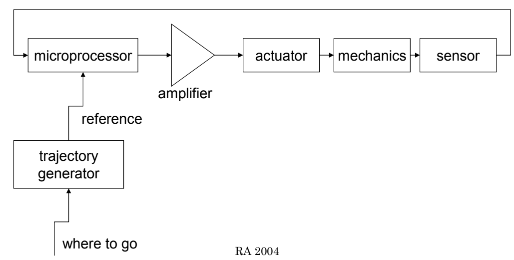
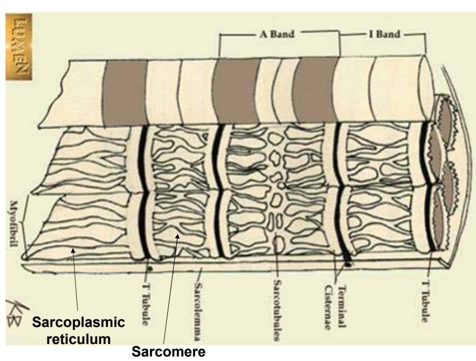
Robotica Antropomorfa

Lezione 8

Back to the global view



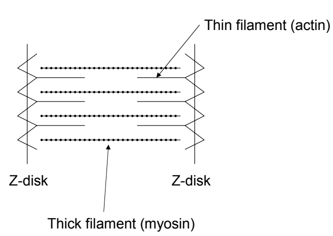
Muscle functioning



Composition

- Muscles: consist of muscle fibers
- Fibers: cells
- Cells: contain myofibrils
  - That contract in response to neural or electrical stimuli
- Cylindrical elements (sarcomere)
  - Smallest contractile elements

More in details



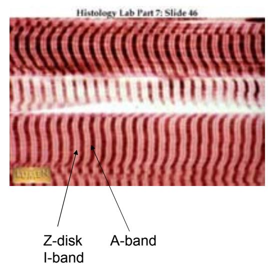
How force is generated

- Cyclical interaction between actin and myosin molecules
  - Forming cross-bridges → conformational change of the myosin heads
  - Access of the attachment sites (e.g. where the myosin attaches to the actin filament is regulated by ATP and Ca ions
  - This is called the “sliding filament theory of muscle contraction”

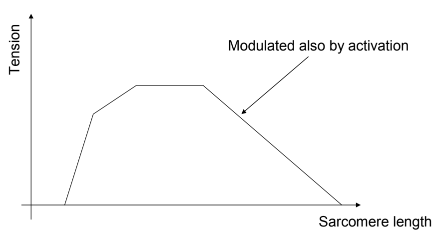
In addition

- The action potential (control signal) needs to spread all along the fibers, otherwise contraction of a part would disperse along the slack sarcomeres

A few pictures

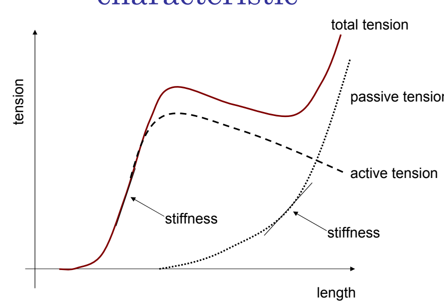


Characteristic of muscles



- Isometric (static), consistent with the sliding filament theory (liner because it's a function of the number of sites that can bind

Measuring the muscle's characteristic

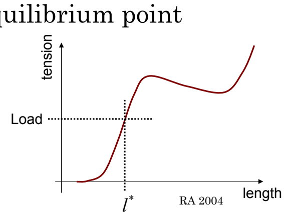


Stiffness

- Derivative of force/tension over length

$$\frac{dF}{dl} \qquad F = k(l - l_0) \Rightarrow k$$

- Equilibrium point



If the muscle is in motion…

- Changes the number of cross bridges, we get a different set of curves (dependence of the derivative of the length)
- Filtering effect of Ca kinetics:
  - Action potential 1-3ms
  - Single muscle twitch 10-100ms
  - Twitches fuse, forces summate

Motor unit

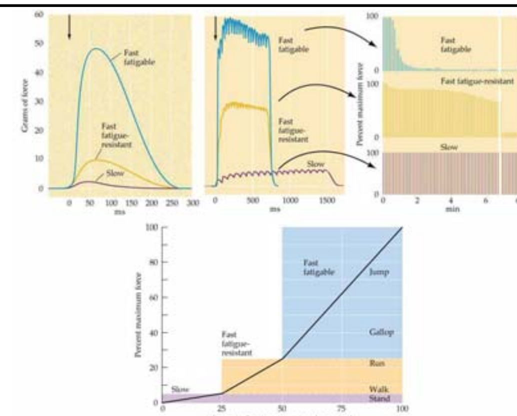
- A motor neuron innervates many fibers
  - number of fibers/number of motor neurons → innervation ratio
- 10 → finer control (eye muscles)
- 100 → hand muscles
- 2000 → leg muscles (big)

Different types of fibers

Fast fatigable	Slow fatigue resistant (1-10% of total force)	Fast fatigue resistant
Few mitochondria (ATP) Anaerobic glycogen (for energy)	Oxidative metabolism More mitochondria Low rate of ATP consumption	In between the fast and slow
100 times more force		
Periphery of muscle (do not consume much)	Central part (more blood, more oxygen)	
Ocular muscle (mostly fast)		

Moreover…

Fast fatigable	Slow fatigue resistant (1-10% of total force)	Fast fatigue resistant
Diameter and conduction velocities are greater for fast fibers Higher frequency	Lower frequency	

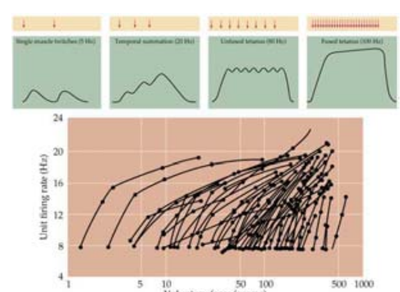


How force is graded (control)

- Recruitment
  - Size principle (Henneman)
  - Fixed order: small first [slow units], then intermediate, and fast fibers at last
  - In principle similar to Weber's law (small forces, more graded)

Second method

- Firing rate: higher frequency → more force



Same equilibrium point, different muscular activation

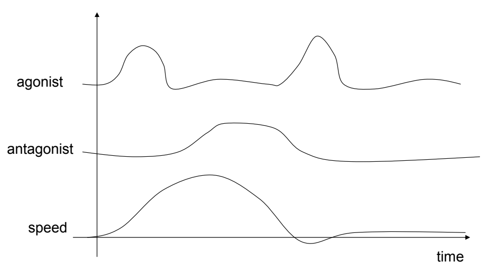
- Reciprocal activation
- Co-contraction

- If the model is known (e.g. the load, limb parameters, etc.) reciprocal activation is better

Low-pass behavior

- Empirically measured
  - Sinusoidal stimulations, measure the force
- The muscle behaves as a low pass filter of the neural input

Three-phasic activation



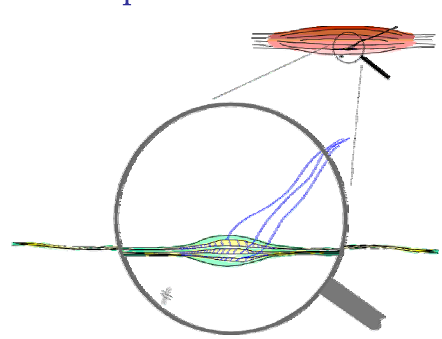
Receptors

- Spindles
  - Sensitive to position and speed
- Golgi tendon organs
  - Sensitive to tension

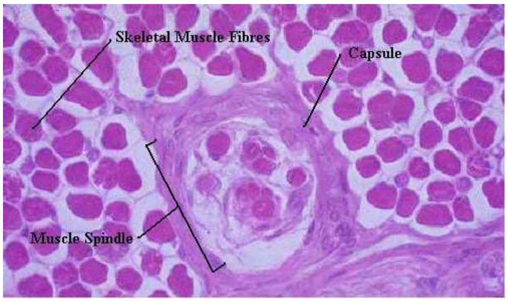
Spindles

- They are muscle fibers:
  - Innervated by afferent fibers
  - Two types of afferents:
    - Group Ia
    - Group II
  - Innervated by motor neurons (called γ motor neurons)

Spindle schematics

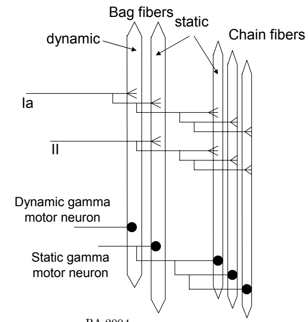


For real



RA 2004

Schematics of innervation



RA 2004

Responses

- Ia → dynamic, sensitive to the rate of change of stretch
- II → static, sensitive to stretch per se

- γ motor neurons innervate spindles
- α motor neurons innervate contractile fibers

RA 2004

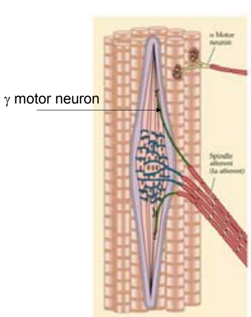
In mammalians

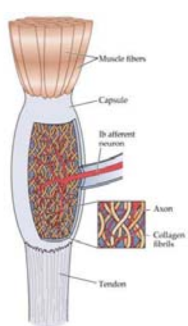
- γ and α control are separate

- In practice, the sensitivity of the sensor can be controlled!
- Also, sensitivity to speed and position can be modulated separately (e.g. depending on behavior)

RA 2004

Golgi tendon organs (right)





Golgi tendon organs

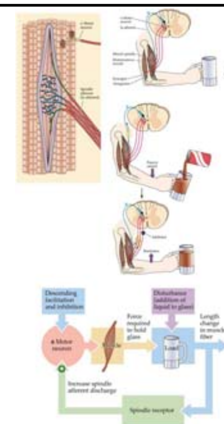
- Measure tension
- Afferent fibers are called group Ib

- Can build a feedback loop to maintain a certain tension

RA 2004

Pattern of control

- α-γ co-activation → to maintain spindles in range
- α-γ separate control → depending on behavioral context
  - Passive → high dynamic, low static
  - Walk → low dynamic, high static
  - Dynamic is needed when position might change unpredictably



Muscle tone – stretch reflex

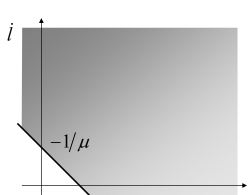
- Negative feedback on the spindle signal
- Goal: maintain posture in spite of external disturbances
- See previous slide

More biologically inspired control

- From muscle functioning to control
- Can trajectories (straight and bell-shaped velocity profile) be generated by simple neural commands?

λ model of motor control

- α motor neurons
  - change of threshold length (λ) for recruitment (activation of a muscle/fiber)



Muscle activation

$$A = |l - \lambda - \mu \dot{l}|^{+} \qquad |x|^{+} = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{if } x < 0 \end{cases}$$

- μ is the relative measure of spindle's primary vs. secondary gain (damping) – in reality it could be another control parameter
- λ is the control variable
- l is the length

More…

$$A = \left| l(t-d) - \lambda(t) - \mu\dot{l}(t-d) \right|^{+}$$

- d is a delay of about 25ms

$$\tilde{M} = \rho[\exp(cA) - 1]$$

- ρ, c are two fitting parameters
  - ρ represents a scaling (size of muscle)
  - c represents the recruitment (speed of activation of different fibers)

Further…

$$\tau^2\ddot{M} + 2\tau\dot{M} + M = \tilde{M}$$

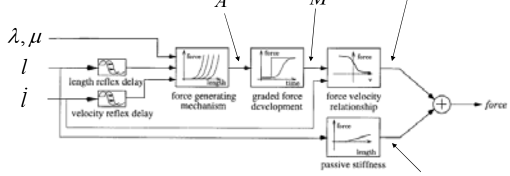
- Filtering effect due to calcium kinetics

$$F = M[f_1 + f_2 \tan^{-1}(f_3 + f_4\dot{l})] + k(l - r)$$

- Actual dependency on speed and length (reflexes) modeled as a sigmoid plus a linear function

Model of muscle activation

$$F = M[f_1 + f_2 \tan^{-1}(f_3 + f_4\dot{l})]$$



$$F = k(l - r)$$

Two classes of commands

- R → reciprocal activation
- C → co-contraction

- R,C can be used to compute the λs
- Clearly to set λs exactly we need to have a knowledge of muscles' geometry and forces
- Hypothesize that R,C can be simple enough to generate nice trajectories

Changing R and C

- Changing R and C for various muscles changes the equilibrium point of the limb
- EP hypothesis
  - To control the limb position the brain has "only" to move the EP to the desired position following a certain profile
  - Depending on the stiffness (of the limb) the actual trajectory will be close (or not that close) to the EP trajectory