Molecular mechanisms of biological motion

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Various levels of biological motion

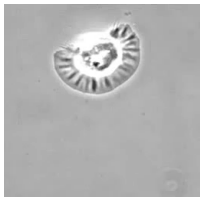
Molecular motion

Bacterial Flagellar Motor

「ERATO 駆流プロトニックナノマシンプロジェクト終了報告ビデオ」より

Bacterial flagellum

Cellular motion



crawling keratinocyte

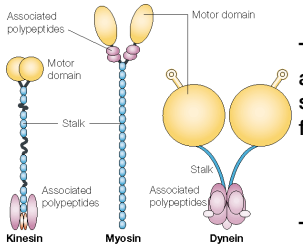
Body motion

Motor proteins

Mechanoenzymes capable of converting chemical energy into mechanical work.

1. Specifically attach to a cytoskeletal filament or other biopolymer (DNA).
2. They generate force when moving along the filament.
3. They utilize energy from nucleotide cleavage for force generation.

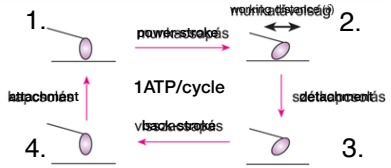
Common characteristics of motor proteins



I. Structural homology

The globular head found at the N-terminus serves as the ***motor domain*** (ATPase) and provides a specific binding-site for the respective cytoskeletal filament.

The C-terminus contains functional binding sites.



II. Cyclic operation

1. Attachment
2. Power-stroke (pull)
3. Detachment (dissociation)
4. Back-stroke (relaxation)

Work done by a single motor protein can be calculated from: $W = F \cdot \delta$

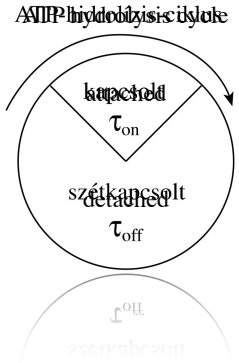
pulling force (F): in the range of pN

working distance (δ): in the range of nm

W: in the range of zJ

$(zeptojoule = 10^{-21}\ J)$

Duty cycle of motor proteins



Duty ratio (r):

$$r = \frac{\tau_{on}}{\tau_{on} + \tau_{off}} = \frac{\tau_{on}}{\tau_{total}}$$

Processive motor protein: r~1
F.e. kinesin, DNA-, RNA-polymerase.
They remain attached in most of the cycle time. They function individually.

Non-processive motor protein: r~0
F.e. conventional myosin (skeletal muscle myosin II.) They remain detached in most of the cycle time. They function in ensembles.

$$v_{stroke} = \frac{\delta}{\tau_{on}}$$

$$\tau_{on} = \frac{\delta}{v_{stroke}}$$

$$\tau_{total} = \frac{1}{k_{ATPase}}$$

$$r = \frac{\delta k_{ATPase}}{v_{stroke}}$$

δ = ***working distance***
v_{stroke} = ***stroke velocity***
k_{ATPase} = ***ATPase rate***

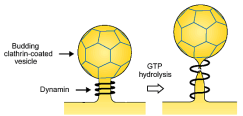
Types of motor proteins

1. Actin based

- ***Myosins:*** They move towards the plus end along the actin filament.
  (lamellipodium formation, muscle contraction)

2. Microtubule based

- ***Dyneins:*** Ciliary (flagellar) and cytoplasmic dyneins. They move towards the minus end along the microtubule. (*axonal retrograde transport)*
- ***Kinesins:*** They move towards the plus end along the microtubule.
  (*axonal anterograde transport)*
- ***Dynamins:*** Microtubule activated GTPase function. *(pinchase)*



3. DNA based mechanoenzymes

- They exert force and move along the DNS double helix.
  (*DNA- and RNA-polymerases, viral capsid portal motor)*

4. Rotary motors

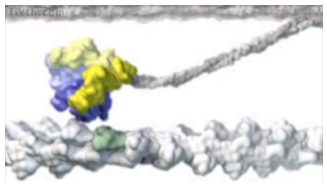
- They are transmembrane mechanoenzymes that utilize the proton gradient across the membrane.
  F1Fo-ATP synthase, bacterial flagellar motor

5. Mechanoenzyme complexes

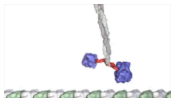
- *Ribosome*

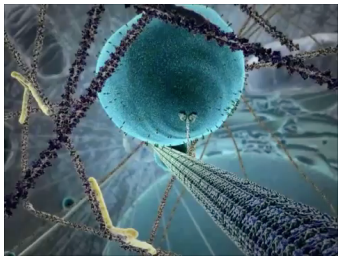
Citoskeleton based motors

Non-processive motor
Skeletal myosin II.
Moves along the actin filament



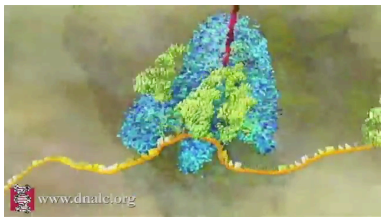
Processive motor
Kinesin
Moves along the microtubule



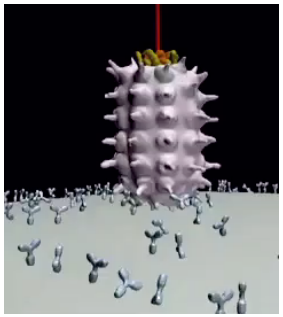


Nucleic acid based motors

Ribosome
mechanoenzyme complex



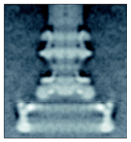
Virus portal motor
DNS „packaging“

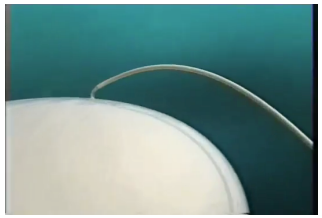


Rotating motors

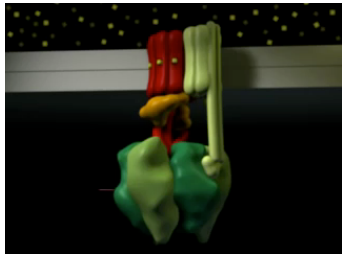
driving force: proton gradient

Flagellar motor
bacterial movement





F_1F_o ATP synthase



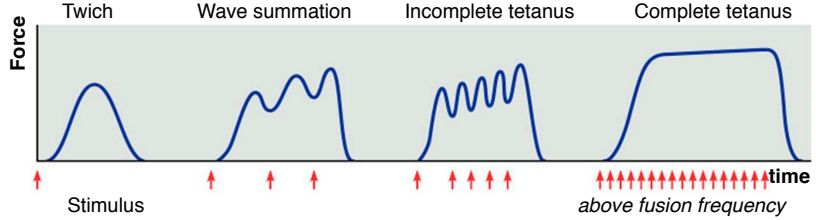
Muscle biophysics

Machina Carnis

Cell and tissue specialized for movement.

It can only pull, not push!

Basic phenomena of muscle function I.



A single stimulus results in a single contractile response – a muscle **twitch** (contracts and relaxes).

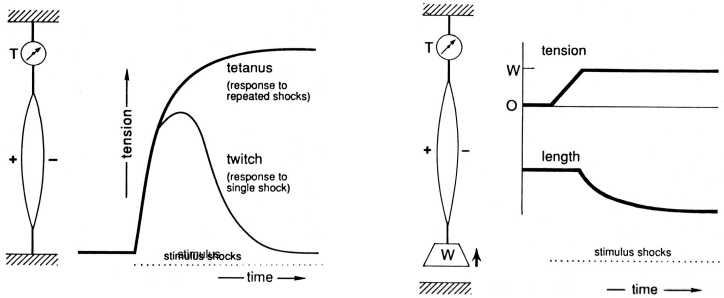
More frequent stimuli increases contractile force – **wave summation** - muscle is already partially contracted when next stimulus arrives and contractions are summed.

A sustained contraction that lacks even partial relaxation is known as **tetanus**.

Basic phenomena of muscle function II.

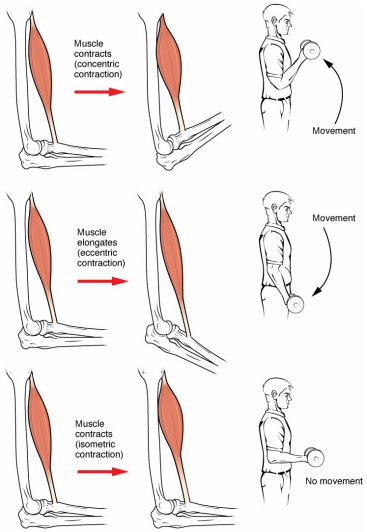
1. Isometric contraction
The muscle does not or cannot shorten, but the tension on the muscle increases.

2. Isotonic contraction
Tension remains unchanged while the muscle's length changes.



Auxotonic contraction (simultaneous shortening and force generation)

Basic phenomena of muscle function III.



1.Concentric muscle action
The muscle shortens during force generation

2. Excentric muscle action
The muscle elongates during force generation

3. Isometric muscle action
The muscle length remains constant during force generation

Basic phenomena of muscle function IV.

1. Work and Power

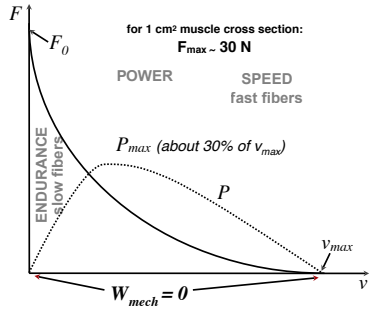
$$W = F \cdot s$$

$$P = \frac{W}{t} = \frac{F \cdot s}{t} = F \cdot v$$

If the shortening velocity is zero, the force is maximal: maximal isometric force (F_0)

If v = maximum, than $F = 0$

2. Force - velocity diagram



Hill equation:

$$(F + a)(v + b) = (F_0 + a)b$$

F: force, v: shortening velocity
a and b: constants,
F_0: maximal isometric force

$$v_{max} = \frac{bF_0}{a}$$

Energetics of muscle contraction

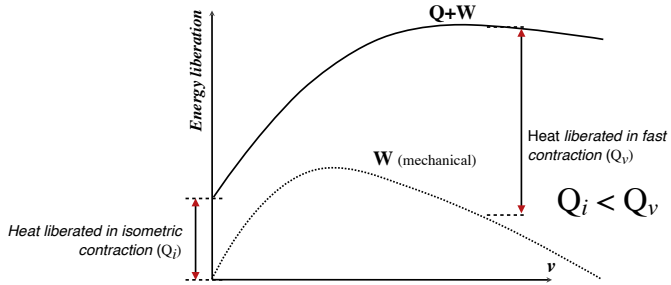
ATP hydrolysis, heat liberation

Source of energy:

$$Mg.ATP^{2-} + H_2O \rightleftharpoons Mg.ADP^{1-} + Pi^{2-} + H^+$$

Fenn effect: The liberation of heat increases when the muscle is doing work during shortening. The amount of heat liberated increases with increasing speed of contraction.

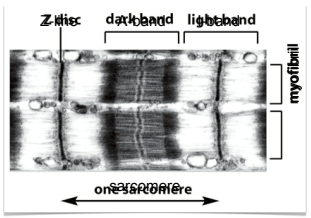
The majority of chemical energy used by the muscle is dissipated as heat



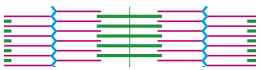
The mechanism of muscle shortening

Phenomenological mechanism: sliding filament model

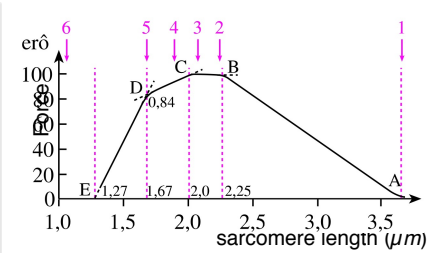
Sarcomere

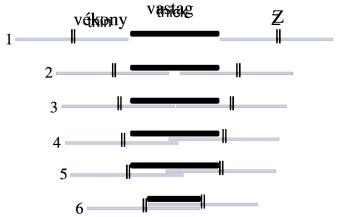


Relaxed



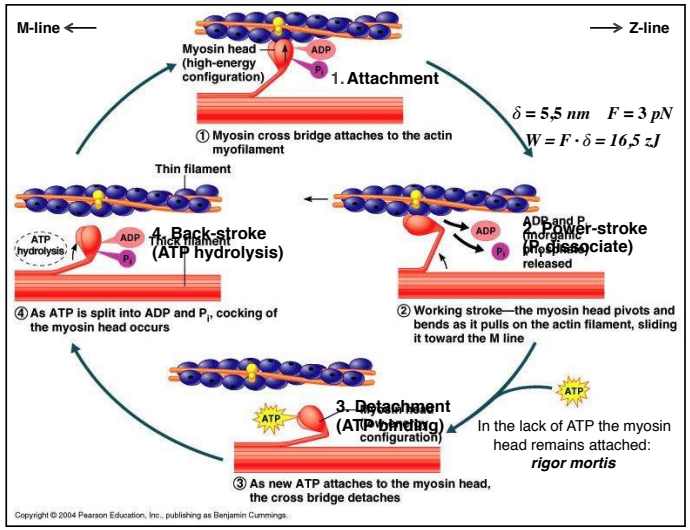
Contracted





The myosin „cross-bridge“ cycle

Molecular bases of muscle contraction



$\delta = 5{,}5\ nm \quad F = 3\ pN$

$W = F \cdot \delta = 16{,}5\ zJ$

In the lack of ATP the myosin head remains attached:
rigor mortis