Biomechanics

Biomechanics

Mechanics – science about forces and movement

Biomechanics – study of forces and movement in living organism

Living tissue has different mechanical properties than solid state matter or liquids. They are more similar to polymerized macromolecular substances called elastomers.

Static properties

- **Strength** of material - structural consistency of the material against external forces
- **Elasticity** - the ability of the body to return after deformation to its original shape

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Static properties

- **Extensibility** - pliability to the action of a substance deformation force
- **Plasticity** - ability of a substance to change shape permanently due to the deforming forces

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Dynamic properties

- **Viscosity** - resistance to shape change of the substance;

These properties can be observed in the living tissue in varying degrees

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1. Elastic substances

- under the limit of elasticity, the deformation has linear progress
- It corresponds to Hooke‘s law

$$\varepsilon = \frac{1}{E}\sigma$$

ε = deformation
E = modulus of elasticity
σ = tensile stress (Pa)

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2. Plastic substances

- exhibit deformation only at a particular value of the stress
- after removal of this stress they retain maximum deformation obtained during the force effect

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3. Viscous substances

- Fluids which can be divided according to dependence of deformation speed on deforming force:
- Newtonian fluids
    - Speed of deformation changes linearly with changing value of tension
- Non-Newtonian fluids
    - Non-linear dependency

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4. Viscoelastic substances
   - Deformation is a function of tension AND time
   - With quickly acting tension of constant value, the deformation grows exponentially; after termination of tension, it also declines exponentially
   - However it cannot reach the former state fully; for the whole cancellation of deformation a tension of opposite direction is needed
   - Some fluids have similar behavior = Maxwell‘s fluids (blood)

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5. Viscoelastic-plastic substances

- Elastic deformation happens only above a certain value of tension (treshold tension)
- Speed of deformation is a function of coefficient of plasticity U; substance has always a degree of hysteresis

$$\sigma = \sigma_0 + U.\frac{\Delta\varepsilon}{\Delta t}$$

- Soft tissues; gels

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Biostatics – studies forces affecting an organism and also forces by which an organism affects its surroundings.

Basic supporting mechanism in humans and all vertebrates is connective tissue

- Composition: cells and extracellular matrix (fibrous and amorphous)
  Ligaments, cartilage, bone

Ligaments

Ligaments

Fibroblasts, collagen fibers, elastic fibers, amorphous mass

Collagen fibers

- Most voluminous component in connective tissue
- Tensile strength, very flexible
- The limited elasticity (elongation max. 10% of its length)
- Load of 50 N per 1 mm^2
- Aging over time = reduction in tensile strength and elasticity

Ligaments

Elastic fibers

- Less numerous; often mixed with collagen fibers
- High elasticity - an extension of up to 200% of its original length
- low tensile strength; maximum load of 3 N per 1 mm^2
- Their function is to increase the elasticity of the tissue

Ligaments

The amorphous intercellular substance

- Gel solution (proteoglycans - hyaluronic acid)
- Stabilizing structures of ligaments
- Aqueous environment – tissue nutrition
- Lubricating ability of HA

Ligaments

Thin collagen tissue

- The supporting structure for the blood vessels and nerves; allow smooth glide of organs

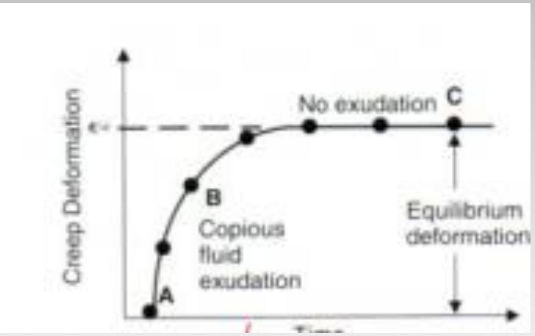
- Rigid collagen tissue
  - Tissue with **disordered** structure - collagen and elastic fibers; Overall, high mechanical strength; connective tissue layer of the skin
  - Tissue with **ordered** structure - tendons (max. 5% of elastic fibers) - transmission of muscle strength on the skeleton, ligaments - fixing the musculoskeletal system

Cartilage

Chondrocytes, collagen fibers, elastic fibers

Intercellular substance

- Similar composition as in ligament
- Isolation of chondrocytes
- Environment facilitating nutrition



The tensile strength of the cartilage is max. 5% of the strength of bone

The elasticity of variable water contents

Cartilage

Hyaline cartilage

- In comparison with other types is fragile; hard, smooth
- Collagen fibers form a three-dimensional network structure of the network the burden of cartilage
- joints

Cartilage

Elastic cartilage

- supple and flexible (elastin)
- After the deformation returns to the original state
- Ear

Fibrous cartilage

- The strong collagen fibers
- Mechanical resistance to tension, compression and torsion
- Intervertebral plate

Bones

Heterogeneous, viscoelastic material, osteoblasts

Extracellular matrix - collagen fibers; amorphous material (mineralized; up to 65% of bone mass)

Lamellar bone

- Compact bone - arrangement of collagen and degree of mineralization determines the tensile, compressive and bending strength

Bones

- **Cancellous bone** - trabecular structure of beams (architectonics of the bones); this structure is the result of the force action on the bone
in injury (fractures) the structure is rebuilded to suit the new force load

Bones

Bone strength - compact bone

- Strength of long bones is 100-200 MPa
- The highest load a bone can withstand is in the direction of its axis
- The lowest strength is in torsion deformation

Bones

Bone strength - compact bone

- Mineralization is not uniform; in places where the energy is absorbed mineralization is lower
- The dynamic load is dependent on the speed of movement

Bone strength - cancellous bone

- Beams form domes at the site of most ongoing field lines of pressure and tension
  Partial load absorption by "fillers"

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Wolf's law of bone transformation – bone structure accommodates to permanent change of affecting forces, when any change occurs (injury), bone remodeling achieves healthy state again

- If gravity in axis of long bones is missing, higher amount of calcium is excluded from an organism (astronauts)

Bone connection

Fixed vs. Mobile

Fixed

- Ligamentous - syndesmosis; enabling a seamless bones connection
- Cartilaginous - synchrondrosis
- Bony - synostosis; formed of the previous two; immobile

Bone connection

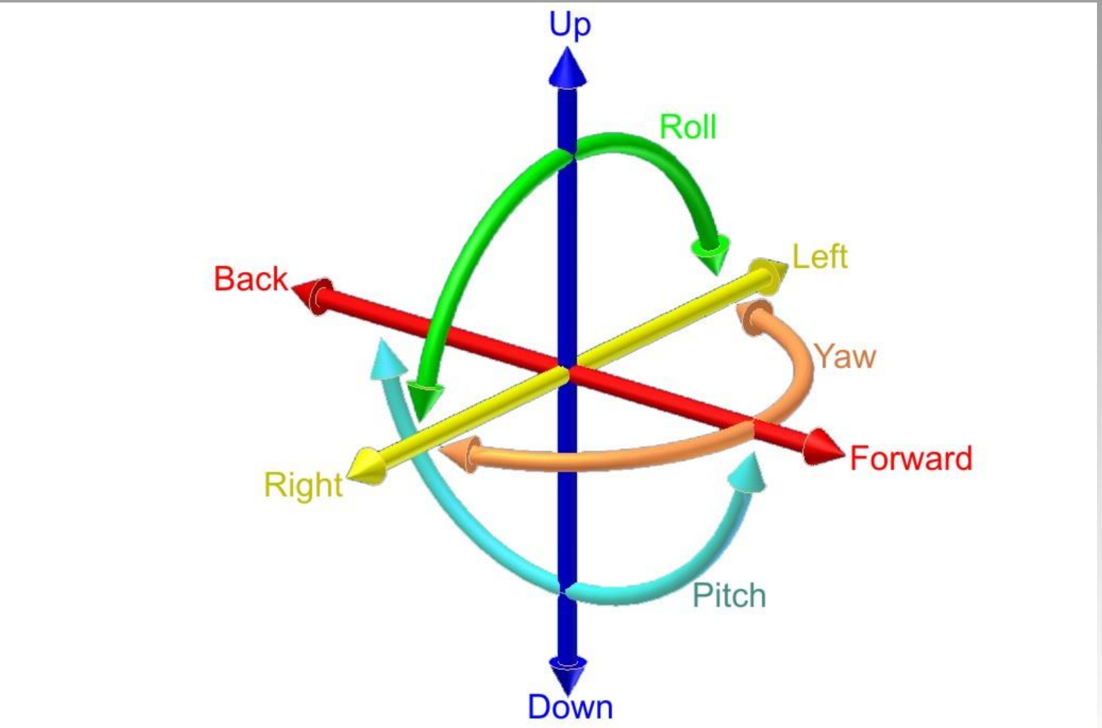
Mobile

Joints - movable bone conections connecting two or more bones

The range of motion depends on the shape of contact surfaces, the ratio of head and socket, muscle apparatus etc.

- Angular movement - points on the moving body describe circular arcs centered on the axis of rotation
- Translational movement - all points of the moving body travels the path of the same length

Bone connection



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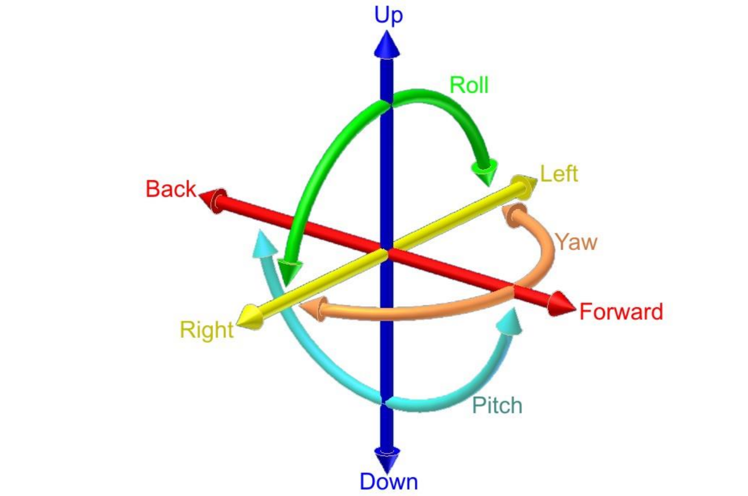
Joints

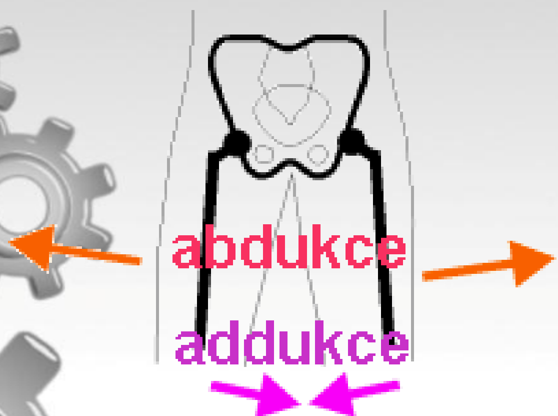
- Different types
- the degree of freedom of movement depends on the shape of interface; maximum is three (shoulder or hip joint)
- There is no „full rotation“ movement
- circumduction

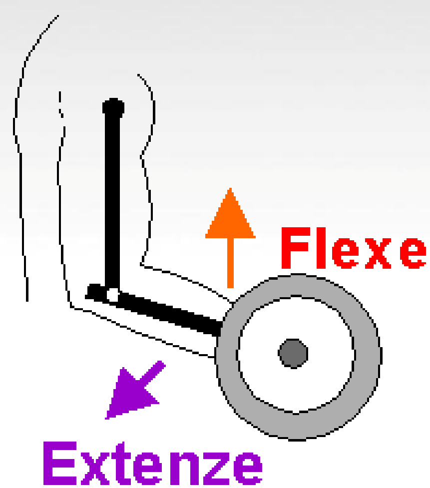


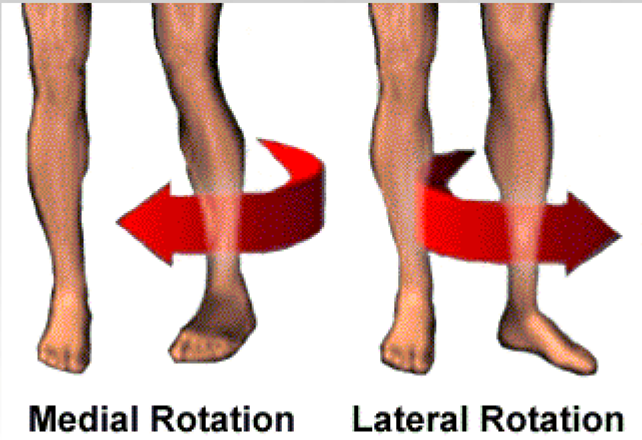
Bone connection

Movement

- X axis: abduction and adduction
- Y axis : flexion and extension
- Z axis : internal and external rotation







Bone connection

Joints

- Several joints together = kinematic chain (greater freedom of movement)
- Joint cartilage
  - Elastic deformation
  - Constant pressure up to 8 kg on 1 cm^2
- Synovial fluid
  - Nutrition
  - Flexibility of cartilage
  - reduces friction

Muscles

Muscles

- Motoric organ
- Changes chemical energy of chemical bonds to mechanical work (performed by contraction)
- Muscle contraction principle is insertion of actin fibers into myosin fibers; energy comes from ATP

Muscles

Muscles

- agonists; antagonists; synergists
  - Balancing these groups is important to stabilize the position - e.g. torso muscles and the lower limbs muscles = stabilization of upright position (antigravity muscular system)

- Function
  - Fixation and kinetic
  - Main function x secondary

Muscles

Muscles

- One-joint
  - Movement in one joint

- Multiple-joint
  - Main joint - movement; in connection with other joints - stabilization

Muscles

Muscles

- Two subtypes of muscle contraction
  - Izotonic (constant load)
  - Izometric (constant length)

- Work is performed and heat is released
  - Activation heat (released when muscle starting moving) Q_a
  - Shortening heat (muscle is shortened) Q_z
    - $Qz = k.x$ (x=length; k=constant $3{,}5.10^4$ $J.m^{-3}$

  - Total energy of izotonic contraction $E = Q_a + Q_z + W$

Muscles

Muscles

- After completion of the muscle contractions muscle returns to its original length
- Upon reaching the breaking strength a muscle is torn
- Physiological breaking strength of muscles of 0.4 to 1.2 MPa

Mechanical work of heart

Heart

- Pump
  - Atriums = reservoirs
  - Ventricles = pumps
  - One-way blood flow = heart valves

- By constriction of the ventricles (systole), expulsion of a certain volume of blood (stroke volume) into the bloodstream occurs

Mechanical work of heart

The heart as a pump performs a mechanical work

- If we think of the heart as a piston which performs volume work, a **static work** of the heart (piston), by which the heart pushes blood volume under pressure, can be described:

$$W_p = p.\Delta V$$

Mechanical work of heart

The heart as a pump performs the mechanical work

- When stroke volume is expelled, it is also given a velocity, and **kinetic work** is therefore performed:

$$W_k = \frac{1}{2}\rho.v^2.\Delta V$$

Mechanical work of heart

The heart as a pump performs the mechanical work

- **The total mechanical work is the sum of static and kinetic works**

$$W = W_p + W_k = p.\Delta V + \frac{1}{2}\rho.v^2.\Delta V$$

Mechanical work of heart

$$W = W_p + W_k = p.\Delta V + \frac{1}{2}\rho.v^2.\Delta V$$

- To determine the mechanical work it is necessary to know the blood pressure in systole, stroke volume and velocity of blood ejection

Ideal physiological conditions ($p=13.3$ kPa, $V = 70$ ml, $v = 0.3\ m.s^{-1}$, $\rho = 1.06x10^3 kg.m^{-3}$) static and kinetic work of **left ventricule** is equaled to:

$W_p = 0.93$ J $W_k = 0.003$ J $W = 0.94$J

Mechanical work of heart

- Right ventricle does only 20 % of left ventricule work = 0,19 J
- Total mechanical work in one systole = 1,13 J
- The total energy of the heart muscle is equal to the sum of mechanical work and energy necessary to maintain muscle tone

Mechanical work of heart

- Efficiency
  - myocardium 30 %
  - Whole heart 10%
- Power
  - 13 W (just 1,3 W is mechanical work alone)