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

***A projekt az Európai Unió támogatásával, az Európai Szociális Alap társfinanszírozásával valósul meg.

Neuromorph Movement Control

(Neuromorf mozgás vezérlés)

Neuro and biomechanical characteristics and properties of muscles

(Az izmok neuro-mechanikai tulajdonságai és karakterisztikái**)**

József LACZKÓ PhD; Róbert TIBOLD

Main points of the lecture

- Parameters determining a biomechanical neuro-mechanical model
    - Geometrical considerations
- Biomechanical Charactersitics
    - $F_s(f)$ – Force-stimulation frequency relation
    - $F_c(v)$ – Force-contraction velocity relation
    - $F_a(L)$ – Force-length relation
    - $F_p(L)$ – Passive Force-length relation
- Main parameters and functions to define biomechanical parameters
- Case studies to present biomechanical features of:
    - Lower limb
    - Upper limb

General geometrical, biomechanical and external characteristics of limb movements:

- Muscle attachment sites
- Muscle length-force relationship
- Contraction velocity- force relationship
- Stimulation frequency - force relationship
- Inertial limb properties
- External Load,
- Gravity

A 3D kinematical model can be capable of

- Determining:
  - muscle attachment sites
  - muscle lengths
- Visualize motion

Methods:

- without invasive or imaging techniques
- based on quantitative experimental studies

  (for lower extremity Brand and Hoy)

  (for upper extremity

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– adjust the parameters measured on cadavers to our living subjects.

Such parameters are body weight, segment lengths.

– perform coordinate transformation

(muscle attachment coordinates are given in local reference frame respect to bony landmarks. These coordinates must be transformed into general external coordinates)

– Apply medical imaging techniques

(e.g. ultrasound images of tendons,

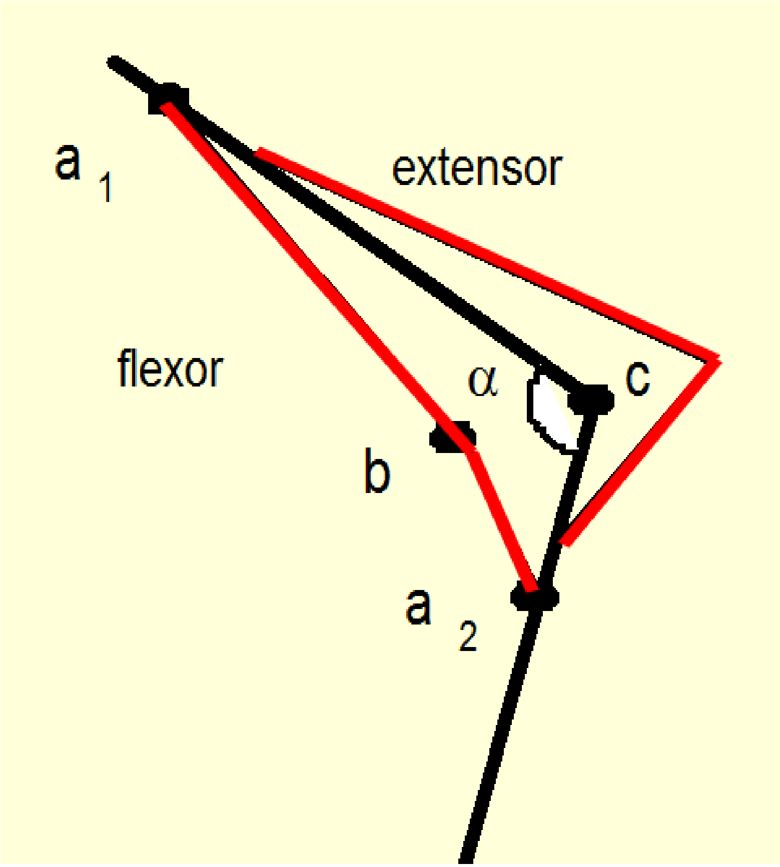
MRI images of muscles)

– EMG is used to measure muscle action potentials, while Magnetic Resonance Image (MRI) can be used to measure contractile activity of muscle.

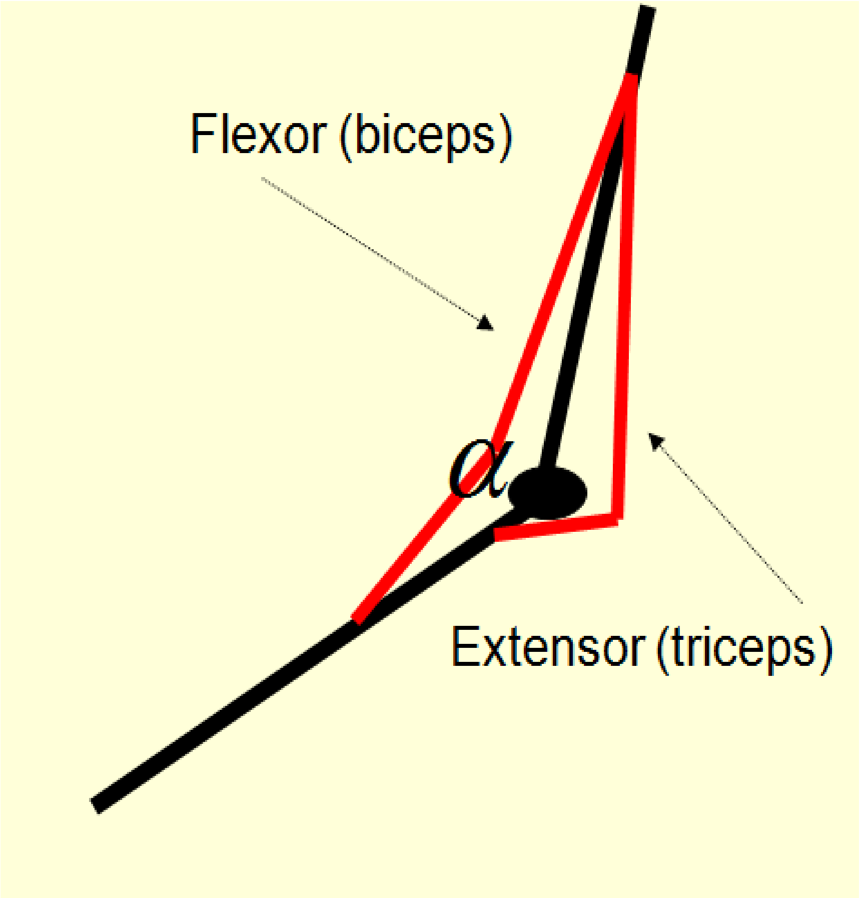
– MRI is used for studying both the action and structure of muscles.

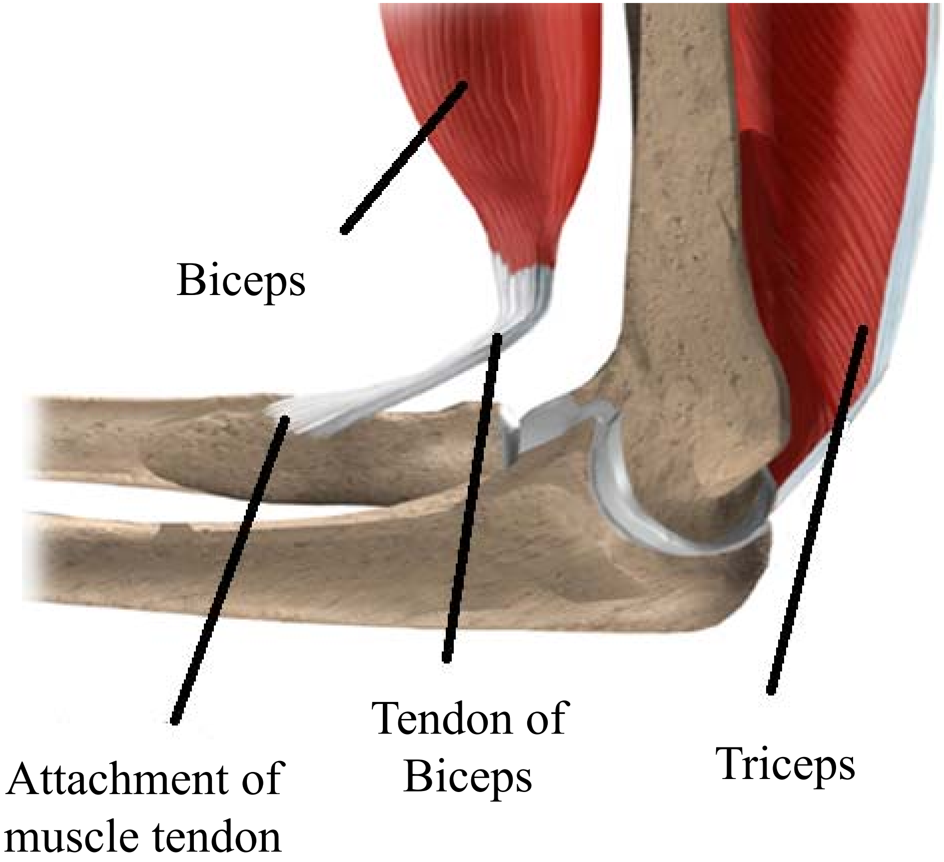
– It gives information about relaxation time that is an important parameter of muscle force – time relations.

– Measurement (recordings) are made before and after the performance of a given motor task. Muscle usage can be evaluated quantitatively through comparison of these recordings



one flexor and one extensor muscle for each joint





one flexor and one extensor muscle for each joint

- The force that a muscle fiber can generate depends on the actual length of the fiber and on the contraction velocity of the fiber.

- The force exerted by the whole-muscle is the combination of the forces exerted by the individual fibers of the muscle.

- The total muscle force depends on the pennation angle. This is the angle between the direction of the fiber and the pulling direction (action line) of the muscle. If these direction are not parallel, than the contribution of the force exerted by the fiber to the whole-muscle force is smaller then the fiber force itself.
- If the pennation angle is not zero than more fibers can be placed into a given muscle volume.

The muscle force depends on the cross sectional area of muscle.
Larger cross sectional area - larger force.

Anatomical cross sectional area (ACSA):
the area of the largest cross-section of a muscle

Physiological cross sectional area (PCSA):
the average cross sectional area of the muscle,
PCSA depends on the pennation angle

If the pennation angle is not zero than the physiological cross sectional area is smaller than the anatomical

Fibers can be arranged serially and parallelly in a given muscle.

- We face the question how to compute angular changes in the joints if we know the firing rates of the muscles' motoneuron pools. We consider this as a direct problem.

- Activated muscles develop tension and shorten, this shortening generate torque across each joint that may increase (extensor muscles) or decrease (flexor muscles) the joint angle.

- In addition to the muscle force a gravitational force may also cause torque and angular acceleration in the joint. Thus the masses of limb segments or external loads also influence kinematic movement patterns

- **Given:**

  f : stimulation frequency
  v: muscle contraction velocity,
  L: Muscle length

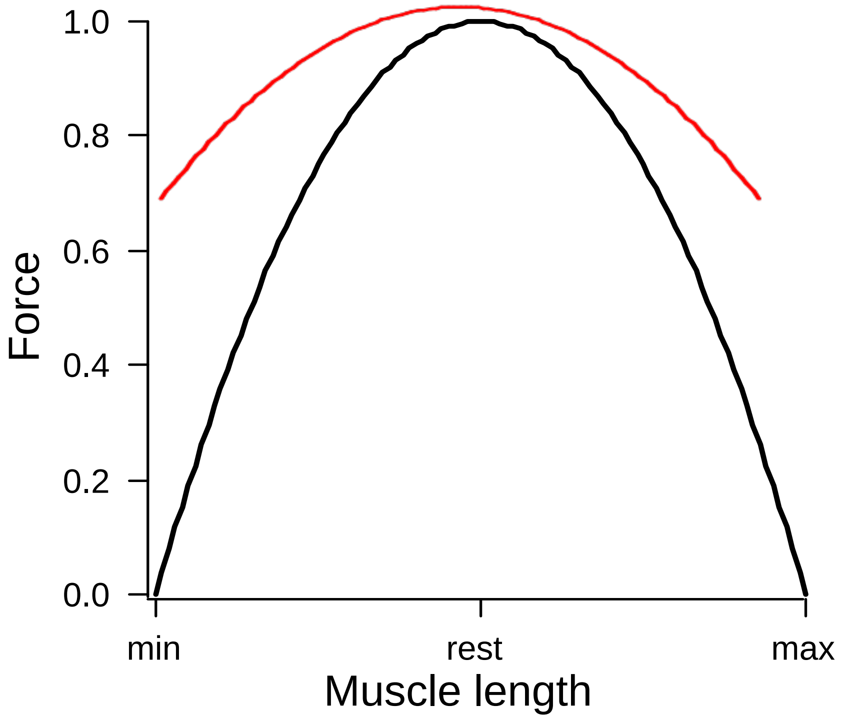
- **Computed Muscle Force:**

$$\mathbf{F_m = F_{max} F_s(f) * F_c(v) * F_a(L) + F_p(L)}$$

- F max is maximal isometric force
- $F_s(f)$ – Force-stimulation frequency relation
- $F_c(v)$ – Force-contraction velocity relation
- $F_a(L)$ – Force-length relation
- $F_p(L)$ – Passive Force-length relation

Examples for theoretical Force-length relations

Fa(L)

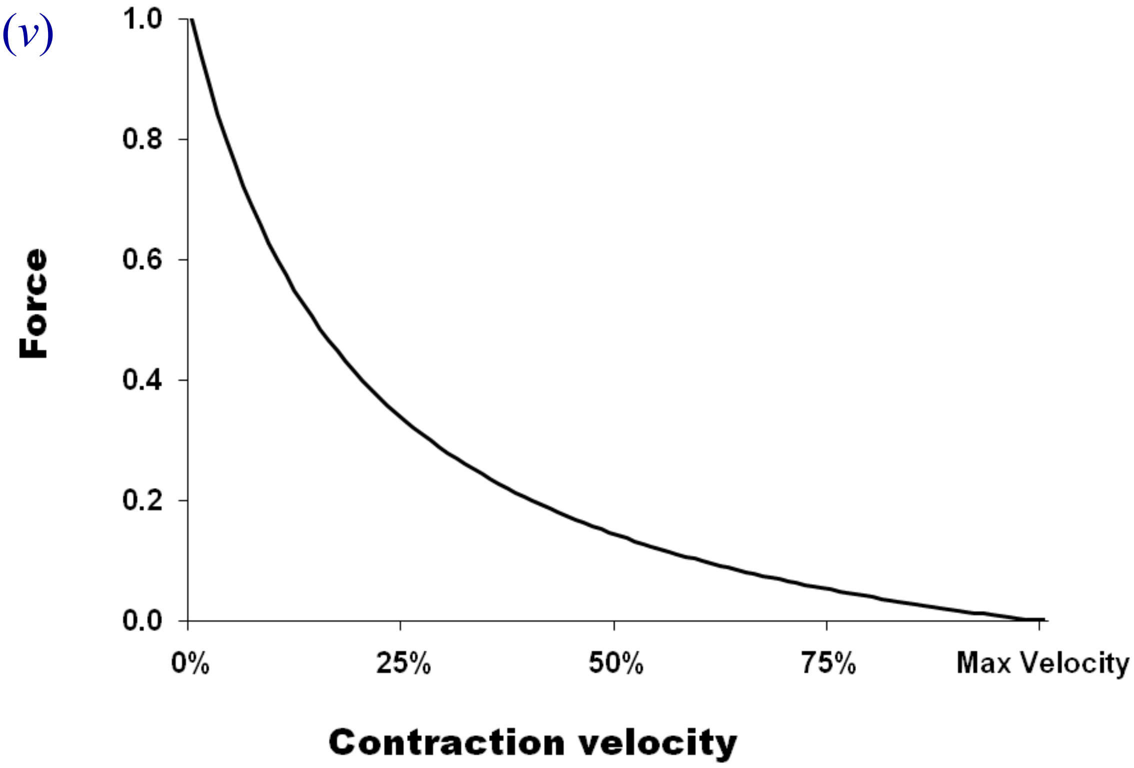


$$F_1(L)=(-4*((L-min)(max-min)-1/2)^2+2)/2 \qquad (1)$$

$$F_1(L)=-4*((L-min)(max-min)-1/2)^2+1 \quad (2)$$

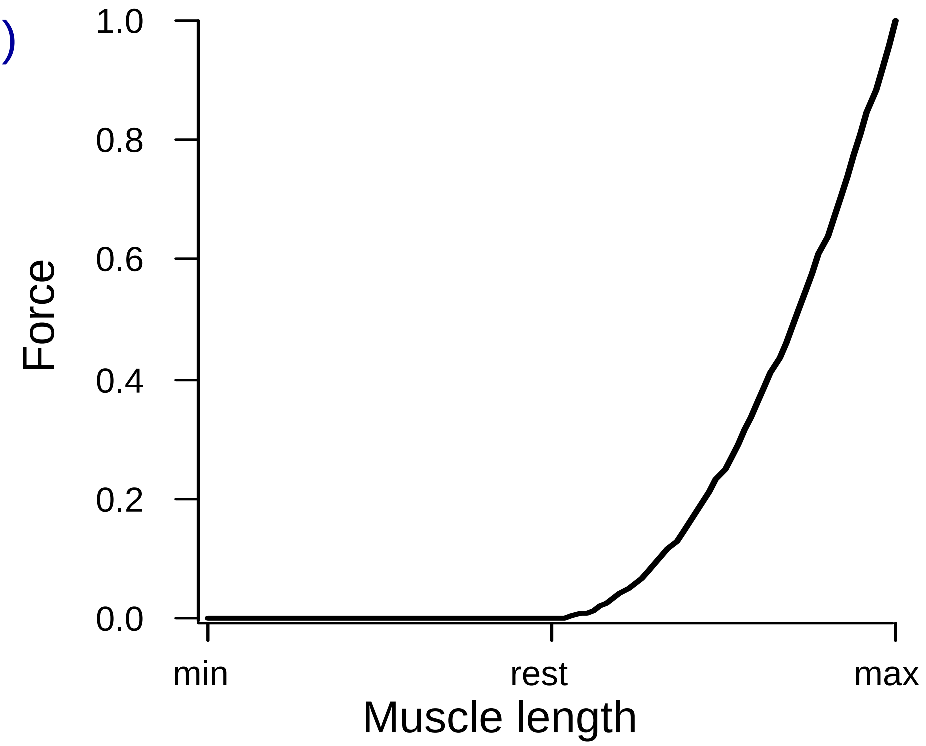
Force-contraction velocity relation

Fc(v)



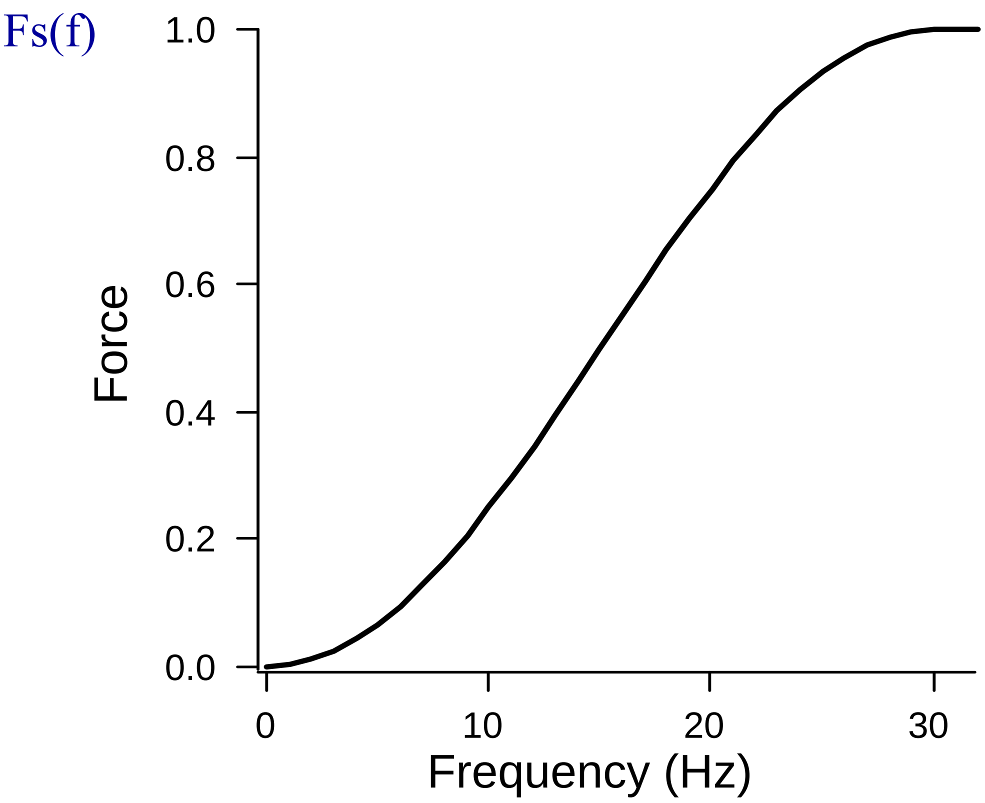
Passive Force-length relation

Fp(L)



$Fp(L)=4*(L–Lp)^2$, if rest<L<max and Fs(L)=0 if L < rest

Theoretical Force-frequency relation



$Fs(f) = \sin(p\,(f/sat-1/2)) + 1 \quad \text{if } 0<f<sat;$

Motor unit:

a motoneuron and the muscle fibers that are connected to this motoneuron.

Motor units differ in speed of contraction. Contraction time is a measure of contractile capacity. If the fibers receive an electrical impulse form the motoneuron than they twitch:
a short duration force appears.

Motor units can send several impulses to the muscle fibers in a short time interval. Thus twitches may overlap and a generate a higher force than a single twitch force.

Motoneuron firing rate, frequency of twitches.

If the frequency of the impulses are high enough, than force-time relation of the muscle fiber shows a “fused tetanus” that is a greater force and show a smooth profile for a longer period of time.

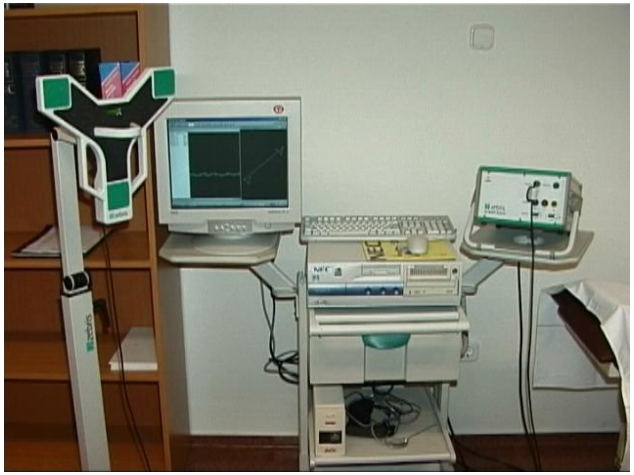
Unfused tetanus appears when tiwtiches overlap but the frequency of the twitches is not high enauph to generate smooth force profile. Instead a a jerky force pofile is generated.

The value of the generated force depends on the frequency of twitches The relation between firing rate of motoneurons and average tetanic force gives the force-frequency relation.

Ultrasound based motion analyzer

- Upper limb
- Lower limb

- **3D** coordinates of anatomical poi
    - β is computable

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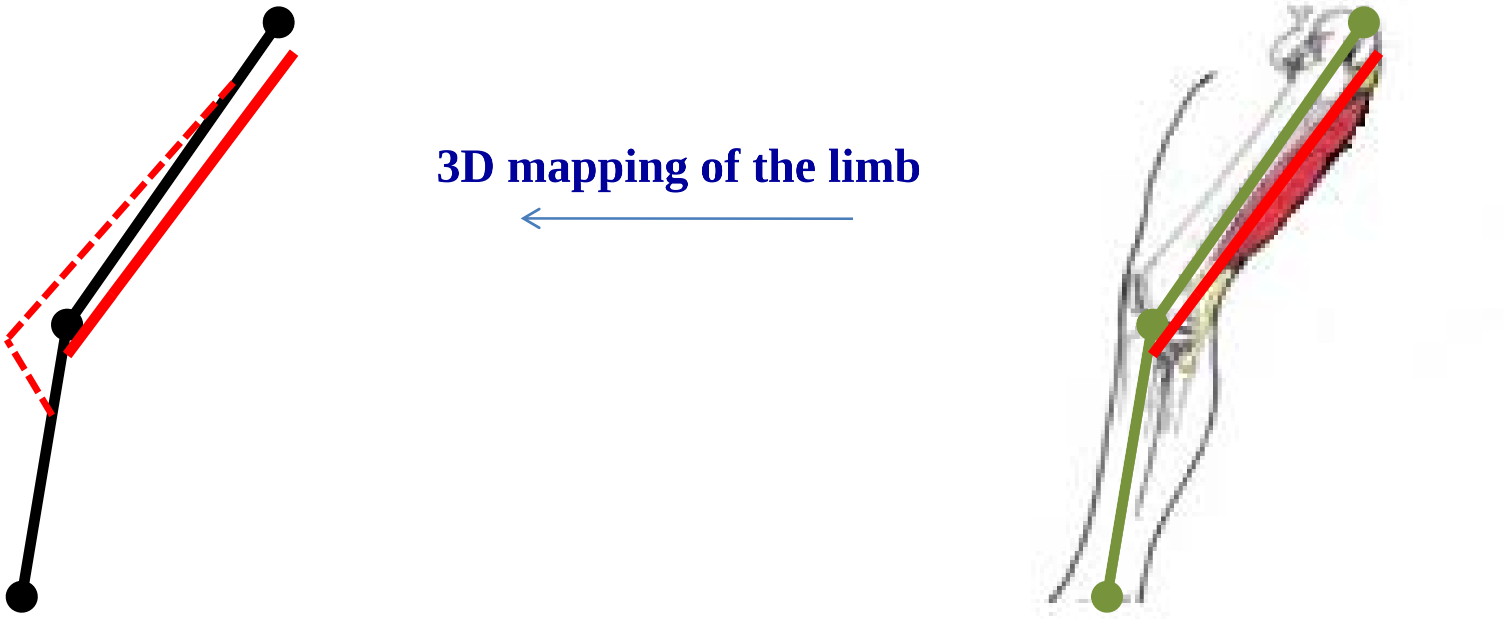
Modeling frame of the upper limb



3D mapping of the limb

▬ Modeled limb segments

▬ Modeled hamstrings (knee flexor)

╌ Further modeled muscle (vastus medialis, knee extensor)

The measured (lower) limb movement

- **Healthy subjects (N=41) were instructed to execute cycling movements on a recumbent stationary bike.**

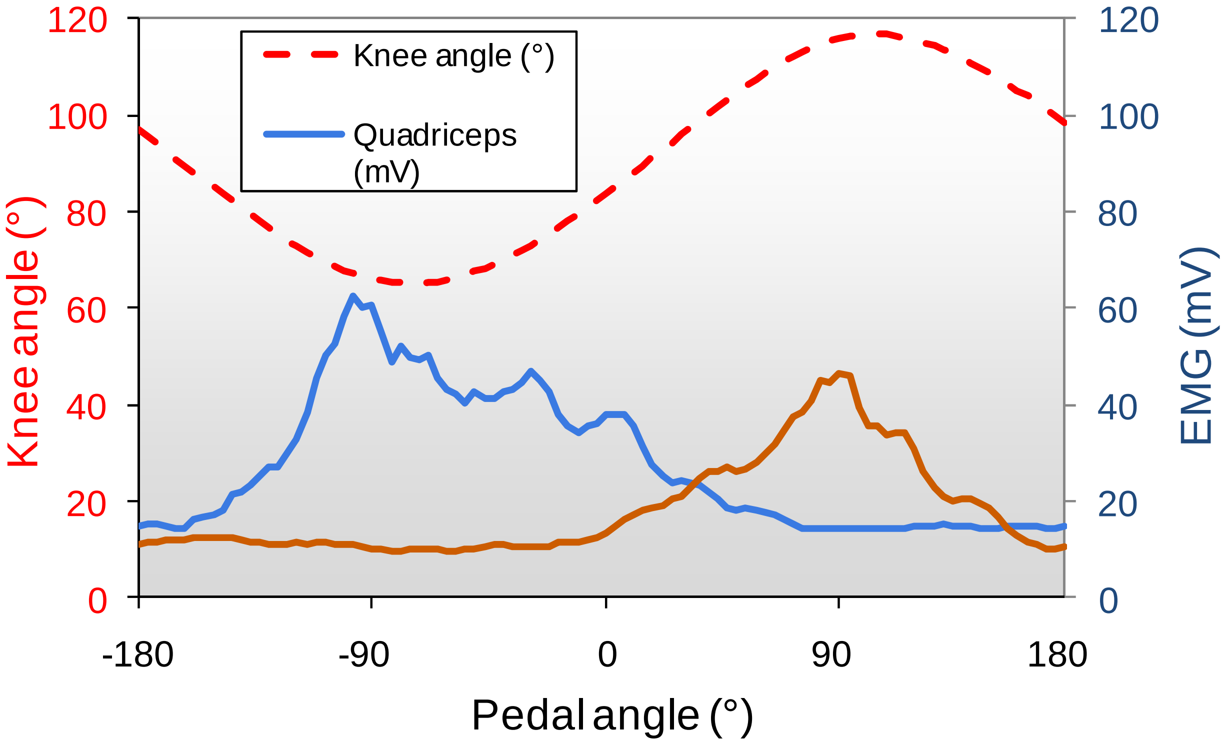
- **Pedaling movements**
- The motor task was executed under **2 different speed conditions**
  - **1) Fast (60rpm)**
  - **2) Slow (45rpm)**

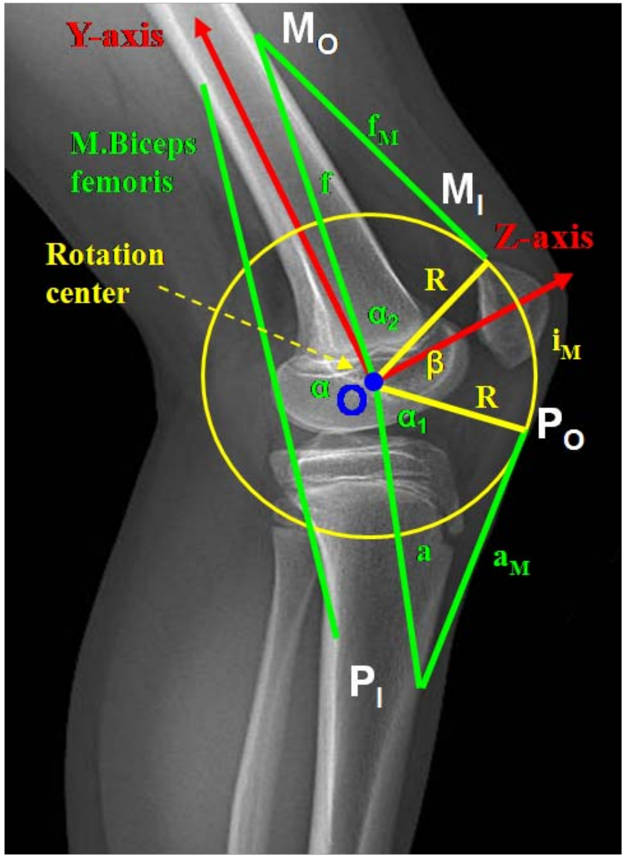
- The resistance of the pedal was alterable
  - 3 different gear levels were applied in both speed conditions
  - the relation of kinematic patterns (joint angles) and muscle activities (EMG) were investigated

- **Kinematics (3D coordinates of the hip, knee and ankle) were recorded.**
- **Vectors between the recorded marker positions defined limb segments and inter-segmental joint angles and pedal angles were computed.**

- **and EMG of 4 muscles were recorded**
  a flexor-extensor muscle pair around the knee
  (hamstrings, quadriceps)
  a flexor-extensor muscle pair around the ankle
  (tibialis anterior and soleus)

Angular changes at the knee with average muscle activity of thigh muscles during one circle





$$M_l = a_M + f_M + i_M$$

$$a_M = \sqrt{a^2 - R^2}$$

$$f_M = \sqrt{f^2 - R^2}$$

$$i_M = R \cdot \beta$$

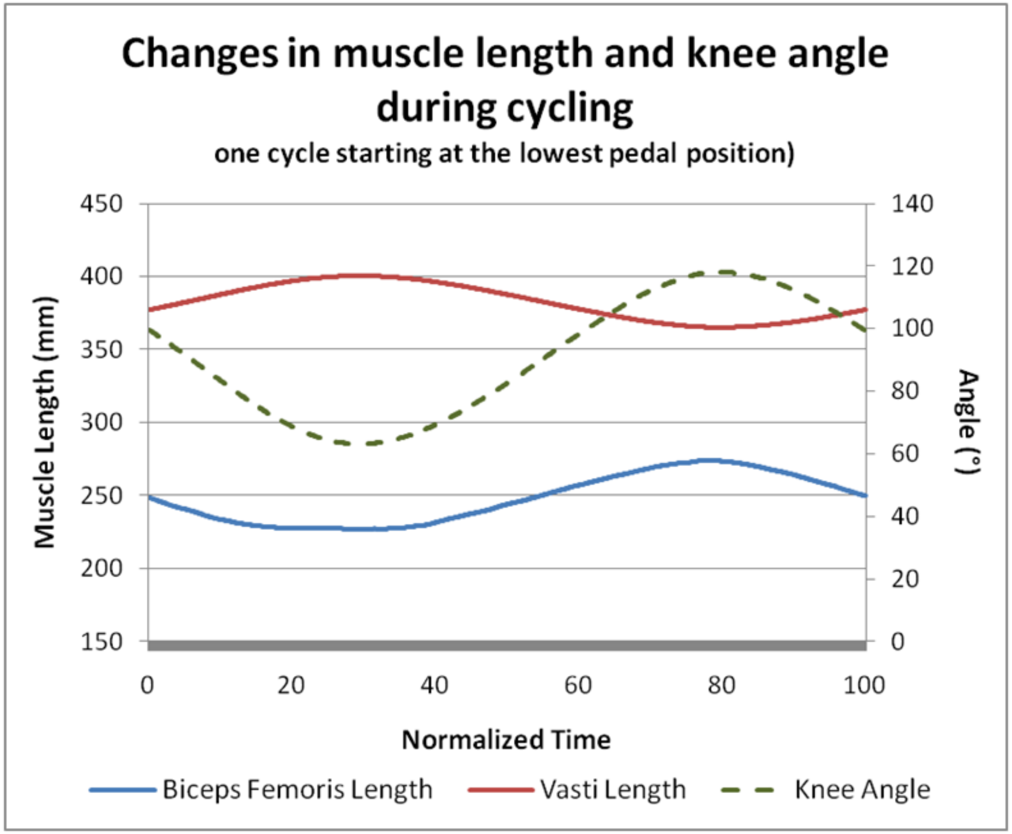
$$\beta = 2\Pi - (\alpha + \alpha_1 + \alpha_2)$$

$$\alpha_1 = \arccos\left(\frac{R}{a}\right)$$

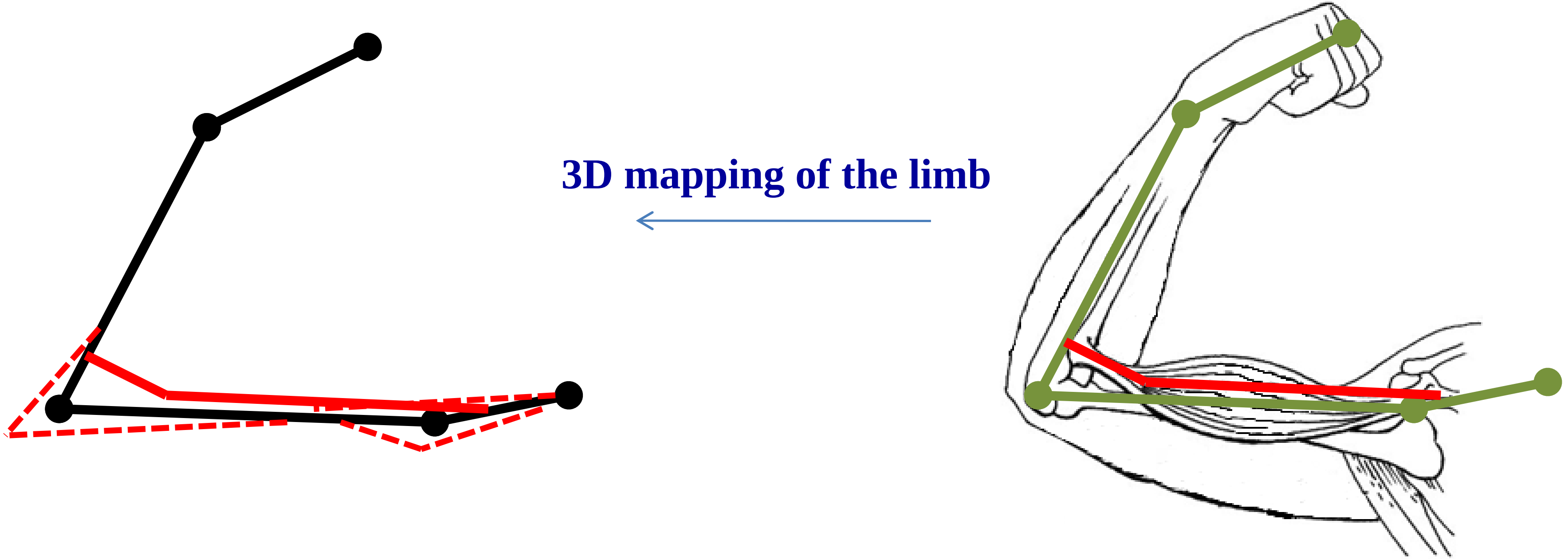
$$\alpha_2 = \arccos\left(\frac{R}{f}\right)$$

Scheme of the algorithm to compute of the length (M_l) of a knee extensor muscle (vastus) if the inter-segmental angle in the knee is α. (The flexor (biceps femoris) length is not written here).

Changes of muscle length at the knee with average muscle activity of thigh muscles during one circle



Modeling frame of the upper limb



━━ Modeled segments

━━ Modeled biceps

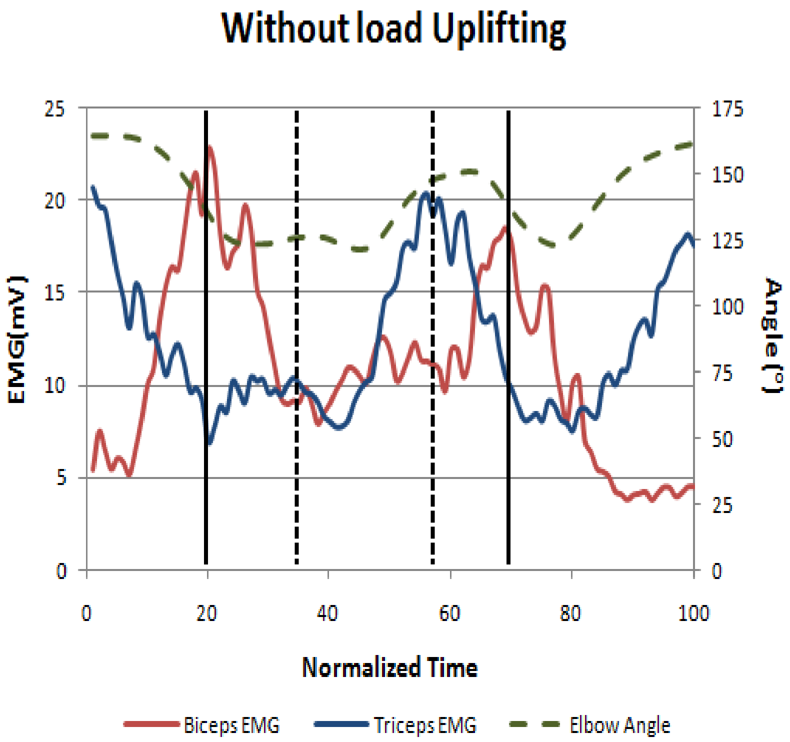
- - - - Further modeled muscles (triceps,deltoid anterior-posterior)

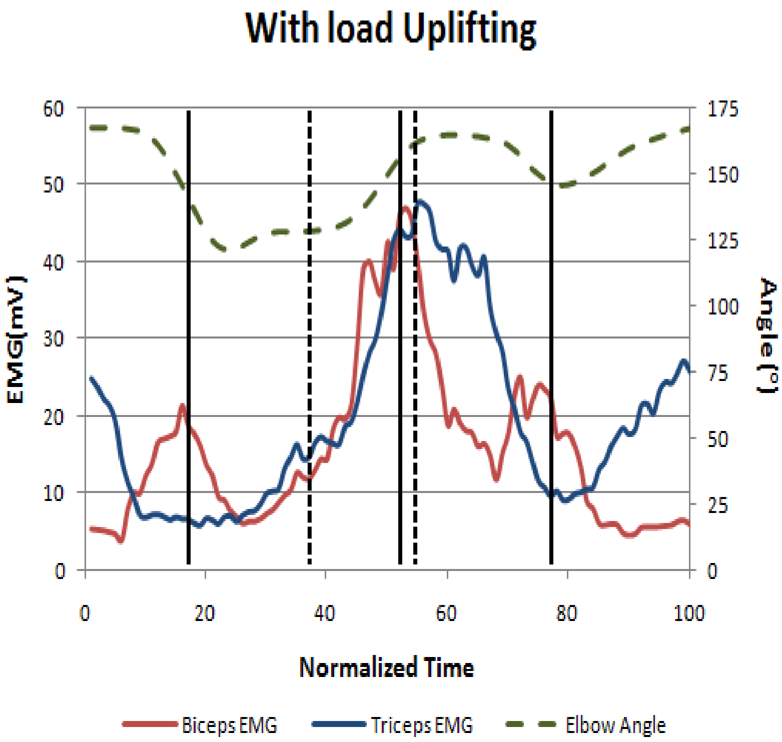
The measured limb (upper) movement

- **Healthy subjects sat in front of a 2-level-computer desk.**
- The motor task was executed under **two load conditions:**
  - 1) CD case(0.06kg)
  - 2) a load (2kg.)
- **uplifting:** the subject had to lift his arm to reach and grasp the object on the lower level of the desk and had to uplift it onto the upper level and finally put the arm back to the initial position

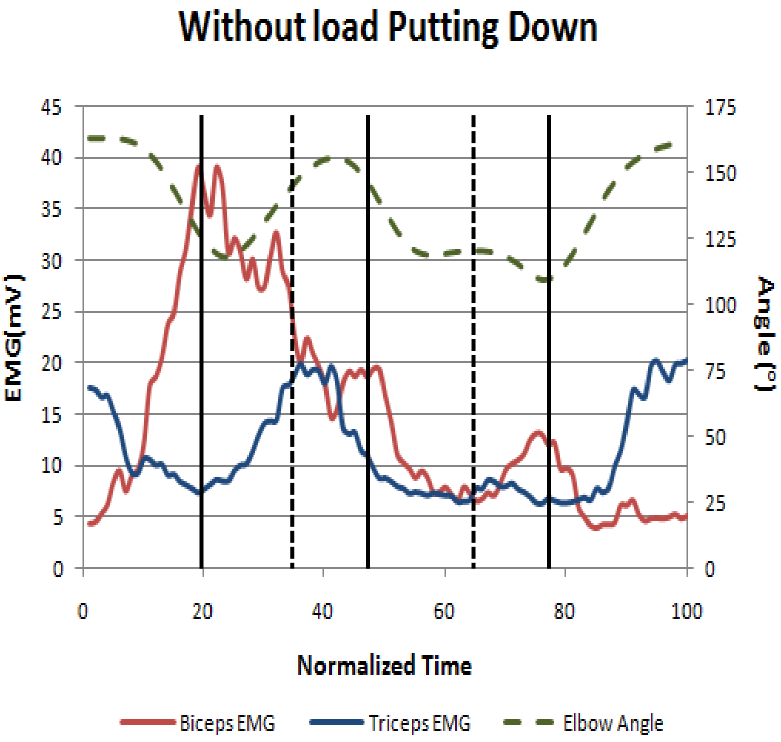
- **putting down:** the subject had to lift his arm to reach the object on the upper level of the desk, put it back down to the lower level, release the object and move the arm back to the starting position.

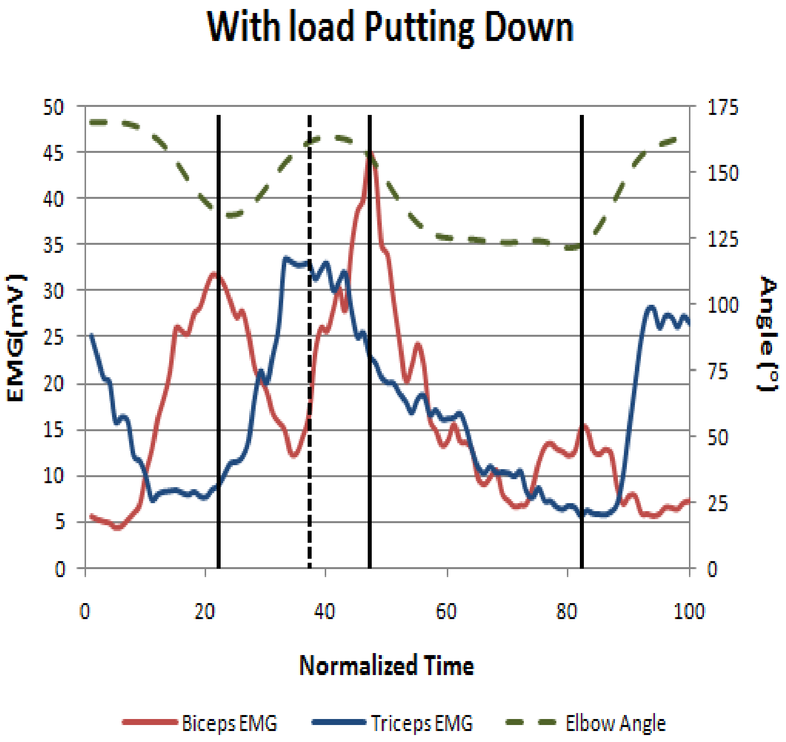
Angular changes at the elbow with average muscle activity of arm muscles in uplifting with/without load


Without load Uplifting

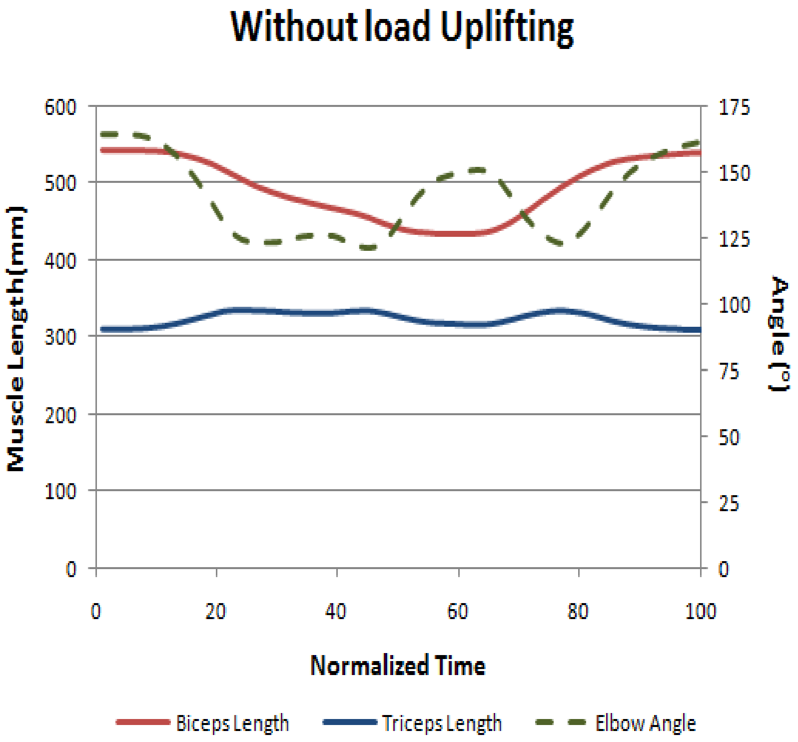

With load Uplifting

Angular changes at the elbow with average muscle activity of arm muscles in putting down with/without load


Without load Putting Down


With load Putting Down

Changes of muscle length at the elbow with average muscle activity of arm muscles in uplifting with/without load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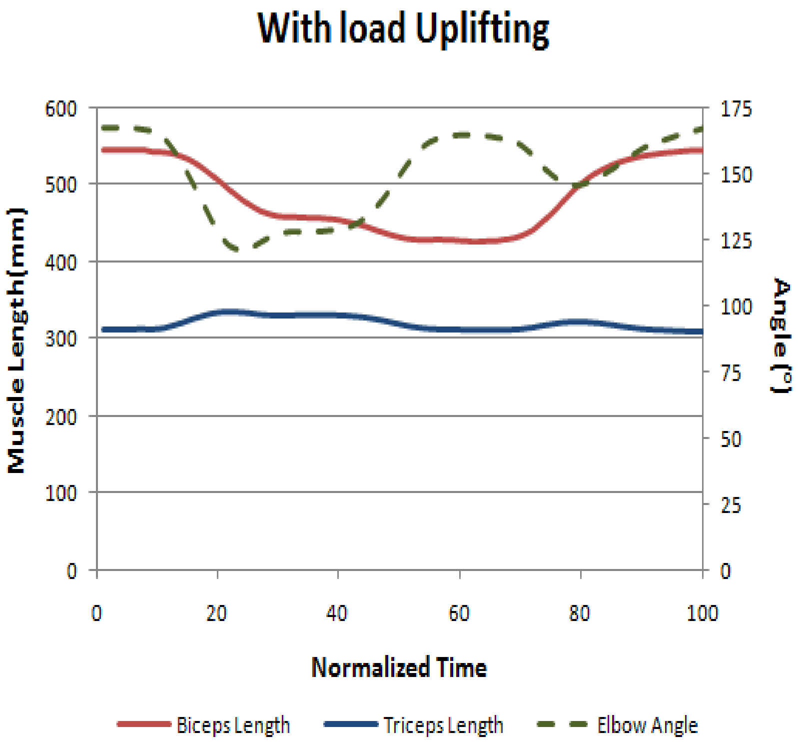
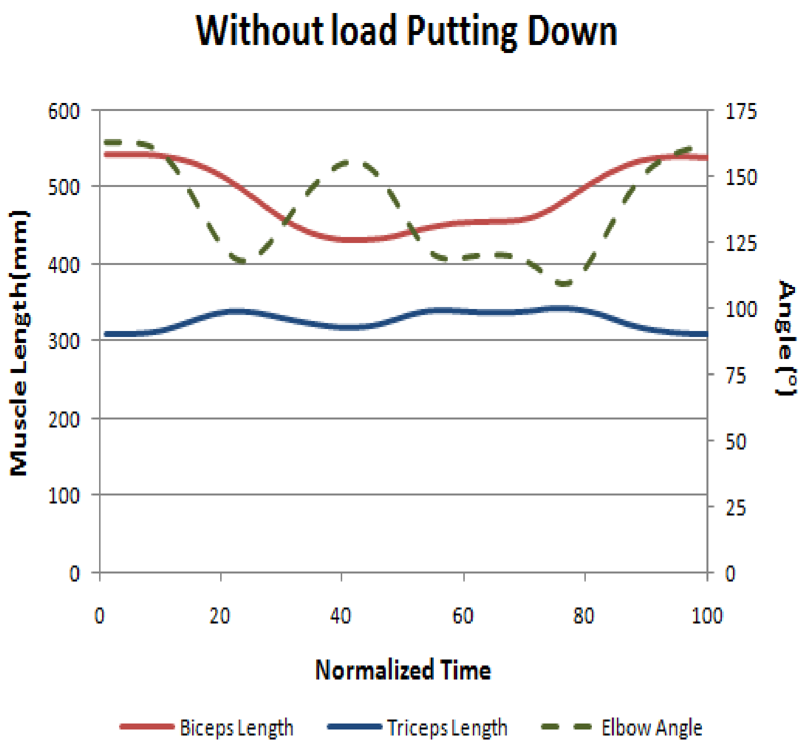
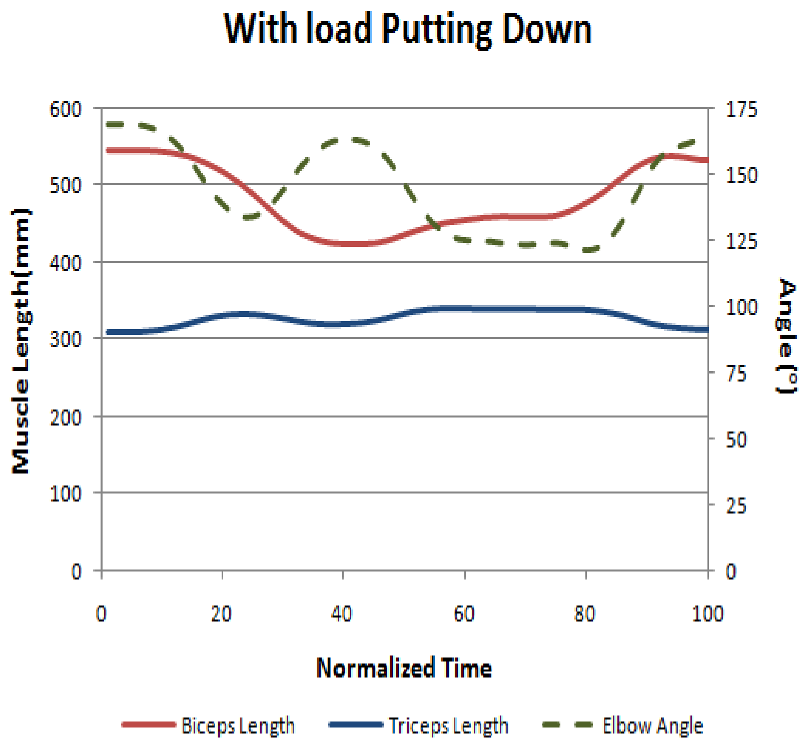

With load Uplifting

Changes of muscle length at the elbow with average muscle activity of arm muscles in putting down with/without load





Summary

- **There are many parameters that required to be taken into account in biomedical movement modeling**
  - These parameters determine the the force exerted by muscles

- Such parameters are **geometrical** and **biomechanical**

- **Biomechanical characteristics**

•**F_s(f)** – Force-stimulation frequency relation (the relation between frequency domain and exerted muscle force)

•**F_c(v)** – Force-contraction velocity relation

•**F_a(L)** – Force-length relation (at which muscle length the muscle is able to exert a given amount of force)

•**F_p(L)** – Passive Force-length relation

Suggested literature

- **Modeling of neural activities**
  (Arbib, Érdi, Szentágothai 1998, Székely 1989, Pellionisz et.al. 1985, 1987)

- **Joint and Muscle models**

Muscle and tendon properties: Enoka 1994
Modeling of joint rotations: Zajac et. al. 1990: Joint and body segmental dynamics

Models of Multijoint systems: Zatsiorsky V. (2008), *Kinematics of Human Motion.* Champaign IL: Human Kinetics.

Laczko,J.,Walton,K.,Llinas,R. A model for swimming motor control in rats reared from P14 to P30 microgravity.(2003). *Society for Neuroscience. Abstract. 2003, No.493.11.*

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- Paul, R. J. and J. W. Peterson (1975). "Relation between Length, Isometric Force, and O2 Consumption Rate in Vascular Smooth-Muscle." American Journal of Physiology 228(3): 915-922.

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