Fyhrie and Carter, 1986; Huiskes et al., 1987; Hart and Davy, 1989; Weinans et al., 1992)

- Strain rate (Hart and Davy, 1989; Siffert et al., 1996)

- Strain energy is a positive scalar quantity
The significance of bone remodeling

Imbalance: bone diseases (osteoporosis,…).
The significance of bone remodeling

Orthopedics: e.g., screw loosening,....
Cortical and cancellous bones

- At the macroscopic level:
  - Cortical (Haversian or compact) & Cancellous (spongy or trabecular)
Compact bone

- It’s a dense, solid mass with only microscopic channels; cover the outer walls of long bones
- The basic structural unit is Osteon or HS
- An Osteon: Haversian canal, osteocyte lacunae, osteocytic processes within canaliculi
- Max. density: 1.9 gr/cm$^3$; 80% of the skeletal mass; largely responsible for the supportive and protective function of the skeleton

Haversian system or Osteon
Spongy bone

- Basic structural unit: a trabecula; networks of plates and rods
Spongy bone

- An inhomogeneous porous anisotropic structure
- The symmetry depends upon the direction of applied loads
- If the stress pattern in SB complex, then the structure of the network is also complex and highly asymmetric
- In bones where the loading is largely uniaxial, such as the vertebrae, the trabeculae often develop a columnar structure with cylindrical symmetry
- The average thickness of a trabecula is 100-150 μm
- The trabeculae are surrounded by marrow that is vascular and provides nutrients and waste disposal from the bone cells
Spongy bone

- Approximately 20% of the skeletal mass in the adult human skeleton
- SP as a cellular material: a network of rods produces open cells while one of plates gives closed cells
- At low apparent densities the cells form an open network of rods
- As the relative density increases, structure transforms into a more closed network of plates
- Open cell, rod like structures develop in regions of low stress
- The plate-like is typically found in vertebrae
- There are no blood vessels within the trabeculae, but there are vessels immediately adjacent to the tissue
Bone surfaces

- Cartilage: Interstitial and appositional growth

- Bone: Only appositional growth (because of the nonexpandable nature of mineralized bone tissue)

- All bone activities occur at the bone surfaces

- Free surfaces: Endosteum, periosteum, trabeculae, and Haversian canals

- Cancellous bone surface contributes more than 61% of the total bone surface

- The mean trabecular surface to volume ratio is 8 times greater than in CB

- Bone surfaces: resorption (OCs), formation (OBs), or quiscent (BLc)
Bone cells

- Osteoclasts, osteoblasts, osteocytes, and bone lining cells
Osteoclasts

- Osteoclasts: Bone resorbing cells; form a ruffled border when resorbing bone; proton pumps
Osteoblasts

- Osteoblasts: bone forming cells

Two stages: first, matrix formation, then mineralization

The OB becomes a flat bone lining cell, or an osteocyte, or undergo apoptosis
Osteocytes

Mechanosenors, most abundant cell type in mature bone; lie within 150µm of a blood vessel; cellular density of 25000 OCs within 1 mm²

Mechanosenors, react quickly to mechanical stimuli *in vivo*; Extremely sensitive to fluid shear stresses *in vitro*

Most of the OCs lie within 150µm of a blood vessel
How do bone cells sense mechanical stimuli?

- Hypothesis: Osteocytes act as sensors

- Different mechanisms:
  1. Direct stimulation (strain,...),
  2. Fatigue damage,
  3. Fluid flow
Bone lining cells

- When OBs are not active, they are flattened, elongated cells covering quiescent surfaces of bone.

- Surface density of BLCs: 19 cells/mm bone surface perimeter, decreases with age.

- 3D networks of BLCs and OCs sense the shapes of bone and its reaction to MS, and transmit these sensations as signals to the bone surface; modeling and remodeling.
Anisotropy in bone

- Orthotropy: Cancellous bone, transversely isotropic: cortical bone
Anisotropy in bone

- Orthotropy: cancellous bone, transversely isotropic: cortical bone