# Human Motion Control

Course (Wb 2407)

Lecture 4

## Muscles

physiology, morphology and models



Part 1

## Muscle morphology and physiology

**Morphology:**

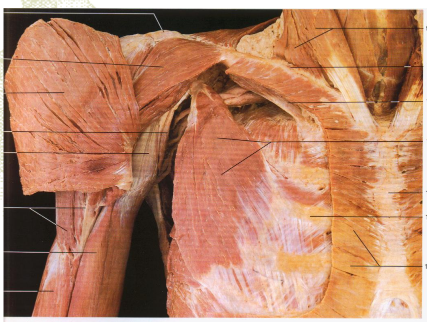
- fiber arrangement
- force-velocity relation
- force-length relation
- sarcomeres and fibers
- motor units

**Physiology:**

- chemical energy to mechanical energy
- activation dynamics: calcium release and take-up
- contraction dynamics: cross-bridge formation
- muscle energy



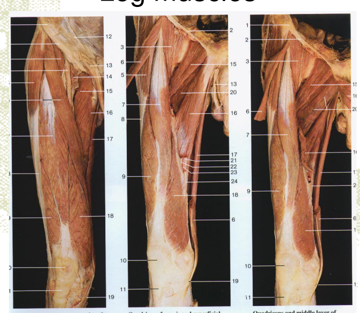
## Shoulder muscles



...uscles of shoulder and arm, deep layer (ventral aspect).



## Leg muscles



**Extensor and adductor muscles of thigh** (right thigh, ventral aspect).

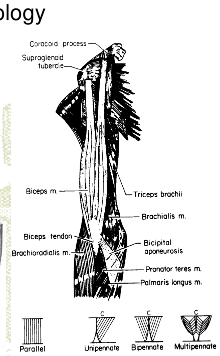
**Quadriceps femoris and superficial layer of adductor muscles** (right thigh, ventral aspect). The sartorius has been divided.

**Quadriceps and middle layer of adductor muscles** (right thigh, ventral aspect). The sartorius and adductor longus have been divided.



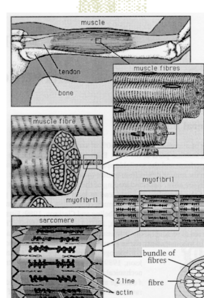
## Muscle morphology

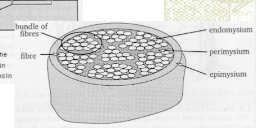
- muscle belly + tendon or bony attachment
- parallel fibered - pennate (uni-, bi-, multi-)
- single - or mutiple headed
- single - or multiple bellied
- uni-, bi-, or multi articular

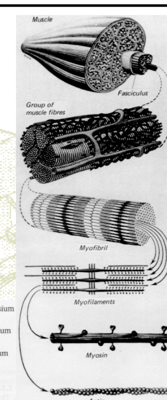





## Muscle morphology

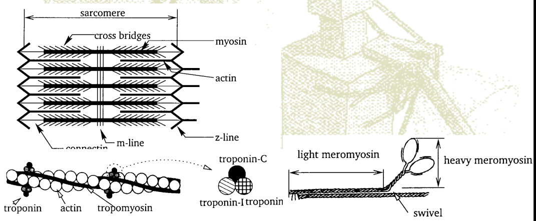


## Force producing units: Sarcomeres

- Structure that actively generates the force
- cross-bridges
- release of cross-bridge: ATPase

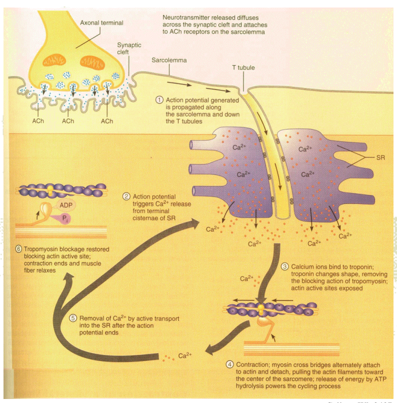




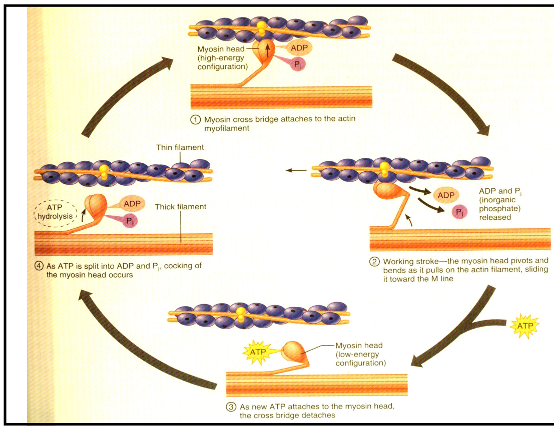

## contraction mechanism

- action potential from nerve system
- transport along fiber (1-5 m/s) and into fiber
- triggering sarcoplasmatic reticulum (0.5-3 ms), release $CA^{2+}$
- detachment cross-bridge
- constant pump of $CA^{2+}$ back in sarcoplasmatic reticulum
- attachment cross-bridge



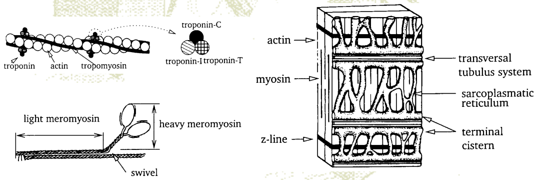




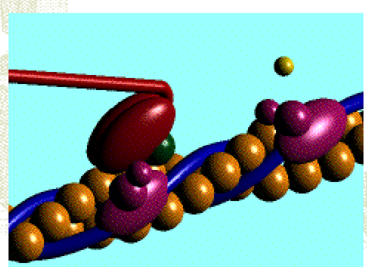




## Contraction process: cross-bridge binding

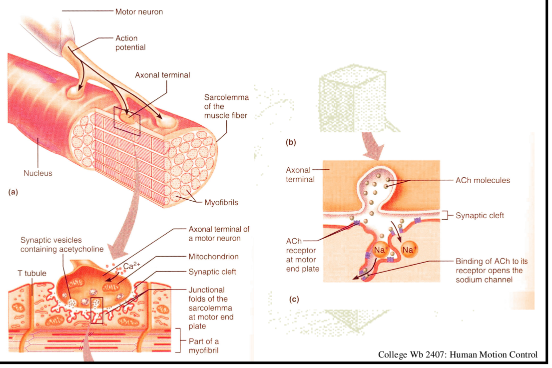
- cross-bridges
- release of cross-bridge: Energy required (ATPase)
  ATP $\rightarrow$ ADP+P +energy (with $CA^{2+}$ as catalysor)





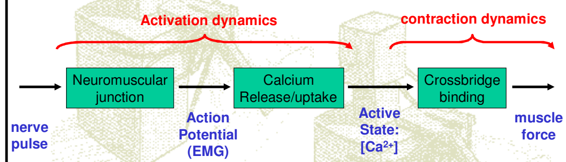



## Muscle activation






## Transfer of information: from nerve pulse to muscle force



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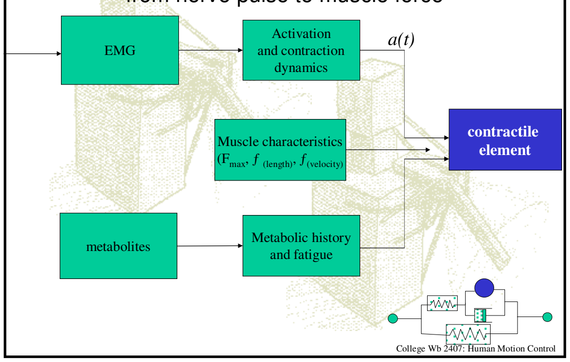




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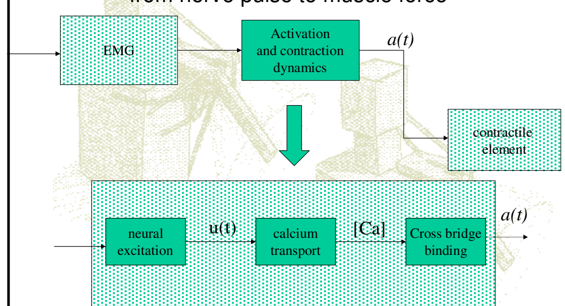
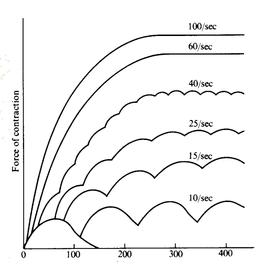





## Muscle force

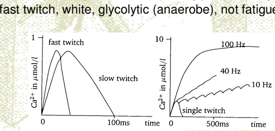
- one twitch
- tetanus: repeating twitches






## fiber types

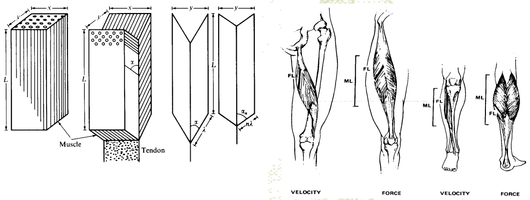
- Type I: slow twitch, red, oxidative (aerobe), fatigue resistant
- Type IIa: fast twitch, red/pink, oxidative and glycolytic, fatigue resistant
- Type IIb: fast twitch, white, glycolytic (anaerobe), not fatigue resistant




- motor units: combination of fibers
  - size principle
  - force production: number of motor units or frequency

## Consequences of morphology

- Effect of pennation (equal fiber length and volume)
  - Larger force
  - Lower speed (but higher initial speed!)
  - Shorter trajectory

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## Influence of architecture: fiber length

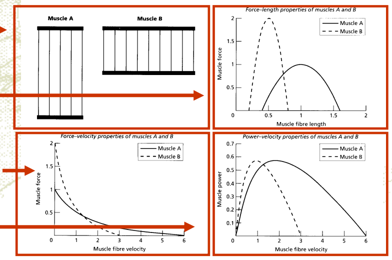
| | Hypothetical muscle A | Hypothetical muscle B |
|---|---|---|
| Length | 2 units | 1 unit |
| Cross-sectional area | 1 unit$^2$ | 2 units$^2$ |

Muscle structure

Force-length relationship

Force-velocity relationship

Power-velocity relationship



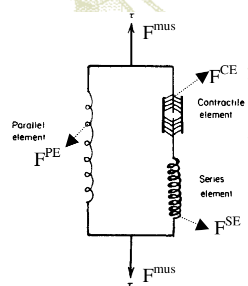

Peak Power

**Key functional properties summary**

| | Hypothetical muscle A | Hypothetical muscle B |
|---|---|---|
| Contraction time | 1 | 1 |
| Maximum force | 1 | 2 |
| Range of motion | 2 | 1 |
| Maximum velocity | 2 | 1 |
| Peak power | 2 | 2 |

Control

## Hill type models




1. Based on empirical relations
2. Input-output mapping of well defined experiments

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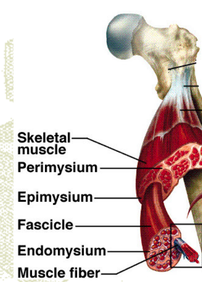
## Myofascial force transmission

- Musculoskeletal model often include muscles as separate actuators,
  - Force from attachment to attachment
- but muscles do transfer force across their fascia's
  - To other fibers
  - To neighbouring agonists
  - To nerves and vessels
  - Even to antagonists
- Effects are not large, but might be important in low-force, or large displacement conditions

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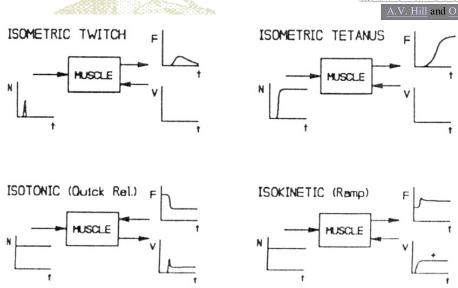
## Hill type model: experimental basis (1)

A.V. Hill and O Meyerhof

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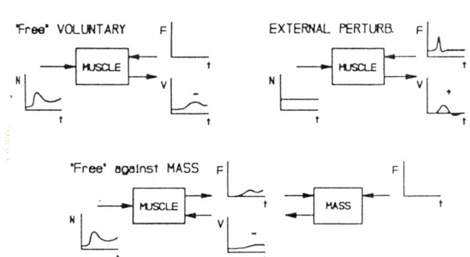
## Hill type model: experimental basis (1)

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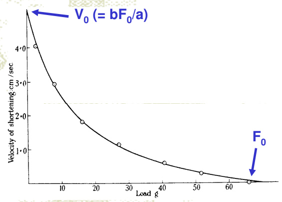
## Hill's equation for tetanized muscle

**Empirical relation for the force-velocity curve (A.V. Hill, 1938)**

**Based on thermo-dynamics !!** → **Nobel Prize 1922**

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

| | |
|---|---|
| *v* | contraction velocity |
| *F* | muscle force |
| $F_0$ | isometric tetanic force (constant) |
| *a,b* | constants |

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## Hill's equation for tetanized muscle

Energy Balance: $E=A+S+W$

| | |
|---|---|
| *E* | Energy release |
| *A* | Maintenance (activation) heat |
| *S* | Shortening heat |
| *W* | Work done |

| | |
|---|---|
| isometric condition: | $E = A$ |
| quick release experiment, 'extra energy': | $S+W = b(F_0-F)$ |
| Work done | $W = F.v$ |
| empirically: | $S = a.v$ |

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## Hill's equation for tetanized muscle

**Alternative formulations of force – velocity relationship**

- force generating element + non-linear damper

$$F = F_0 - \frac{F_0+a}{v+b}v = F_0 - k(v)v$$

- dimensionless force-velocity relation *g(v)*, usually assumed independent of $F_0$

$$F = F_0 \frac{1-(v/v_0)}{1+c(v/v_0)} = F_0 \cdot g(v)$$

$$c = F_0/a \,; v_0 = b \cdot c$$

What is $F_0$?

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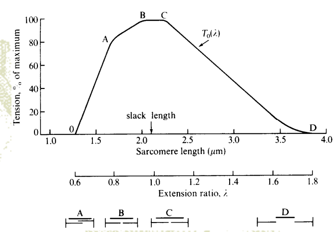
## Force-length relationship

$$F_i = F_0 \cdot f(l)$$




| | |
|---|---|
| $F_o$ | : isometric tetanic force at optimum length |
| *f(l)* | : dimensionless force-length relationship |

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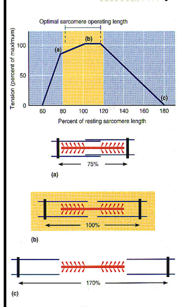
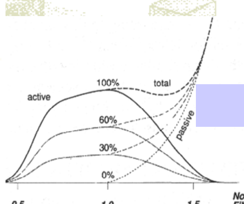
## Force Length relationship




Optimum fiber length 2,6 μm

Maximal force range ~±50%




$$F_i = F_0 \cdot f(l)$$

*Figure 2.13.* Normalized force-length curves, where tensile force has been scaled by $a(t)$ and normalized by $F_o^M$ and length has been normalized by $\ell_o^M$. Note that the same passive force is added to the various active force curves to produce the total isometric force length curves.

## Sarcomere force

$$F = F_0 \cdot q(t) \cdot f(l) \cdot g(v)$$

*q(t)*: dimensionless activation dynamics (active state ~ [$Ca^{2+}$])

*f(l)*: force – length relationship

*g(v)*: force – velocity relationship

$F_0$: maximal isometric force

Sarcomere force + muscle morphology ≈ muscle force

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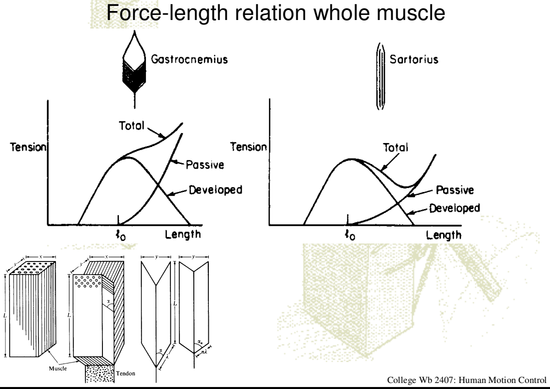
## Force-length relation whole muscle



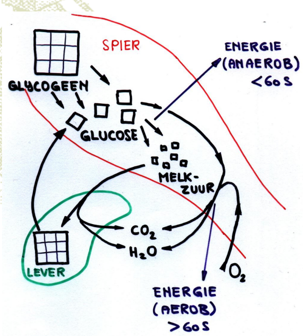



## Main energy consuming processes

- Calcium re-uptake in sarcoplasmatic reticulum:
  - Related to active state
- Cross-bridge unbinding:
  - Related to number of bound cross-bridges

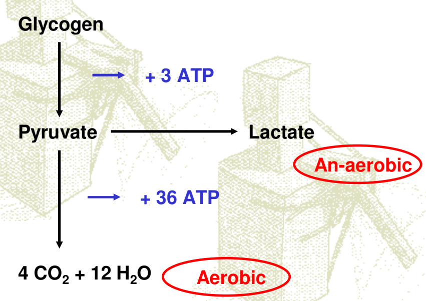


## Energy from glucose breakdown





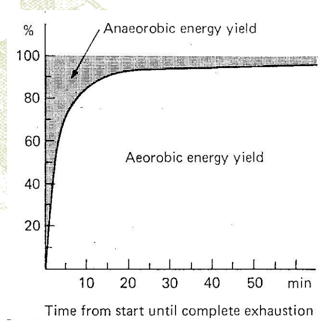

## Glycogen turn-over




**1 liter $O_2$ provides 21 kJ energy !**



## Usage anaerobic energy






## Oxygen consumption

- 1 liter oxygen provides 21 kJ energy
  - 80% heat
  - 20% external power (mechanical energy)
- $VO_2$-max: Maximal oxygen consumption (liters/minute)
- $VO_2$-max men > $VO_2$-max women
- decrease $VO_2$-max with age
- increase $VO_2$-max by training
- range $VO_2$-max: 1.2 - 7.0 liters/minute

## Efficiency

- $$\text{Efficiency} = \frac{\text{external power}}{\text{consumed power}}$$
- External power
  - Moment x angular velocity
  - External force x velocity
- Consumed power
- $VO_2$: liters $O_2$/minute
- 1 liter $O_2 \approx$ 21 kJ

- Cycling, walking: E ≈ 20 - 25%
- Manual wheelchair propulsion: E ≈ 8 - 10%



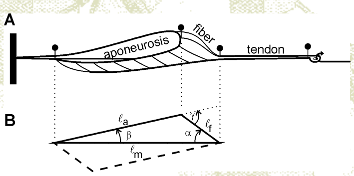
Part 2
## Muscle models

Contents
- Hill-type models
  - Hill (1938)
  - Winters and Stark (1985)
- Cross-bridge models
  - Huxley (1957)
  - Zahalak (1981)
- Finite element models



## Planimetric models

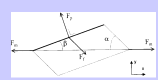
- simplified geometry 2-D
- constant muscle volume (Swammerdam, 1767)





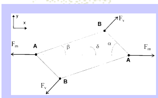

## Planimetric models

alternatives:
model Otten

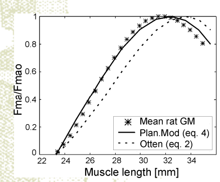


$$F_m = F_f \frac{\cos(\alpha+\beta)}{\cos\beta}$$

revised model



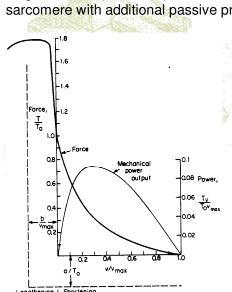
$$F_m = F_f \frac{\sin(\alpha+\beta)}{\sin\beta}$$

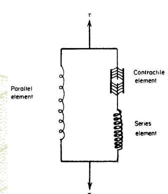


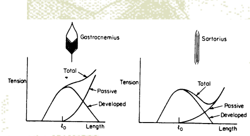



## Hill-type models

Original model (Hill, 1938): muscle as a large sarcomere with additional passive properties

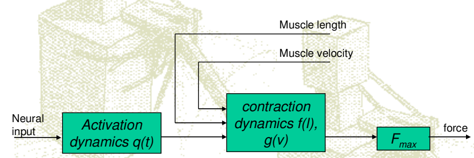




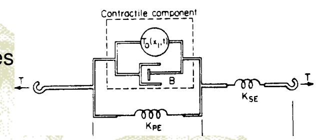

## Hill-type models

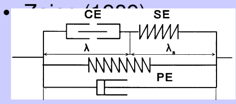



$$F = F_0 \cdot q(t) \cdot f(l) \cdot g(v)$$

## Hill-type models

Many alternatives
- Hatze (1981)
- Winters and Stark (1985)
- Zajac (1989)




$$F_{mus} = \frac{F_{SE}}{\cos\alpha} + F_{PE} + F_{PV}$$
$$F_{SE} = F_{CE}$$
$$F_{CE} = F_{max} \cdot q(t) \cdot f(l) \cdot g(v)$$



## Hill-type models

Activation dynamics

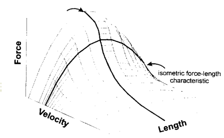
$$F_{CE} = F_0 \cdot q(t) \cdot f(l) \cdot g(v)$$

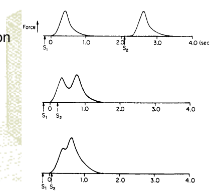
1. $q$ single parameter, $0<q<1$

or

2. $q$ defined by two 1st order differential equations related to Neural activation ($N_a$) and calcium dynamics ($\psi$)

$$\tau_1 \frac{dN_a}{dt} + N_a = u(t)\,;$$
$$\tau_2 \frac{d\psi}{dt} + \psi = N_a\,;$$
$$q(t) = q(\psi)$$

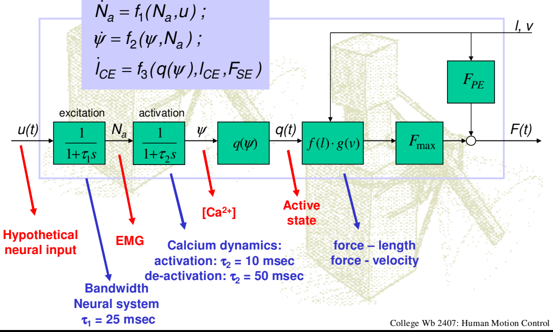




## Muscle dynamics

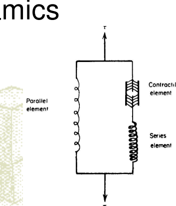
$$\dot{N}_a = f_1(N_a, u)\,;$$
$$\dot{\psi} = f_2(\psi, N_a)\,;$$
$$\dot{l}_{CE} = f_3(q(\psi), l_{CE}, F_{SE})$$






## Contraction dynamics

- Input: active state q(t), muscle length $l_{mus}$
- State variable: length CE, $l_{ce}$
- Length SE: $l_{se} = l_{mus} - l_{ce}$
- Output: $F_{ce} = F_{se} = f_1(l_{se})$
- Derivative state variable: contraction velocity $v_{ce} = f(l_{ce}, q(t))$
- $F_{se} = q(t) * f(l_{ce}) * g(v_{ce}) * F_{max}$
  $g(v_{ce}) = q(t) * f(l_{ce}) * F_{max} / F_{se}$ (= $F_{rel}$)
- Inverse force – velocity relation
  $v_{ce} = g^{-1}(F_{rel})$






## Hill-type models

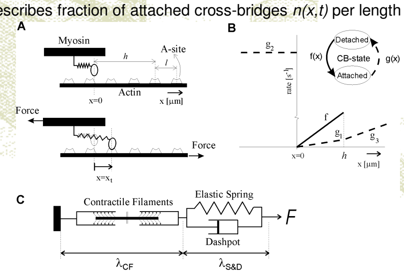
**remarks**
- Are active state, force-length and force-velocity independent?
- Large number of (unknown) parameters for each human muscle (>100), data based on animal experiments
- Parameters constant?
- No link to microscopic mechanism
- Negative stiffness in force-length characteristic, but
- Force-velocity relation increases impedance



## Cross-bridge models (Huxley, 1957)

**Nobel Prize 1963!!**

- attachment and detachment rate functions *f* and *g* describe probabilities
- describes fraction of attached cross-bridges *n(x,t)* per length x

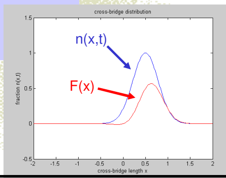


## Cross-bridge models

- attachment and detachment rate functions *f* and *g* describe probabilities
- describes fraction of attached cross-bridges *n(x,t)* per length x
- k is linear cross-bridge stiffness
- $F_x = k.x$ is cross-bridge force
- Muscle force F depends on distribution *n(x,t)* of cross-bridges

$$\frac{dn(x,t)}{dt} = \frac{\partial n}{\partial t} + v\frac{\partial n}{\partial x} = f(x)\{N - n(x,t)\} - g(x)n(x,t)$$

$$F = k\int_{-\infty}^{\infty} x \cdot n(x,t) \cdot dx$$



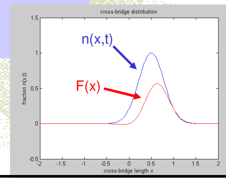

## Cross-bridge models

- k is linear cross-bridge stiffness
- $F_x = k.x$ is cross-bridge force
- Muscle force F depends on distribution *n(x,t)* of cross-bridges
- Muscle stiffness K depends on cross-bridge stiffness k

$$\frac{dn(x,t)}{dt} = \frac{\partial n}{\partial t} + v\frac{\partial n}{\partial x} = f(x)\{N - n(x,t)\} - g(x)n(x,t)$$

$$F = k\int_{-\infty}^{\infty} x \cdot n(x,t) \cdot dx$$

$$K = \frac{dF}{dx} = k\int_{-\infty}^{\infty} n(x,t) \cdot dx$$




## Cross-bridge models (Zahalak, 1981)

- Rewrite distribution equation in set of ordinary differential equations with distribution moments $Q_\lambda$

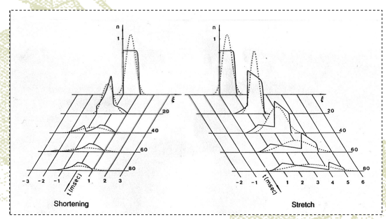
$$Q_\lambda(t) = \int_{-\infty}^{\infty} x^\lambda \cdot n(x,t) \cdot dx \qquad \lambda = 0,1,2,...$$

$$\dot{Q}_\lambda(t) = h(t) + \lambda \cdot v \cdot Q_{\lambda-1}(t)$$

- Assume a normal distribution (Gaussian curve) for *n(x,t)*



## Cross-bridge distribution (Zahalak, 1981)




**Huxley-model** (solid line)

**Zahalak-model** (dashed line)



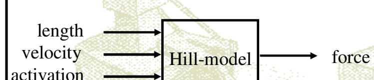
## Cross-bridge models

**remarks**

- rather complex
- shape of functions *f* and *g* is arbitrary to a certain extent
- explains force-velocity curve
- activation dynamics that has to be added is more complex
- possible to predict chemical energy
- good prediction of force and stiffness

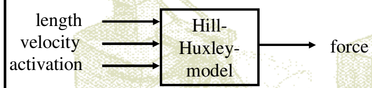


## Summary Hill-type models




- 3 inputs, 1 output
- Reasonable good for activation input
- Not good for length input (~ stiffness)
  - derivative force-length relationship
  - Underestimation muscle stiffness
- Not good for velocity input (~ viscosity)
  - Derivative force-velocity relationship
  - Overestimation muscle viscosity

## Combined Hill-Huxley-type models




- Force-velocity curve from cross-bridge model
- Force-length & activation dynamics from Hill model
- Does not exist yet !

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## Summary Huxley-type models


- 1 inputs, 1 output
- No force-length relationship, no activation dynamics

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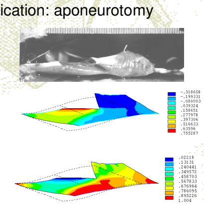
## Finite element models

- Combining shape and function
- Hill type CE in user defined elements
- large deformations
- application: aponeurotomy

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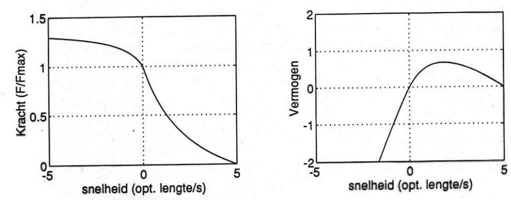
## Muscle power

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