2011 summer school on impedance

Human legs / Robot legs

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Impedance in robots

- Active Compliance
  - Compliant behaviour by means of software control
- Constant Passive Compliance
  - Passive element (eg spring is introduced)
  - One motor
- Adaptable Passive Compliance
  - Stiffness can be changed
  - Two motors

Categorization of adaptable compliant actuators

- ☐ Equilibrium Controlled Stiffness
- ☐ Antagonistically Controlled Stiffness
- ☐ Structure Controlled Stiffness
- ☐ Mechanically Controlled Stiffness

BY RONALD VAN HAM, THOMAS G. SUGAR, BRAM VANDERBORGHT, KEVIN W. HOLLANDER, AND DIRK LEFEBER

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Compliant Actuator Designs

Review of Actuators with Passive Adjustable Compliance/Controllable Stiffness for Robotic Applications

In the growing fields of wearable robotics, rehabilitation robotics, prosthetics, and walking robots, variable stiffness actuators (VSAs) or adjustable compliant actuators are being designed and implemented because of their ability to minimize large forces due to shocks, to safely interact with the user, and their ability to store and release energy in passive elastic elements. This review article describes the state of the art in the design of actuators with adaptable passive compliance. This new type of actuator is not preferred for classical position-controlled applications such as pick and place operations but is preferred in novel robots where safe human–robot interaction is required or in applications where energy efficiency must be increased by adapting the actuator's resonance frequency. The working principles of the different existing designs are explained and compared. The designs are divided into four groups: equilibrium-controlled stiffness, antagonistic-controlled stiffness, structure-controlled stiffness (SCS), and mechanically controlled stiffness.

In classical robotic applications, actuators are preferred to be as stiff as possible to make precise position movements or trajectory tracking control easier (faster systems with high bandwidth). The biological counterpart is the muscle that has superior functional performance and a neuromechanical control system that is much more advanced at adapting and tuning its parameters. The superior power-to-weight ratio, force-to-weight ratio, compliance, and control of muscle, when compared with traditional robotic actuators, are the main barriers for the development of machines that can match the motion, safety, and energy efficiency of human or other animals. One of the key differences of these systems is the compliance or springlike behavior found in biological systems [1]. Although such compliant

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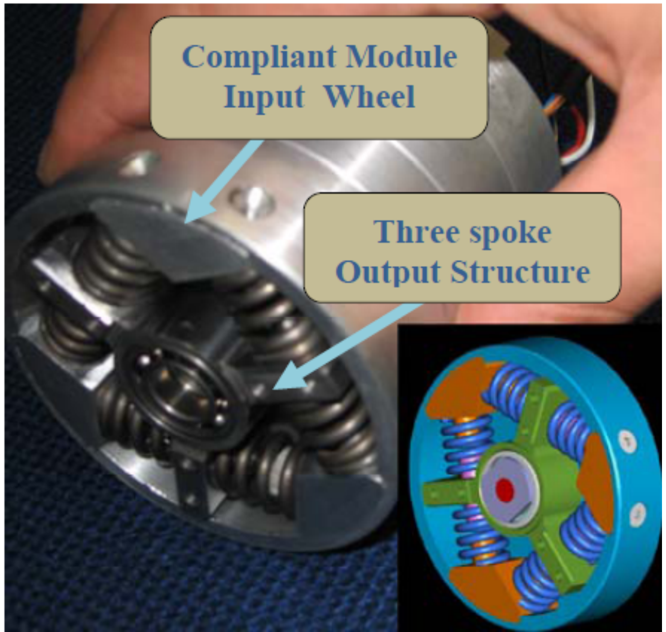
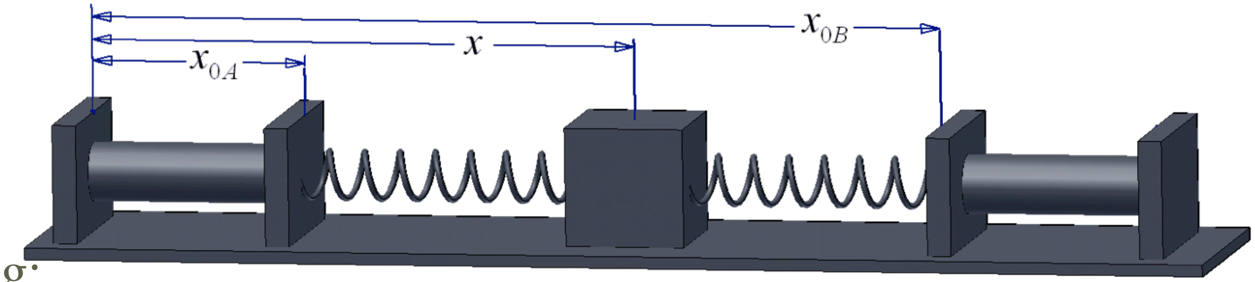


Tsagarakis IIT

Antagonistically Controlled Stiffness



- Linear spring:

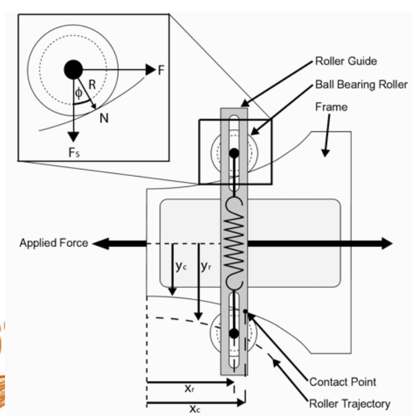
$$F = -\kappa(x - x_{0A}) + \kappa(x_{0B} - x) = -2\kappa x + \kappa(x_{0A} - x_{0B})$$

$$k = -\frac{dF}{dx} = 2\kappa$$

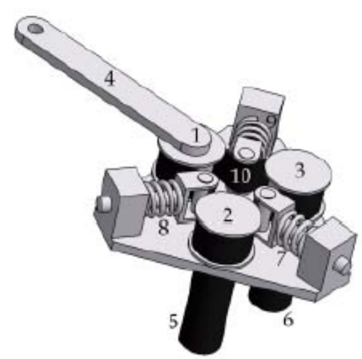
- Quadratic spring:

$$F = -\kappa(x - x_{0A})^2 + \kappa(x_{0B} - x)^2 = 2\kappa x(x_{0A} - x_{0B}) + \kappa\left(x_{0B}{}^2 - x_{0A}{}^2\right)$$

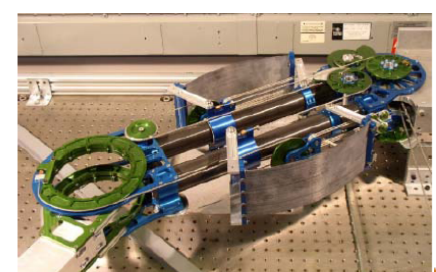
$$k = -\frac{dF}{dx} = 2\kappa(x_{0B} - x_{0A})$$



S. A. Migliore et al.

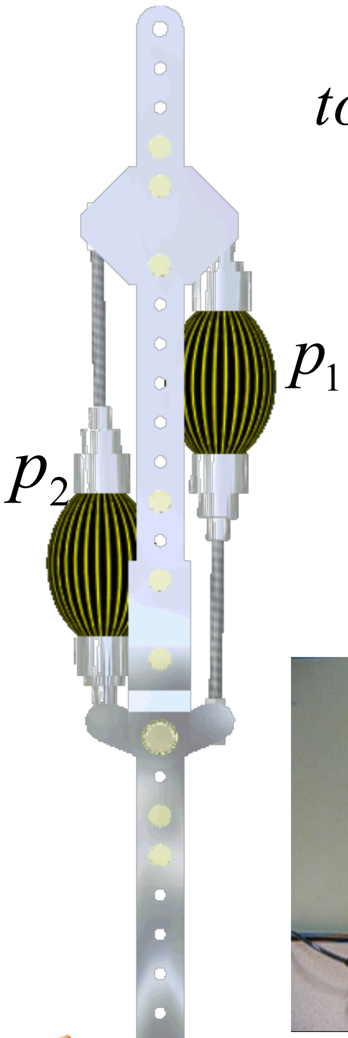


VSA - Tonietti et al.



AMASC – Hurst et al.

Antagonistic setup of two pneumatic muscles



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

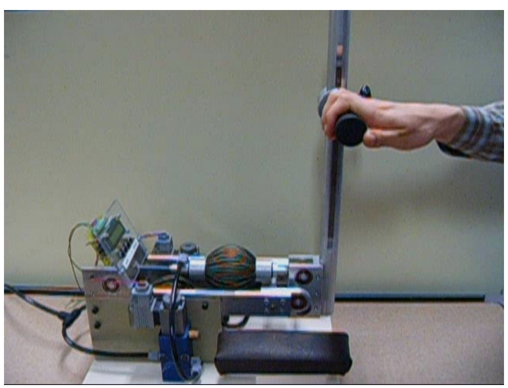
$$\tilde{p}_1 = p_m + \Delta\tilde{p}$$

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

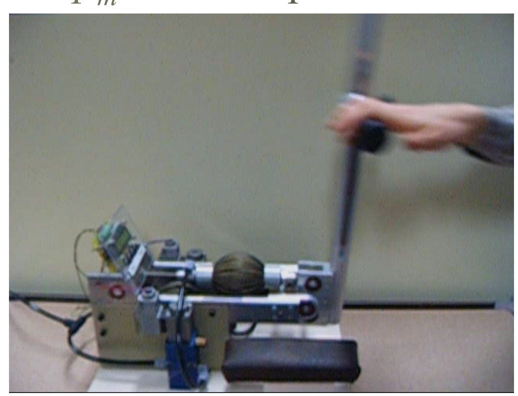
$\sim$ stiffness

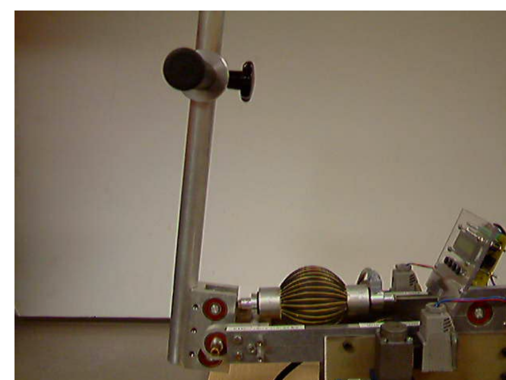
$\sim$ torque

p_m high: stiff



p_m low: compliant



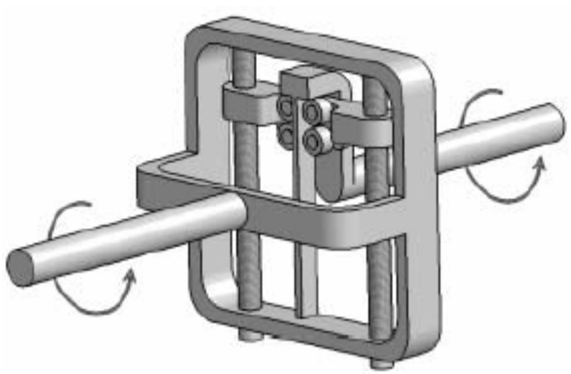


Structure Controlled Stiffness

Bending of a leaf spring:

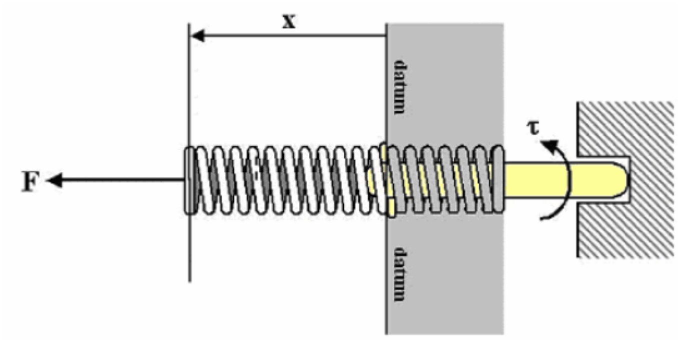
$$M = \left(\frac{E.I}{L}\right).\theta$$

EI/L =the bending stiffness



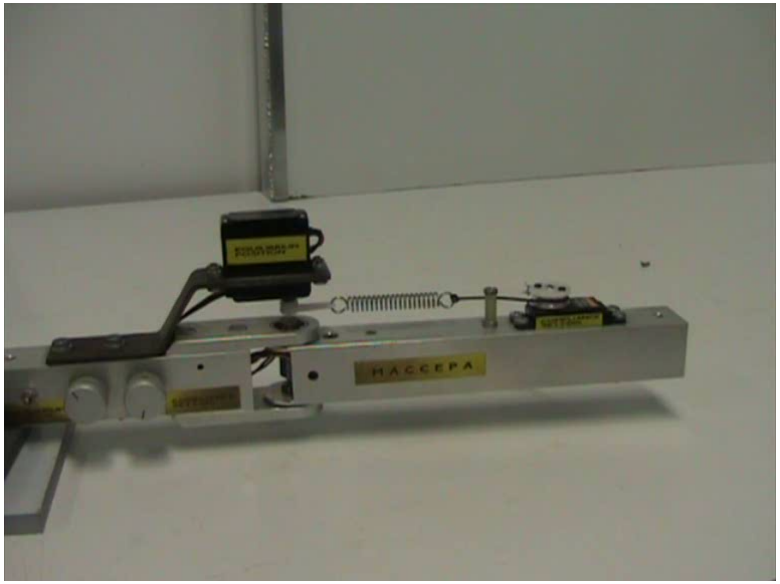
Mechanical Compliance Adjuster
Morita et Sugano

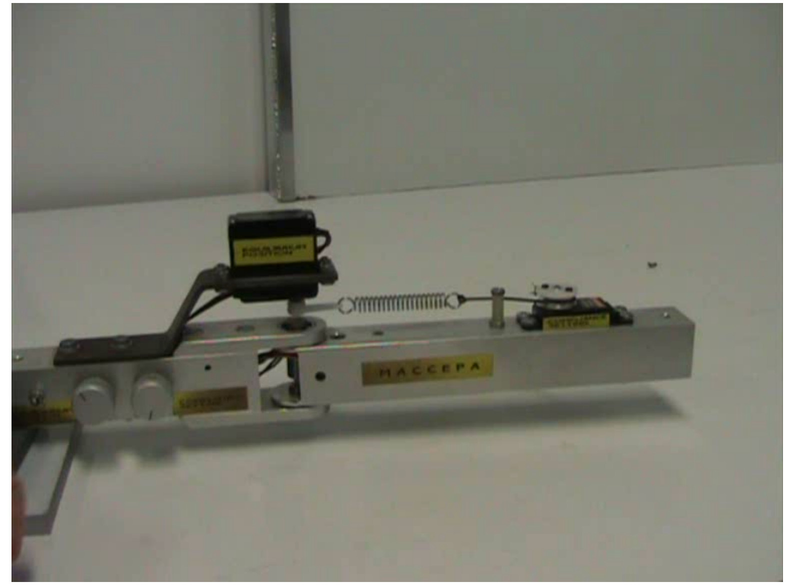
Hollander et Sugar



Jack Spring Actuator
Hollander et al.

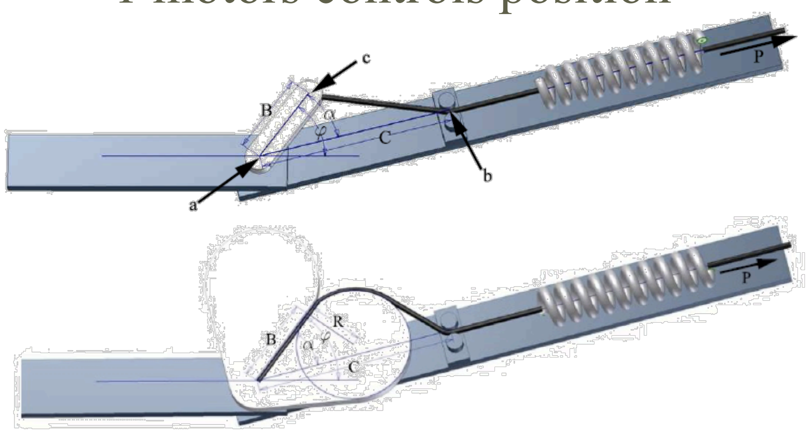
Mechanically Controlled Stiffness



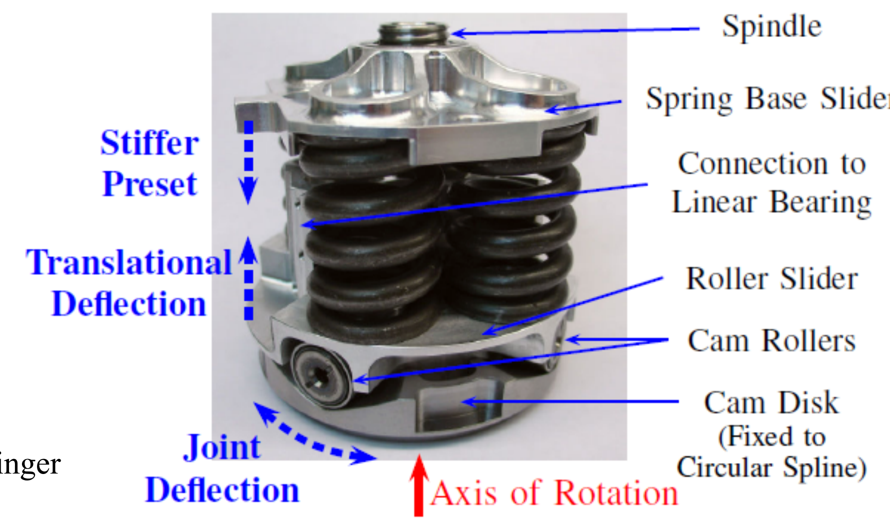


1 motors controls position

1 motor controls stiffness

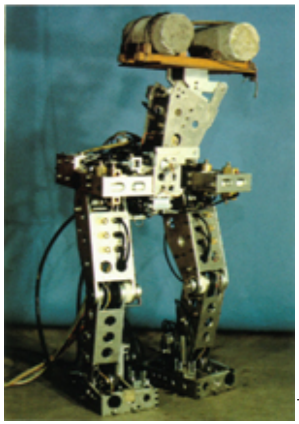


Maccepa
Van Ham et al.

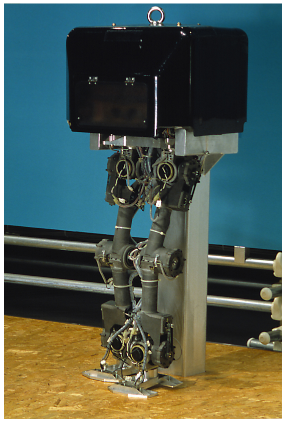


VS-joint
Wolf et Hirzinger

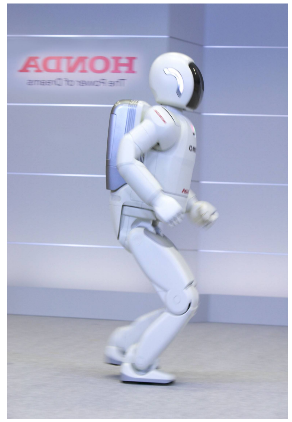
Speed of robots



WL-5
(1970):
45s/step



E2
('87-'91):
1,2km/h



Asimo:
6km/h

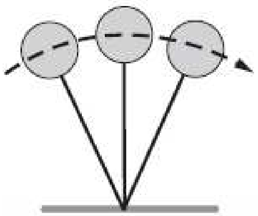
Partner robot:
7km/h

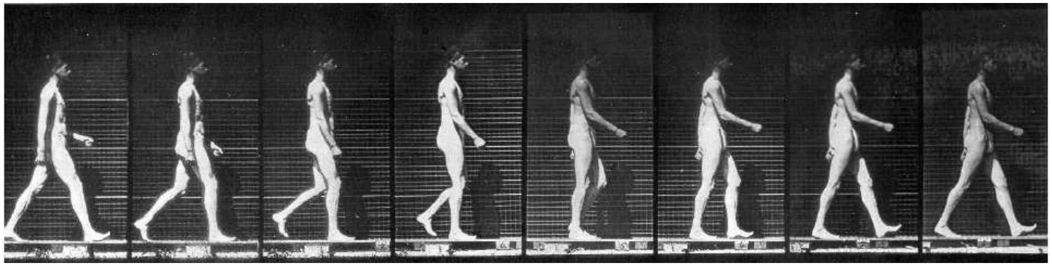
Walking men
+/- 5km/h

Usain Bolt
WR 100m:
36,8km/h

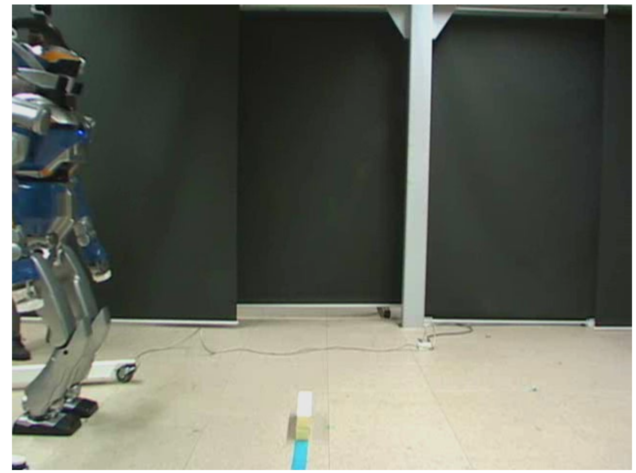
Copy nature?

Walking: inverted pendulum



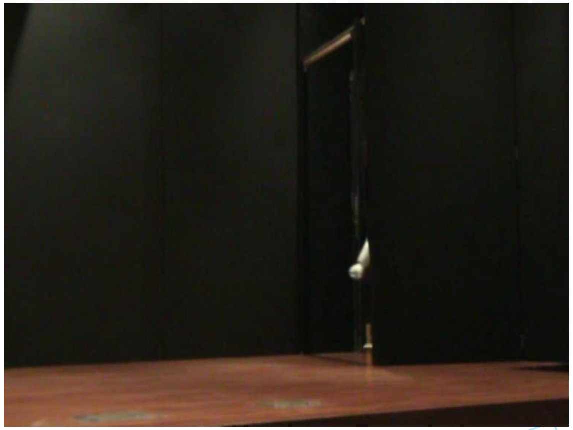


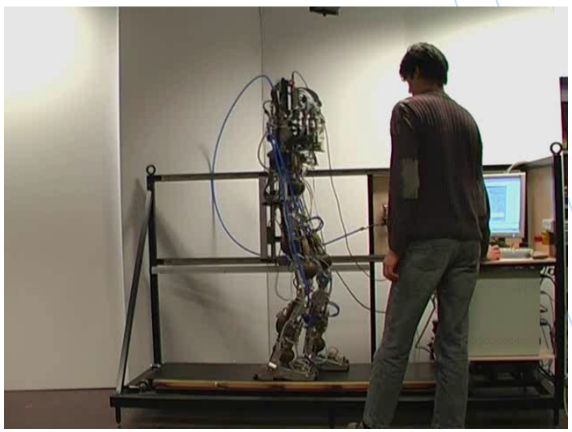
- ☐ No aerial phase
- ☐ Straight supporting leg
- ☐ Potential energy and kinetic energy out of phase
- ☐ Energy storage by interchange of gravitational potential energy and kinetic energy



Wisse

Active walkers





Active walkers
with explotation of
natural dynamics

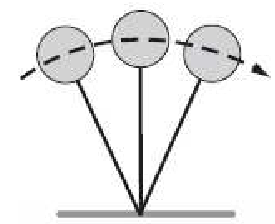
Passive walkers

powered
passive walkers

Controlled
passive walking

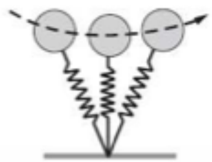
Optimal

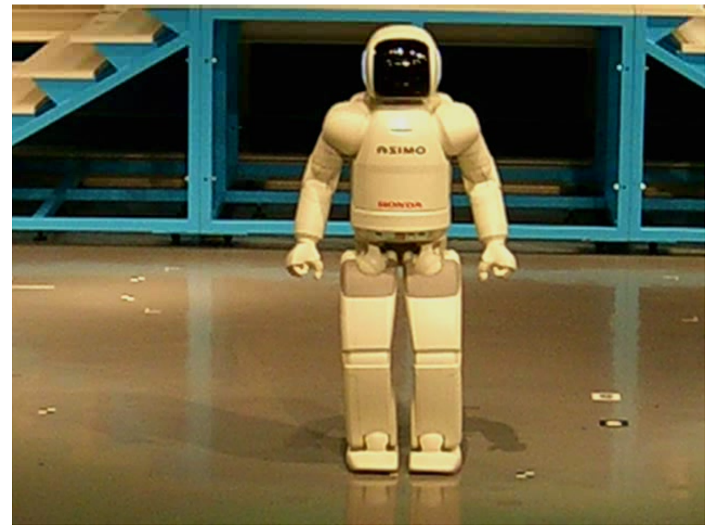
From walking to running



- ☐ $F_{centrifugal} = mv^2/L < F_{gravitational} = mg$
- ☐ $v < \mathrm{sqrt}(gL)$ ($g = 10 m/s^2$, $L = 0.9m$: $v = 3m/s$)
- ☐ Race walker: 4m/s
- ☐ Froude number=v^2/gL has to stay below 1 for walking
  - → normally transition at Froude=0.4-0.5

Running: bouncing ball





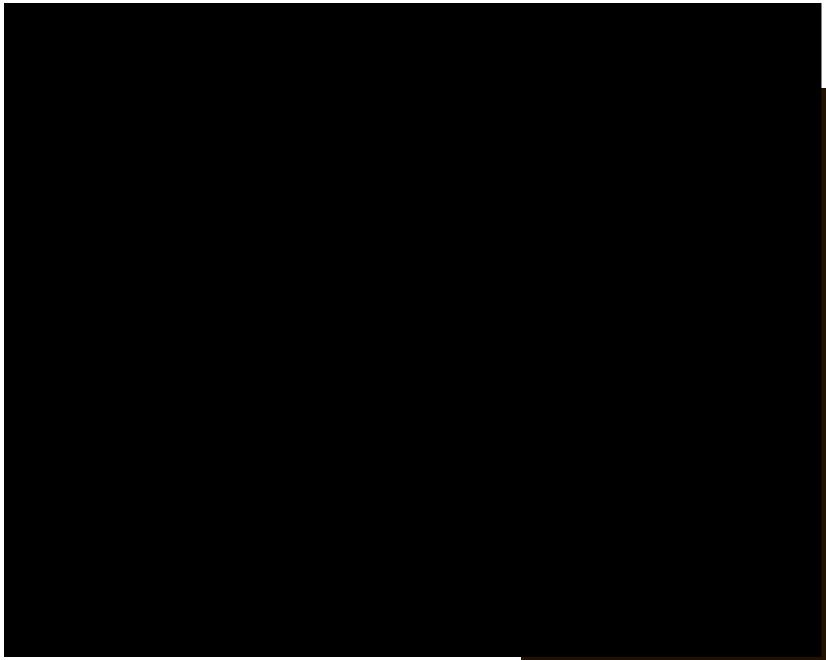
- ☐ Aerial phase
- ☐ Bent legs store energy in springs
- ☐ Potential energy and kinetic energy in phase
- ☐ Energy storage by elastic properties of the joints (Achilles tendon)

Hurst

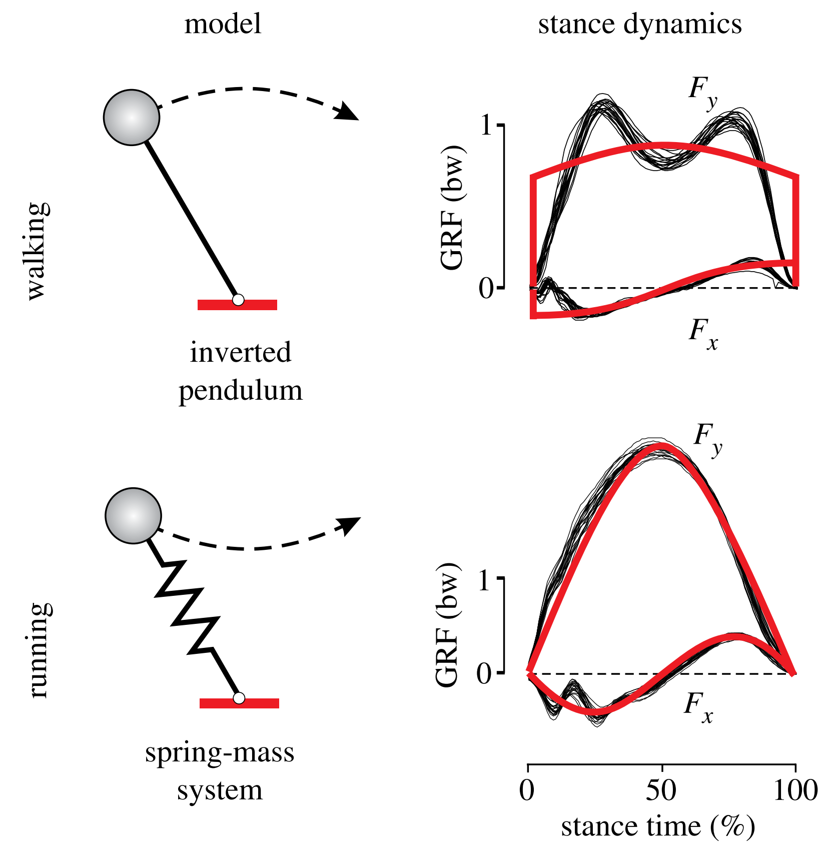
Use of springs

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

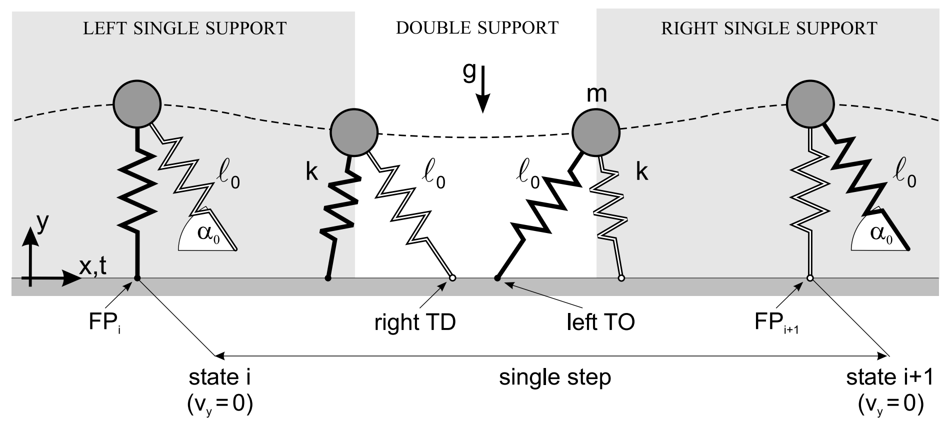
Oscar Pistorius



Spring-mass model for walking

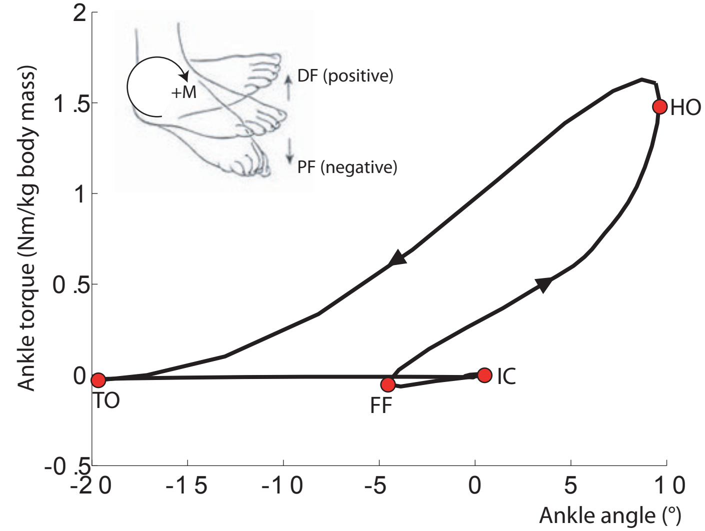


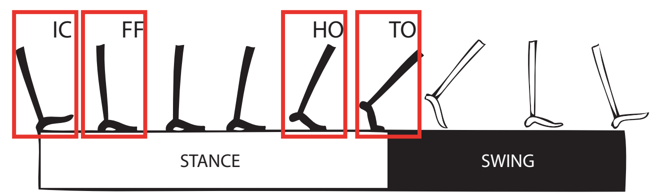
Characteristic ground reaction force (GRF) patterns observed during the stance phase in walking and running

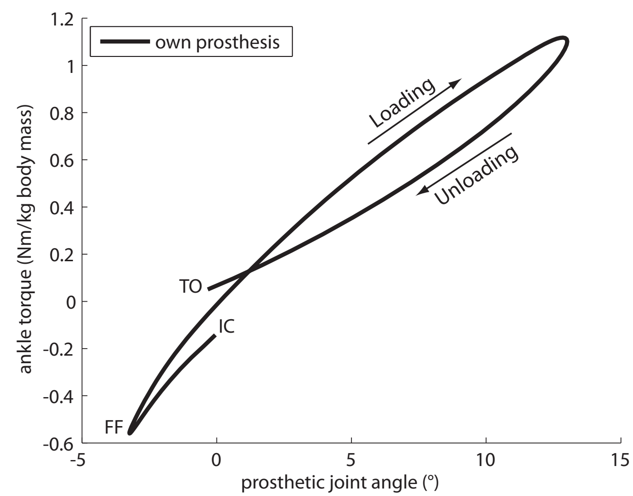


Geyer et al. 2006

Ankle prostheses

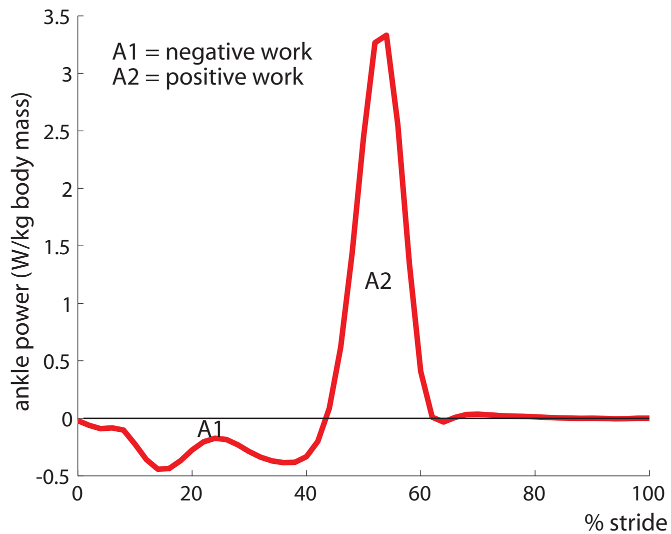


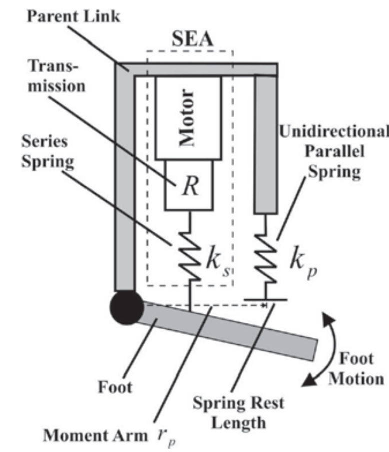




Traditional prosthesis:
walk with closed ski boots

Active prostheses

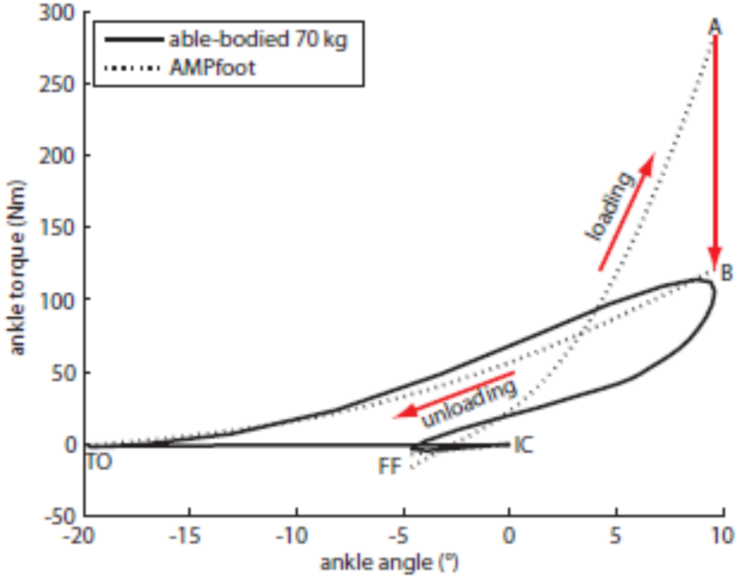


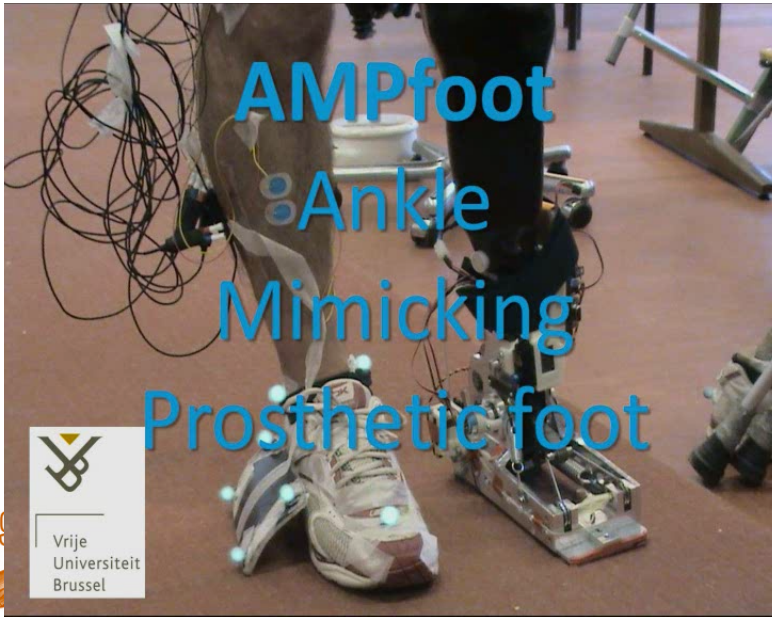


Sugar: 77W instead of 250W

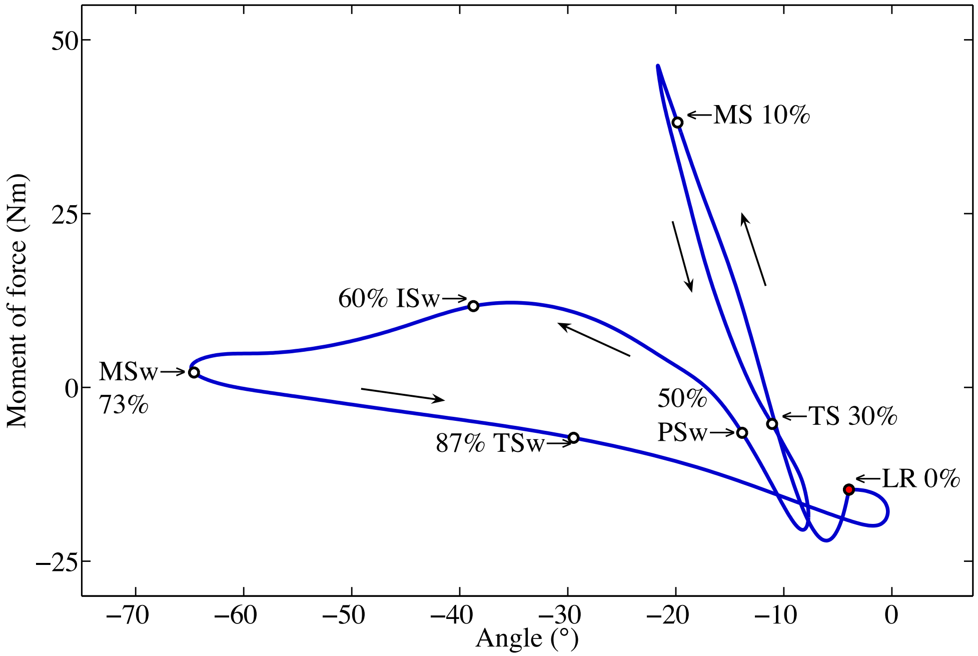
Herr: 150W instead of 250W
20J/step

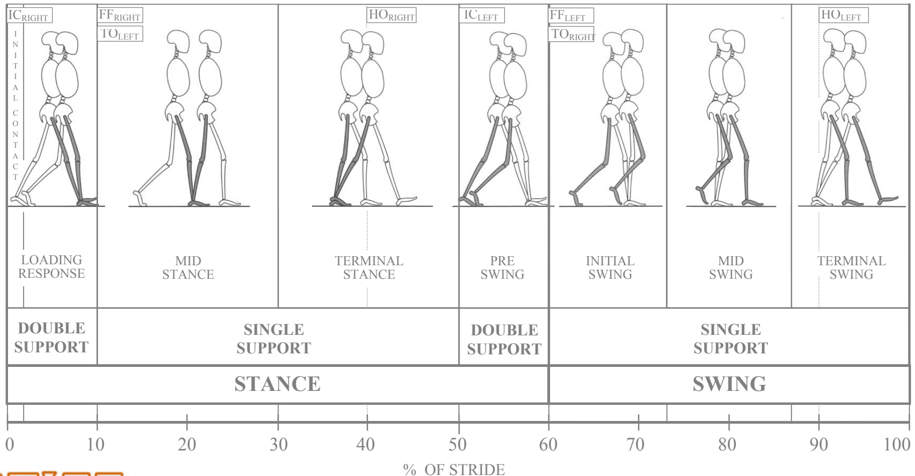
Passive prostheses





Knee model

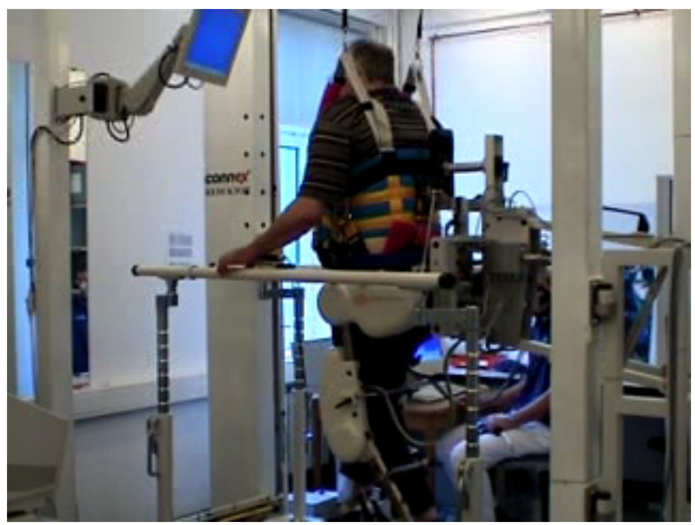




Rheo knee Herr

Energy harvester Kuo

Gait rehabilitation



KNEXO: Unimpaired, Assisted

DIFFERENT CONTROLLER SETTINGS ⇨ DIFFERENT ASSISTIVE MODES

GUIDELINES

τ_{LIM}

↗ ENSURE "NORMAL" TRACKING RANGE

↘ LIMIT RESTORING TORQUE
AVOID HIGH SPEEDS AND OVERSHOOTS

λ

↗ APPROPRIATELY SLOW ⇨ 0.1s

↘ ENSURE GAIT CONTINUITY

F
F

TORQUE LIMITATION AROUND τ_{FF}

WEIGHT BEARING SUPPORT

KNEXO: MS Patient, Assisted

GAIT ASSESSMENT

STANCE: KNEE HYPEREXTENSION

SWING: UNSMOOTH KNEE FLEX/EXT

L/R ASYMMETRY

PATIENT SPECIFIC TUNING

DIFFERENT TARGET TRAJECTORIES

DIFFERENT CONTROLLER SETTINGS

Conclusions

- ☐ Compliance important from biological evidence
- ☐ Influence of compliance in human locomotion is not yet fully understood
- ☐ Current robots, prostheses and ortheses do not yet fully exploit the possibilities of variable compliance
- ☐ Synergy between biology-engineering

References

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