Bio-Inspired Design

BioEnergy: Biological Springs

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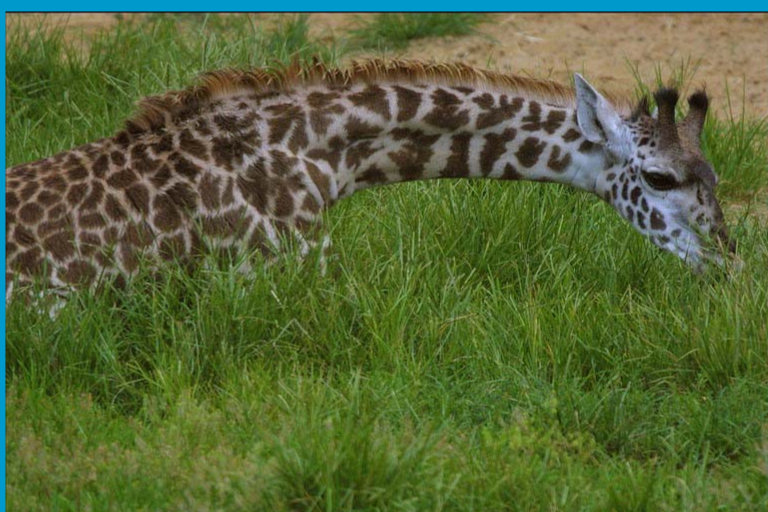
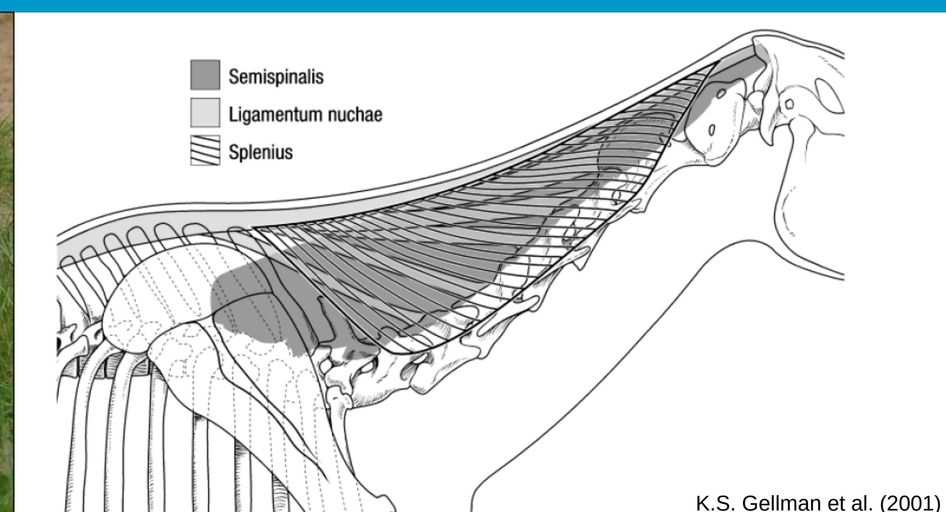
Lecture 3: Bioconstruction
Bioenergy (biological springs)

- **Feb 17, 8:45-10:30, room F, Just**
- Contents: bioenergy: storing energy in springs (neck of giraffe, chameleon, grasshopper, tendons in human ankles), vibration (birds, flying insects), etc.





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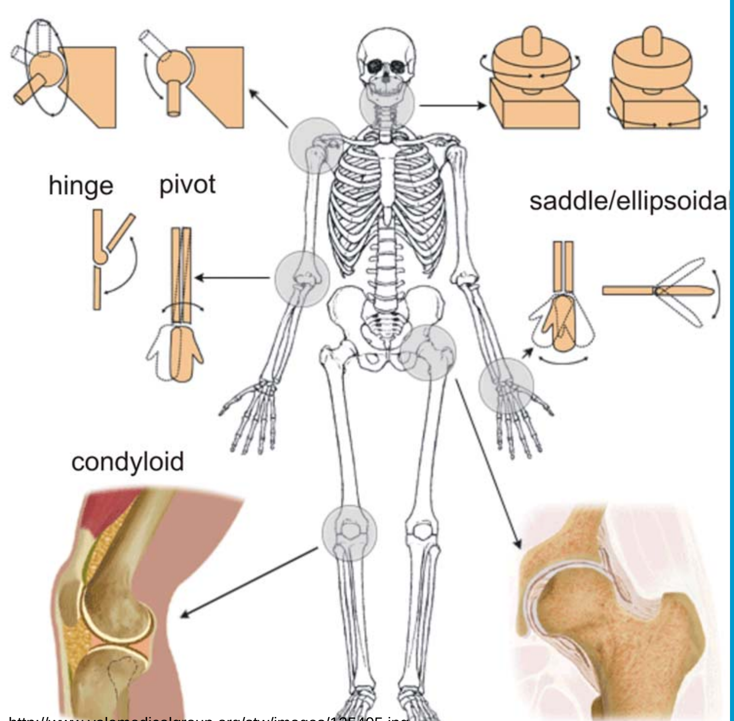
Lecture 3: Bioconstruction
Bioenergy (biological springs)

- Springs: muscles and tendons
- Vibration examples: insect wings, legged locomotion
- Storage examples: chameleon tongue, neck ligaments
- Engineering example: human-friendly robotic arm

Vertebrates: joints

- Synarthroses: hardly movable (sutures in human skull)
- Amphiarthroses: slightly movable (cartilage attachments in ribs and vertebrae disks)
- Larger range of motion:
  - Ball-and socket (e.g. hip, GH-joint)
  - Ellipsoidal (e.g. fingers)
  - Condyloid (e.g. knee joint)
  - Saddle (e.g. part of the wrist joint)
  - Pivot (e.g. radius/ulna joint)
  - Hinge (e.g. elbow joint)
  - Plane/gliding (e.g. scapula joint)



http://www.yalemedicalgroup.org/stw/images/125405.jpg

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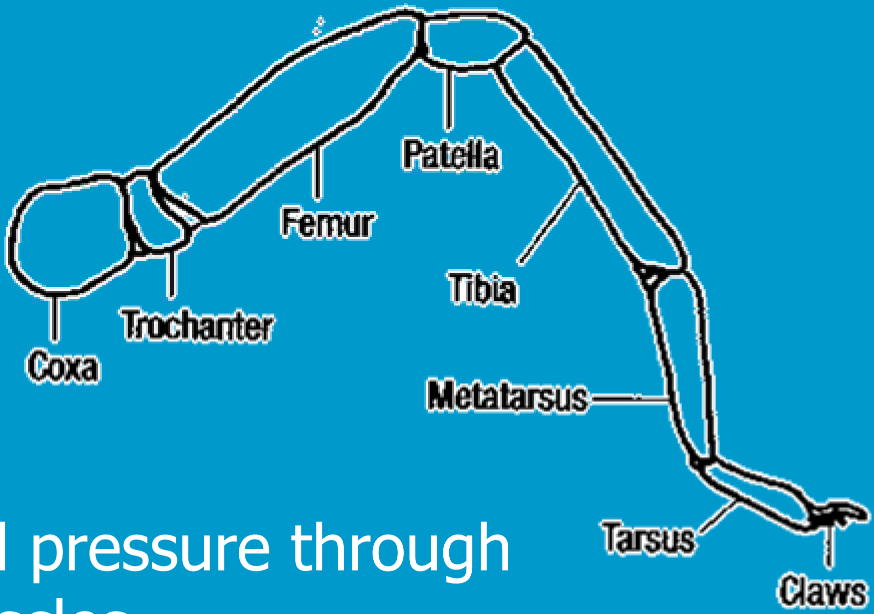
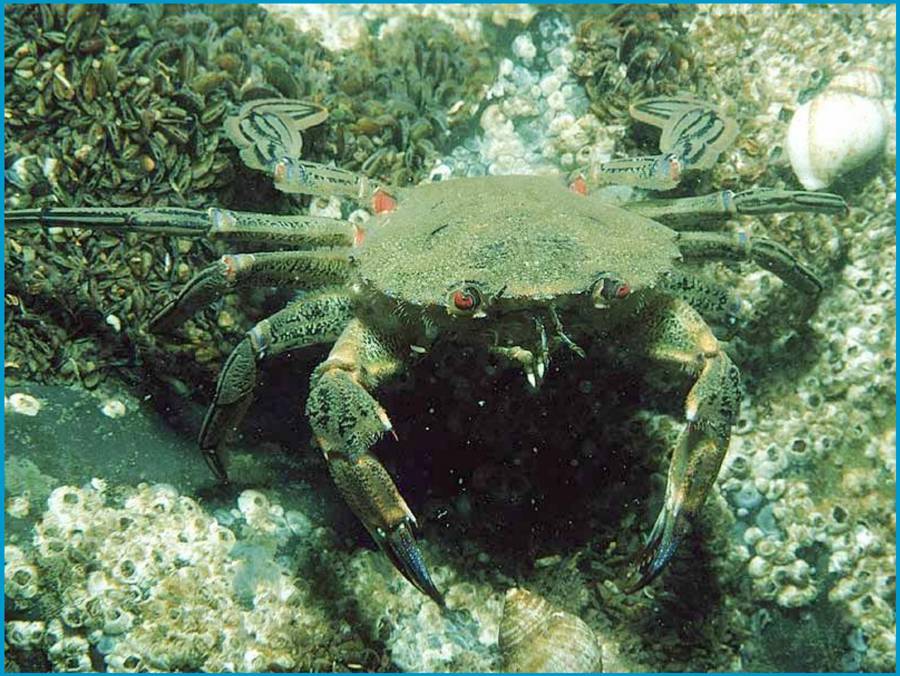
Muscles: Arthropods (e.g. spiders)



- External cuticular skeleton
- Harder and softer sections
- Motion by regulating blood pressure through contraction of thoracic muscles
- Per leg 7 segments and 30 muscles for extension, none for flexion (dead spiders curl up)
- Regular molting required (growth)
- Also during ‘soft period’ motion possible

Muscles: Crabs

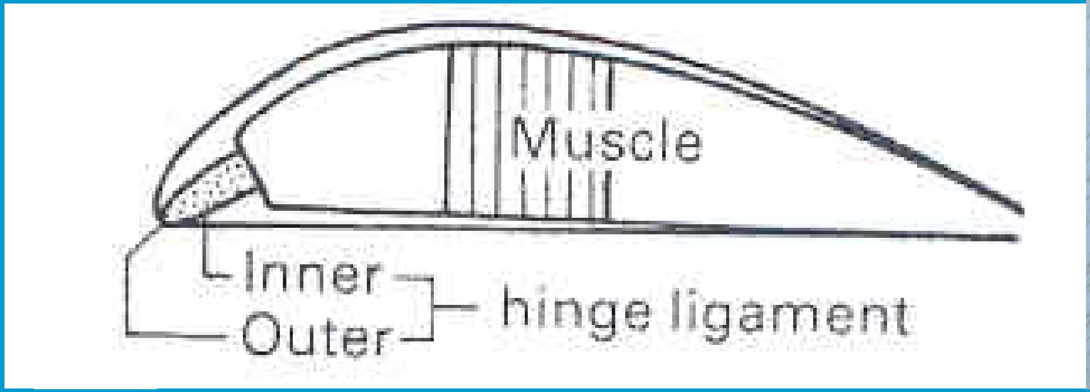
- Also hard enclosure
- Danger of tendon passing though joint axis
- Limited range of motion



Muscles: return spring

E.g.: Scallops (Pecten, Cyprina, Mytilus)

- Compliant joint tends to open
- Open scallop from the inside!
- Eliminates need for agonist-antagonist pair
- Without muscle force → open



Trueman (1953) in Alexander (1988)

Muscles: Energy Storage

Energy Storage

- Tendon material (e.g. Achilles tendon, foot arch)
- Muscle fibres (for small length changes).
- Ligamentum nuchae (spinal ligaments of hoofed animals)
- Mesogloea (collagen fibres in anemones and jellyfish)
- ...

Ligaments: Energy Storage

Hoofed animals

- Cow, giraffe, deer, camel, sheep
- Head statically balanced by ligament
- Potential energy exchange
- Easy conversion from feeding to alert
- Sleep with neck in vertical plane

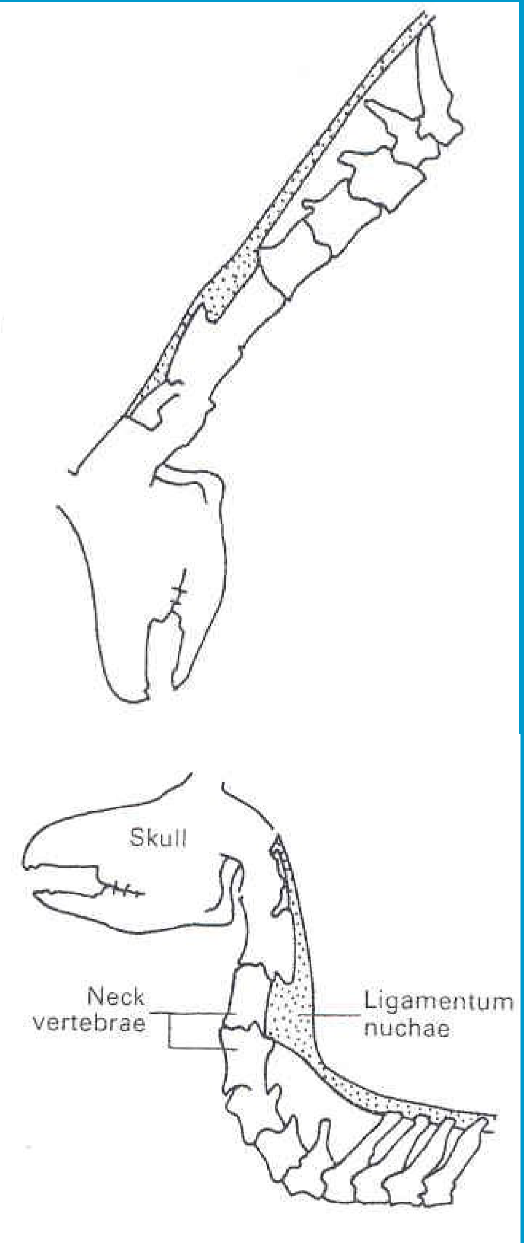
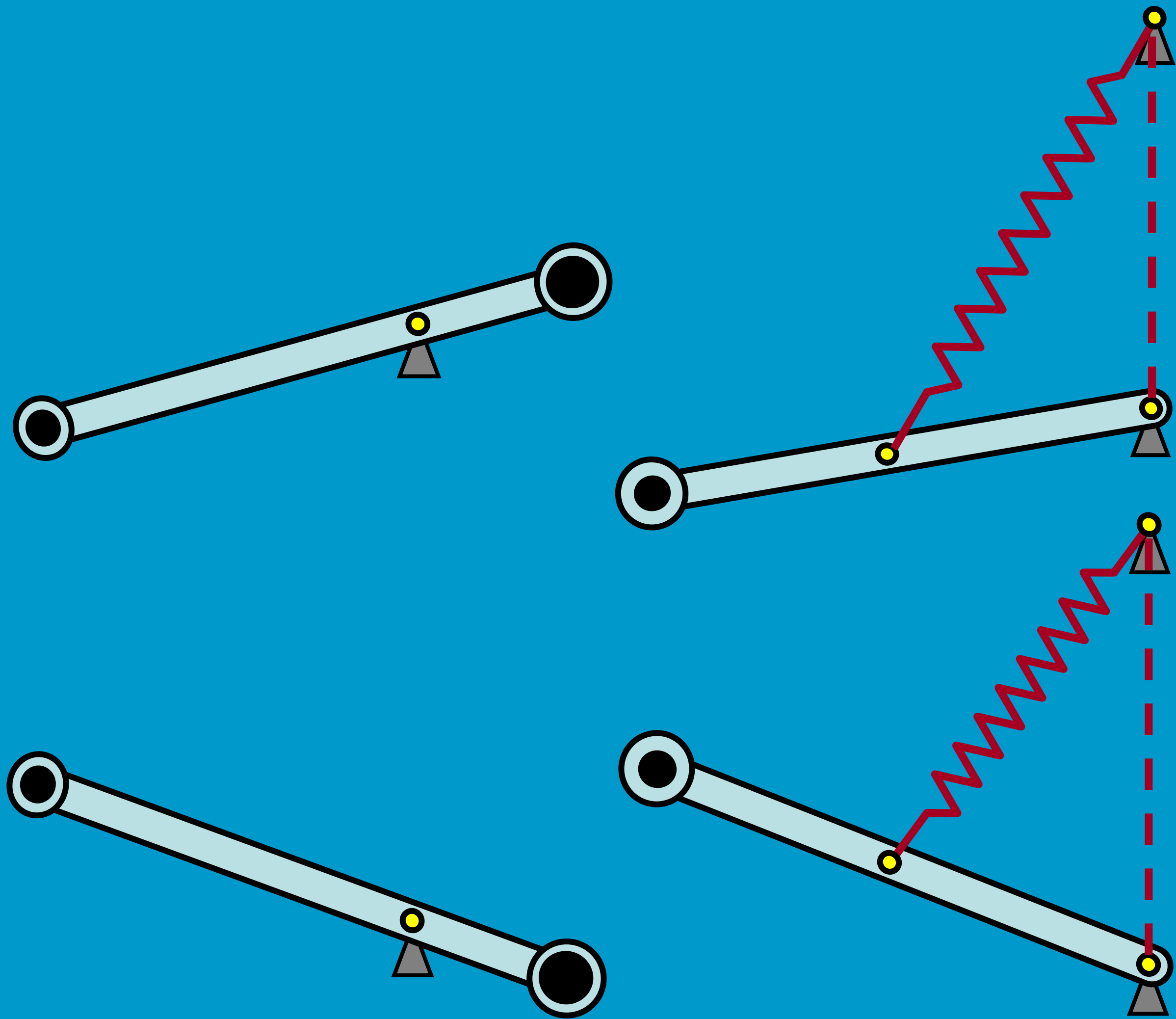
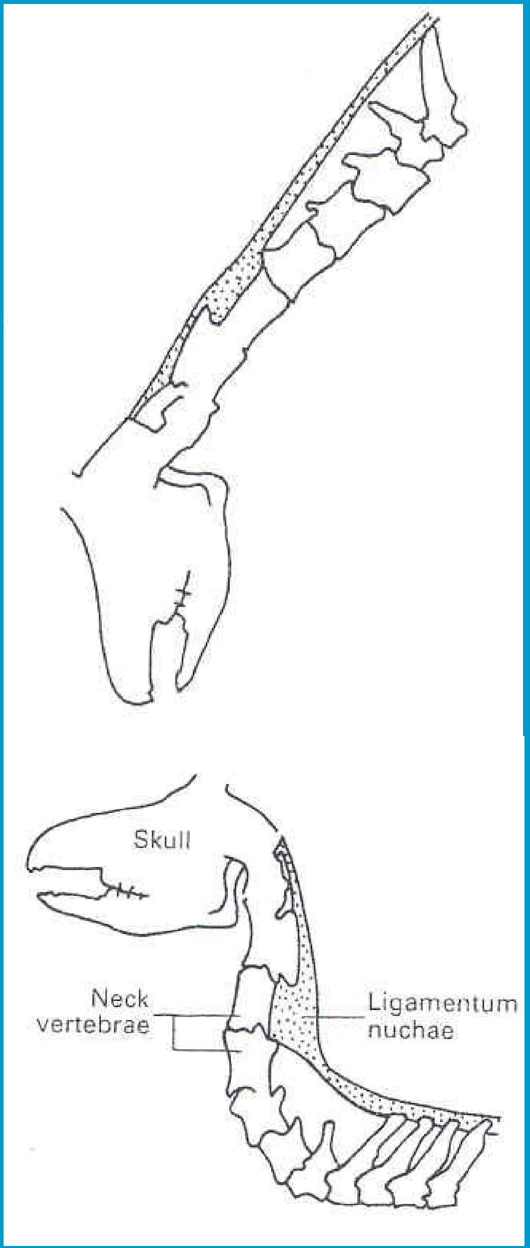


Figure from Dimery, Alexander and Deyst (1985)

Ligaments: Energy Storage

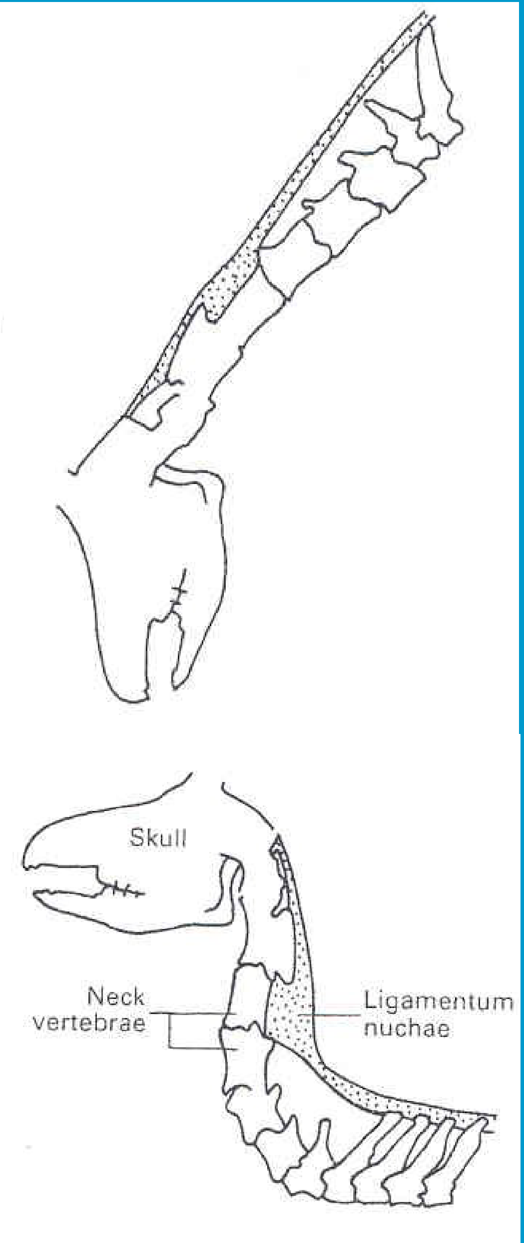




Ligaments: Energy Storage

Sheep:

- Force in ligament in alert position around 10 N
- Force in ligament in feeding position around 80 N
- Sufficient for equilibrating head
- Strain up to 0.8 (close to breaking)
- Experiments with deer and camel yield similar results

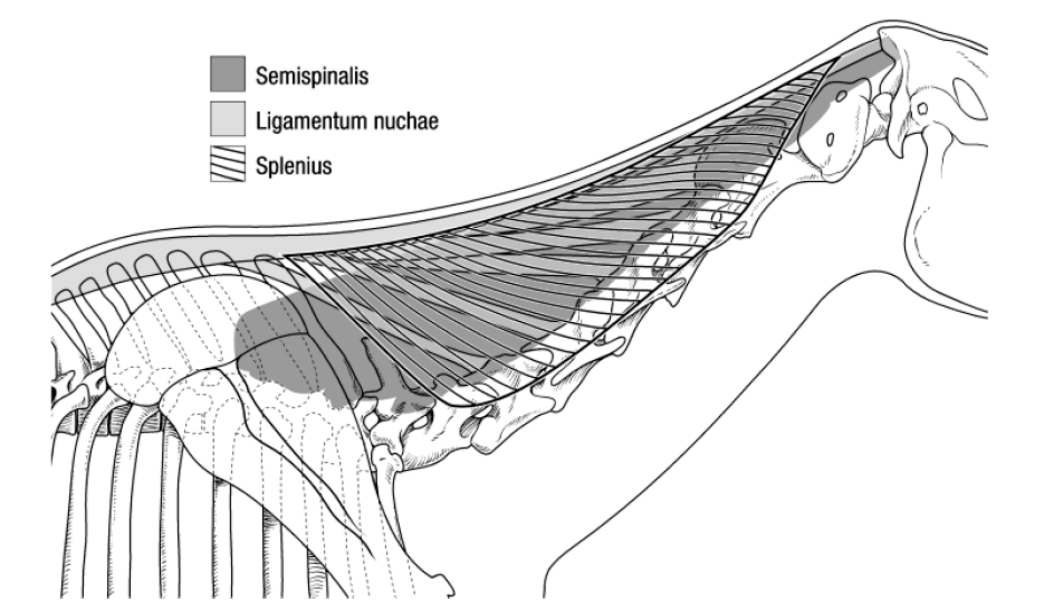


Dimery, Alexander and Deyst (1985)

Ligaments: Energy Storage

Ligamentum Nuchae

$$W = \int F dx = \int \frac{F}{k} dF = \frac{F^2}{2k} = \frac{F^2 L}{2EA} = \frac{\sigma^2}{2} \frac{V}{E}$$



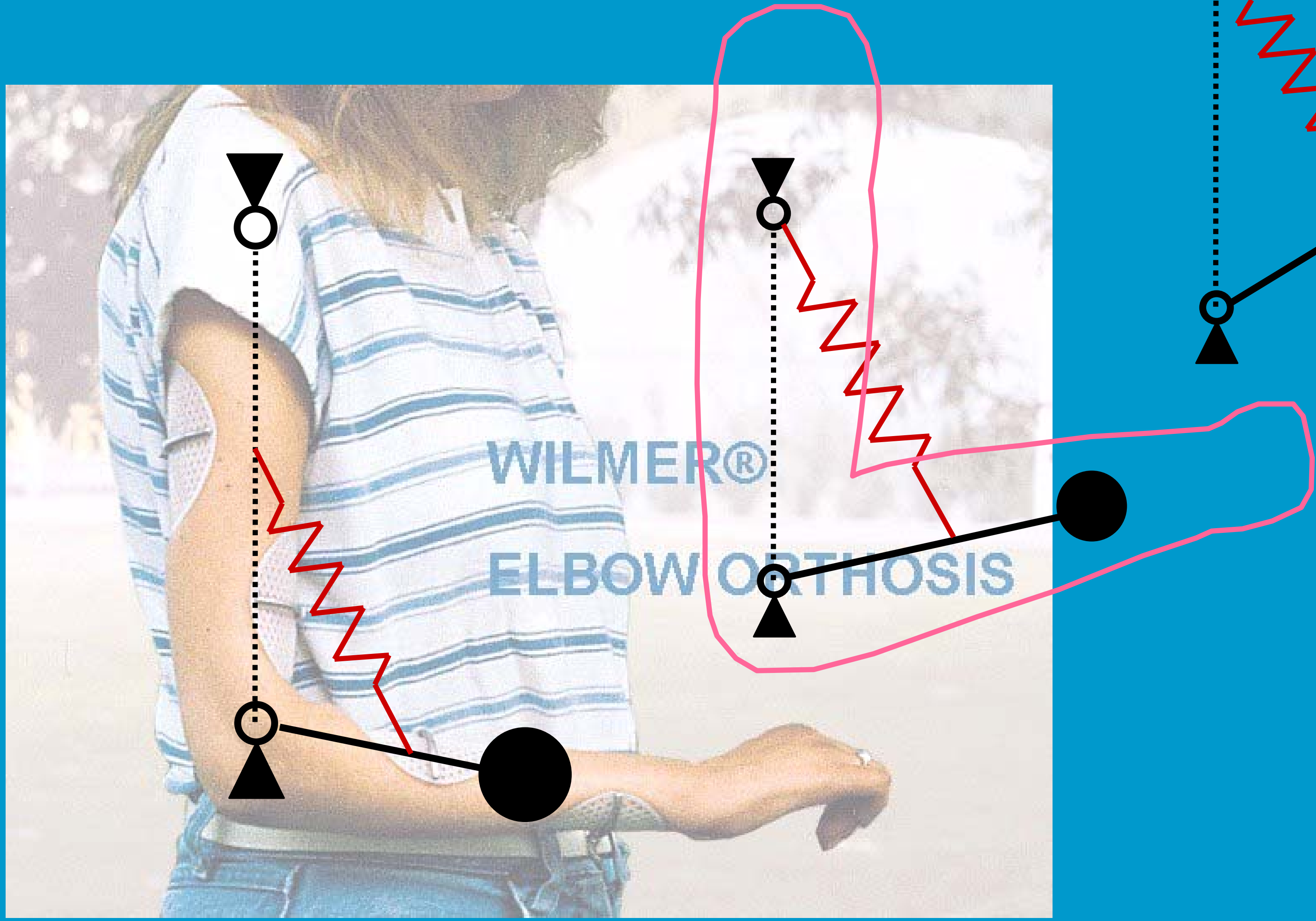
With[1)] $\sigma \approx 6E5\ N/m^2$, $V \approx 5E\text{-}4\ m^3$ (500cc), $E \approx 8E5\ N/m^2$:

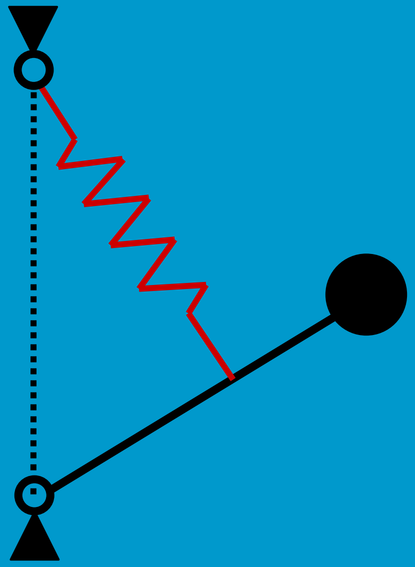
W≈100 J

(equiv. 5 kg over 2 m)

1) Data and figure from K.S. Gellman et al. (2001)

Elbow Orthosis

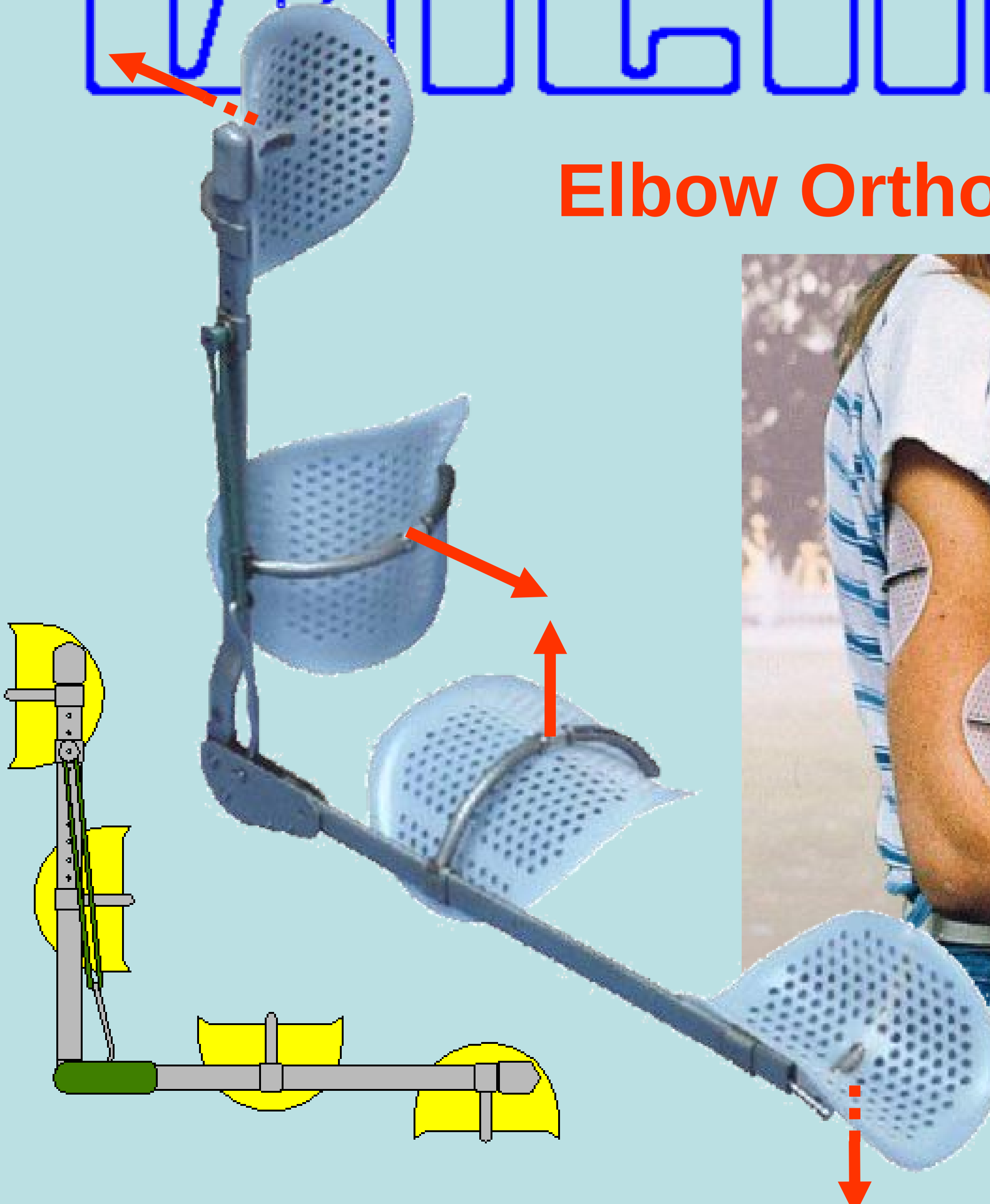


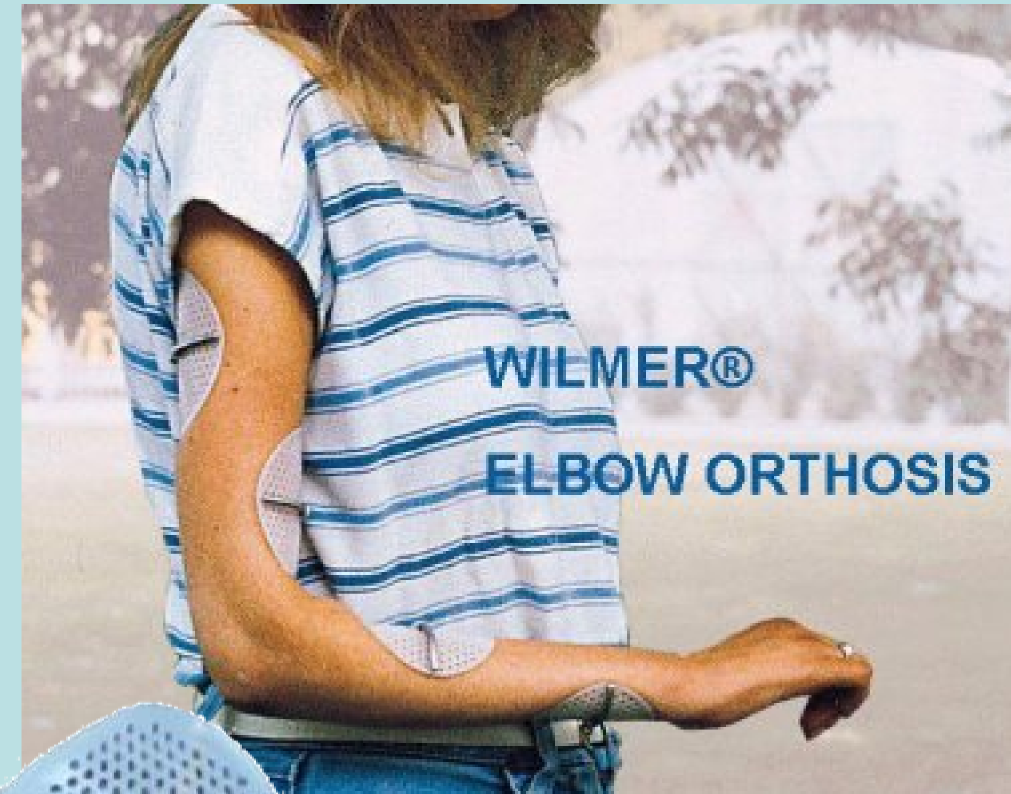


J.C. Cool et al. (1976)

WILMER

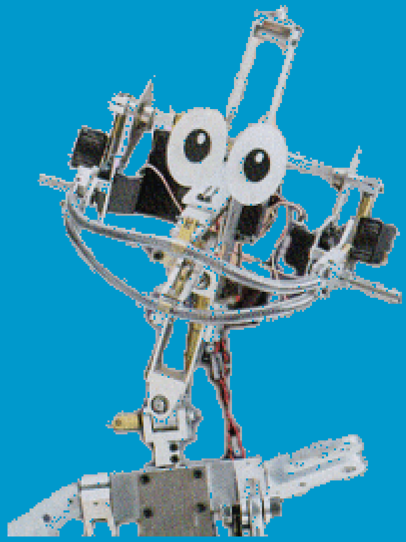
Elbow Orthosis





Safe Robotic Arm

- Harmless, small actuators
  → Elimination of gravity forces
  → Adjustable springs: artificial muscles
- Harmless, soft control
  → No trajectory control
  → Equilibrium point hypothesis control
- Construction



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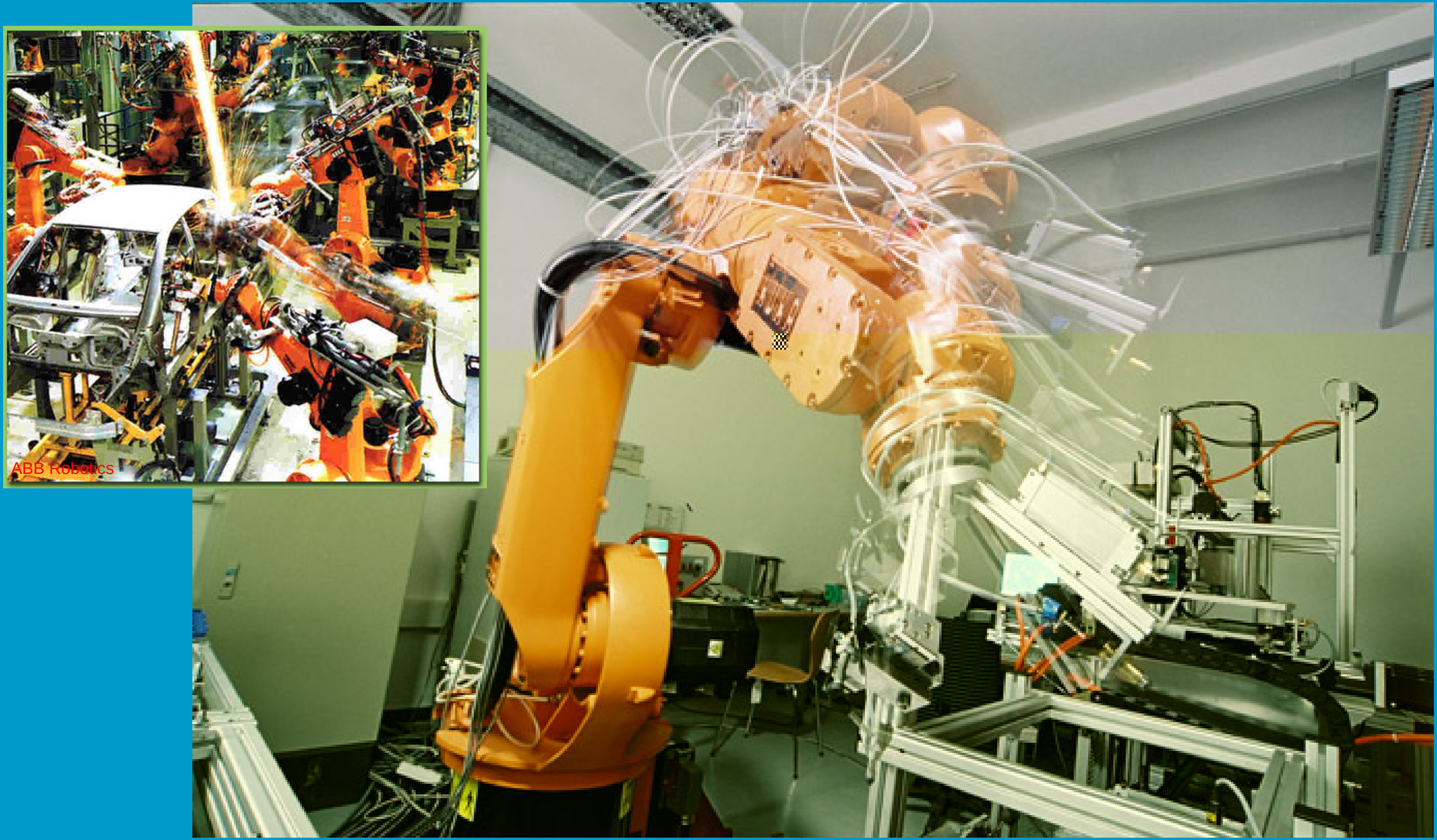
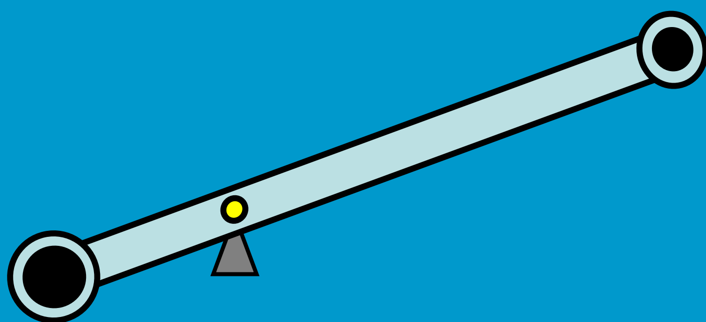
Current robots are unsafe



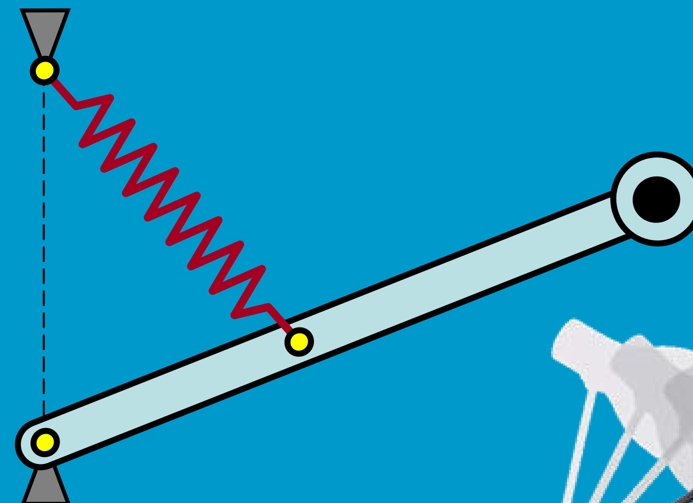
...which can be undesirable

Static Balancing

Any conservative force can be canceled out!



Meager Bridge (Amsterdam)

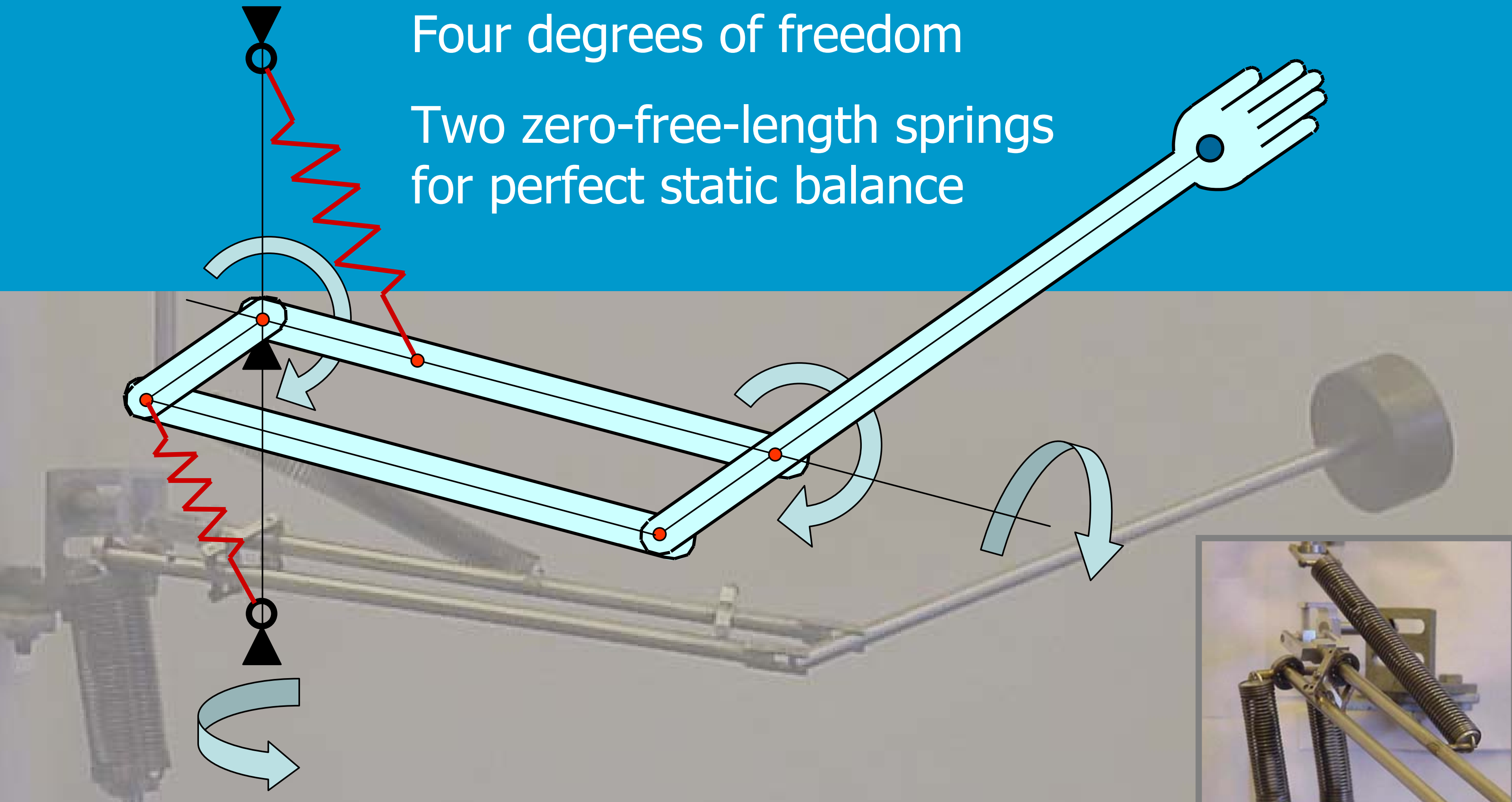


Anglepoise™

Anthropomobile balanced arm

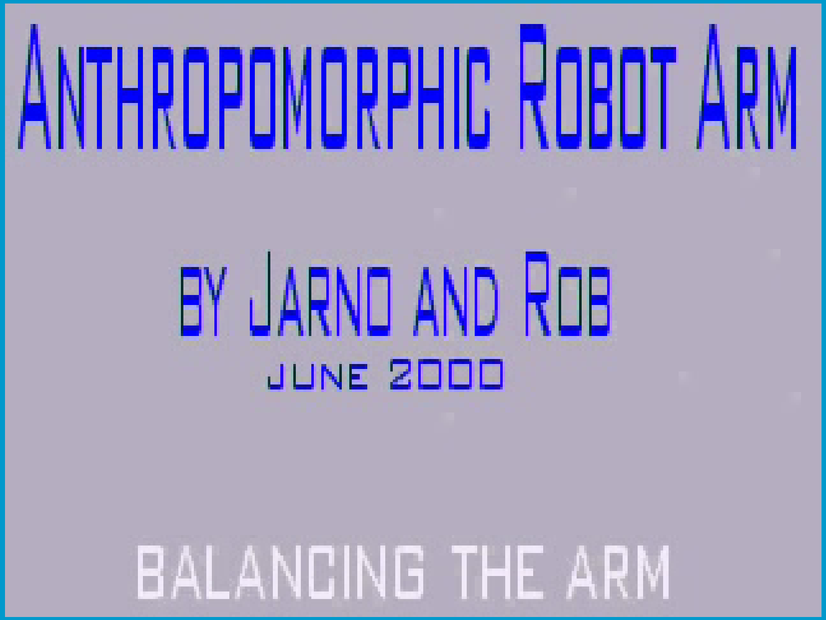
Four degrees of freedom

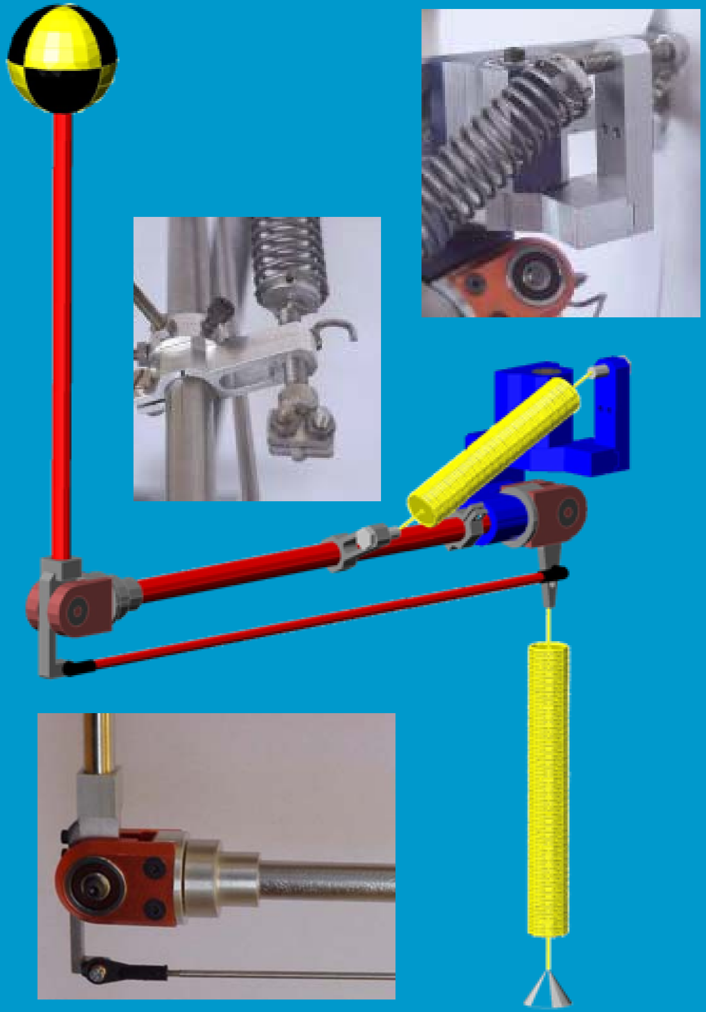
Two zero-free-length springs for perfect static balance



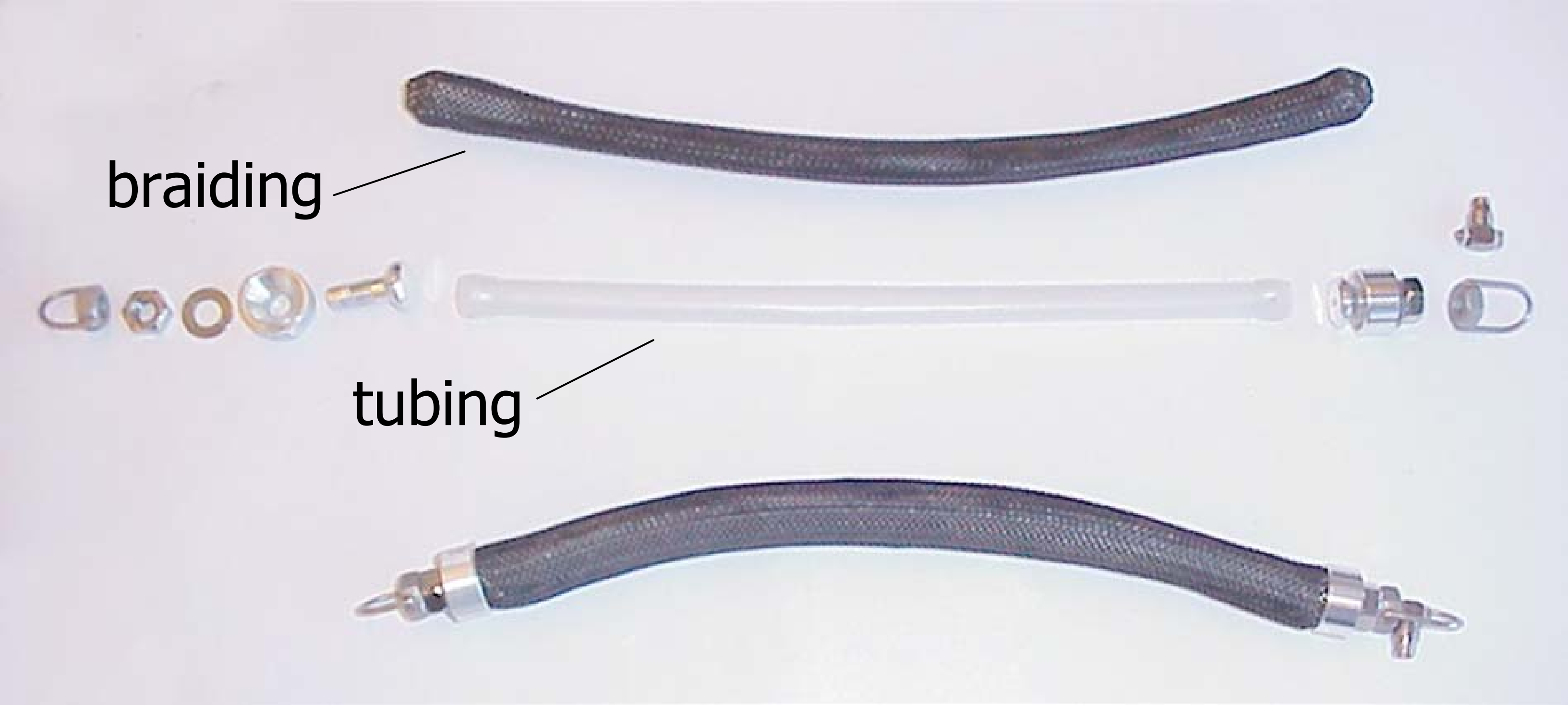
Herder and Tuijthof (1998)

Anthropomobile balanced arm



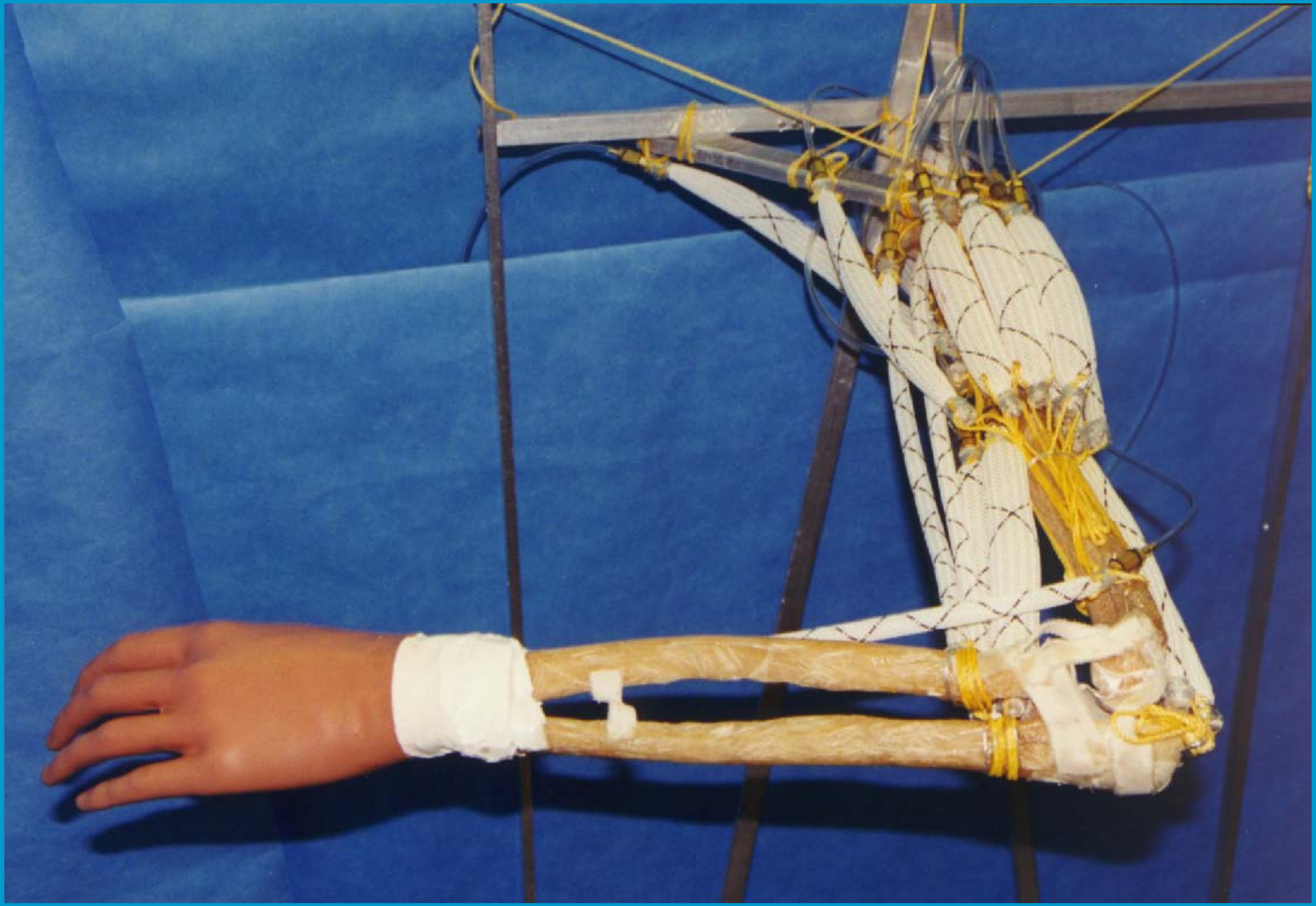


Artifical Muscles
McKibben actuator



JE Surentu (1999)

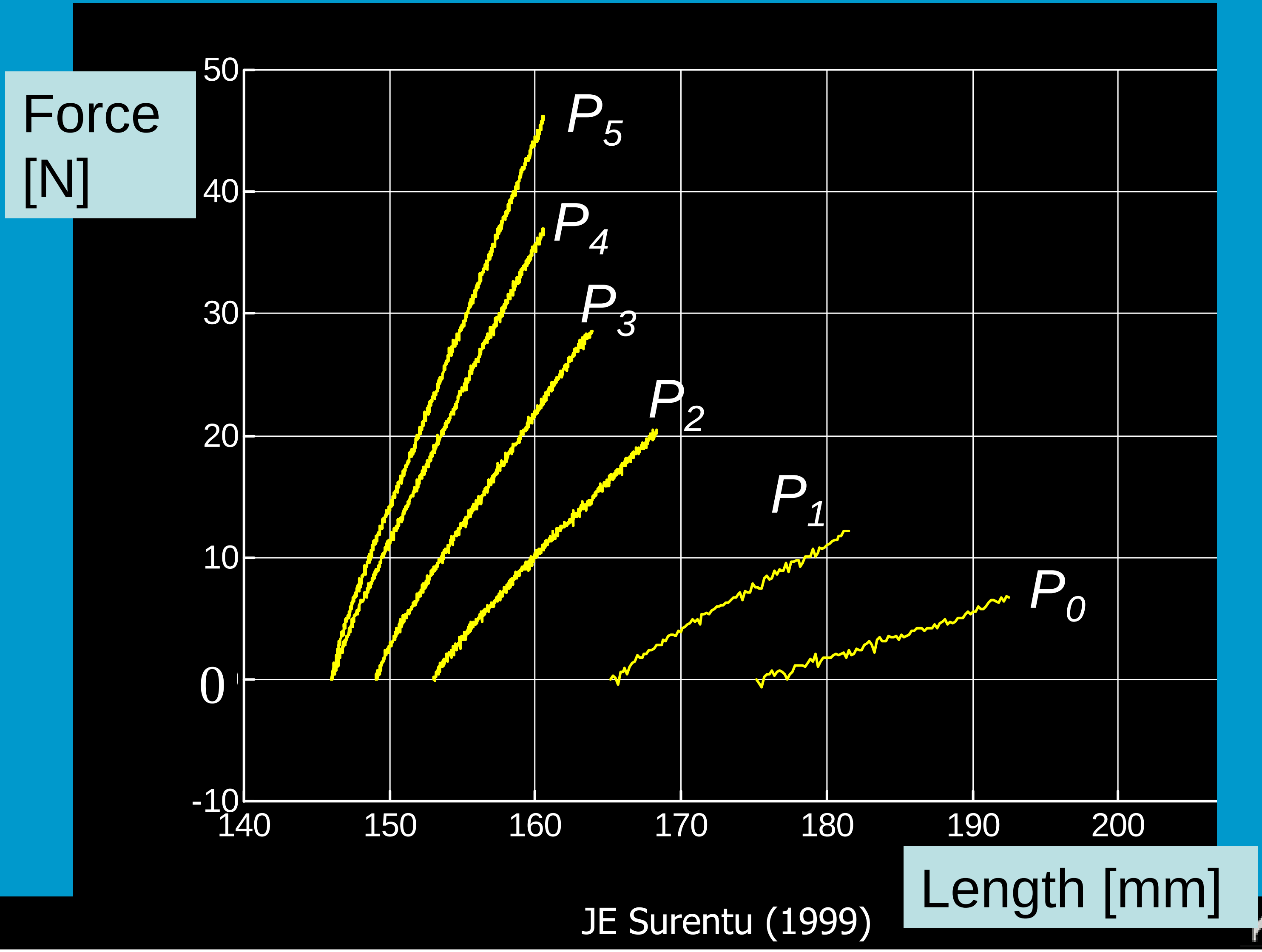
Artifical Muscles
McKibben actuator



B. Hannaford, J.M. Winters, C.P. Chou (1994)

Artificial Muscles

Force-length characterisitic of a silicon McKibben muscle



Extension of the model

$$F.dL = -P.dV + dU_{tub}$$

$$F = F_1 + F_2$$

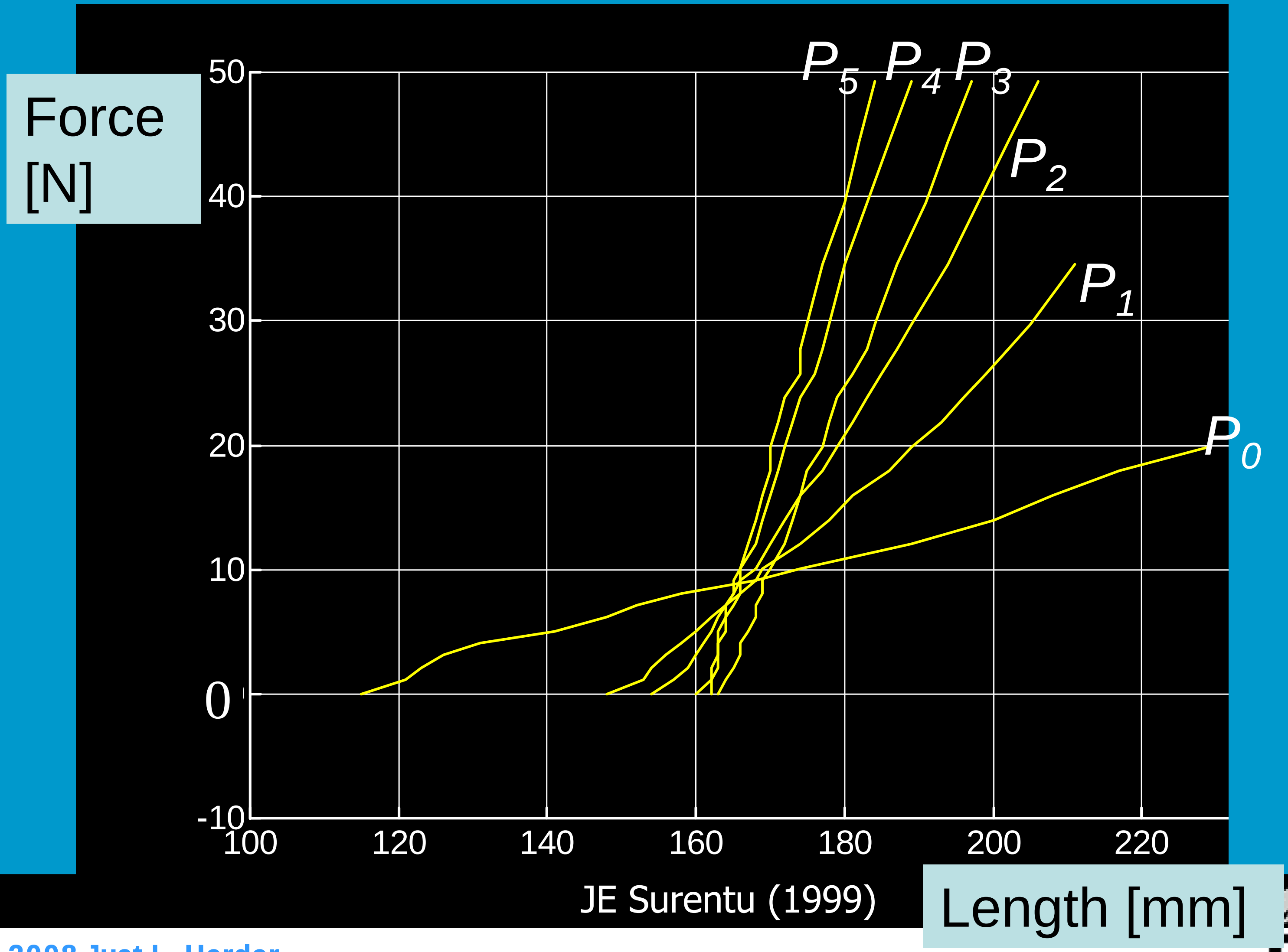
$$F_1 = P.\frac{3\pi}{8}.\frac{D_0^{\ 2}}{L_0^{\ 2}}.(L^2 - L_0^2)$$

$$F_2 = \frac{dU_{tub}}{dL} = V_r\left(\sigma_x \frac{d\varepsilon_x}{dL} + \sigma_y \frac{d\varepsilon_y}{dL}\right)$$

JE Surentu (1999)

Artifical Muscles

Measured characteristics of corrected McKibben muscle



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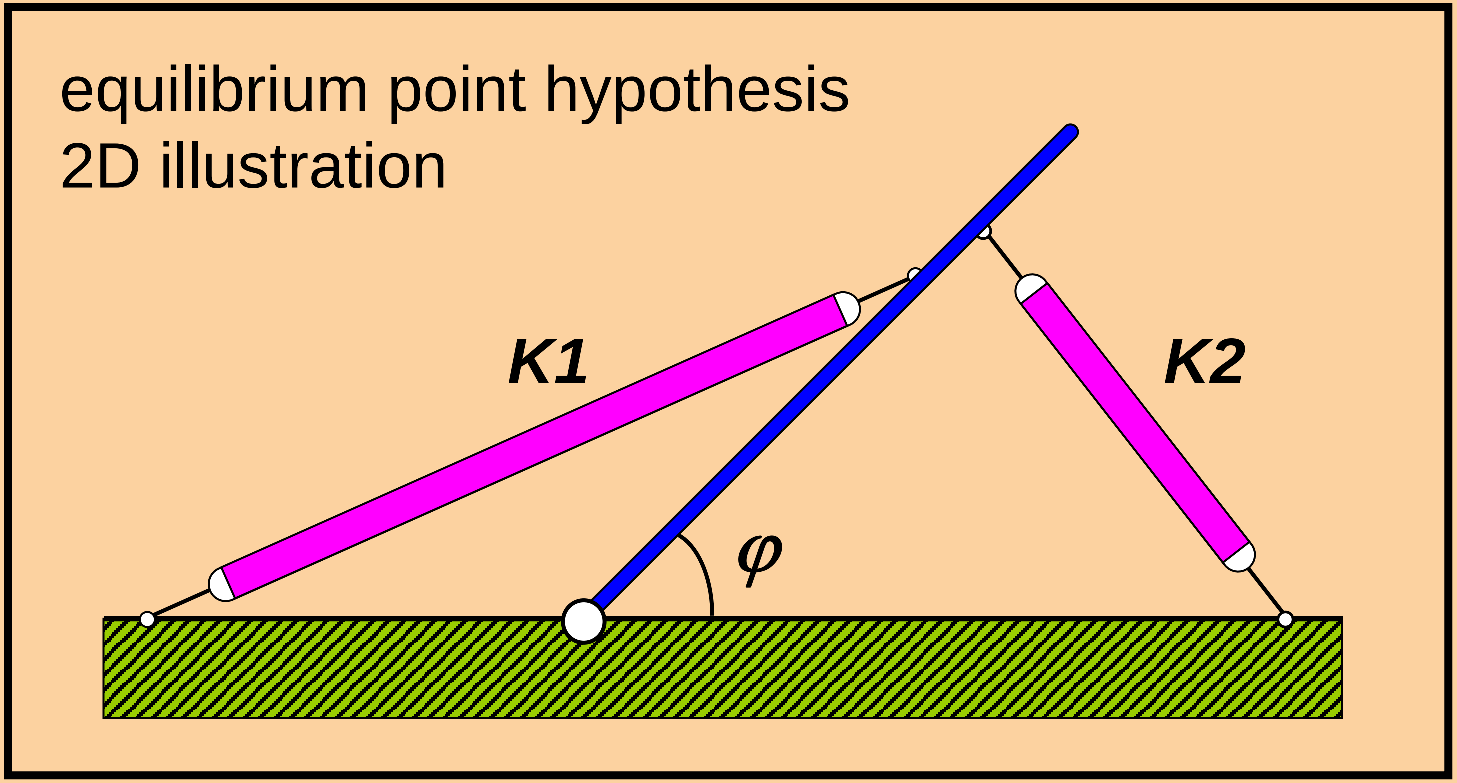
Compliant control

- Safe
- Natural

- Biomechanics
  - equilibrium point hypothesis (Feldman, Bizzi *et al.*)
- Robotics
  - impedance control (Hogan)

Equilibrium point hypothesis

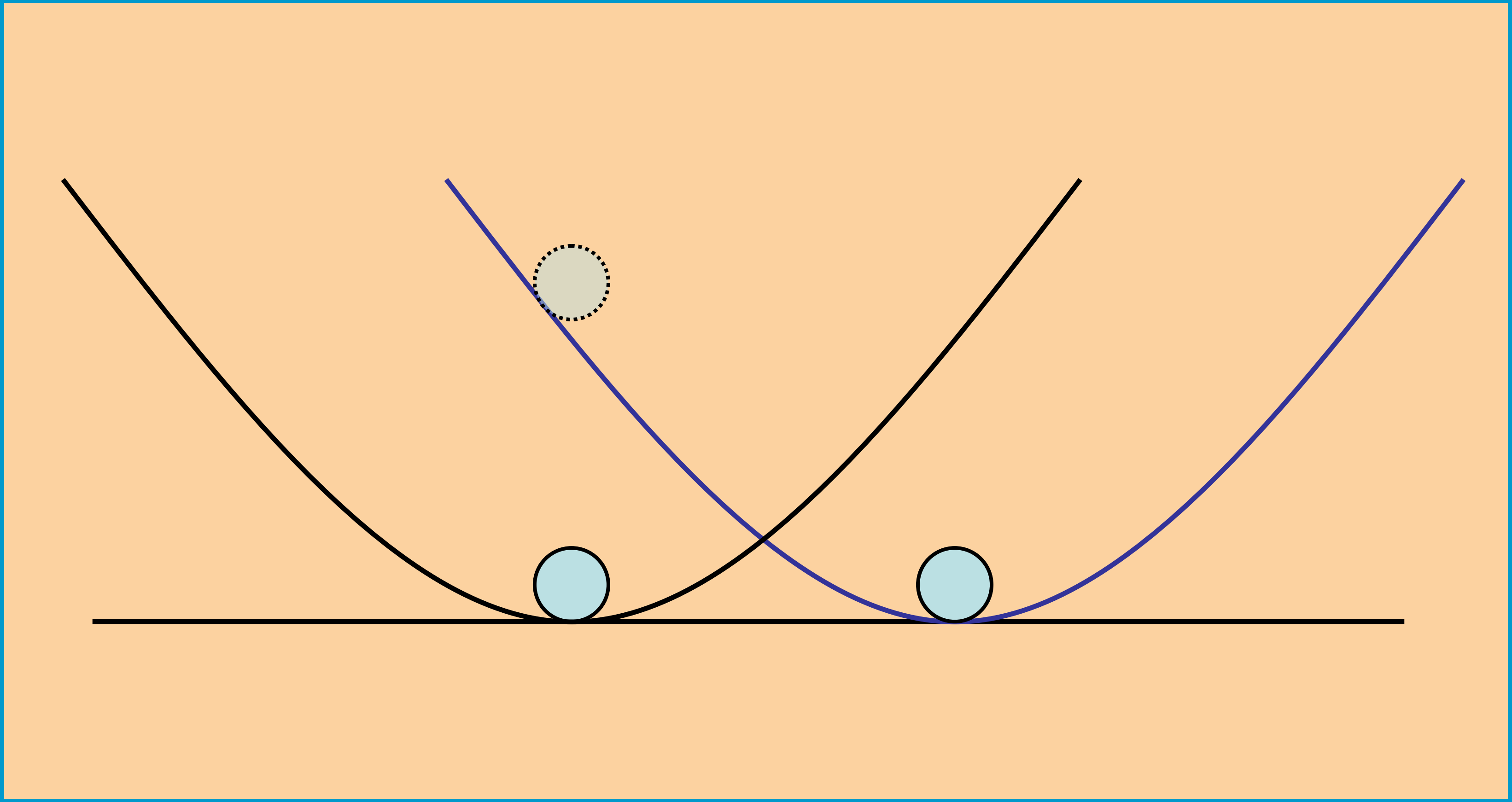
Feldman, Bizzi *et al.*



JE Surentu (1999)

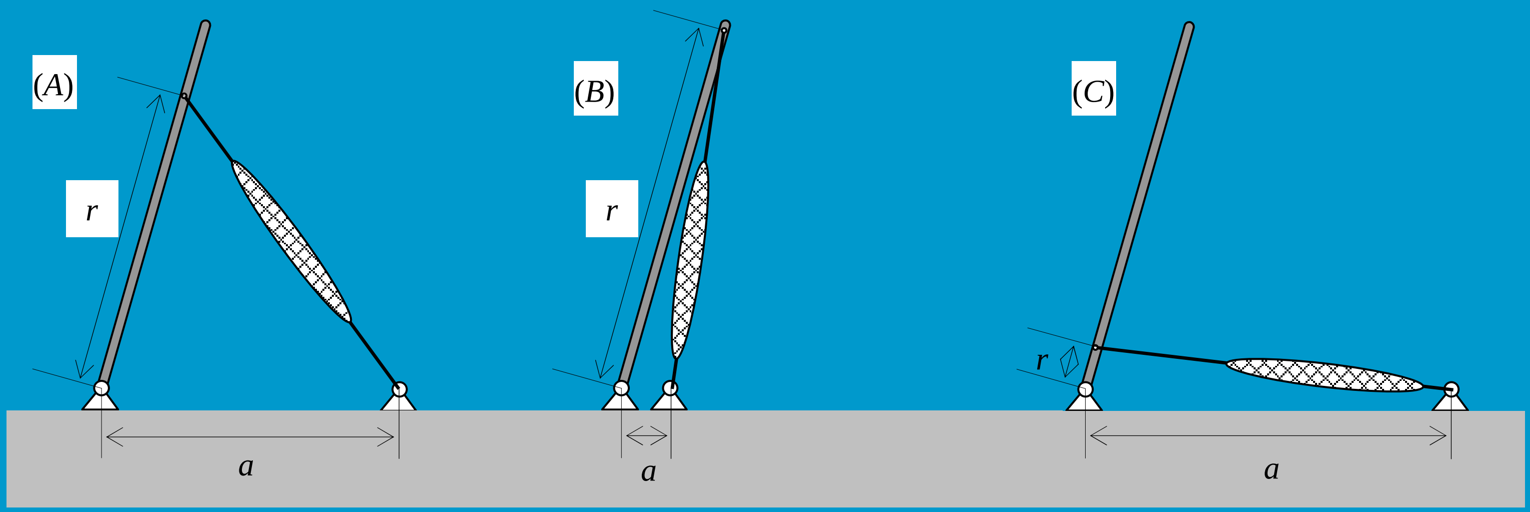
Equilibrium point hypothesis

Feldman, Bizzi *et al.*

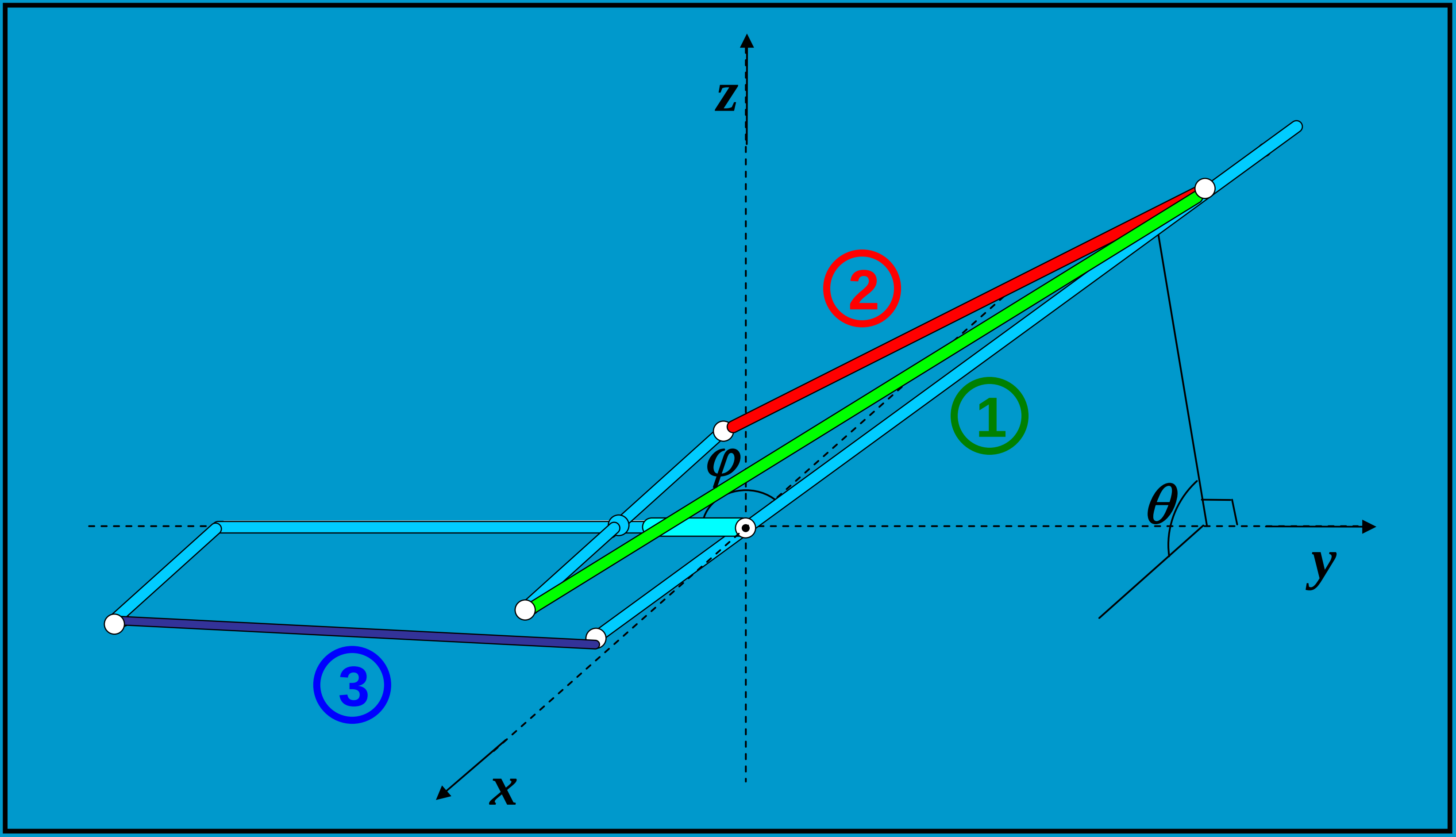


Range of motion

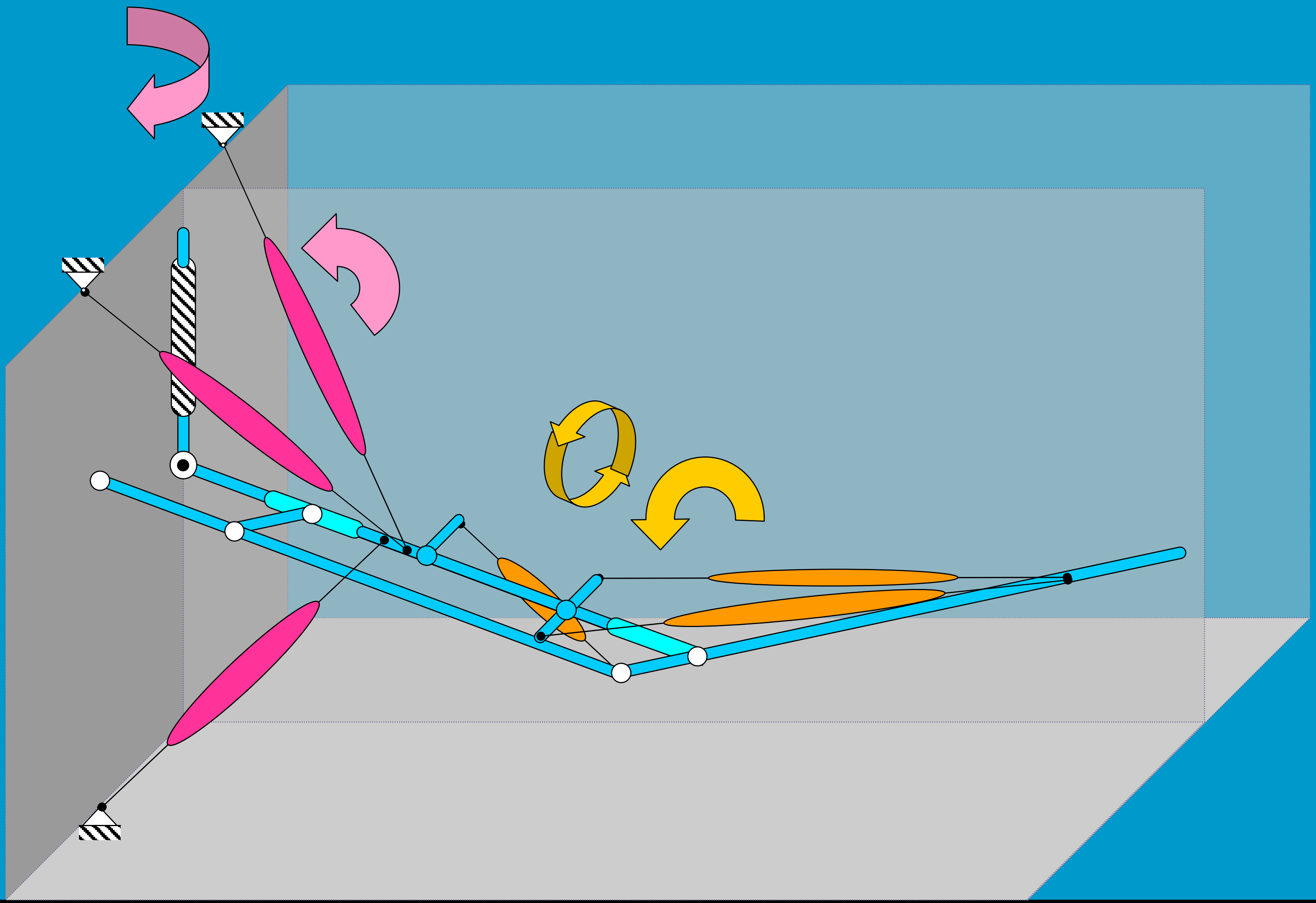
Muscle attachment points



Muscle-lever System



Actuator locations



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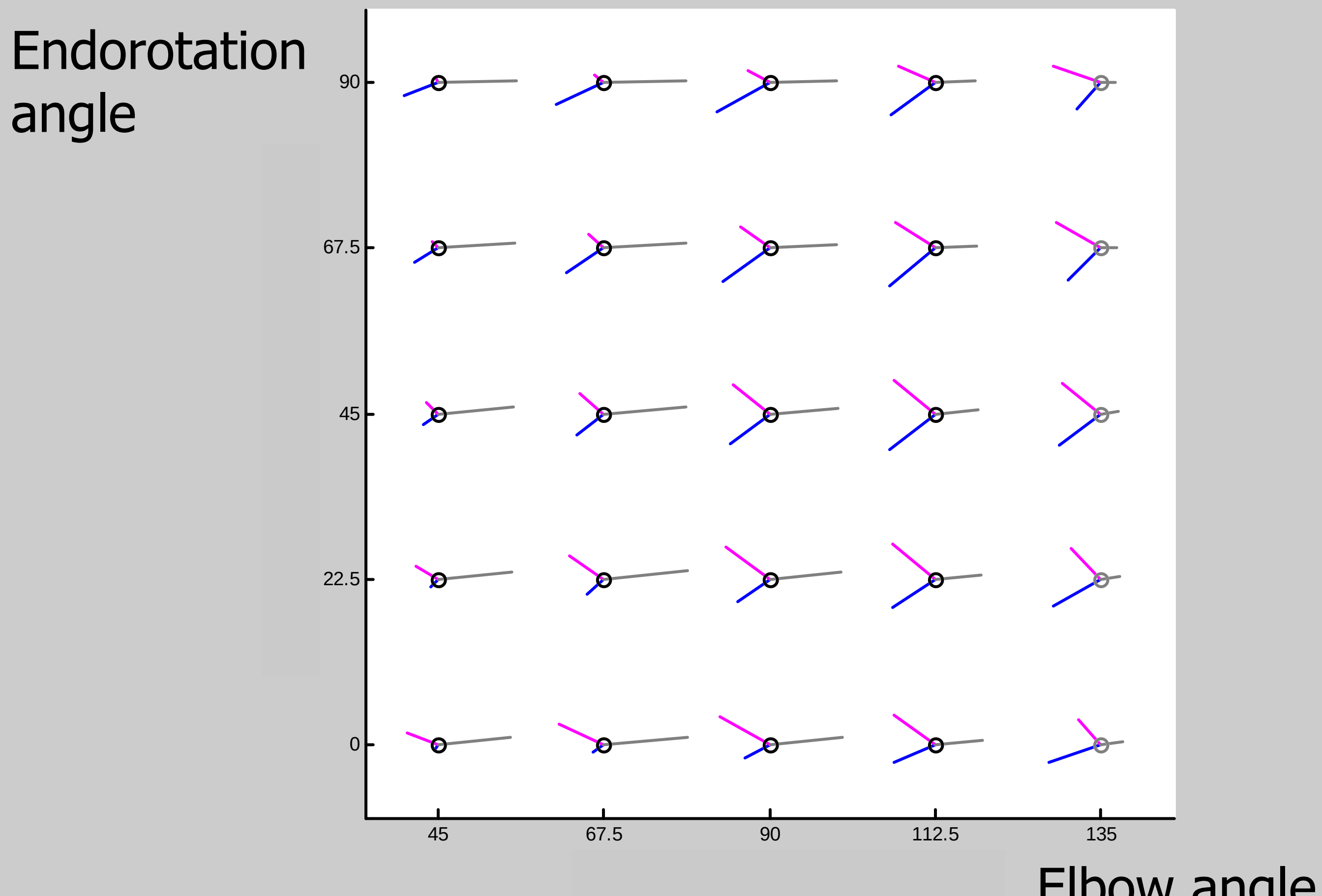
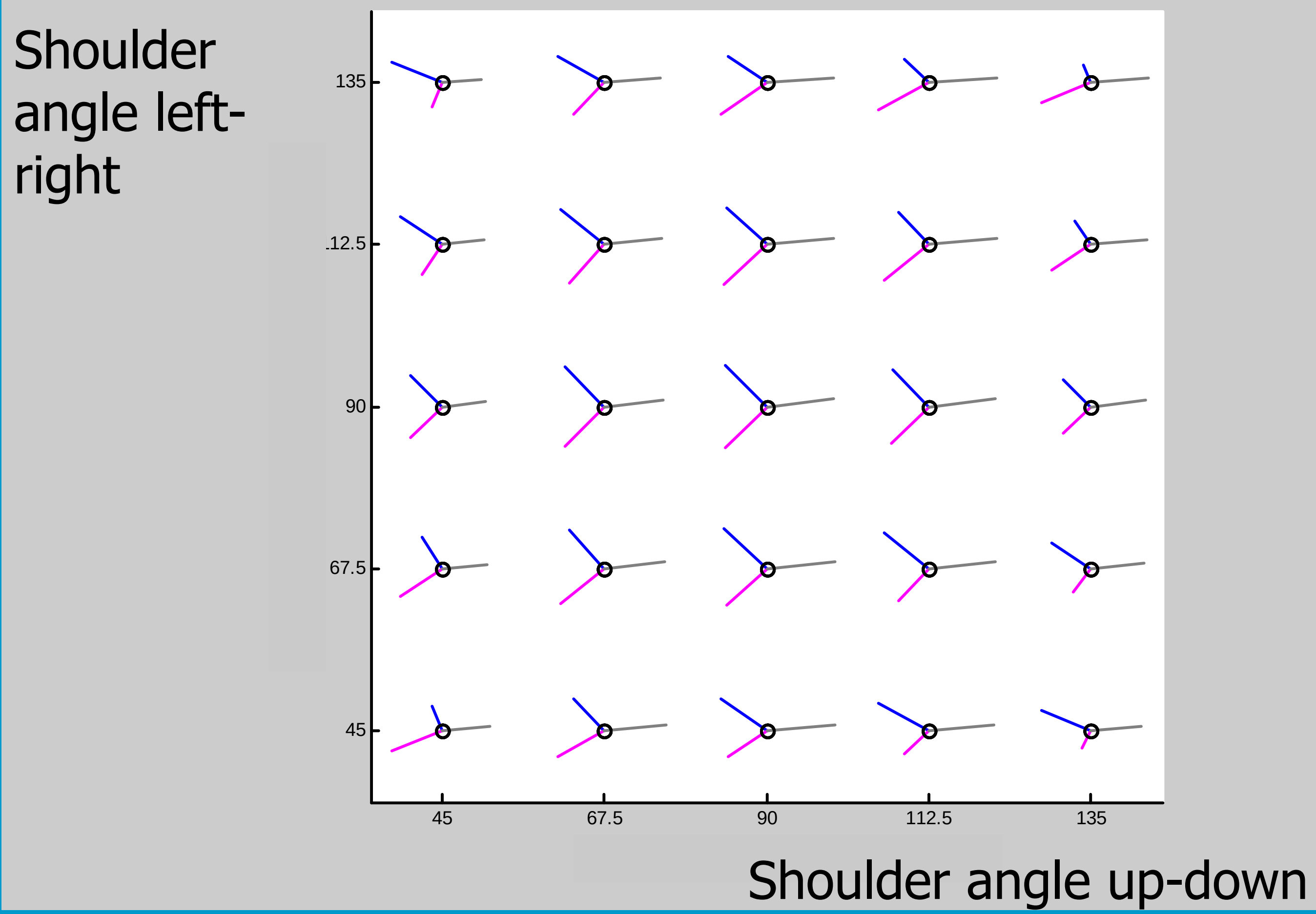
Natural behavior

Muscle moments elbow

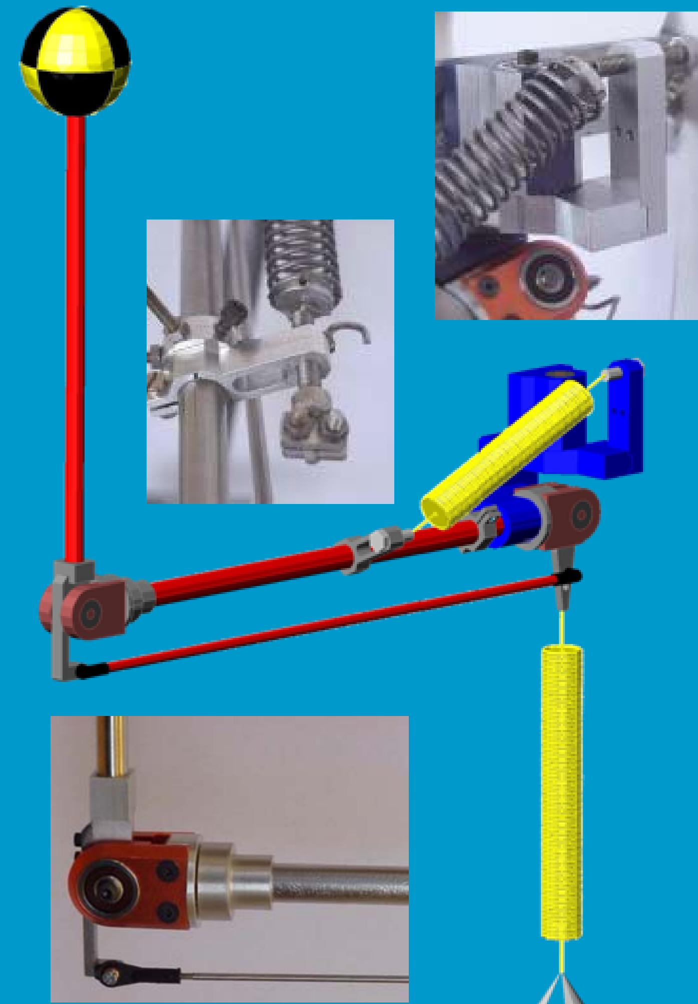


Natural behavior

Muscle moments shoulder



Anthropomobile balanced arm



Variable stiffness control

McKibben actuators

Statically balanced

Inherently safe

ARMON (Mark I)

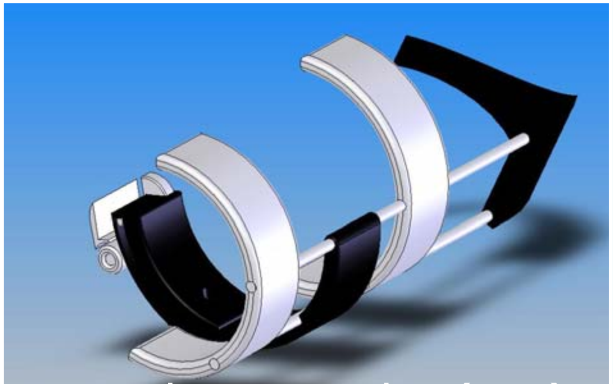
Sergio Tomazio and Luis Cardoso recieving the Premio Engenheiro Jaime Philipe award

Patient performing important ADL with device

Herder, Tomazio, Cardoso, Gil and Koopman, 2002

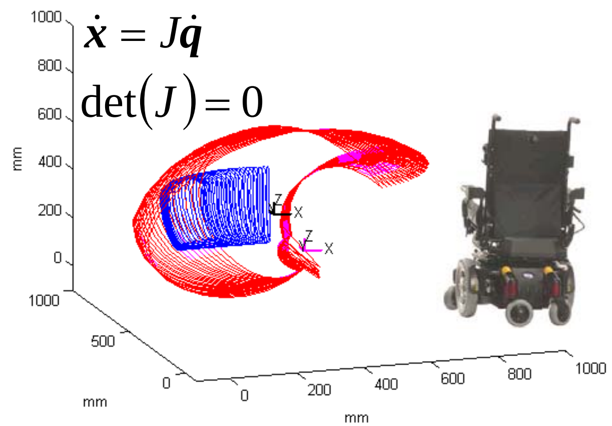
ARMON (Mark II)

Team: 2 ME and 2 IDE students

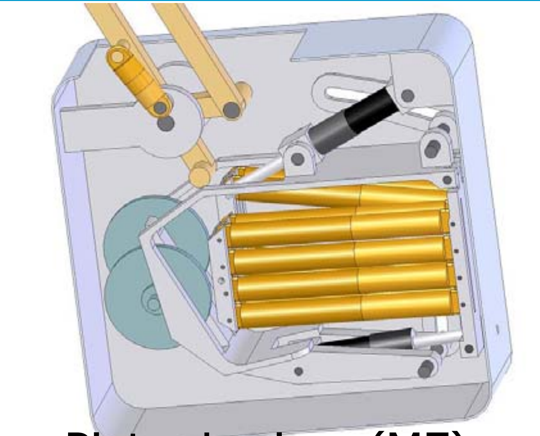


Tonko Antonides (IDE)

Sabine Gal (IDE)



Wendy van Stralen (ME)



Pieter Lucieer (ME)

Herder, Stralen, Lucieer, Gal and Antonides, 2004

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ARMON (Mark II) Patients with the device

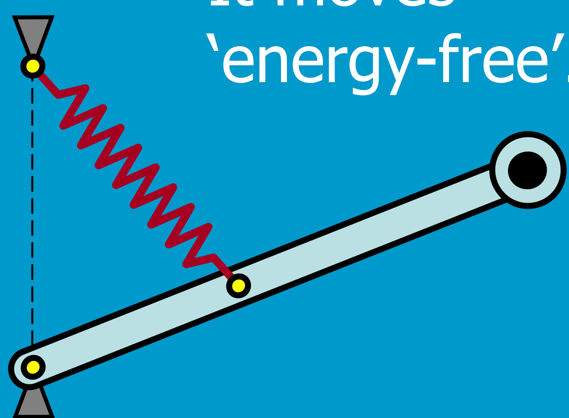
Herder, Stralen, Lucieer, Gal and Antonides, 2004

ARMON (Mark III)
Patients with the product

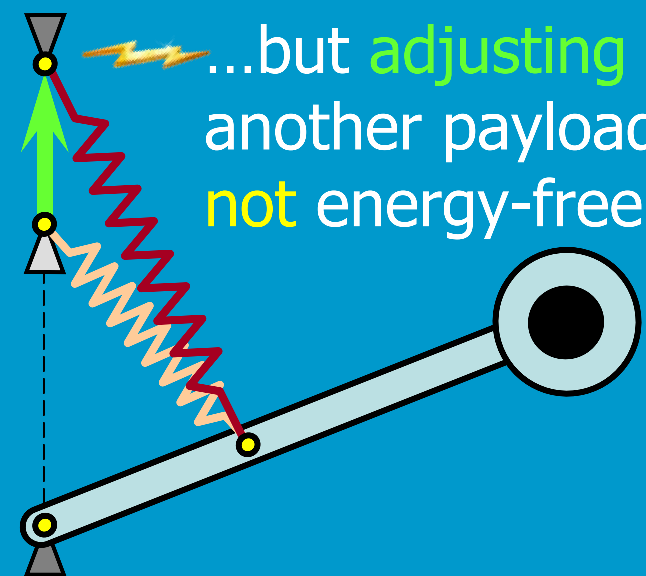
Herder, Vrijlandt, Antonides, Cloosterman, Mastenbroek, 2006

Research

Balancing of balancers



It moves 'energy-free'...



...but adjusting to another payload is not energy-free!

R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

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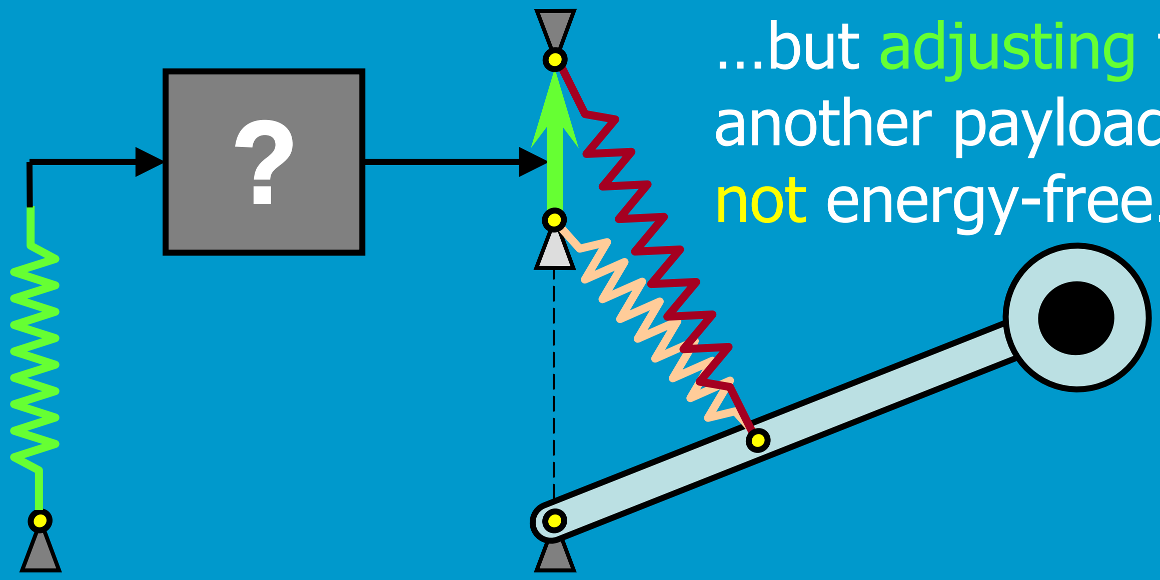
Research

Balancing of balancers

...unless the energy comes from **another spring!**



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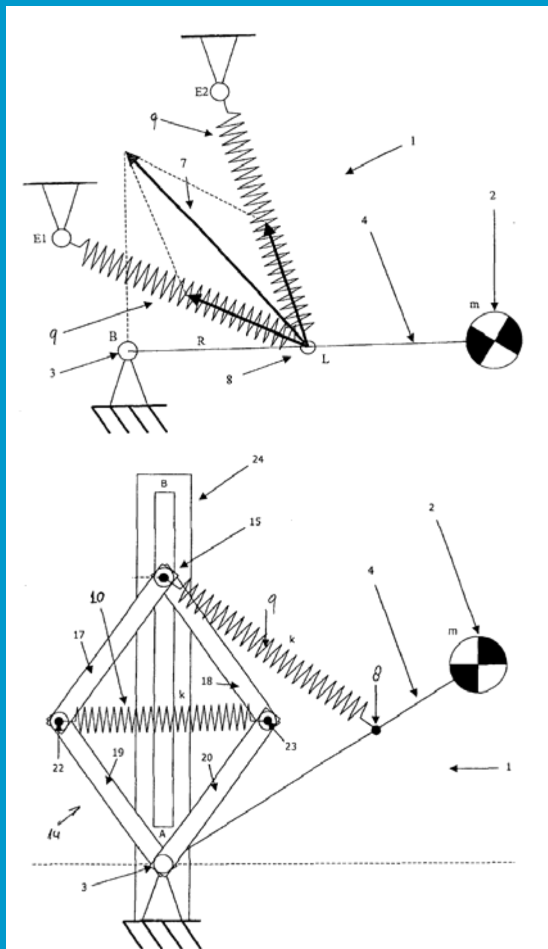
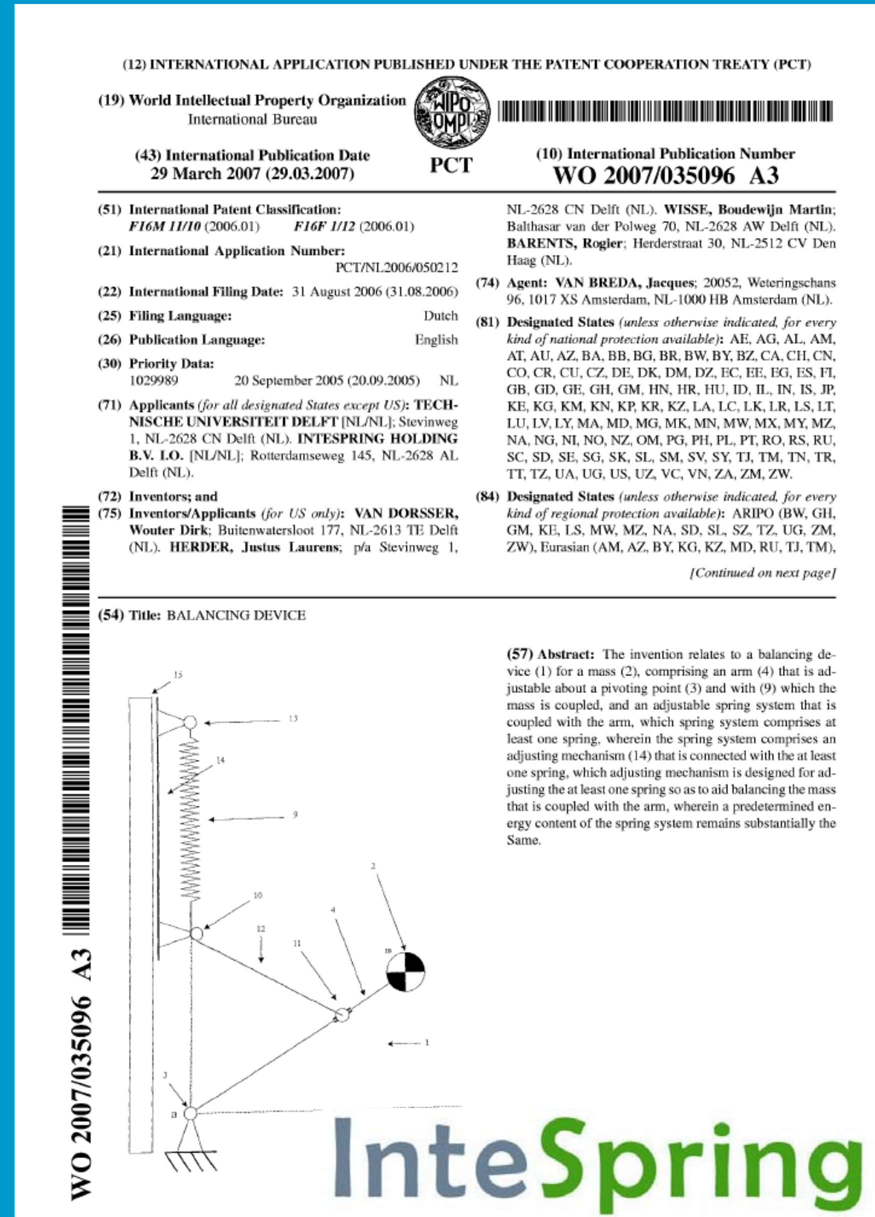
Research

Balancing of balancers





(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 March 2007 (29.03.2007)

PCT

(10) International Publication Number
WO 2007/035096 A3

(51) International Patent Classification:
F16M 11/10 (2006.01) *F16F 1/12* (2006.01)

(21) International Application Number: PCT/NL2006/050212

(22) International Filing Date: 31 August 2006 (31.08.2006)

(25) Filing Language: Dutch

(26) Publication Language: English

(30) Priority Data:
1029989 20 September 2005 (20.09.2005) NL

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(74) Agent: VAN BREDA, Jacques; 20052, Weteringschans 96, 1017 XS Amsterdam, NL-1000 HB Amsterdam (NL).

(81) Designated States (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),

[Continued on next page]

(54) Title: BALANCING DEVICE

(57) Abstract: The invention relates to a balancing device (1) for a mass (2), comprising an arm (4) that is adjustable about a pivoting point (3) and with (9) which the mass is coupled, and an adjustable spring system that is coupled with the arm, which spring system comprises at least one spring, wherein the spring system comprises an adjusting mechanism (14) that is connected with the at least one spring, which adjusting mechanism is designed for adjusting the at least one spring so as to aid balancing the mass that is coupled with the arm, wherein a predetermined energy content of the spring system remains substantially the Same.

WO 2007/035096 A3

InteSpring

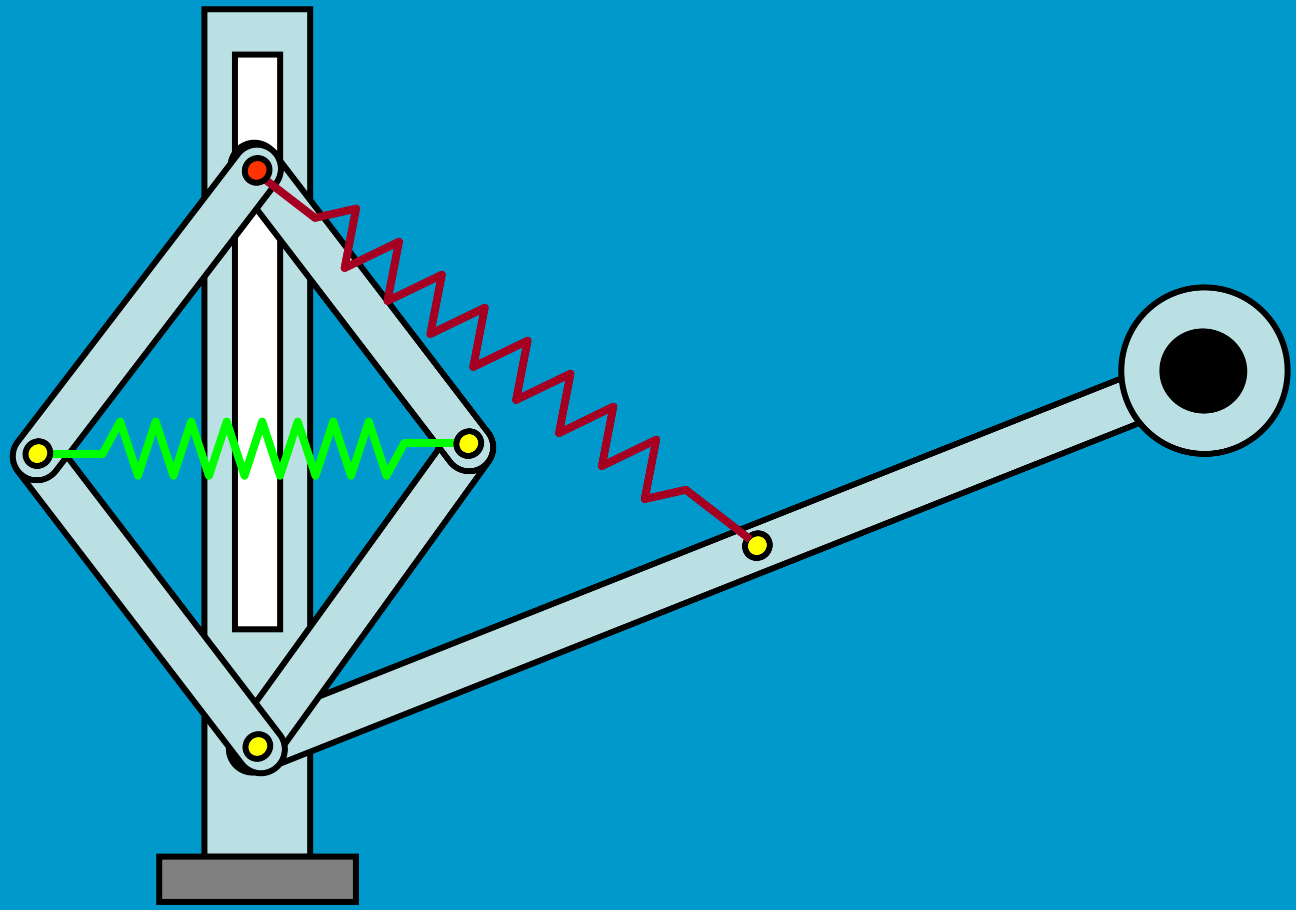
R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

World Patent: WO2007/035096 (2007-03-29)

TU Delft

Energy-free adjustment

Balancing of balancers



R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

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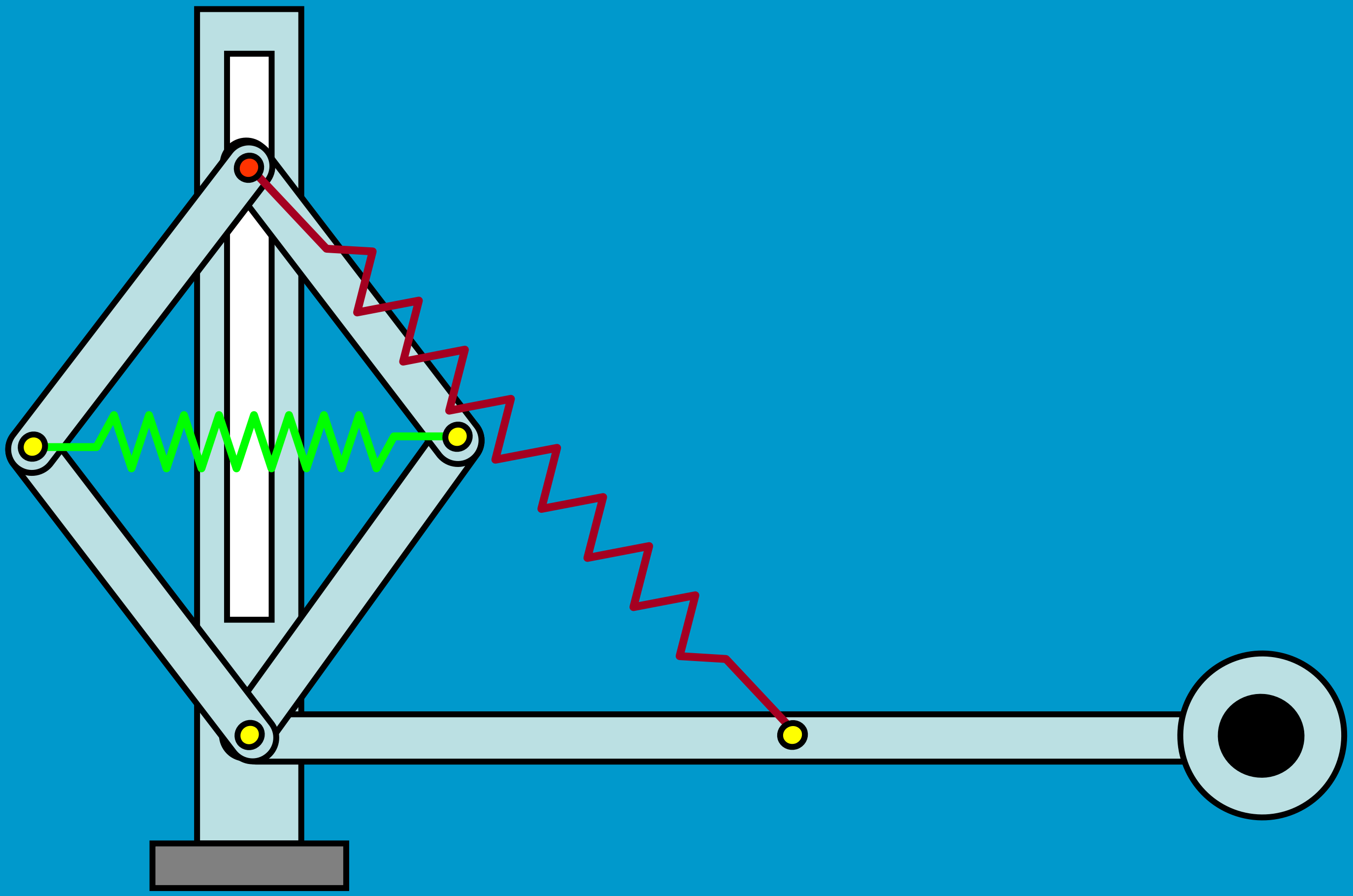
Balancing of balancers



R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

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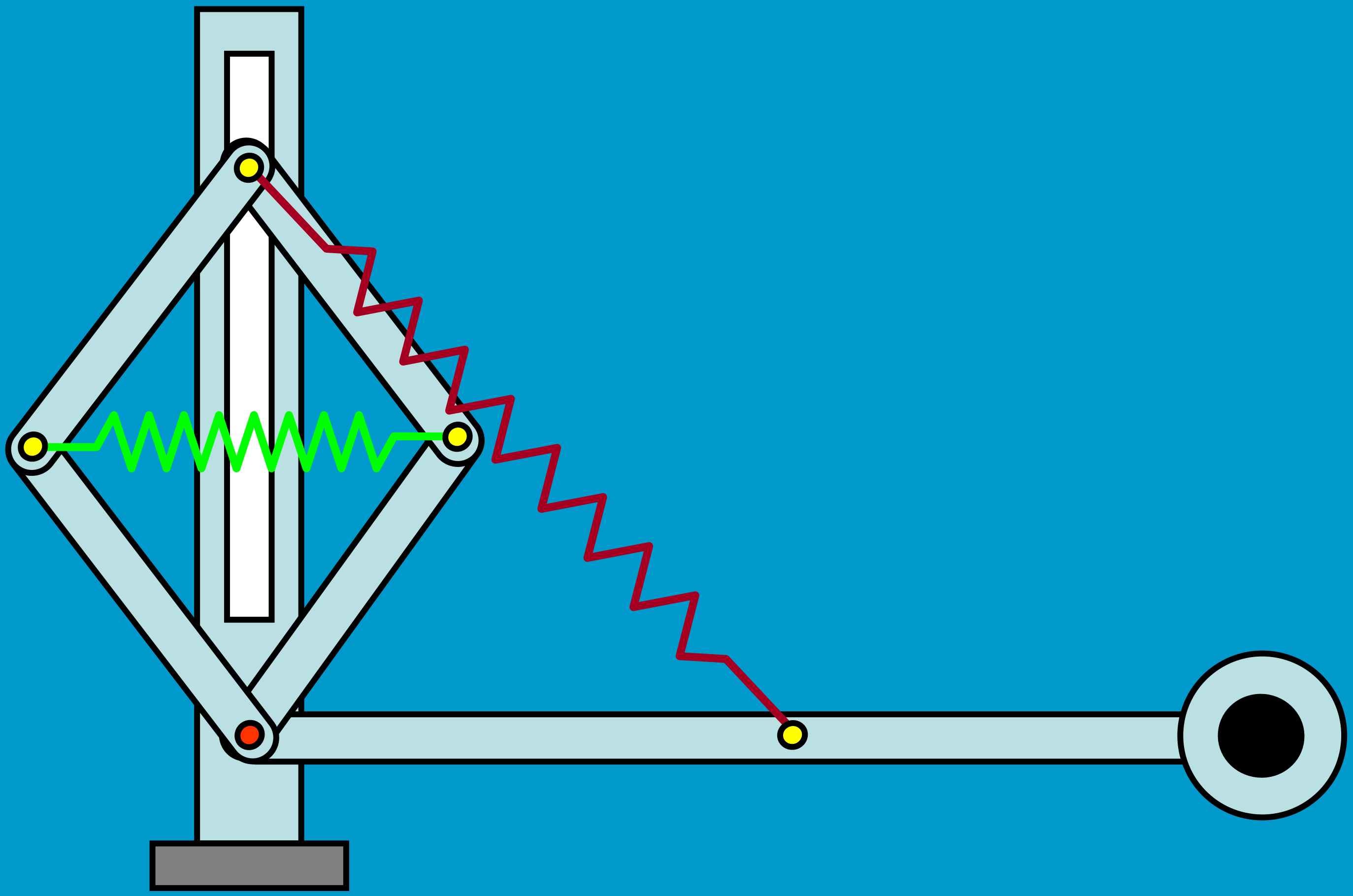
Balancing of balancers



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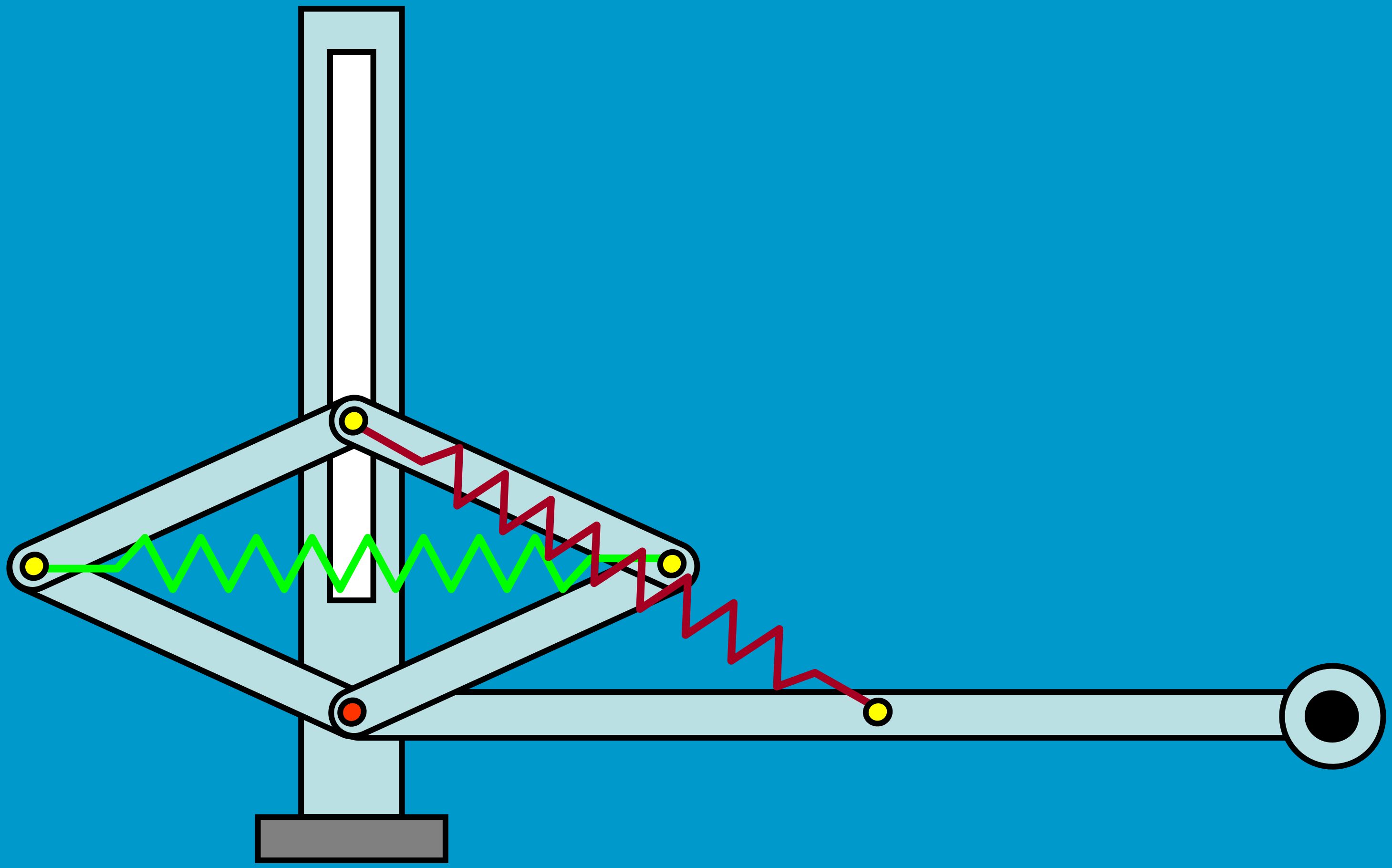

R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

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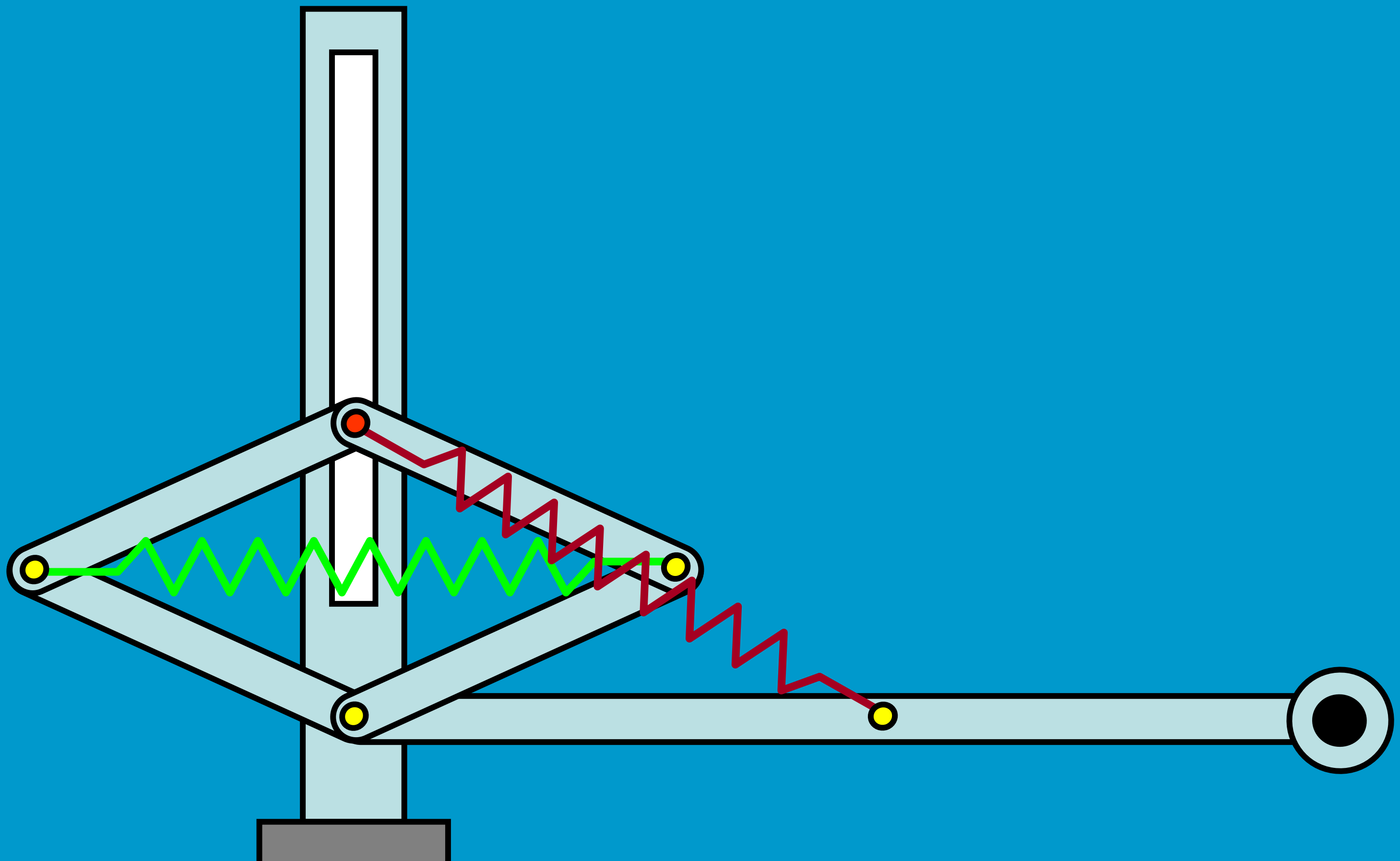

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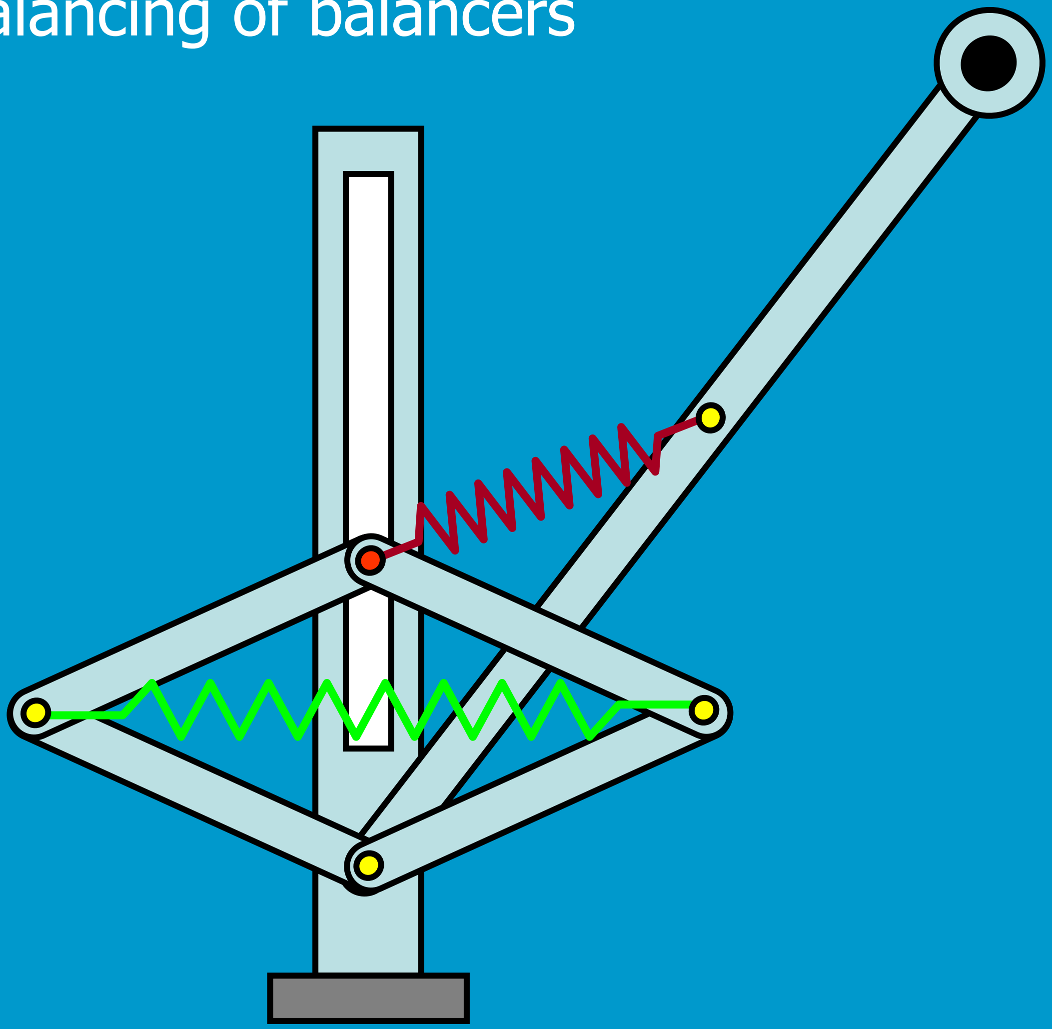
Balancing of balancers



R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

Energy-free adjustment

Balancing of balancers

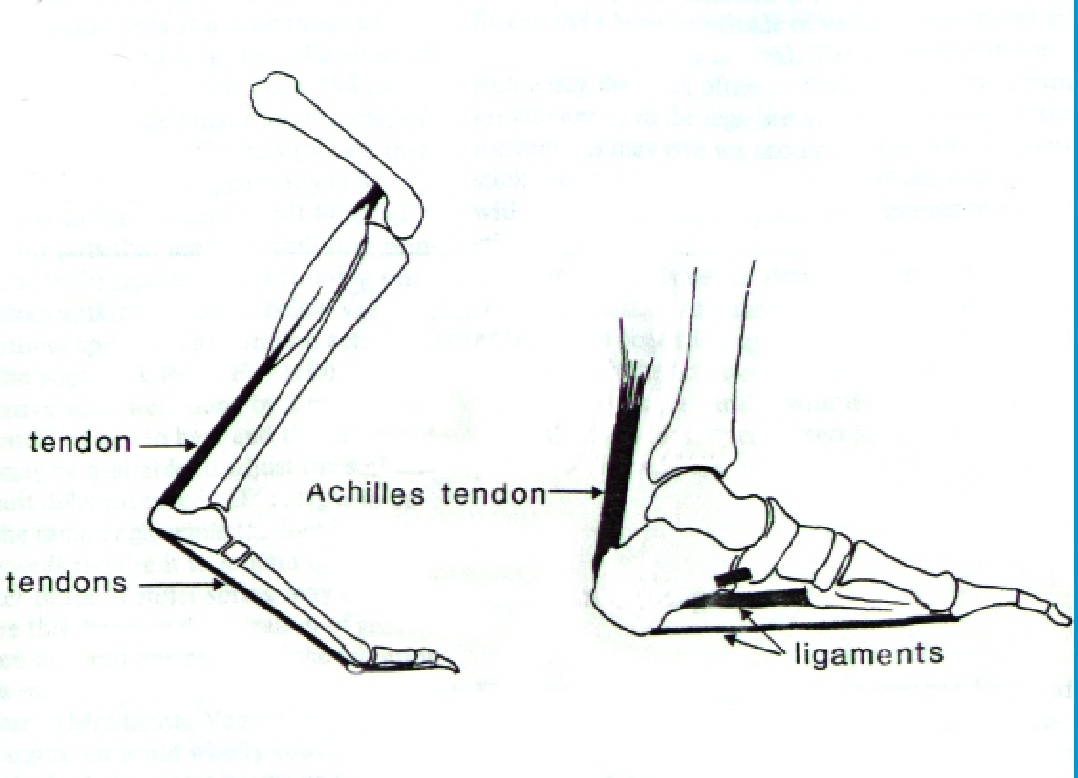
ASME IDETC
Best Paper Award
2008

R Barents, WD van Dorsser, BM Wisse, JL Herder (2006)

Muscles: Energy Storage

- Oscillations: human legs, Walibi (kangaroos), and hoofed animals
- Proof by measuring metabolic energy uptake during walking, and by stretch measurements of tendons
- Main advantage: reduces the amount of work that needs to be done by the muscles (or actuators)

Tendons: Energy Storage



- Human foot: main storage in Achilles tendon and foot arch

Tendons: Energy Storage

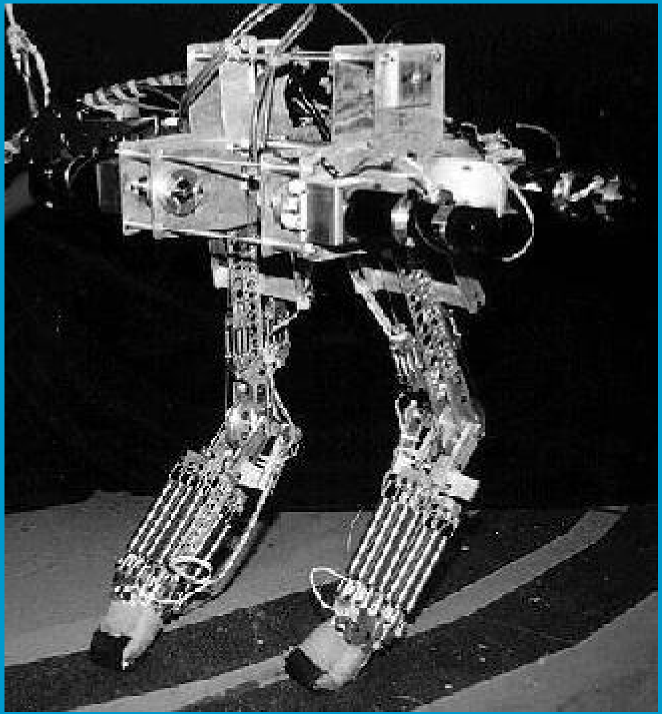
High efficiency:

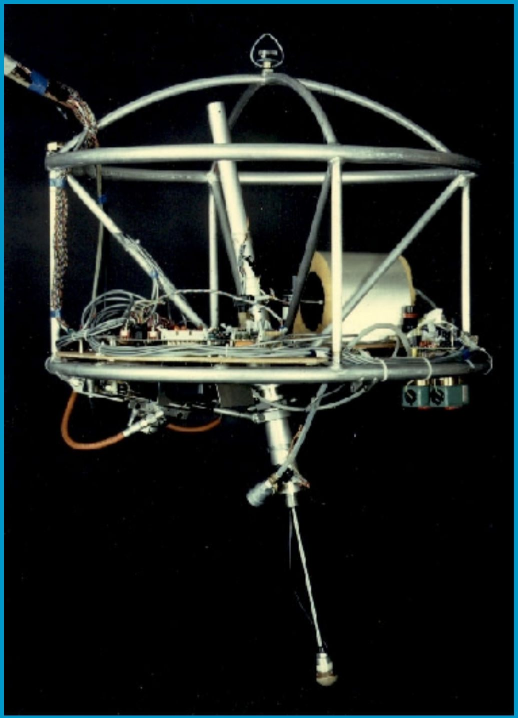
- Energy dissipation collagen around 7% (Ker et al., 1986)
- Energy dissipation resilin around 3% (Weis-Fogh, 1960, in Vogel, 1998)
- Not a big difference in efficiency (93% vs 97%) but heat generation about a factor of 2 (!)

Muscles: Energy Storage

- Oscillations: human legs, Walibi (kangaroos), and hoofed animals
- Proof by measuring metabolic energy uptake during walking, and by stretch measurements of tendons
- Main advantage: reduces the amount of work that needs to be done by the muscles (or actuators)
- This principle has been applied in running robots (perhaps less complicated than walking robots!)

Muscles: Energy Storage

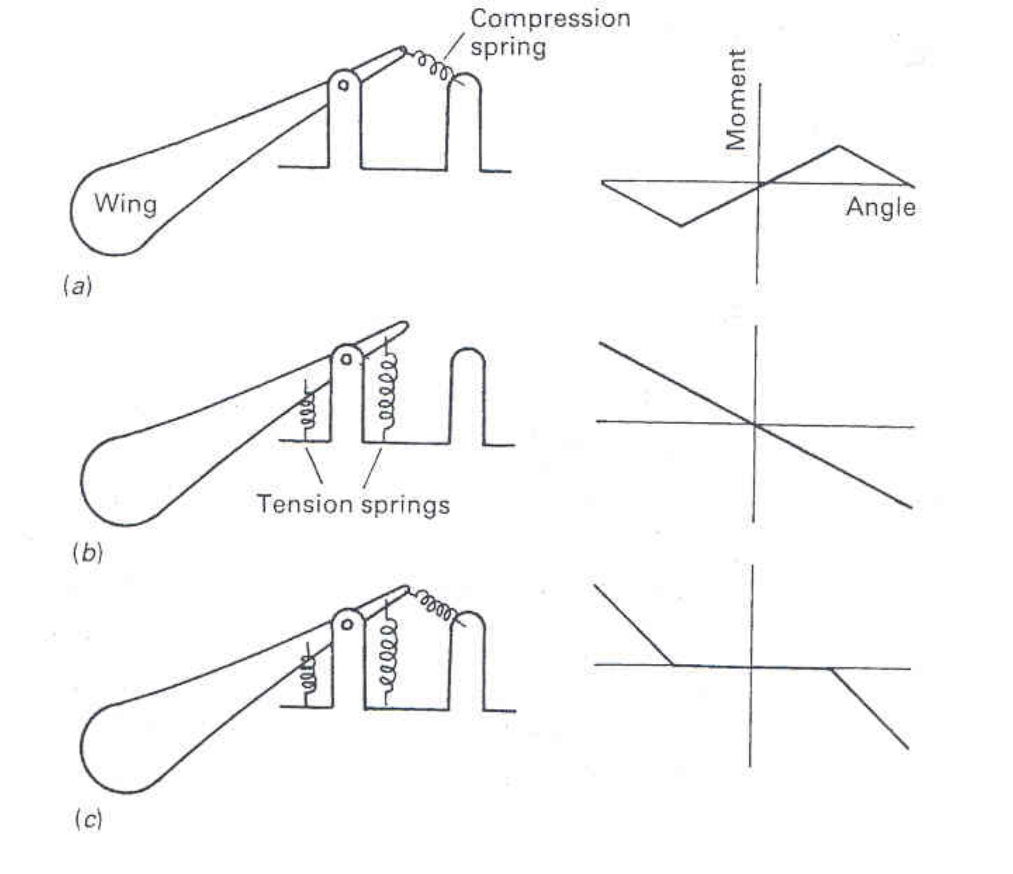




Marc Raibert

Muscles: Energy Storage

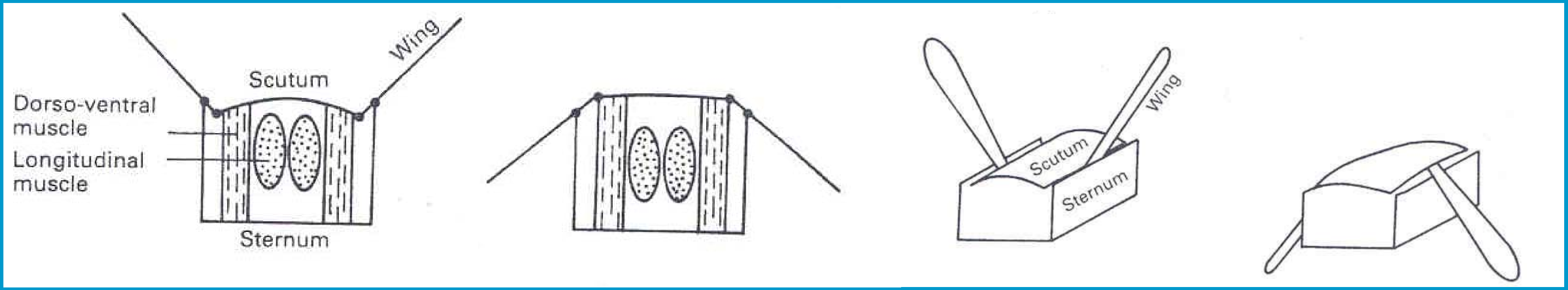
- Sarcophaga (flesh flies)
- Bistable spring mechanism



Alexander (1988)

TUDelft

Muscles: Energy Storage

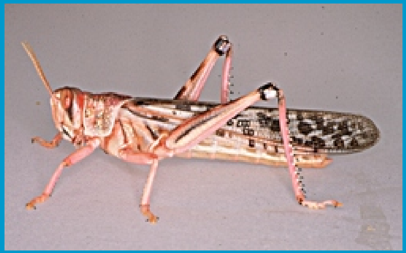


- Longitudinal muscles: tend to shorten the thorax and make Scutum buckle upward, so drive wings down
- Dorso-ventral muscles: restore shape Scutum, raise wings.
- Note that also Scutum stores energy (buckling)
- Wings run faster than fly's brain (1 action potential for 40 wing cycles!)

Ennos (1987) in Alexander (1988)

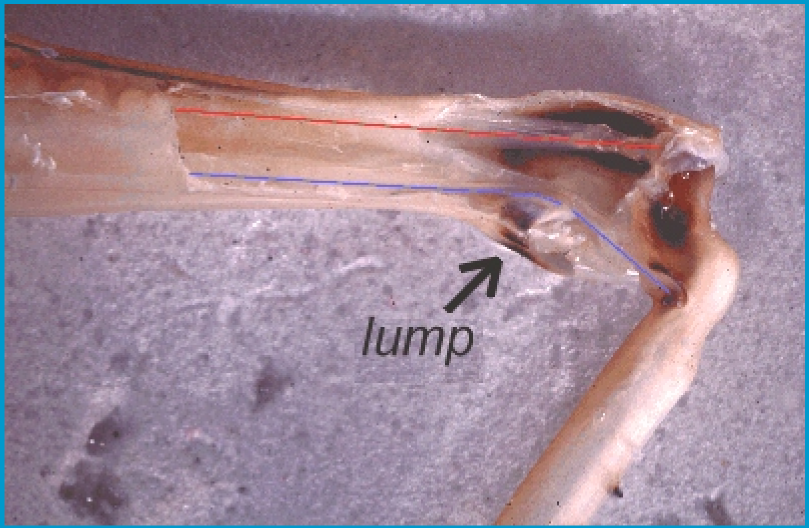
TU Delft

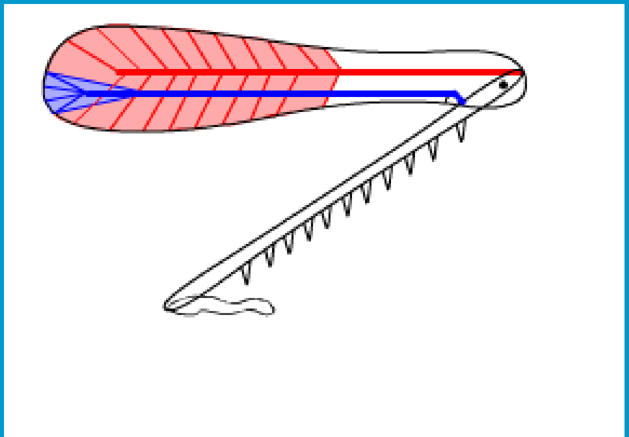
Storing gradually, releasing instantly



Grasshopper leg:

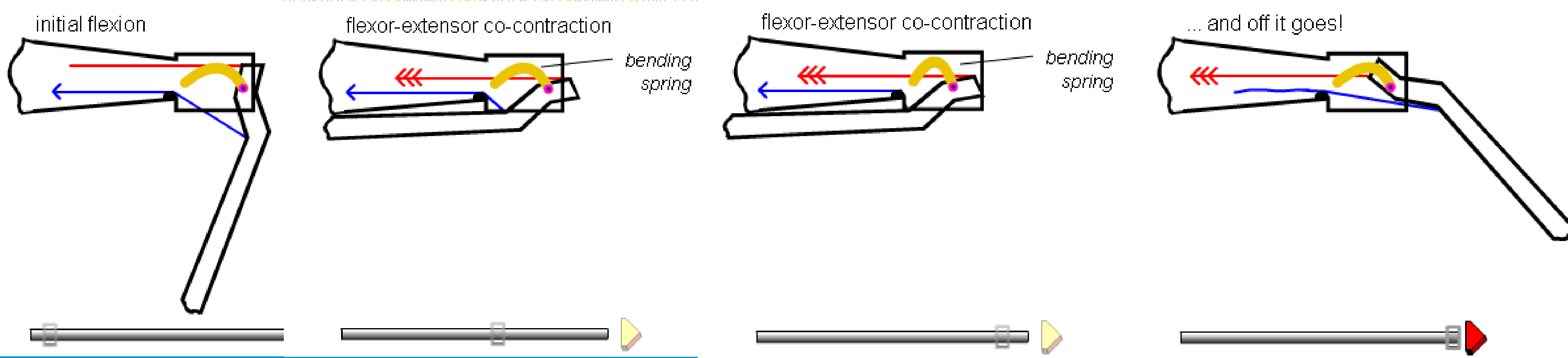
- Overall length 40 mm
- Extensor lever ratio on tibia around 1:35, so for 15 grams of thrust, 500 grams muscle force
- This is average, peak up to 1500 grams
- Big force through 'herring' arrangment of muscle

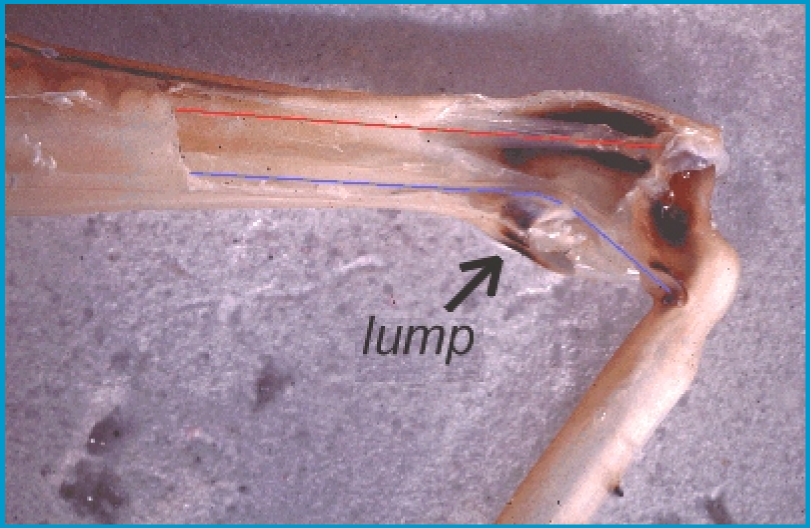


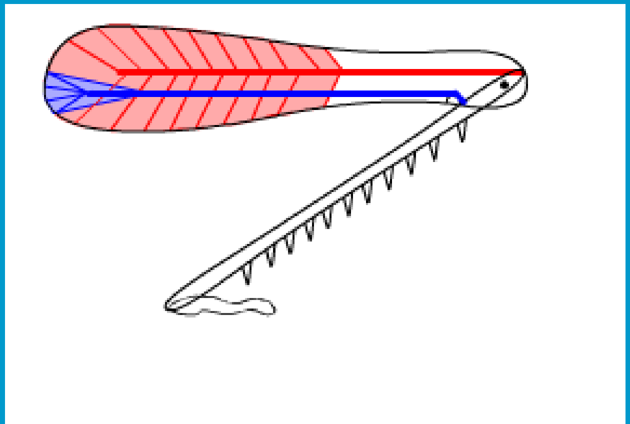


WJ Heitler, http://www.st-andrews.ac.uk/~wjh/jumping/

Storing gradually, releasing instantly





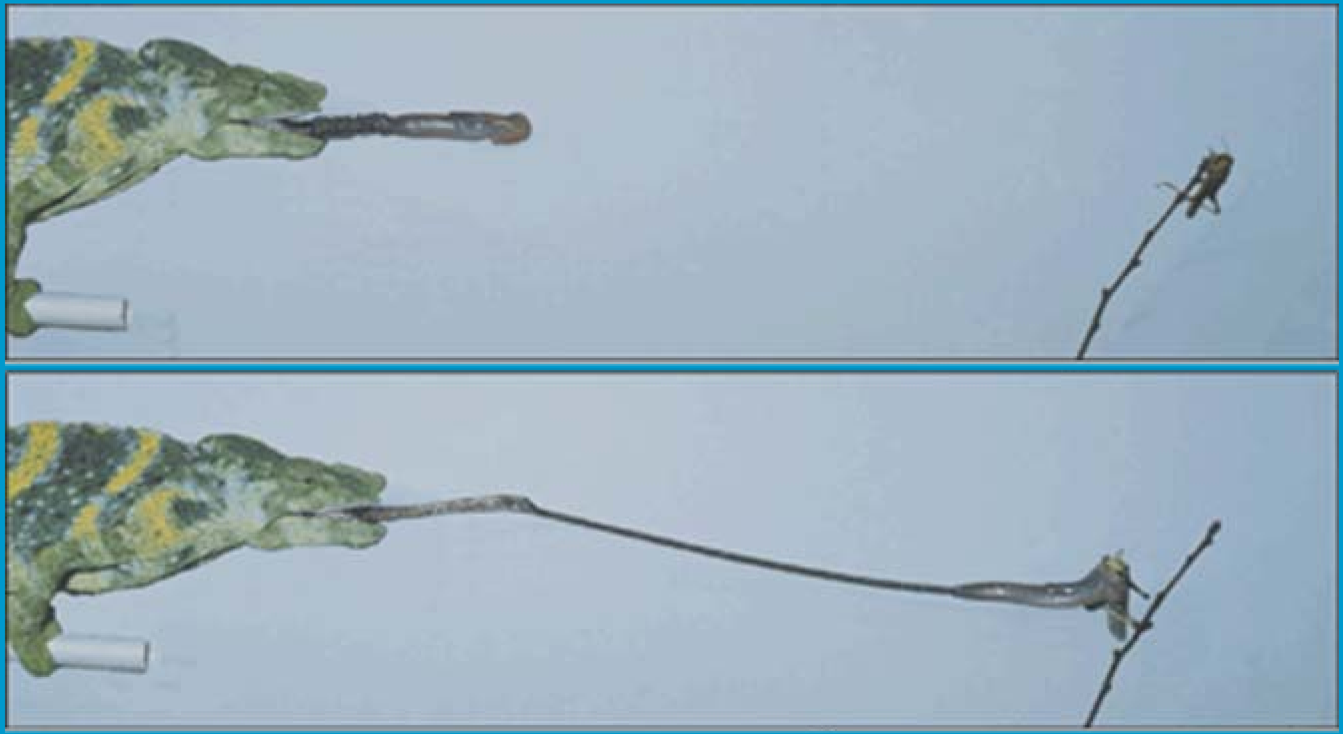


WJ Heitler, http://www.st-andrews.ac.uk/~wjh/jumping/

Storing gradually, releasing instantly

Tongue of chameleon

- < 0.1 sec to prey, 500 m/s^2, 6 m/s
- More powerful (3kW) than any known muscle…



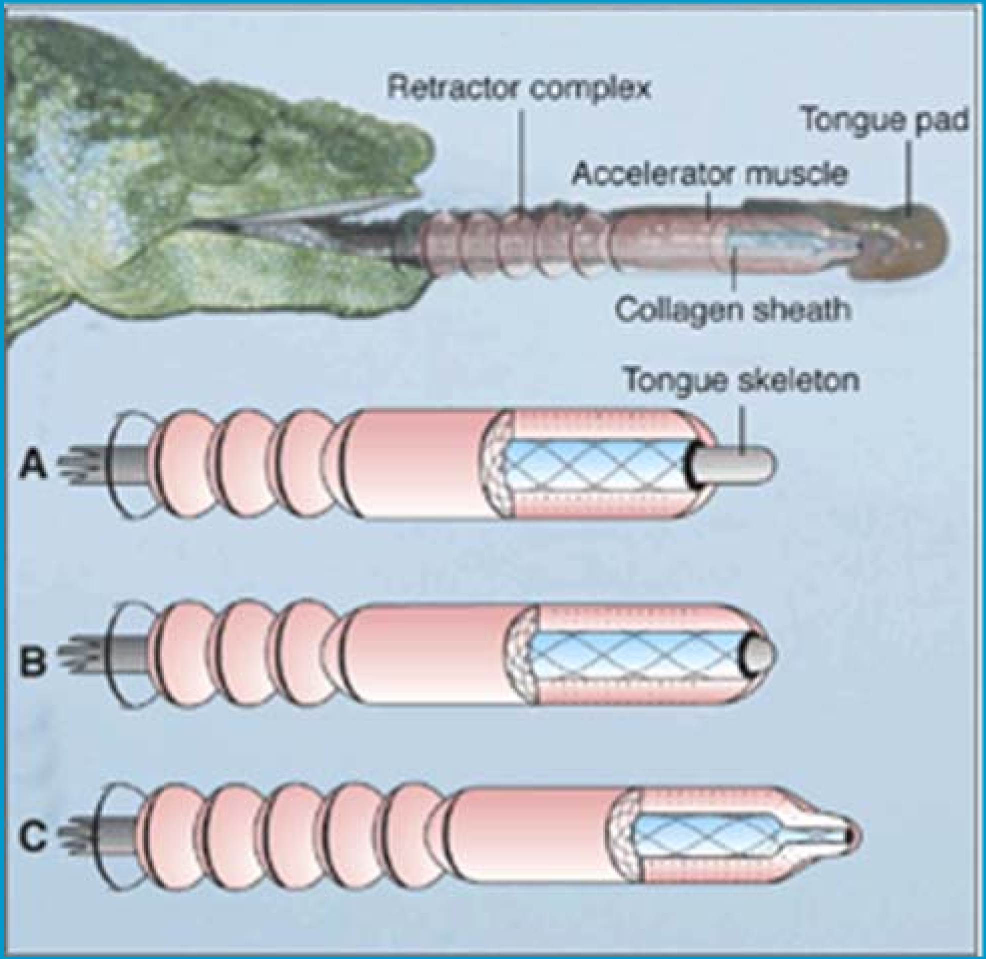
Video available at http://noorderlicht.vpro.nl/artikelen/17184463/

JH de Groot, JL van Leeuwen, 2004

Storing gradually, releasing instantly

- A Tongue at rest
- B Force builds up, axial elongation
- C Tip slides of skeleton, acts as inversion of soap sliding out of hands

Extraordinary degree of function integration



JH de Groot, JL van Leeuwen, 2004

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