Development of Complex Curricula for Molecular Bionics and Infobionics Programs within a consortial* framework**

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**Molekuláris bionika és Infobionika Szakok tananyagának komplex fejlesztése konzorciumi keretben

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Neuromorph Movement Control

Neuromorf mozgás szabályozás

Material and special physical muscle properties

(Az izom anyagi és speciális fizikai jellemzői)

József LACZKÓ PhD; Róbert TIBOLD

Main points of the lecture

- **Main functions and task of skeletal muscles**
- **Motor units and muscle fibers innervated**
  - **Types of muscle fibers**
- **Classification of muscle contractions**
  - **Concentric,eccentric,isometric,isotonic,isokinetic**
- **Material considerations of muscles**
  - **Physical laws applied to understand material features of muscles**
    - **Elasticity,viscosity,viscoelasticity,stiffness**
    - **Newton's 2nd motion law; Moment of inertia**
- **Force production capability**
  - **Types of muscle geometry (parallel; pennate fibers)**
- **Muscle models (Hill's model; Sliding filament model,Cross-bridge theory)**

Main task of the muscle

- **Basically there are two very important tasks of muscles playing important role in movement generation**

  1. **Exerting and generating muscle force**

     - Muscles convert chemical energy into mechanical work
     - The series of impulses generated by the nervous system evoke action potential(AP)
     - As a result of these APs (low voltage current) the muscle contracts (it shortens)
     - During muscle contraction muscle force is generated

- **Force generation capacity of muscles is determined by:**

  - Muscle geometry (fiber type, pennation angle)
  - Material features of the muscle
    (elasticity, viscosity, stiffness, compliance)
    these properties may depend on temperature.
  - The ability to respond to stimulus
  - Conductivity – the ability to propagate stimuli
  - Contractility – the ability to alter muscle length
  - Resistance against stretch
  - Adaptability – the ability to regenerate

Main task of the muscle

- **Basically there are two important tasks of muscles playing role in movement generation**

2. **To react or resist to perturbations of the external world**
    - Resulted by reflex processes
    - Caused by external forces (e.g. gravity)

Skeletal muscles may rotate body segments around each other and produce compensatory movements to stabilize posture (e.g. vestibulo-collic reflex, phasic stretch reflex)

Maintenance of a vertical posture is an important task in human motor control.

Motor units and innervated muscle fibers

- Motor unit (MU): a single α-motor neuron with its dendrites and the branches of its axon and all of the muscle fibers innervated by the motor neuron.
- All muscle fibers in a motor unit are the same fiber type:

  fast twitch or **slow twitch**
  - **If a MU is activated by the central nervous system (CNS), all of the innervated fibers generate contraction.**
  - Groups of MUs may be activated together to coordinate the contractions of a single muscle;

- MUs serving the same single muscle are called: **motor unit pool**

- **The number of muscle fibers contained by a MU is varying.**

  Innervation ratio of a muscle: the average number of muscle fibers innervated by a motor neuron

  - **Depends on the function the questionable muscle is to execute.**

    e.g. biceps brachii is connected to about 800 motor neurons and contains about 560.000 muscle fibers,

    thus its innervation ratio ≈ 700

  - The smaller the MU, the more precise the action of the muscle

Motor units and innervated muscle fibers (fast twitch or slow twitch)

- There are two different methods to categorize muscle fibers:
  - the type of myosin present
  - the degree of oxidative phosphorylation (ATP production)

Humans have slow (Type I) and fast (Type II)

- **Fast twitch:** (have large axons that are less excitable)

  Contraction time is about 30-80ms
  - develop high forces
  - at high contraction velocity (fatigue quickly)
  - „Red” due to the presence of the oxygen binding proteins (myoglobin)

- **Slow twitch:** (have small excitable axons) and few muscle fibers
  - develop low force
  - at slow contraction velocity (they are very resistant to fatigue)
  - „White" due to the absence of myoglobin
  - Contraction time is about 80-120 ms

Contraction time is the time to reach maximal foorce as a response to an electrical impulse

Difference in contraction time and contraction velocity depends on biochemical processes

However peak tetanic force is not related to contraction time.

An extended table of the two fibre types (fast - Type II;slow - Type I) and features

Feature	Type I	Type II a	Type II b	Type II x
Size of motor neuron	Small	Medium	Very large	Large
Contraction time	Slow	Fast	Very fast	Fast
Fatigue resistance	High	High	Low	Medium
Type of activity	Aerobic	Long term anaerobic	Short term anaerobic	Short term anaerobic
Duration of use	hours	Less than 30 mins	Less than 1 min	Less than 5 mins
Force production	Low	Medium	Very high	High
Oxidative capacity	High	High	Low	Medium

Some important features representing the applicability of the major muscle fibre types

Voluntary muscle contractions (classification)

1. Classification as a function of duration of the stimulation

- Skeletal muscle contractions are basically separated into 2 types of contractions

twitch and tetanic contractions

- **Twitch:** a short stimulation burst makes the muscle contract
  - **the duration is short** in time thus the muscle begins it's relaxing period before reaching peak force

- **Tetanic: if the stimulation is long enough (there are a high number of twitches in a short time)** the muscle may **reach the peak force** and **stays at maximum level**

2. Classification as a function of:

- **Muscle length changes**
- **Changes in force**

- **concentric contraction:** the muscle shortens during contraction (the exerted force is enough to beat the resistance originating from material features or external load)
  - Muscle is capable of contracting based on the sliding filament theory.
  - Force is generated along tendons to decrease the inter-segmental angles in the joint.
    (e.g. biceps decreases elbow angle)

- **eccentric contraction** (lengthening contraction):

the force generated is not enough to beat the external load or material features of the muscle

  - Muscle lengthens as it contracts. (elongate while being under tension due to an opposing force)
  - In eccentric contraction of the biceps: the elbow starts the movement while bent and then straightens as the hand moves away from the shoulder

Control of eccentric contraction is different from control of concetric contraction. The feedback from the spinal cord is different and the information received from muscle fiber lengthening play an important role in eccentric contraction.

Classification as a function of muscle length changes or changes of force levels

- **isometric contraction:** the muscle remains at the same length.
  - Holding an object without moving it (the exerted force precisely matches the load without moving it)

- **isotonic contraction:**

  The tension in the muscle remains constant despite the change of muscle length.
  - It occurs if the maximal force of a muscle during contraction exceeds the total load acting on the muscle.

Classification as a function of muscle length changes or changes of force levels

- **isokinetic contraction:** the muscle contraction velocity remains constant, while force is allowed to vary.
  - Really rare in the human body (occurs artificially under experimental conditions)

Important definitions determining material features of muscles

- **Elasticity:** the physical property of a material that returns to its original shape after the external force that made it deform is removed
- (strain instantaneously when stretched and just as quickly return to their original state after stress is ended)

Important definitions determining material features of muscles

- **Stiffness:** (material property) the resistance of an elastic material to deformation by a force.
- **Viscosity:** describes a fluid's internal resistance to flow and may be regarded as the measure of fluid friction (resist shear flow and strain linearly with time)
  - water is "thin” with lower viscosity,
  - honey is "thick" with higher viscosity
- **Viscoelasticity:** the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation

Physical laws (Newton's 2nd law)

- **Newton's 2nd law of motion (**how the velocity of an object changes when it is subjected to an external force**):** the net force on a particle is equal to the time rate of change of its linear momentum **p** in an inertial reference frame:

$$F = \frac{dp}{dt} = \frac{d(mv)}{dt} \xrightarrow{\text{Valid only for constant mass}} F = m\frac{dv}{dt} = ma$$

Where: F is the force, **m** is the mass of the body, and **a** is acceleration of the body and **v** is the velocity

- **Velocity:** moving through a displacement (ds) during a time interval (dt) v=ds/dt which is the 1st time derivative of the displacement.
- **Acceleration:** the rate of change of the velocity a=dv/dt which is the 2nd time derivative of the displacement.

Physical laws (Moment of inertia of multisegment limb)

- **Moment of inertia (MoI) of a multisegment** limb: is calculated by using the parallel axis theorem.

  (θ_{cm} is the MoI about the center of mass; M is the mass of the segment; d is the distance between the axis through the center of mass and the parallel axis through the rotation center)

- parallel axis theorem: $$\Theta_{parallel} = \Theta_{cm} + Md^2$$

- Arm segments can be regarded as uniform cylinders with different thickness.

Moment of Inertia about the center of mass of a rotated segment:

$$\underset{center}{\overset{(segment)}{\Theta}} = \frac{1}{4}Mr^2 + \frac{1}{12}ML^2$$

MoI around the end of a rotated segment:

$$\underset{end}{\overset{(segment)}{\Theta}} = \frac{1}{4}Mr^2 + \frac{1}{3}ML^2$$

Adaptation of muscle force to the environment and to CNS commands based on material features of muscles

- **Stiffness (k)** as a function muscle length changes

  $$k=\Delta F/\Delta l$$

  The force required to a unit change of muscle length

- **Compliance** as a function of muscle length changes

  $$c=\Delta l/\Delta F$$

Where F(t) is the force applied on the muscle (muscle fiber) and Δl is the displacement produced by F(t) (change of the muscle length).

Muscle force based on material features of muscles

- **Inertia (m):** is the measure of resistance against change of muscle contraction velocity
- **Viscosity of a muscle (b):** The ability of a muscle to generate force against muscle length velocity vector.
- $$F(t)= m^* \, l(t)'' + b \, ^*l(t)' + k^*[l(t)-l_o(t)]$$

2nd law of motion

Inertia — Viscosity — Stiffness

Force production capability (pennation angle)

- **From the structural point of view:** skeletal muscles are composed of high amount of muscle fibers.

- Muscles **are discerned** based on the **arrangements of muscle fibers**.
- **2 major classes** are distinguished: (**Figures on the next slides)**
  1. Muscles with muscle fibers arranged in parallel to the action line of the muscle (pennation angle 0)
  2. Muscles with muscle fibers having pennated arrangement

     (pennation is angle is not zero). In this case the fiber force that acts in the direction of the muscle's action line, depends on the cosine of the angle of pennation

Force production capability (pennation angle)

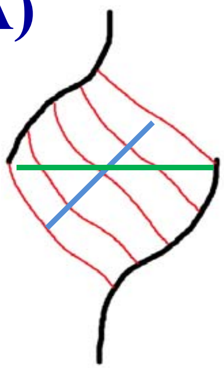
- **Muscles with pennated arrangement:** A **pennated** muscle is a muscle with fibres that are attached to the tendons in a slanting way.
  - These types of muscles are capable of producing **higher peak force** than parallel ones

    but
  - With **less range of motion**.

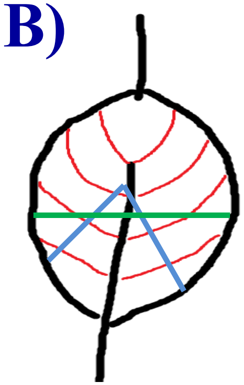
Most muscles have nonzero angle of pennation. More fibers can be arranged in the same volume in this manner.

Force production capability (pennation angle) – Schematic figures

A)



B)



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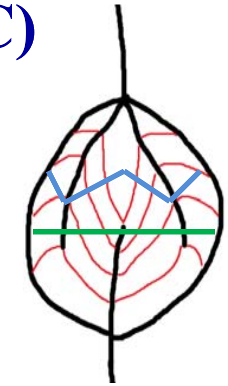


- **A) unipennate:** all muscle fibres are on the same side of the tendon (hand muscles)
- **B) bipennate:** muscle fibres are on both sides of the central tendon (rectus femoris in the lower limb)
- **C) multipennate:** the central tendon branches within a muscle (deltoid anterior-posterior in the shoulder)

- **Green lines:** anatomical cross section area

Physiological cross sectional area (PCSA) and muscle force production

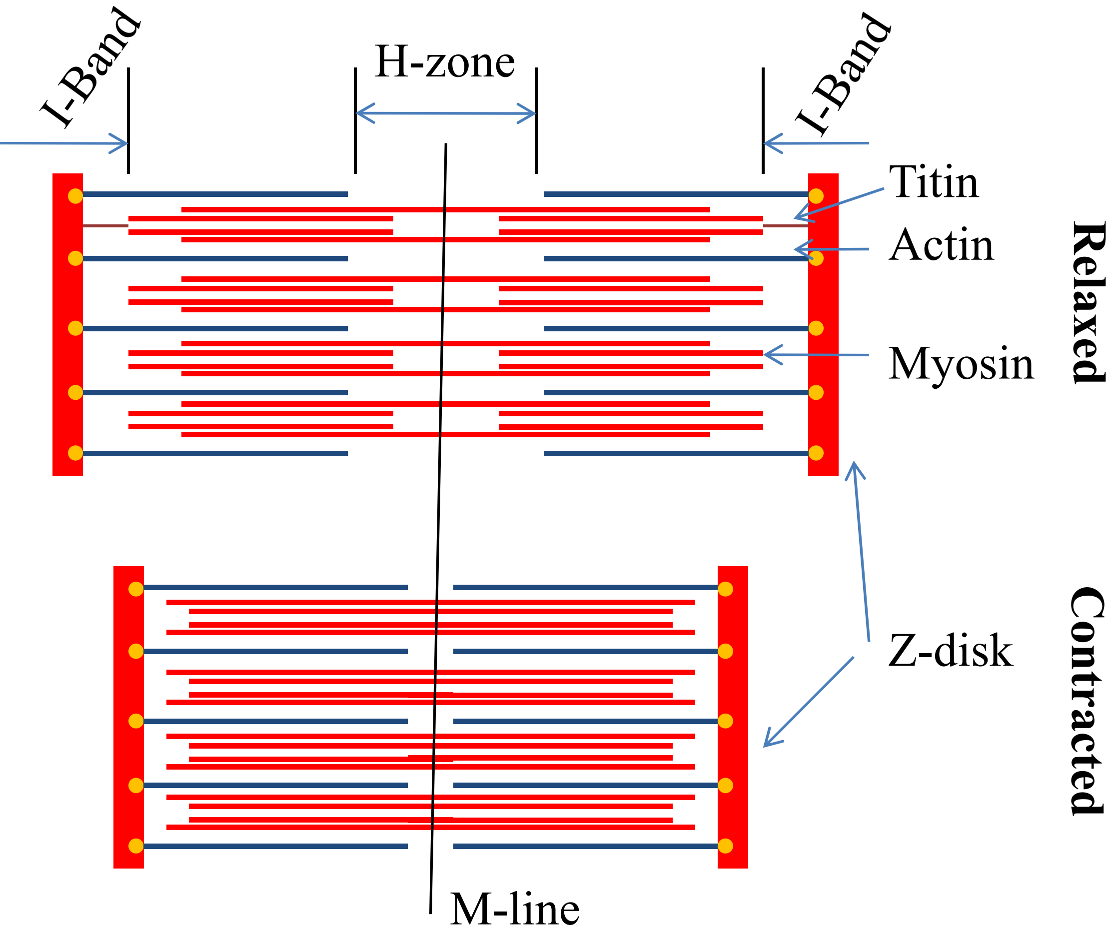
- **PCSA: is the total area (that can be found in pennated muscles) where the cross sections are perpendicular to the muscle fibres. (**blue lines in the previous slide**)**
- **The importance of pennation angle in muscles:** more muscle fibers are placed in parallel. (muscle is capable of exerting more force)
  - **However:** the maximum force in along the direction of the pennation is less than the maximum force in the fiber direction.
- **Thus: the muscle force (F_M) a muscle can exert is computable if the total force and the pennation angle (α) of the muscle is known:**

$$F_T = PCSA * Tension$$

where Tension is the force exerted by the fibers per unit of PCSA

$$F_M = F_T * \cos(\alpha)$$

Muscle models (Sliding filament theory)



Actin: is a molecular motor acting as a ratchet

Myosin: member of the motor protein family in eukaryotic tissues.

Z-disk: sarcomeric bordering component

Muscle models (Sliding filament theory)

1) Myosin heads are attached to the actin (thin) filaments at the myosin (thick) binding sites.

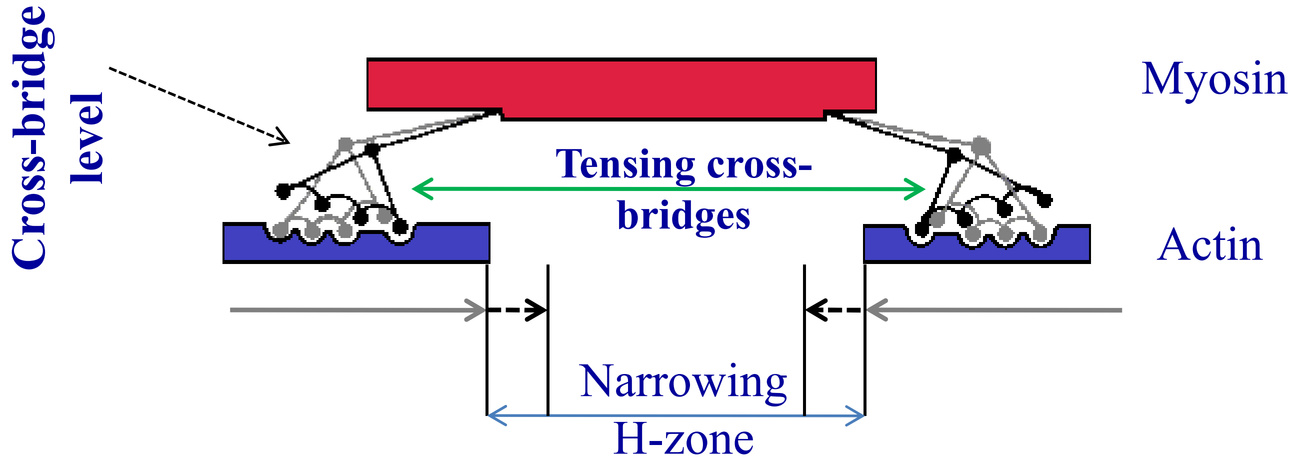
2) Myosin rotates at the myosin-actin binding extending an extensible region in the neck of the myosin head.

3) If the extensible region pulls the filaments across each other: shortening is resulted. (Myosin remains attached to the actin)

4) The binding of ATP „helps” myosin to detach from actin filaments. During detachment recharging of the myosin head occurs. Then myosin can bind actin again if the binding site is available.

5) The collective bending of numerous myosin heads (all in the same direction), combine to move the actin filament relative to the myosin filament. This results in muscle contraction.

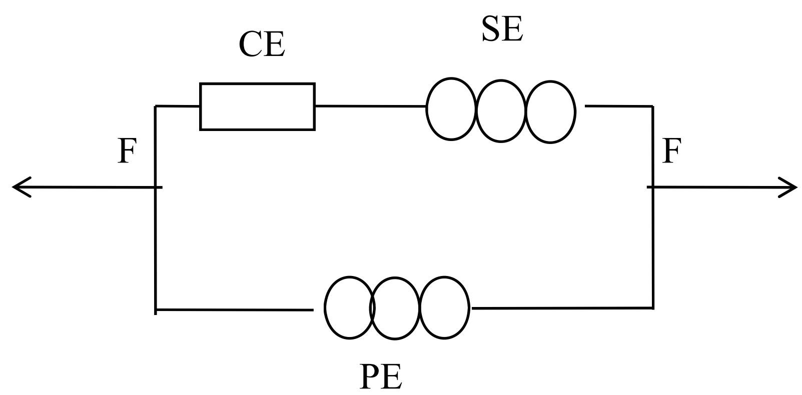
Muscle models (Cross-bridge theory – Huxley model)



Cross-bridge theory (determines how the force is developed chemically): the binding of the myosin head to the actin filament occurs because the hydrolysis of ATP results a rotation of the head around the tail, pulling the arm of the attached cross-bridge.

Result: a pull of actin and myosin filaments across eachother (tensioning,shortening of sarcomere)

Muscle models (Hill's muscle model) – The 3 element muscle model



CE – contractile element **SE – series element** **PE – parallel element**

- The model contains **a contractile element** and **2 non-linear spring element**.
- **It models:** the force generated by the actin and myosin cross-bridge cycles at the sarcomere level. (**CE which is basically the activity of the connective tissue itself**)
- **PE:** passive force-length characteristics; it is responsible for the muscle passive behavior when streched by an external force
- **SE:** represents the tendon and the intrinsic elasticity of the fibres

Muscle models (Hill's muscle model) – The 3 element muscle model

$$F = F_{PE} + F_{SE} \quad \text{and} \quad F_{CE} = -F_{SE}$$

- The net force-length characteristics of a modeled muscle is the sum of both active and passive force-length characteristics.

- Furthermore according to the model:

$$L = L_{PE} \qquad L = L_{CE} + L_{SE}$$

- **Thus: In isometric contractions** (no changes in muscle length) SE generates tension. (stretched a finite amount)
  - Because: muscle length is constant, the stretching of SE occurs if and only if there is an equal shortening of the CE.

Muscle models (Hill's muscle model) – Equation of a tetanized muscle

$$(v+b)*(P+a)=b*(P_0+a)$$

v – contraction velocity

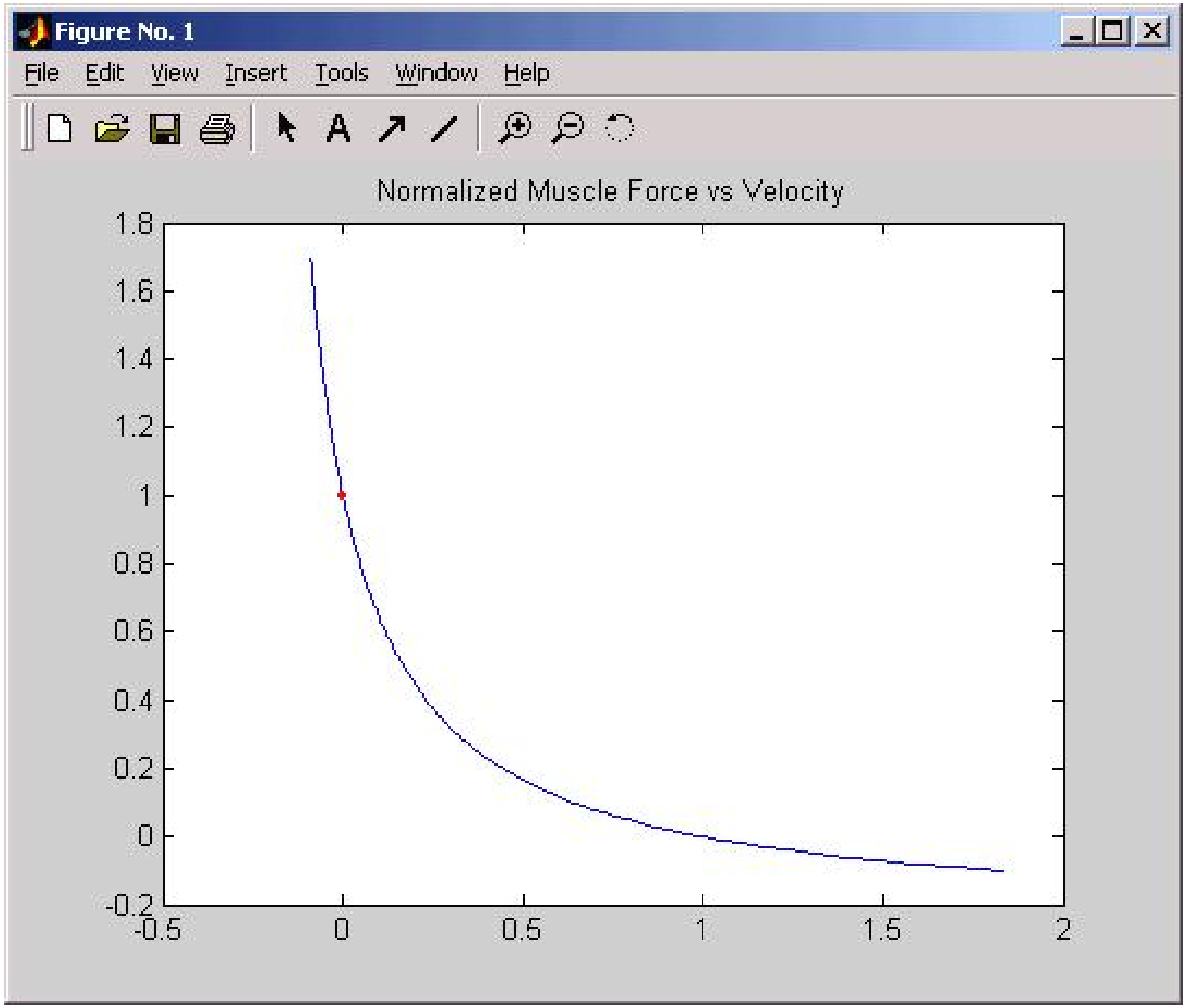
p – tension in the muscle

a – coefficient of shortening heat

P_0 **– maximum isometric tension in the muscle**

$b=a*v_0/P_0$

Force – Velocity relation



Hill’s muscle model

- This state equation can be applied if the skeletal muscle produces **tetanic contraction** (the duration of the stimulation generated by the CNS was long enough so that the muscle could reach maximum force level and stays there)
- The equation proves that the relation between contraction velocity (v) and muscle tension (P) is hyperbolic (**the higher the external force applied on the muscle the lower the contraction velocity**)
- On the curve of the force – length relation (previous slide)
  the red dot refers to isometric contraction.

Summary

- **In the modeling of human movements basically 2 major levels must be taken into account**
  - Mechanical level
  - **Muscle level (material considerations)**
- **In this lecture:** Muscle level was investigated starting from motor units and fibers innervated to the muscle models applied in modeling tasks.
- It is presented that the **force production capability** of muscles **depends on** some important parameters such as:

Summary

- **Types of muscle fibers innervated by motor neurons:**
  - Type I – slow – but high force production and duration
  - Type II – fast – but low force production and duration
- **Muscle geometry:**

  especially in the case of pennated muscles; furthermore the dependency of force production from PCSA was also presented

- **Muscle models:** close relation between biology and modeling issues

Suggested literature

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