Variable Stiffness Actuators

Prof dr ir Bram Vanderborght

Vrije Universiteit Brussel

Vrije Universiteit Brussel

European Research Council

Overview

- Stiff Actuation
- Compliant actuation
  - Series elasticity
  - Parallel elasticity
  - Electric motor efficiencies
- Series-parallel elastic actuation
- Self healing actuators

VUB participants

Tomislav

Raphael

Tom

Glenn

Stiff actuation

Stiff actuation
Excellent trajectory tracking

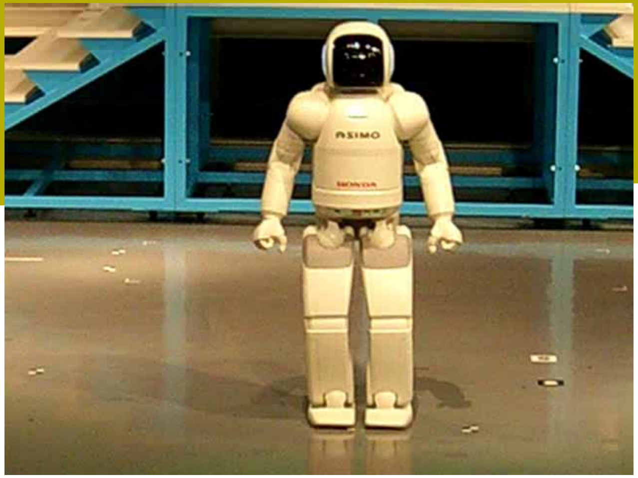
Suitable for static and known environments (often industrial settings)

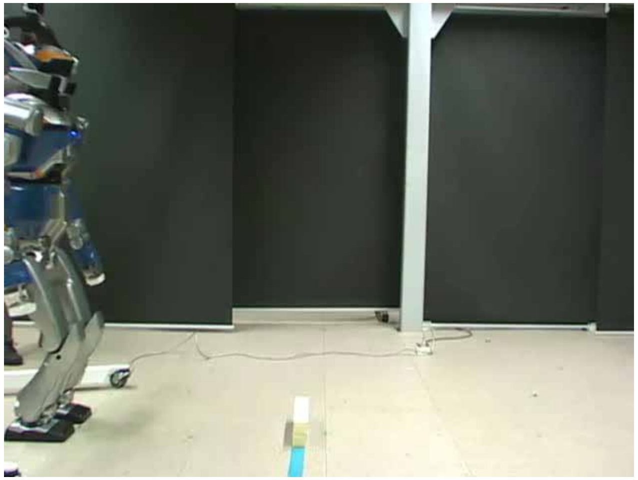
Unsuitable for dynamic unknown environments (including humans)

Vrije Universiteit Brussel

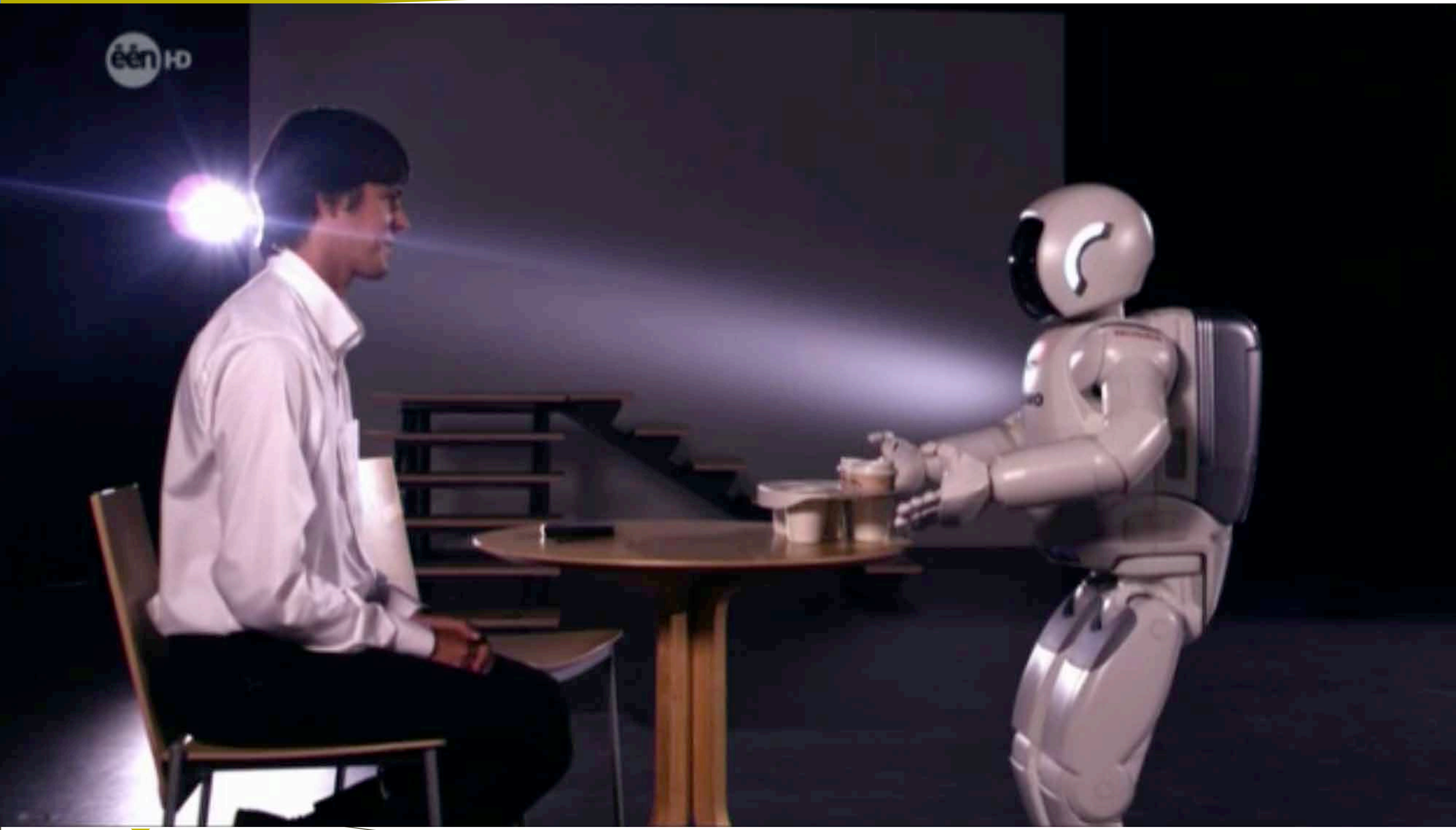
Stiff actuation

- No energy storage
  - (also recuperation in batteries in robotics not efficient)
- No shock absorption
  - Damage on harmonic drives
- Unsafe
  - Kept away from humans





Sorry Asimo



Series Elastic Actuation
Variable Stiffness Actuation

Active – passive compliance

Active Compliant

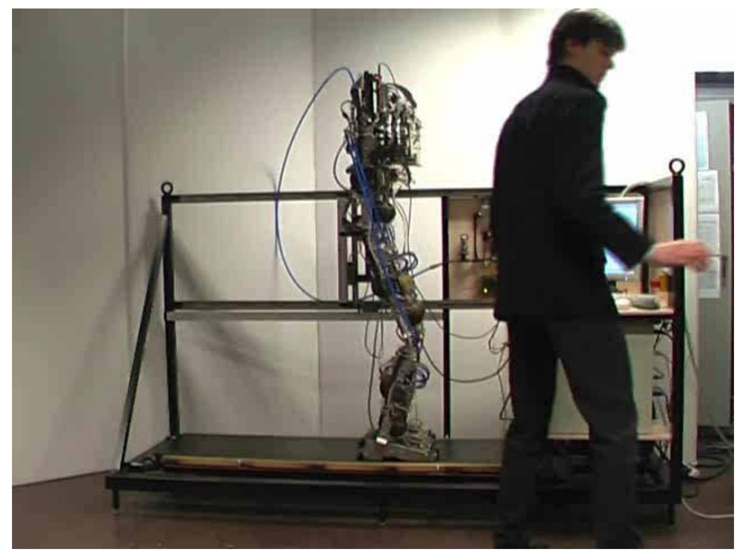
Compliant behaviour of a stiff actuator by software control

- Limited bandwidth
- No energy can be stored
- Easy control stiffness and damping

Passive Compliant

Actuators with an elastic element (spring)

- Unlimited bandwidth to impacts
- Passive compliance
- Energy storage



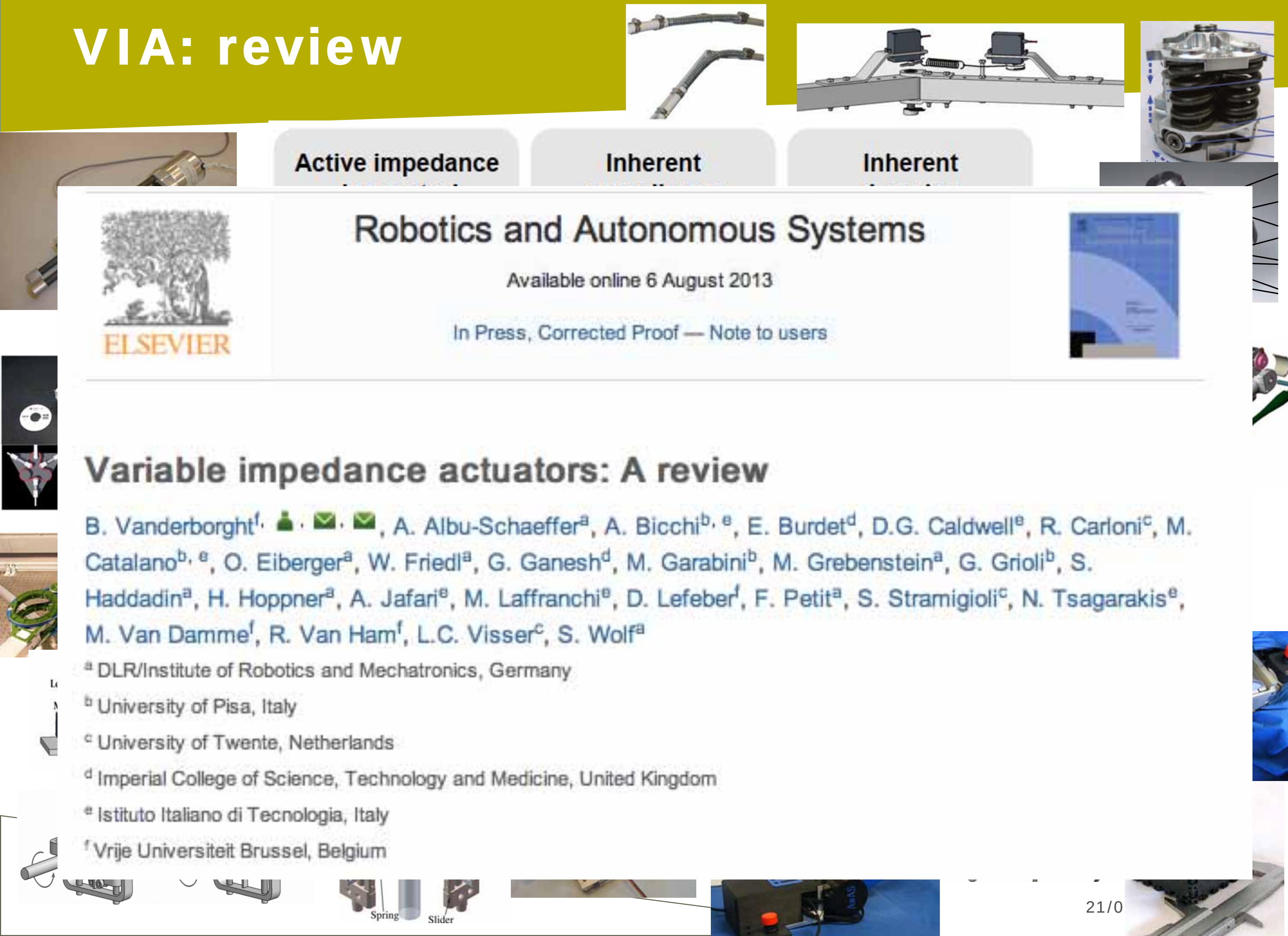
Use of springs in biological systems

The basic mechanisms of energy conservation using springs have been demonstrated in a wide variety of animals that differ in leg number, posture, body shape, body mass, or skeleton type




Video IROS

VIA: review



ELSEVIER

Robotics and Autonomous Systems

Available online 6 August 2013

In Press, Corrected Proof — Note to users

Variable impedance actuators: A review

B. Vanderborght[f], A. Albu-Schaeffer[a], A. Bicchi[b, e], E. Burdet[d], D.G. Caldwell[e], R. Carloni[c], M. Catalano[b, e], O. Eiberger[a], W. Friedl[a], G. Ganesh[d], M. Garabini[b], M. Grebenstein[a], G. Grioli[b], S. Haddadin[a], H. Hoppner[a], A. Jafari[e], M. Laffranchi[e], D. Lefeber[f], F. Petit[a], S. Stramigioli[c], N. Tsagarakis[e], M. Van Damme[f], R. Van Ham[f], L.C. Visser[c], S. Wolf[a]

[a] DLR/Institute of Robotics and Mechatronics, Germany

[b] University of Pisa, Italy

[c] University of Twente, Netherlands

[d] Imperial College of Science, Technology and Medicine, United Kingdom

[e] Istituto Italiano di Tecnologia, Italy

[f] Vrije Universiteit Brussel, Belgium

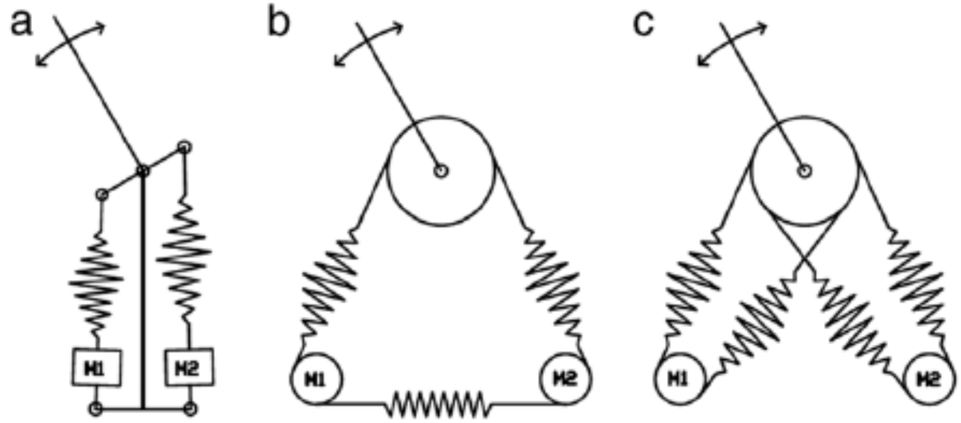
Classification

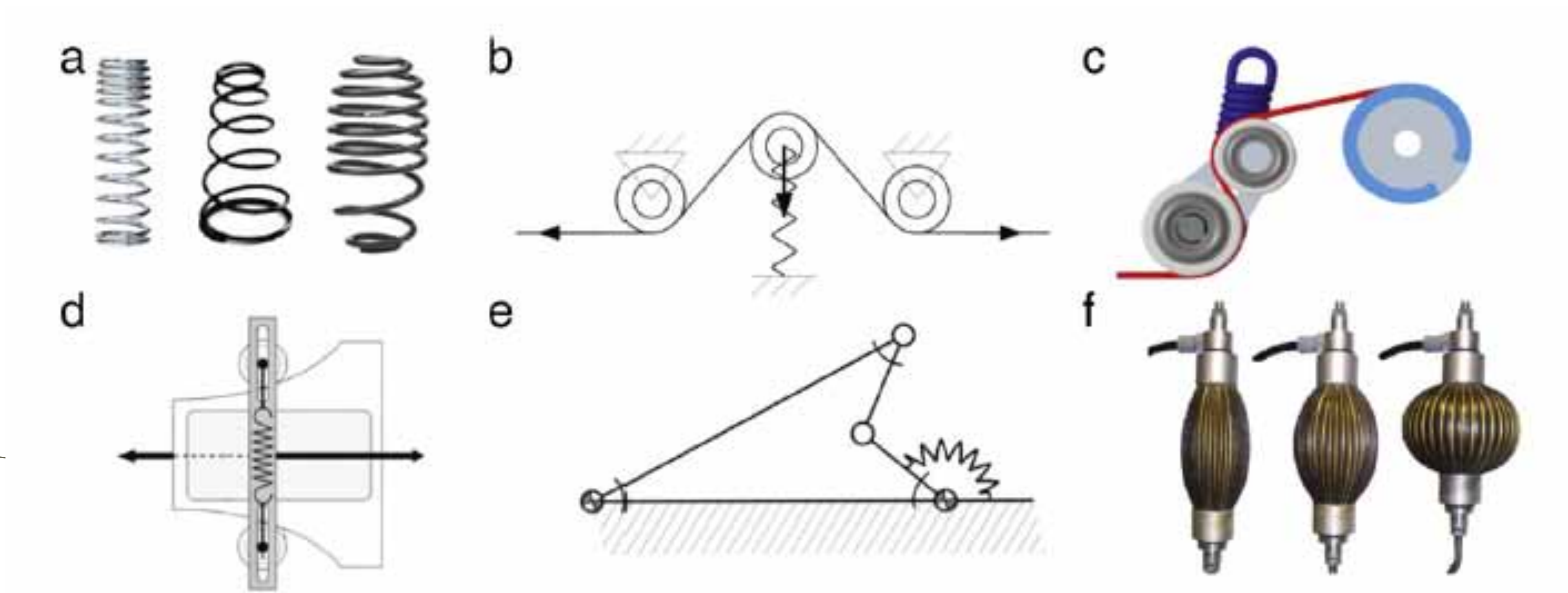
- **Active impedance by control**
- **Inherent compliance**
  - **Fixed compliance properties** (Serial Elastic Actuator - SEA)
  - **Adaptable compliance properties** (Variable Stiffness Actuator - VSA)
    - **Spring Preload**
      - Preload adjustment of single spring
      - Antagonistic springs with independent motors
      - Antagonistic springs with antagonistic motors
    - **Changing transmission load ↔ spring**
      - Lever length
      - Nonlinear mechanical interlink
      - Continuously variable transmission (CVT)
    - **Physical properties of spring**

      $$F = \frac{E \cdot A}{L_0} \Delta L$$

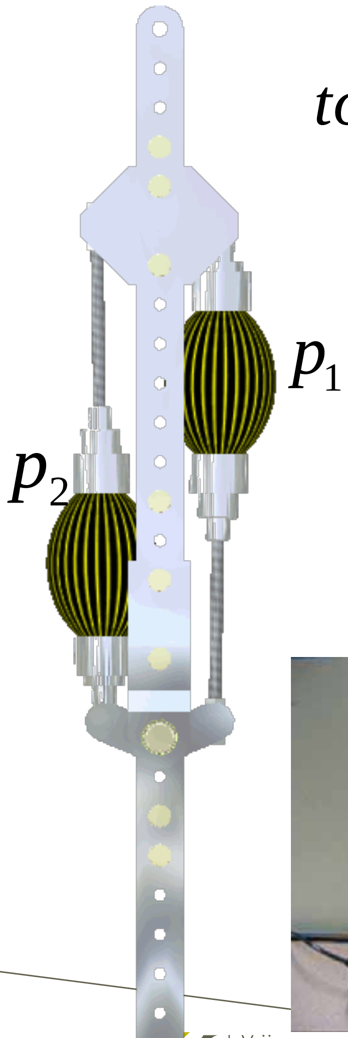
      - E: Elasticity modulus
      - A: Cross section area
      - L_0: Active spring length
- **Inherent damping**

Spring preload: antagonistic





Example: pneumatic muscles



$$torque = p_1 t_1(\beta) - p_2 t_2(\beta)$$

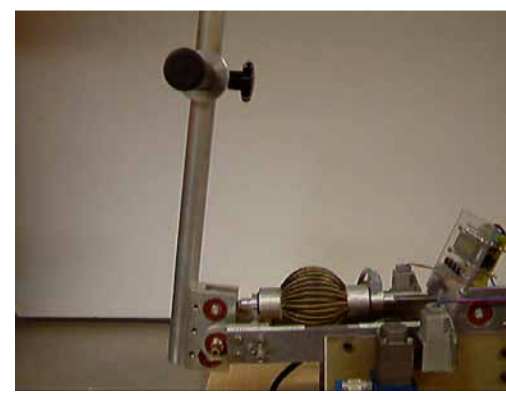
$$\tilde{p}_1 = p_m + \Delta\tilde{p}$$
$$\tilde{p}_2 = p_m - \Delta\tilde{p}$$

~ stiffness

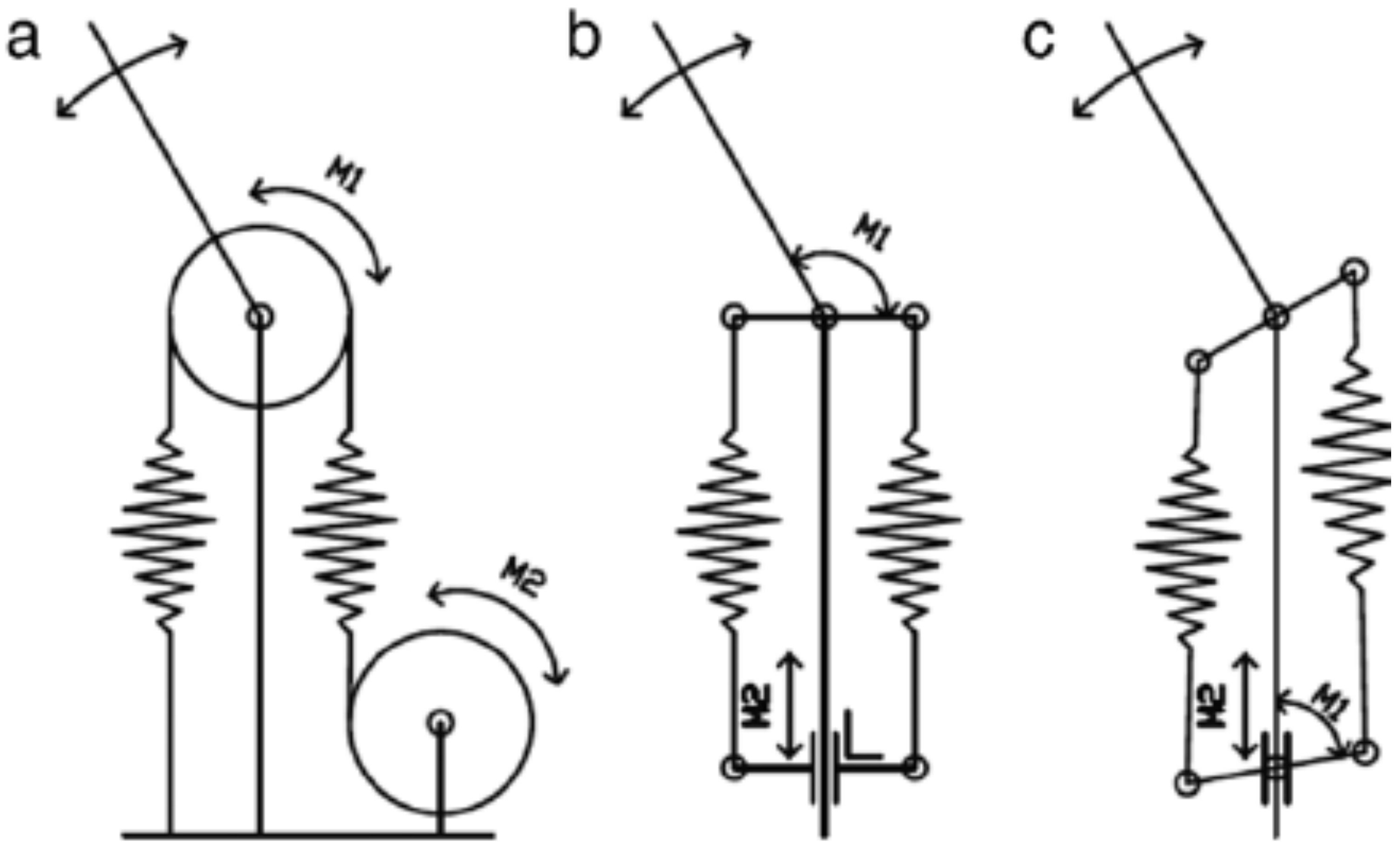
~ torque

p_m high: stiff

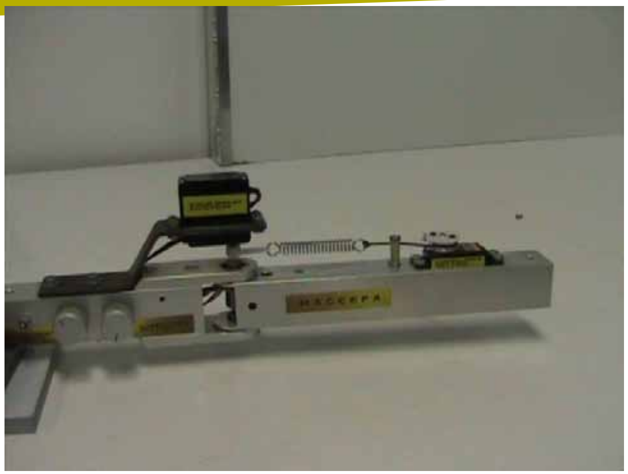
p_m low: compliant



Antagonistic with independent motors

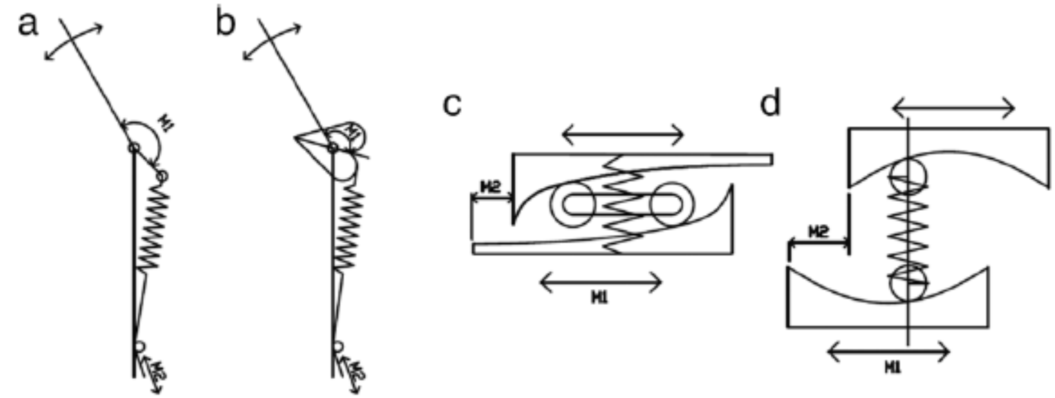


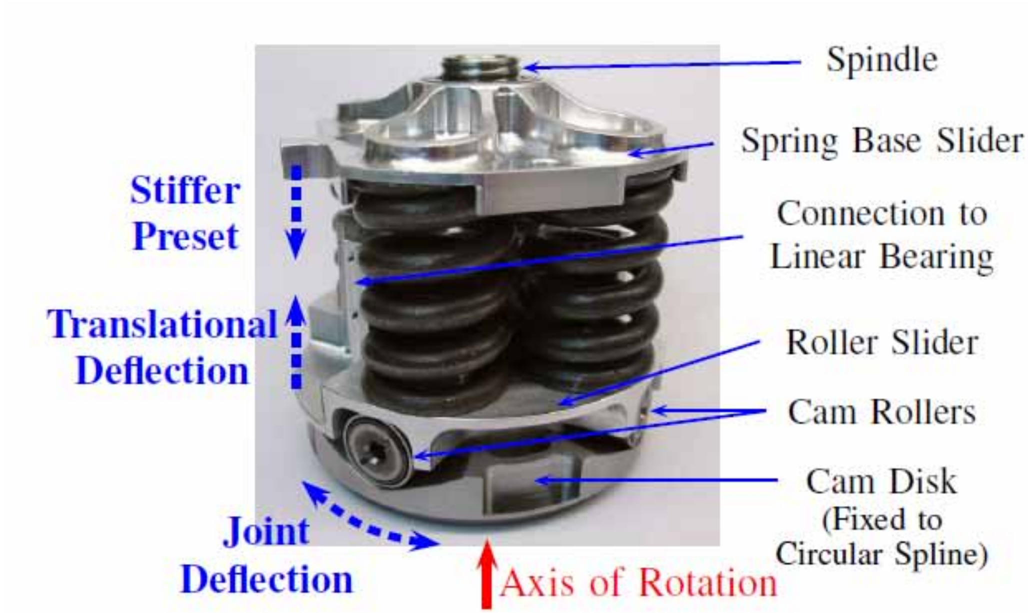
Preload adjustment single spring



1 motors controls position

1 motor controls stiffness

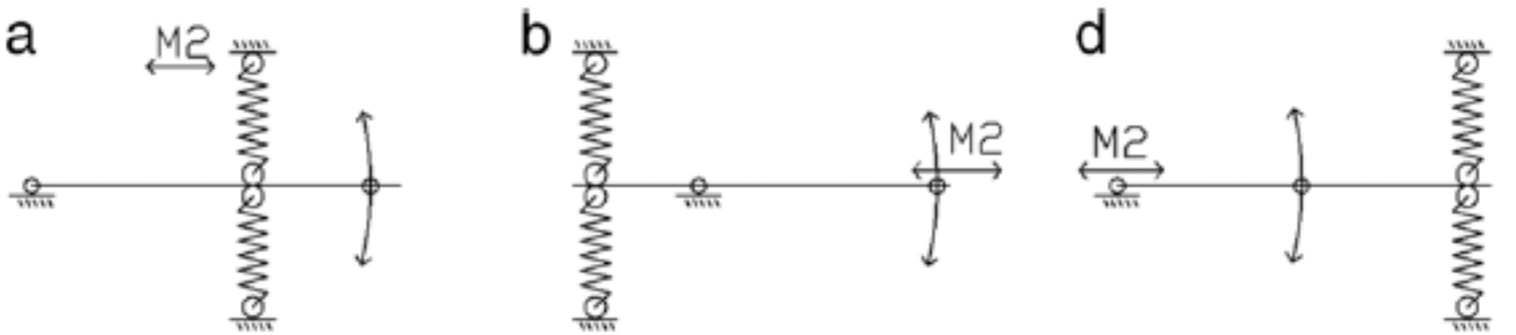




VS-joint
Wolf et Hirzinger

Vrije Universiteit Brussel

Changing transmission

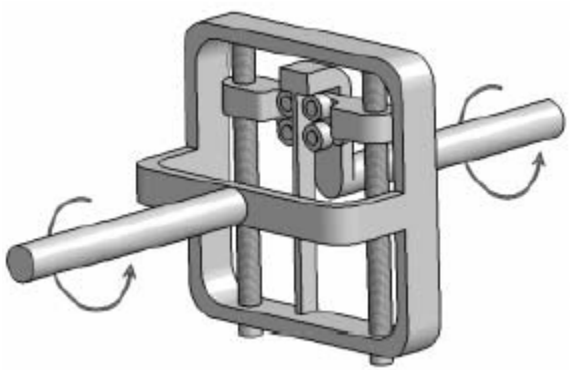


Physical properties of a spring

Bending of a leaf spring:

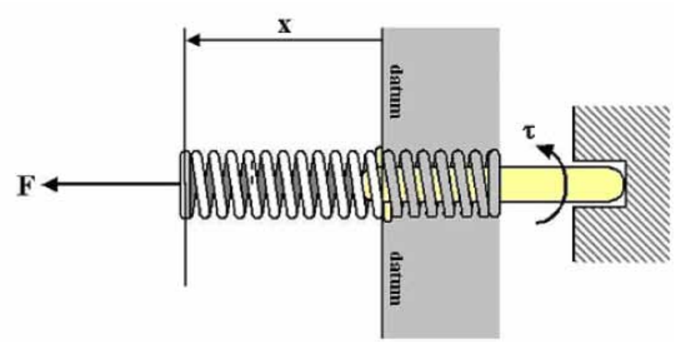
$$M = \left(\frac{E.I}{L}\right).\theta$$

EI/L =the bending stiffness



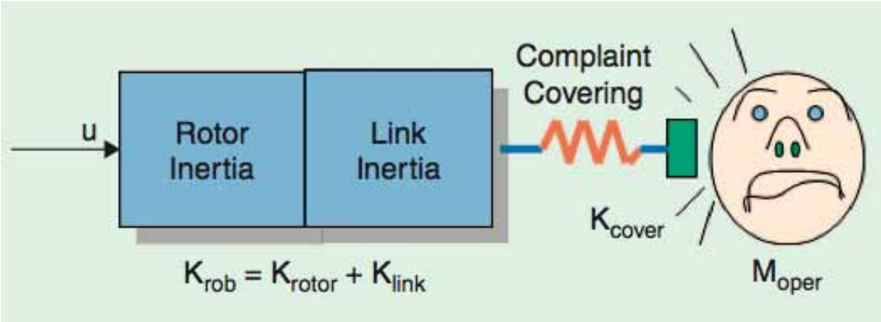
Mechanical Compliance Adjuster
Morita et Sugano

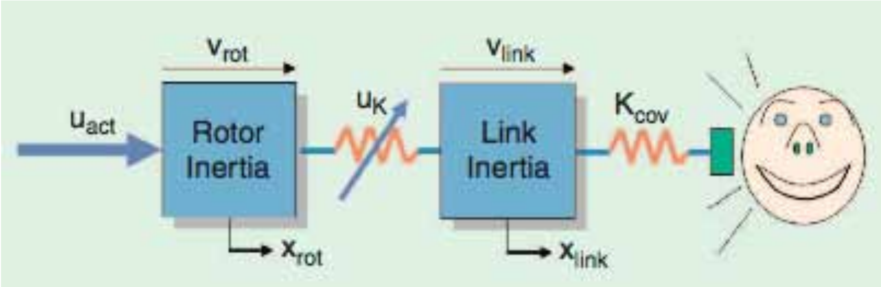
Jack Spring Actuator
Hollander et Sugar



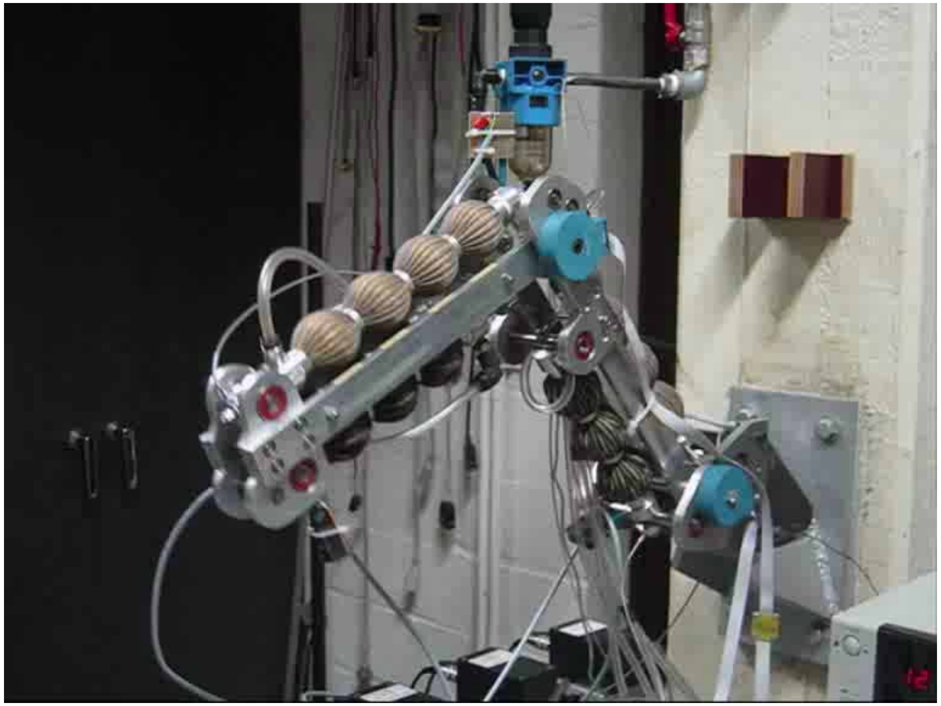
Hollander et al.

Compliant actuation
Safety



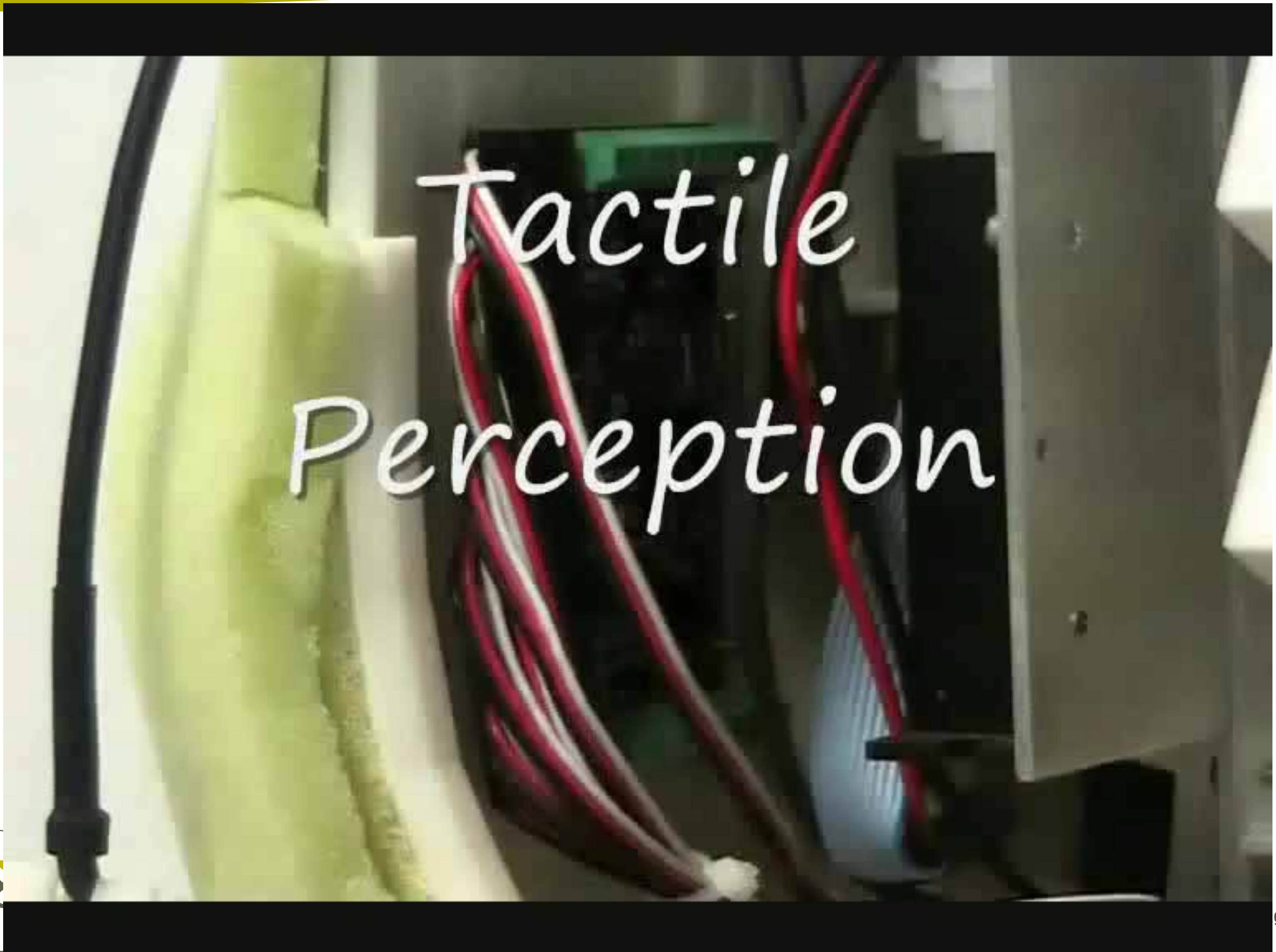


Source: Bicchi

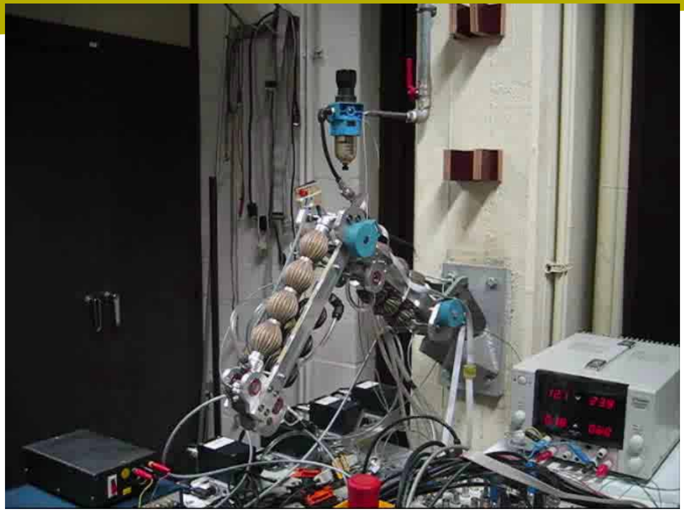


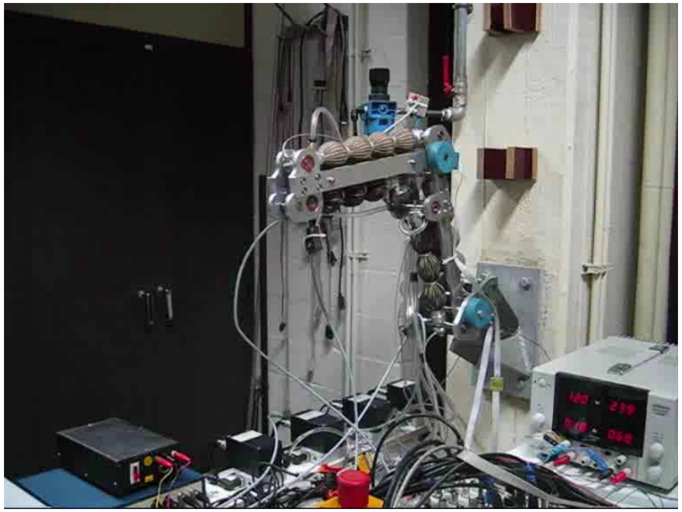
Baxter coworker

Compliant Actuation
Safety



Compliant actuators
Hardware is not always enough for safety





•Passive actuators can store energy which is a potential danger if not properly controlled

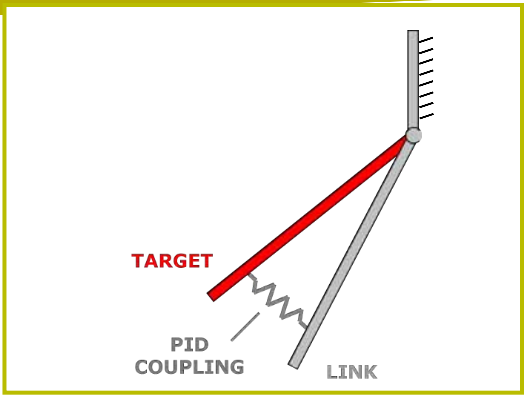
•Use of proxy based sliding mode controller

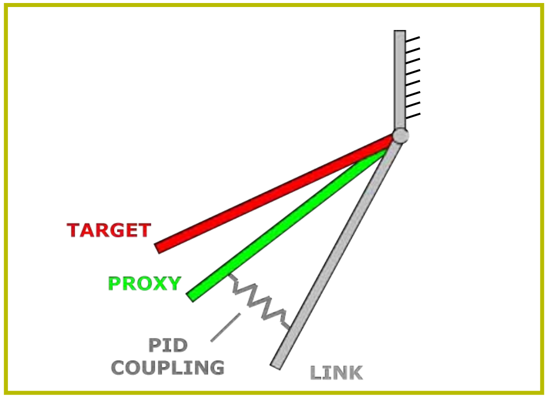
	Step		switch between trajectories		Tracking error for sinus
	HIC	Fmax	HIC	Fmax	
PID	4.81	1524	3.02	1004	0.0146
PSMC	0.1	233	0.03	132	0.0053

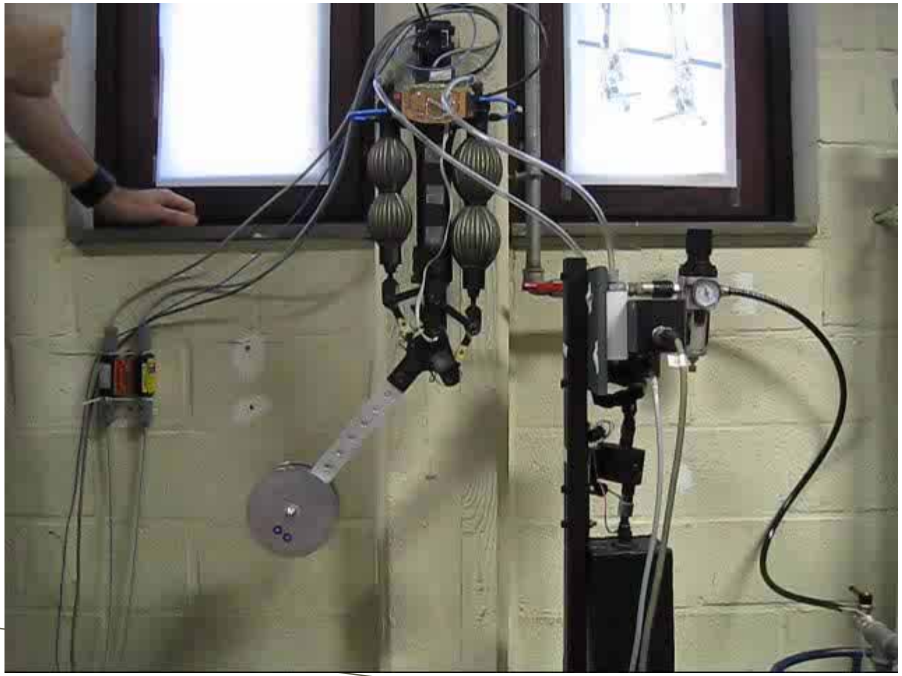
PID = unsafe
PSMC = safe

Vrije Universiteit Brussel

Proxy-based sliding mode controller





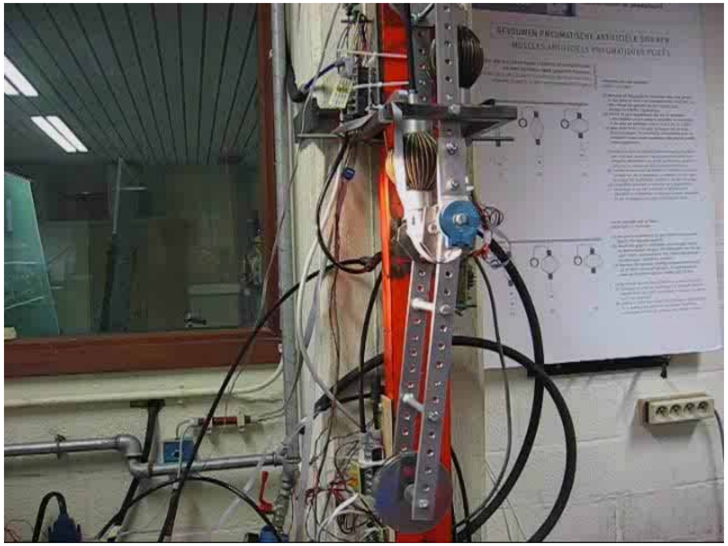


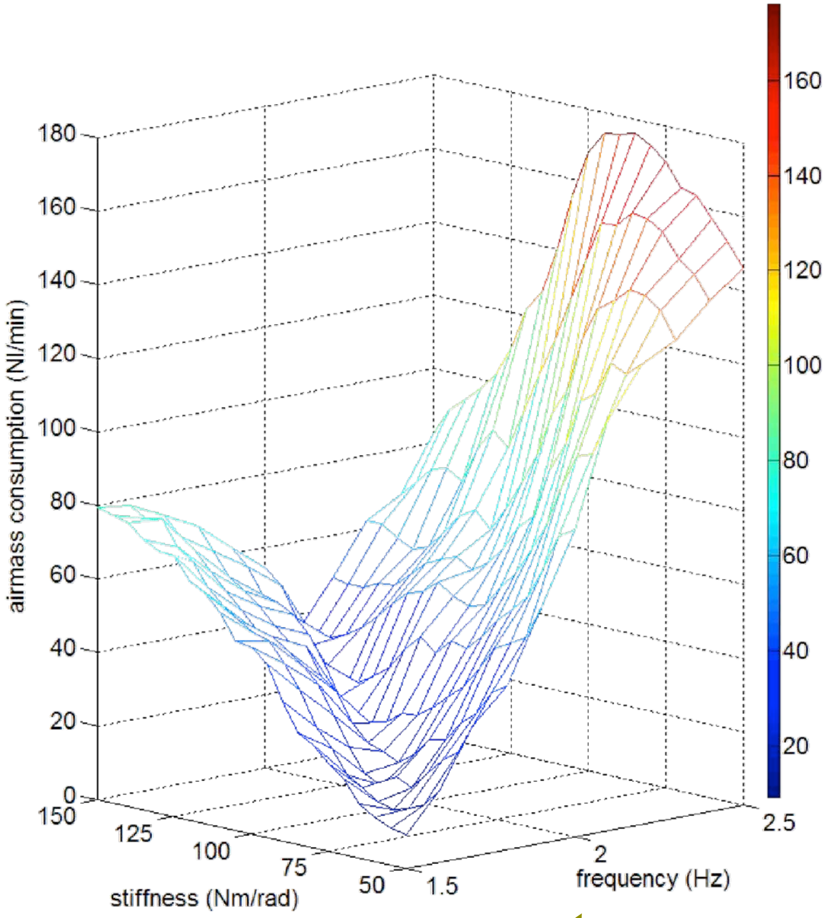
Compliant actuators
Force interaction: Knexo and Altacro

Compliant actuators
Assistive exoskeleton: Mirad

Compliant actuators
Energy efficiency

Choosing optimal stiffness reduces the energy consumption
Developed a compliance controller to select the optimal stiffness.

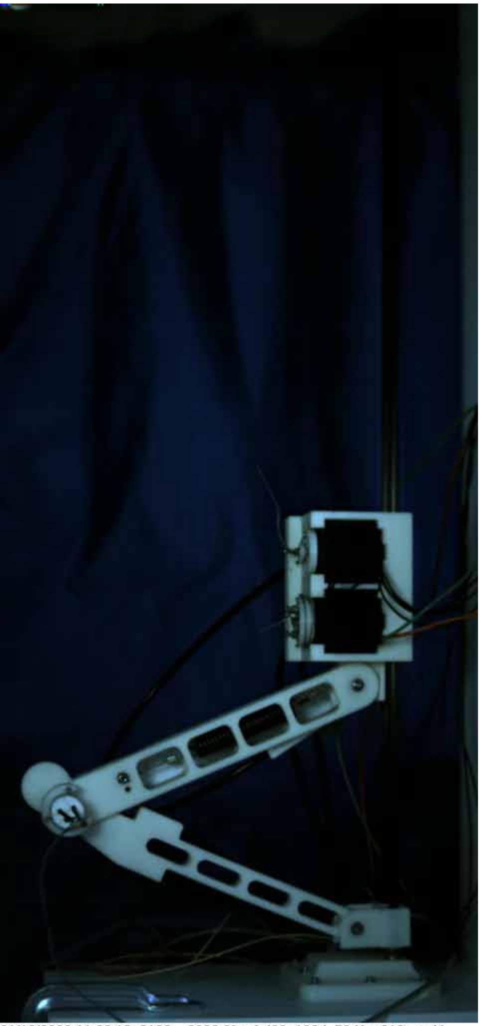




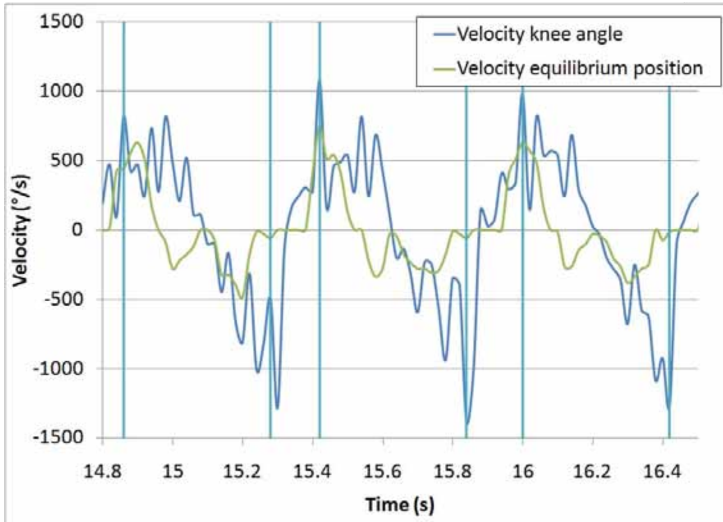
$$\tilde{p}_1 = p_m + \Delta\tilde{p}$$
$$\tilde{p}_2 = p_m - \Delta\tilde{p}$$

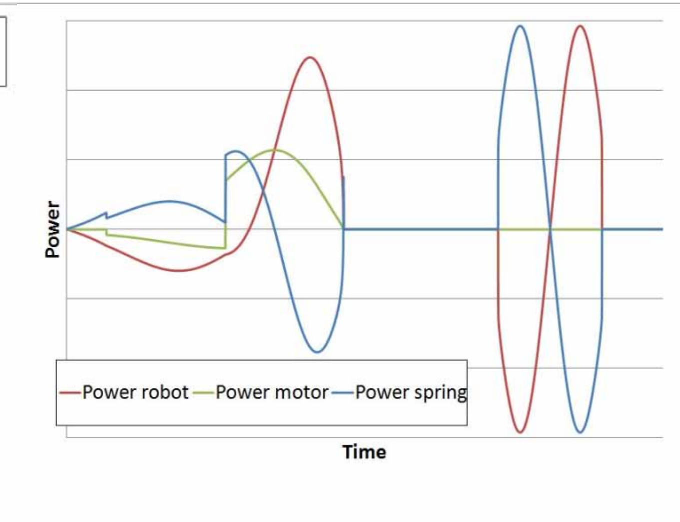
Compliant actuators
Exploitation natural dynamics

Compliant actuation
Explosive motions



01/12/2009 11:29:16 0109 -2038.9[ms] 480×1024, 50 Hz, 818 µs, *1,
SpeedCam HiSpec #00127, V1.9.21

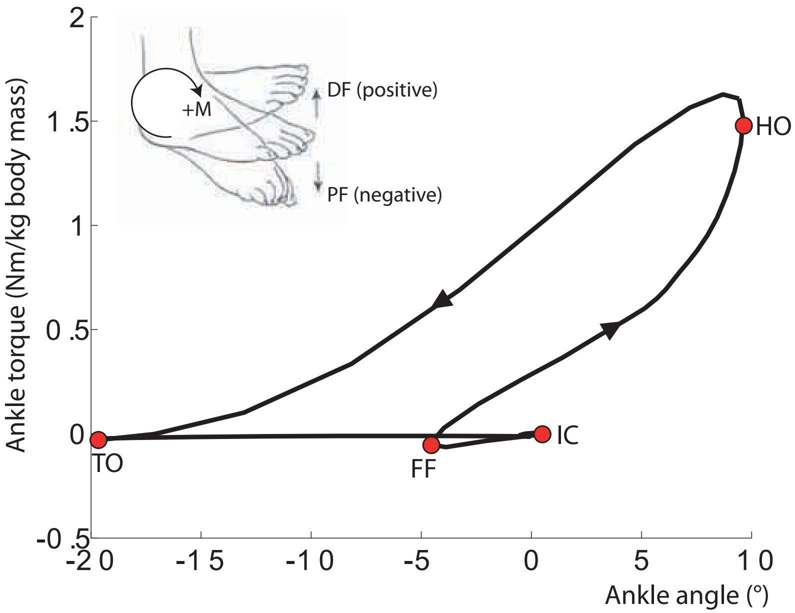


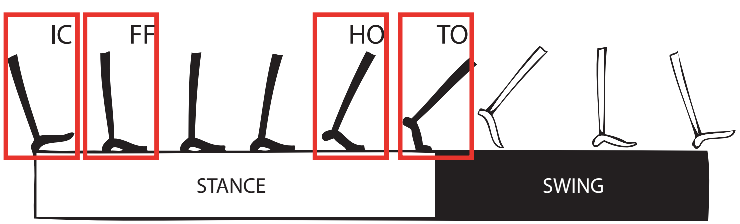


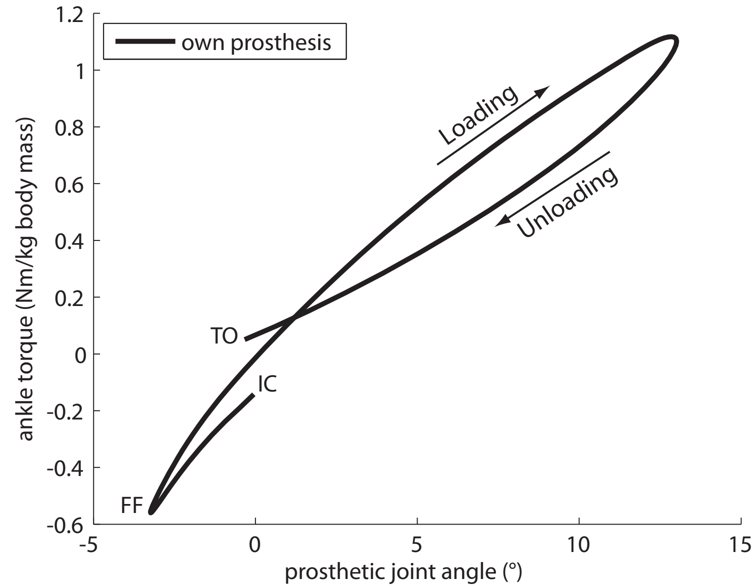
Energy is stored during one phase and released during next phase

Less powerful motor is needed

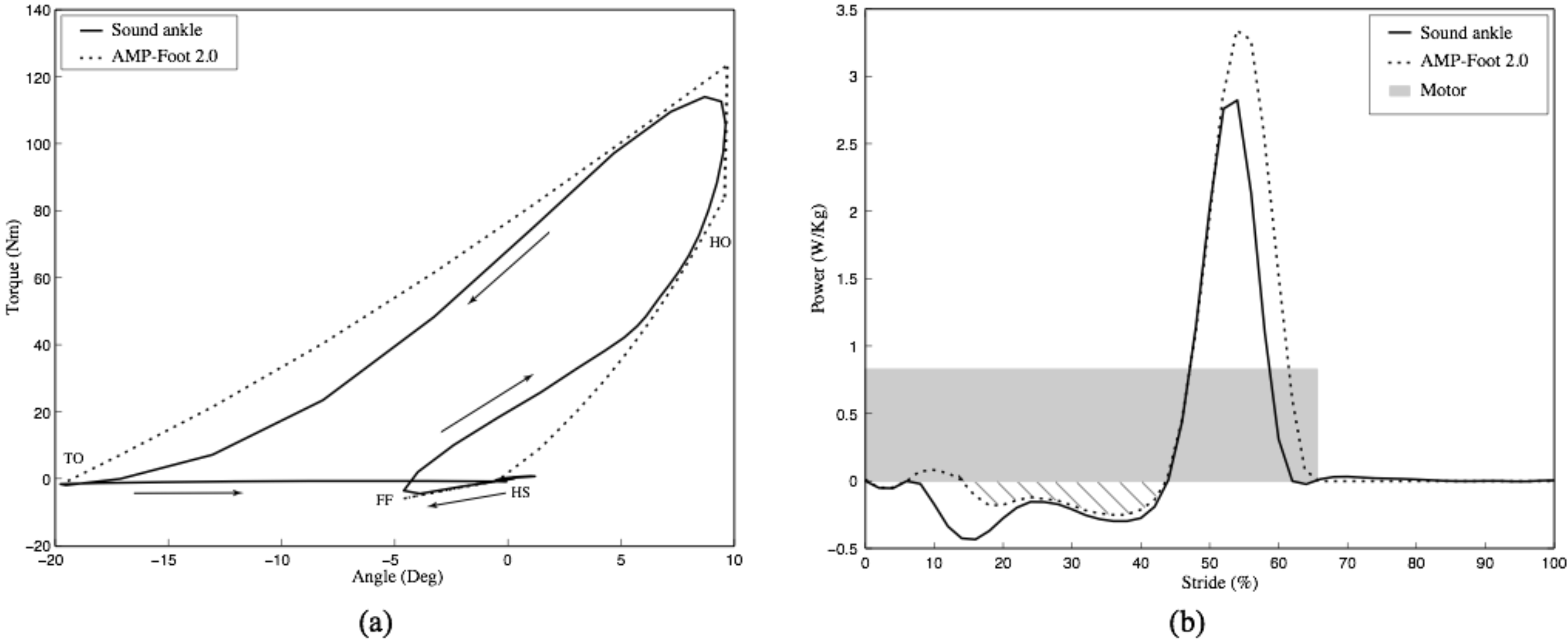
Compliant actuation
Explosive motions







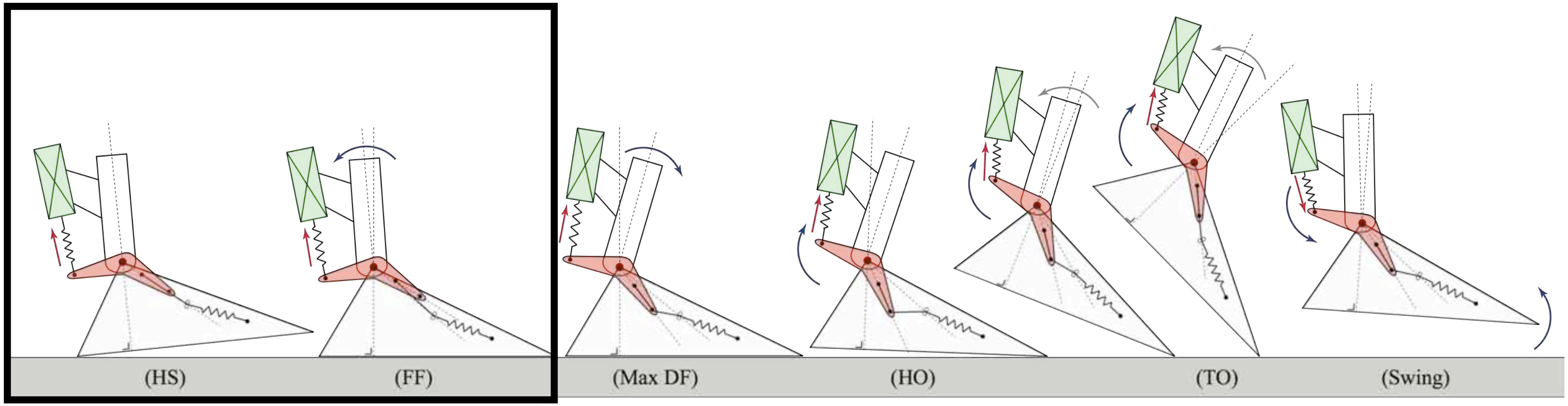
Human foot requirements

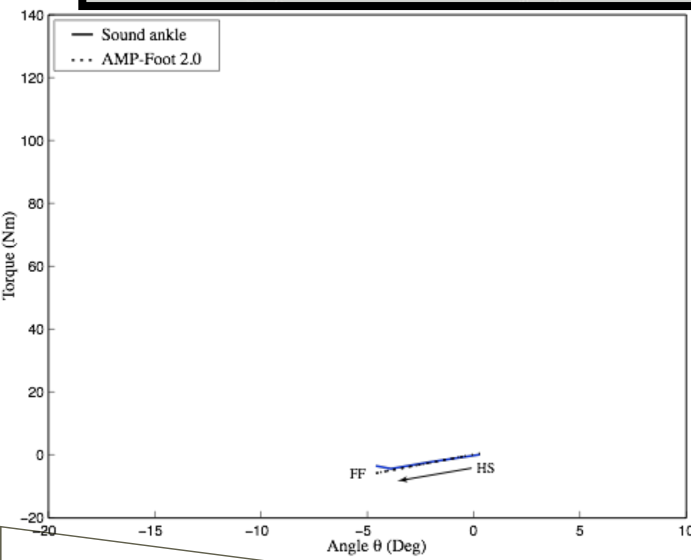


!! Motor works during the complete stance phase !!

Vrije Universiteit Brussel

AMPFoot 2: working principle

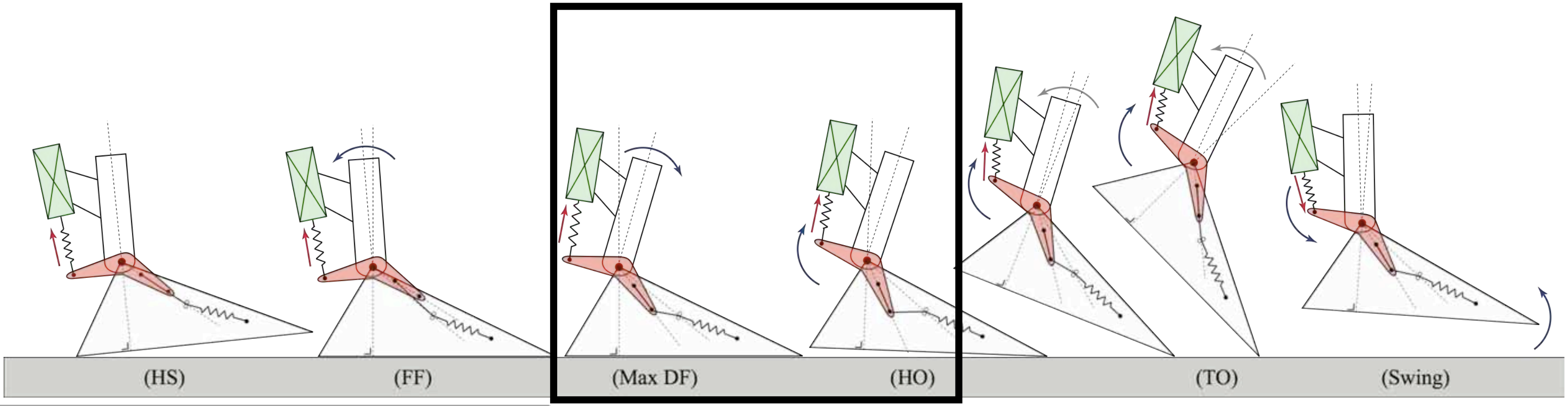


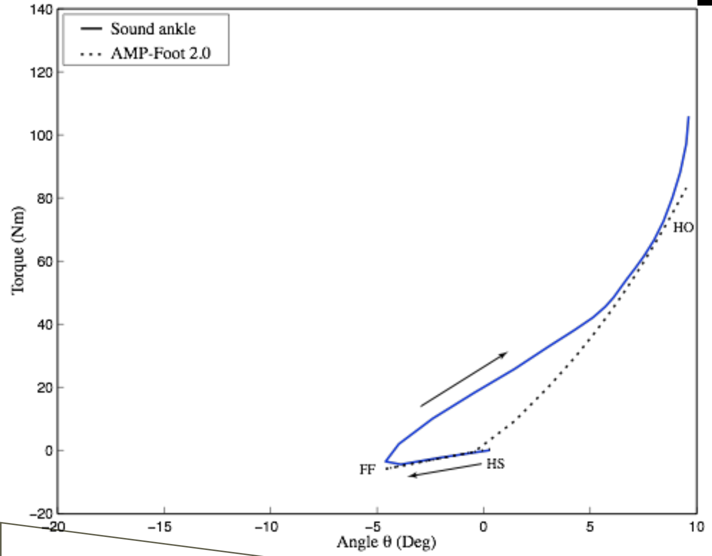


<u>*From heel strike (HS) to foot flat (FF)*</u>

Vrije Universiteit Brussel

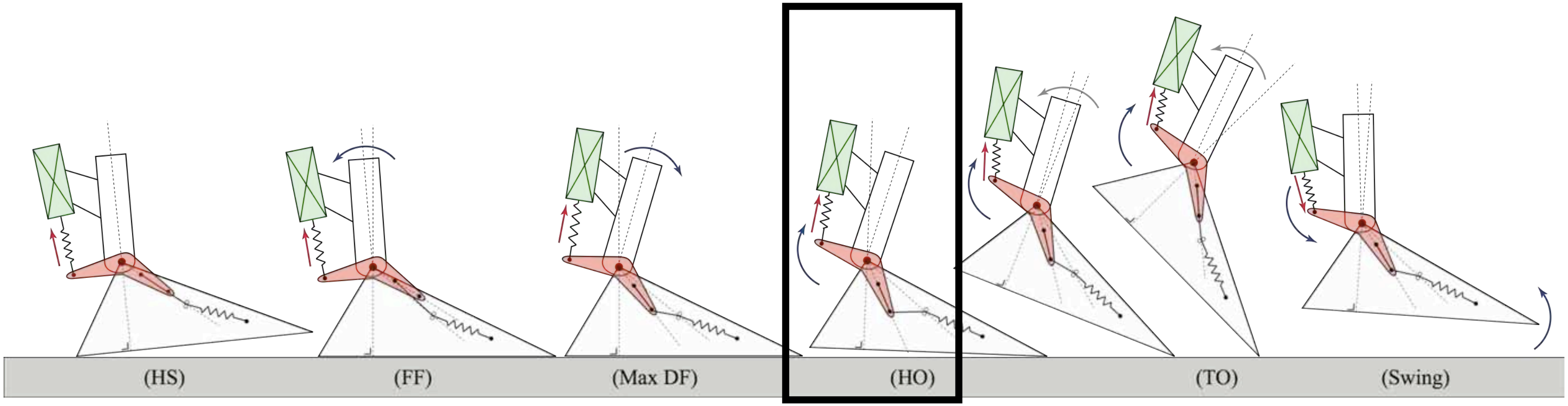
AMPFoot 2: working principle

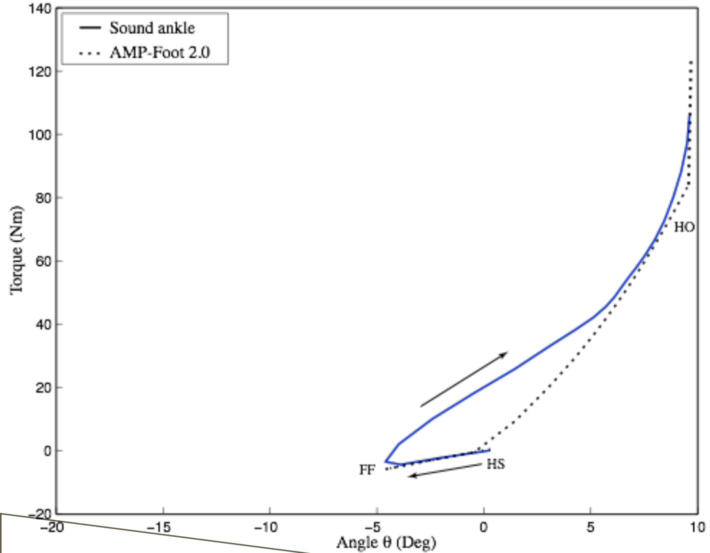




From foot flat (FF) to heel off (HO)

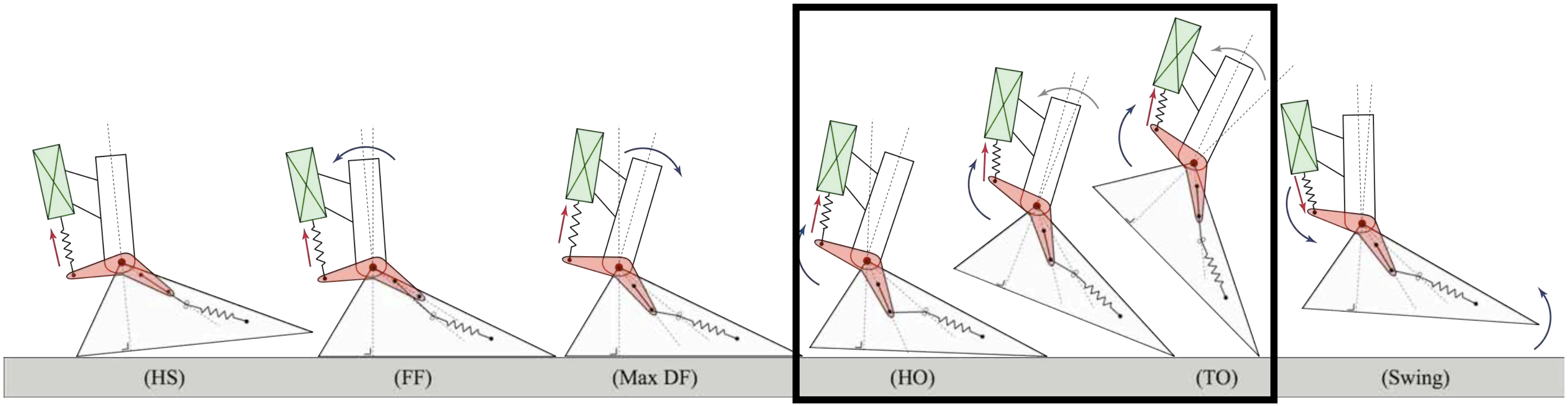
AMPFoot 2: working principle

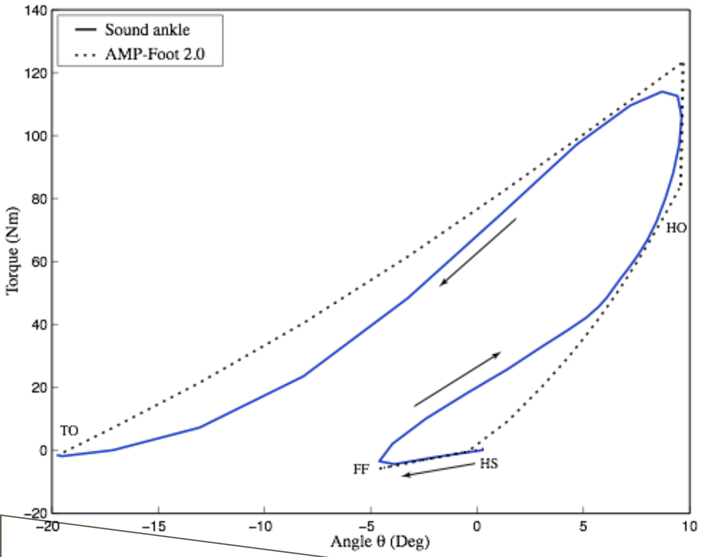




At heel off (HO)

AMPFoot 2: working principle

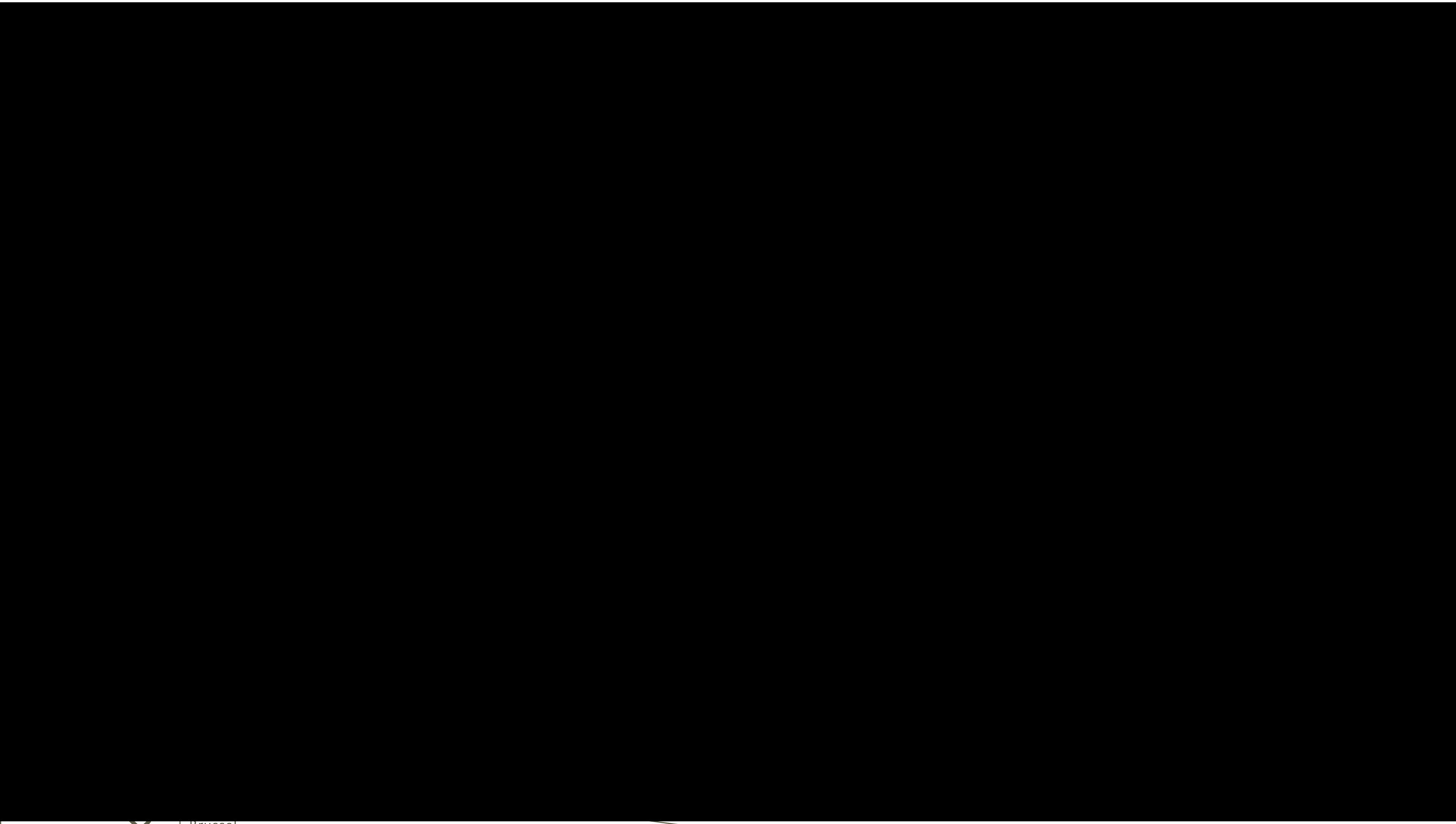




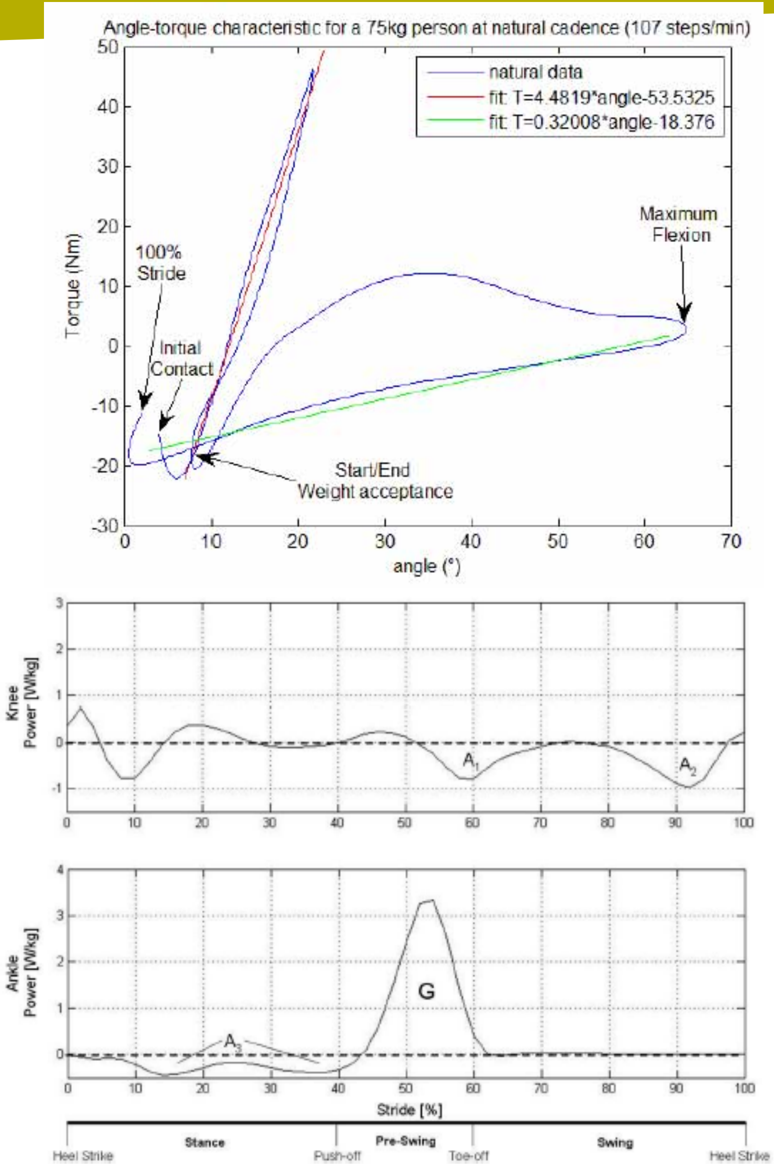
From heel off (HO) to toe off (TO)

AMPfoot 2.0

Prostheses: AMPfoot



Cyberlegs


Angle-torque characteristic for a 75kg person at natural cadence (107 steps/min)
natural data
fit: T=4.4819*angle-53.5325
fit: T=0.32008*angle-18.376
Torque (Nm)
angle (°)
100% Stride
Initial Contact
Start/End Weight acceptance
Maximum Flexion
Knee Power [W/kg]
A_1
A_2
Ankle Power [W/kg]
A_3
G
Stride [%]
Stance
Pre-Swing
Swing
Heel Strike
Push-off
Toe-off
Heel Strike

Locking mechanisms

Mechanical locking devices

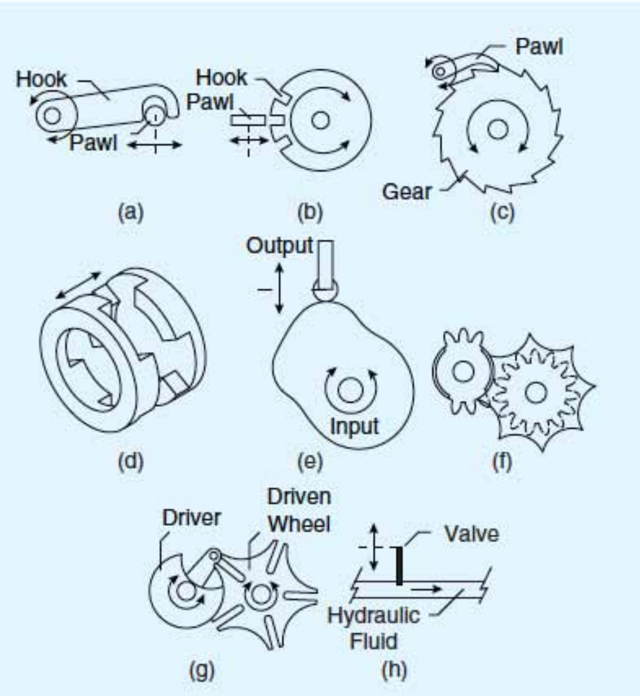
(a) A latch with one locking position, (b) a latch with multiple locking positions, (c) a ratchet, (d) a dog clutch, (e) a cam-based locking device: cam follower, (f) a cam-based locking device: mutilated gears, (g) a cam-based locking device: geneva mechanism, and (h) a hydraulic lock.

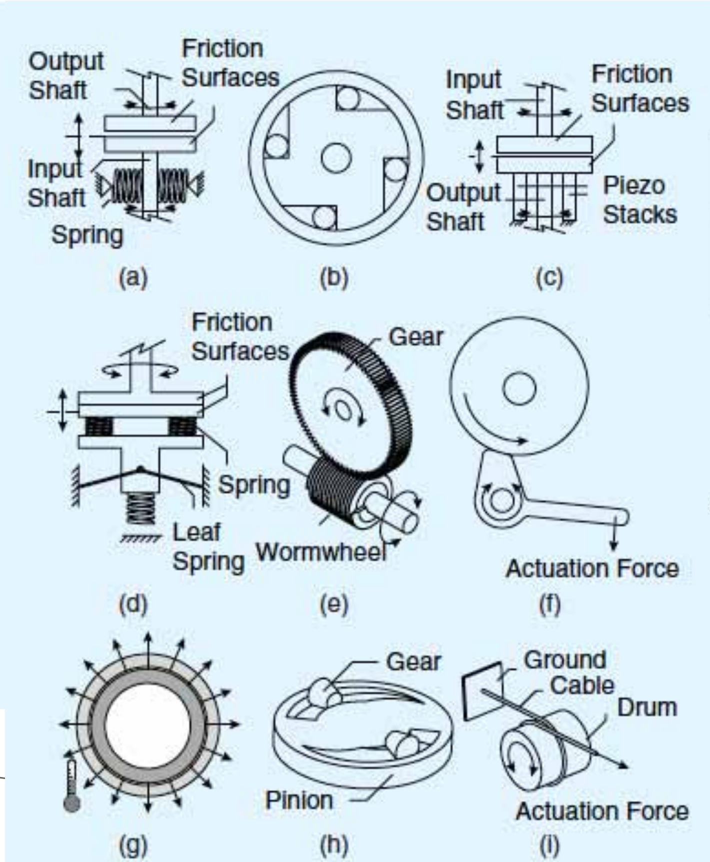
friction-based locking devices

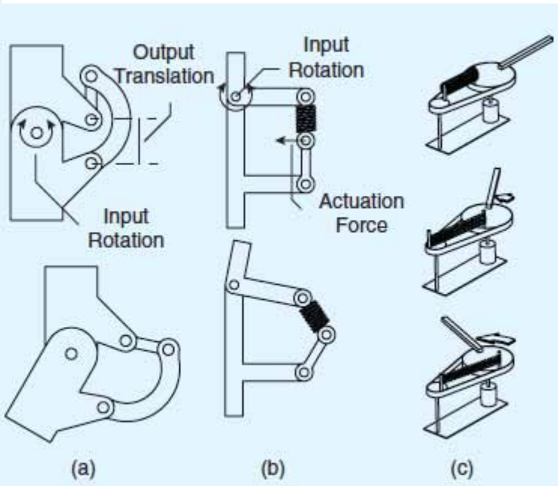
(a) A bistable brake, (b) an overrunning clutch, (c) a piezo-actuated brake, (d) a statically balanced brake, (e) a worm wheel, (f) a self-engaging brake, (g) a thermic lock, (h) a self-engaging pinion-gear mechanism, and (i) a capstan.

singularity locking devices

with (a) and (b) the two different four-bar mechanisms and (c) a nonlinear spring mechanism.







Review of locking devices used in robotics Plooij Michiel, MATHIJSSEN Glenn, CHERELLE Pierre, LEFEBER DIRK, VANDERBORGHT Bram, IEEE Robotics & Automation Magazine, March 2015

Vrije Universiteit Brussel

Flowchart locking devices