'Use of compliant actuators in prosthetic foot designs'

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http://mech.vub.ac.be/multibody_mechanics.htm

IEEE-RAS Humanoids09

IEEE HUMANOIDS 2009 WORKSHOP
MODELING, SIMULATION AND OPTIMIZATION OF BIPEDAL WALKING

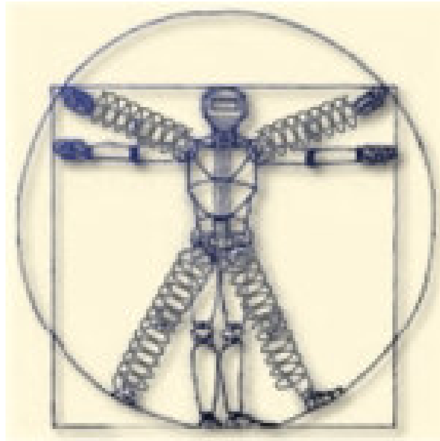
December 7, 2009, Paris, France

Vrije Universiteit Brussel

Outline

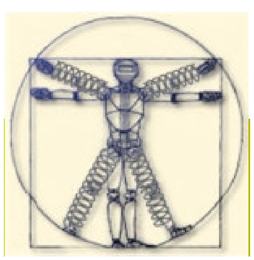
- Introduction
- Compliant and Adaptable Compliant Actuators: working principles
- Prosthetic foot designs
- Conclusions

Introduction



FP7 : VIACTORS
Variable Impedance Actuation Systems
Embodying Advanced Interaction Behaviours
Grant agreement no.: 231554

Review of Actuators with Passive Adjustable Compliance / Controllable Stiffness for Robotic Applications
Ronald Van Ham, Thomas G. Sugar, Bram Vanderborght, Kevin W. Hollander and Dirk Lefeber
IEEE Robotics and Automation Magazine

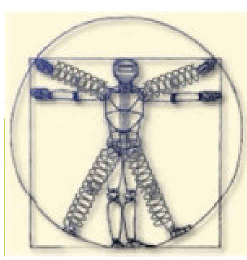


Why using variable impedance actuators in humanoid walking

Efficiency : store energy during negative work; reduce the size of the motors

Cope with impact at heelstrike

'Soft' safe human robot interaction



Compliant Actuators

Active Compliant actuators

Compliant behaviour of a stiff actuator based on software control

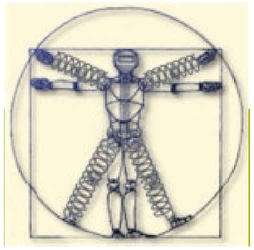
not inherently compliant, no impact

No energy can be stored

power is required both to accelerate and decelerate a mass.
One motor !!!

Passive Compliant Actuators

Actuators with an elastic element (spring)



Passive Compliant Actuators

Passive = contains an elastic element

Inherent compliance : unlimited bandwidth to absorb shocks, energy storage

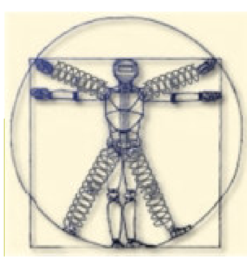
Constant compliance <->Variable compliance

Equilibrium controlled stiffness

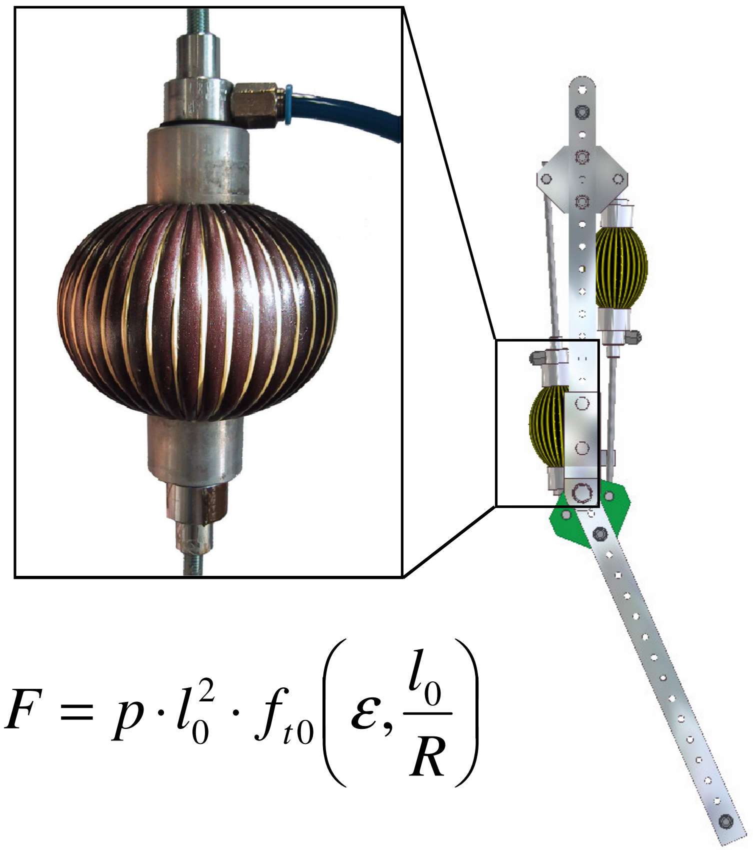
Antagonistic controlled stiffness

Structural controlled stiffness

Mechanically controlled stiffness



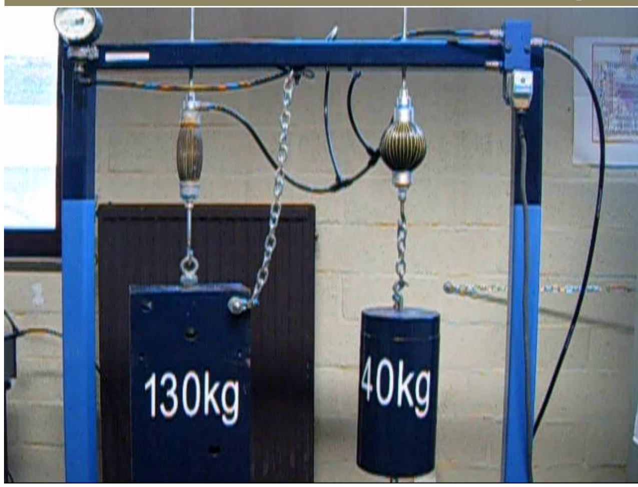
Antagonistic Controlled Stiffness



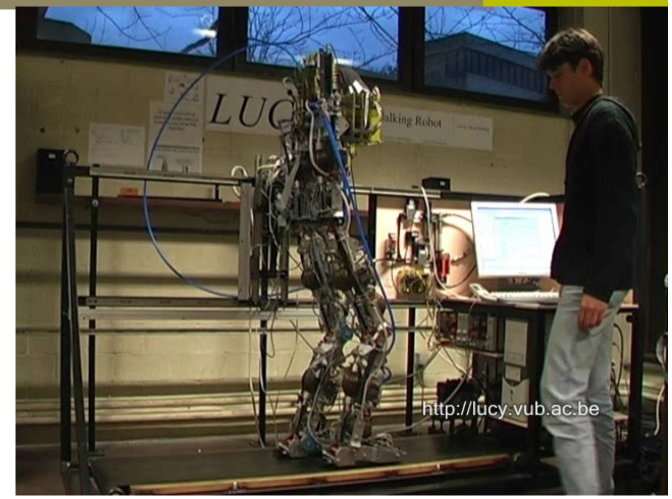
$$F = p \cdot l_0^2 \cdot f_{t0}\left(\varepsilon, \frac{l_0}{R}\right)$$

- Pleated membrane
- Low weight (< 150 g !)
- High force levels
  - ⇨ up to 3000N at 3 bar
- Inherent compliance
- Graceful degradation
- No threshold pressure
- Direct joint attachment
  - ⇨ no gear reduction, no backlash
- Bidirectional rotative actuator

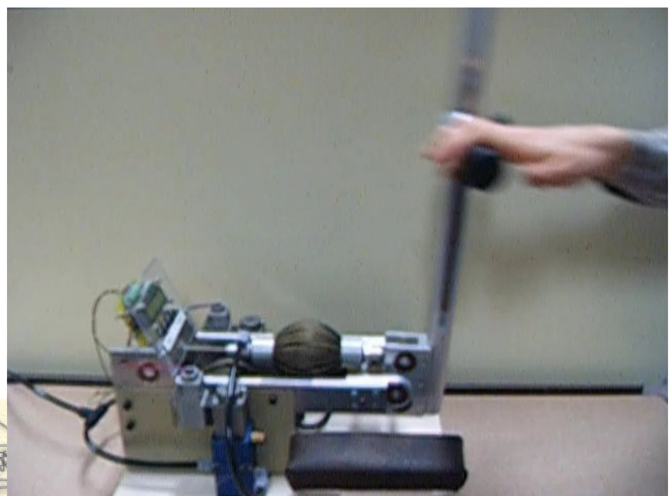
Antagonistic Controlled Stiffness

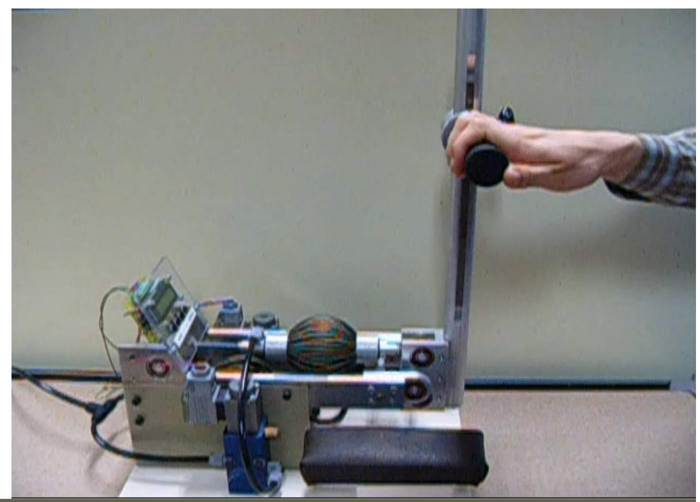


Pleated
Pneumatic
Artificial Muscles



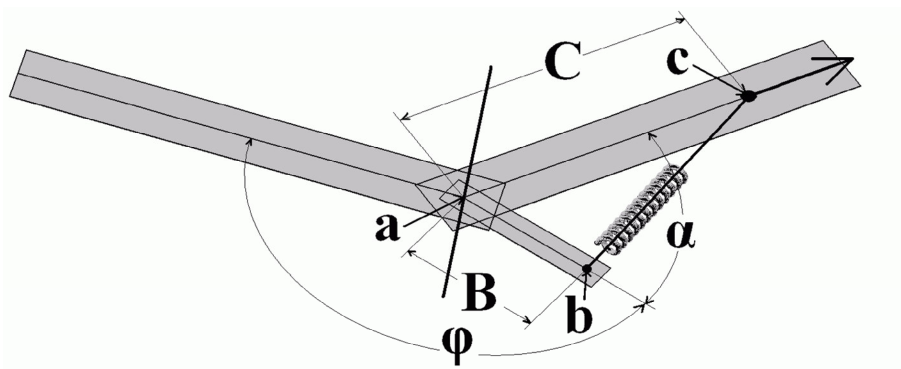
More compliant → **More stiff**





Mechanically Controlled Stiffness

MACCEPA Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (R. Van Ham, VUB, 2006)



- straightforward mechanical concept
- φ ⇨ equilibrium position
  P ⇨ joint stiffness
- linearized torque formula

$$\begin{cases} T = \alpha.\mu.P \\ K = \mu.P \end{cases}$$

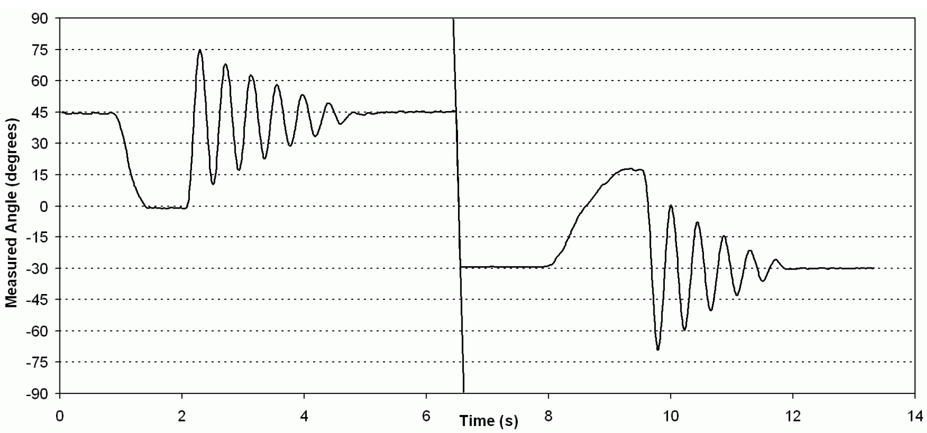
- φ, P independent of actuator state

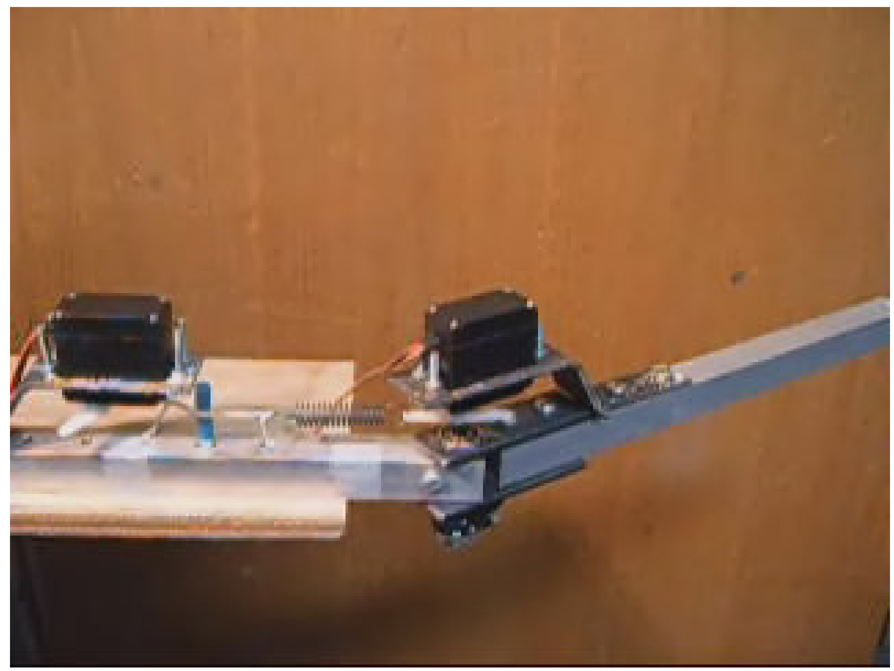
MACCEPA: Changing Equilibrium Position

Torsion Pendulum → MACCEPA

$$f = \frac{1}{2\pi}\sqrt{\frac{\kappa}{I}} \longrightarrow f = \frac{1}{2\pi}\sqrt{\frac{\mu.P}{I}}$$

$$T = \alpha.\mu.P \qquad \mu = \frac{k.B.C}{|C-B|}$$



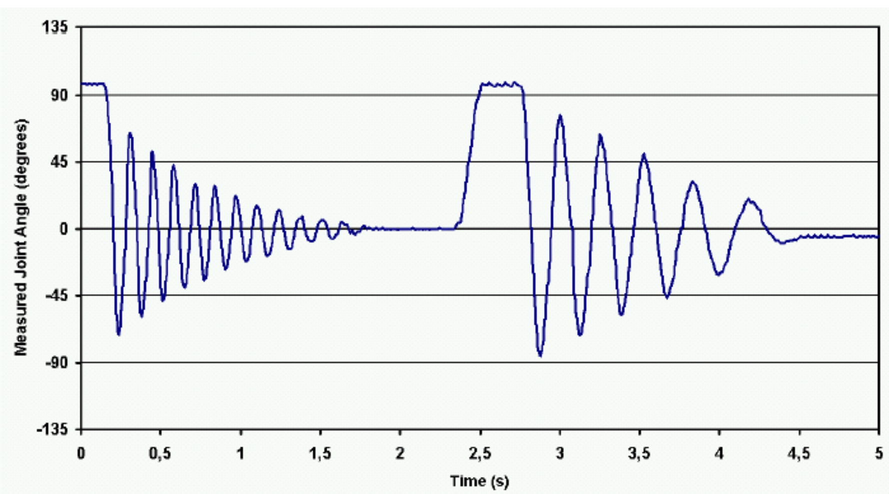


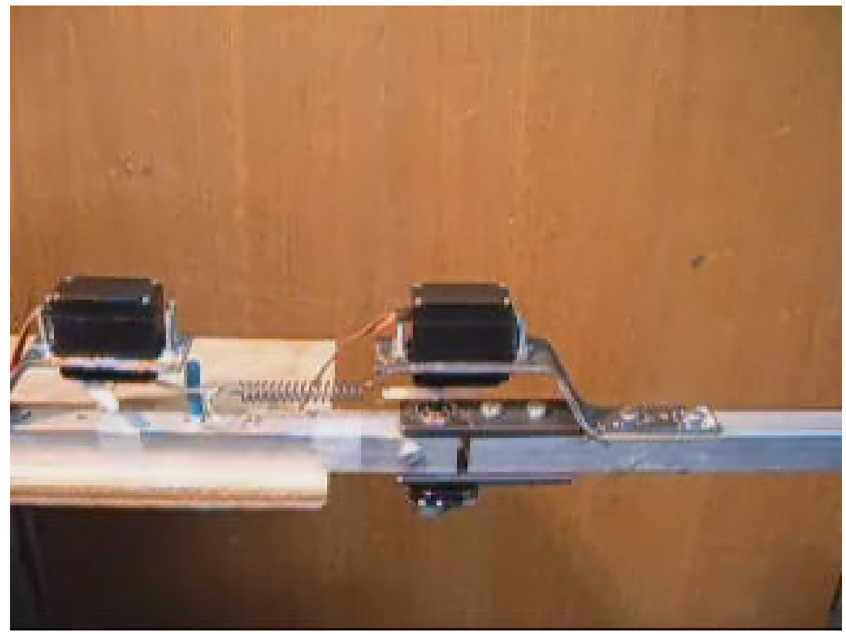
MACCEPA – Changing stiffness

Torsion Pendulum → MACCEPA

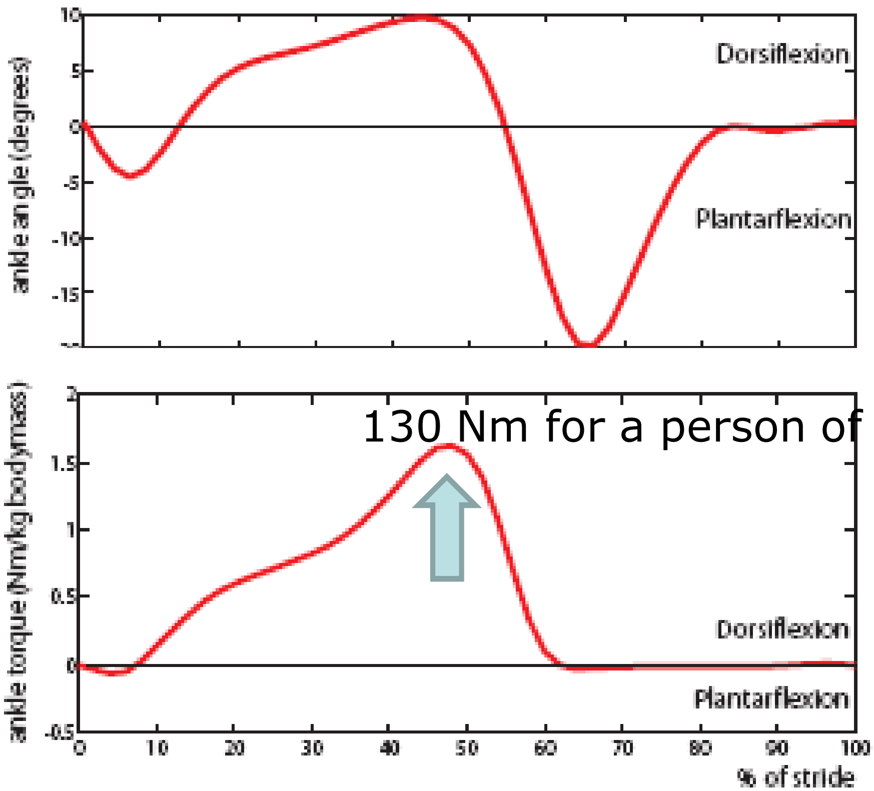
$$f = \frac{1}{2\pi}\sqrt{\frac{\kappa}{I}} \longrightarrow f = \frac{1}{2\pi}\sqrt{\frac{\mu . P}{I}}$$

$$T = \alpha . \mu . P \qquad \mu = \frac{k.B.C}{|C - B|}$$

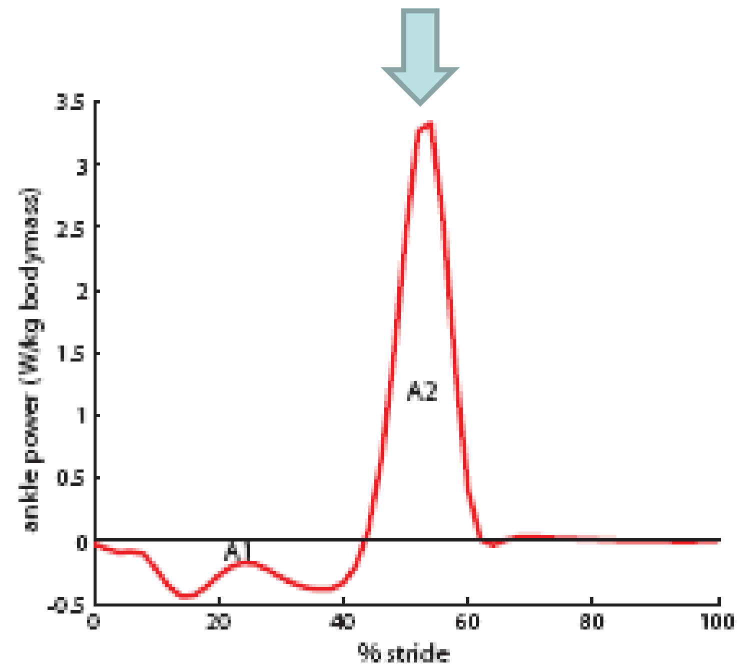




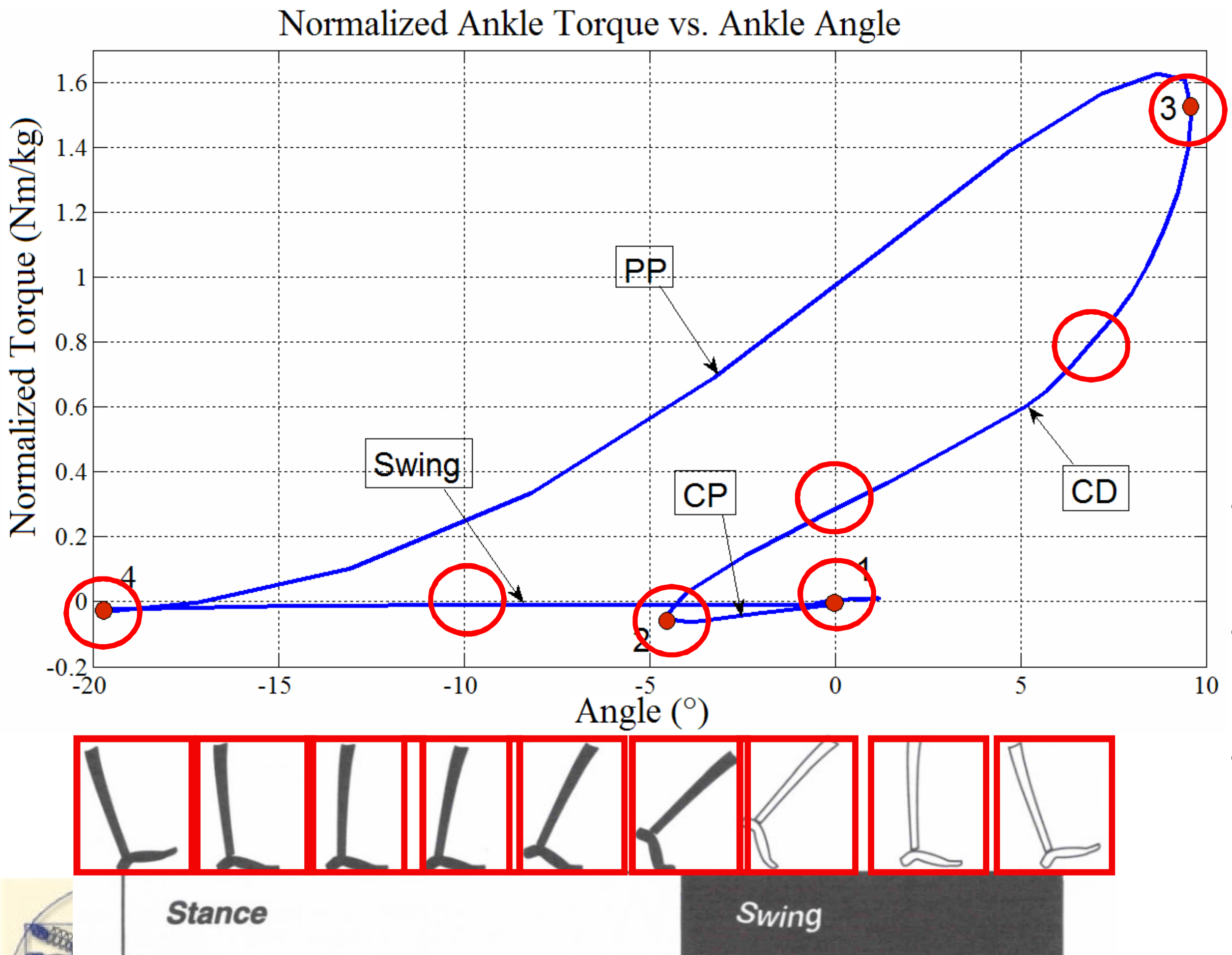
Normalised Ankle-data by Winter



260 W for a person of 75 kg



Torque-angle characteristic of a human ankle

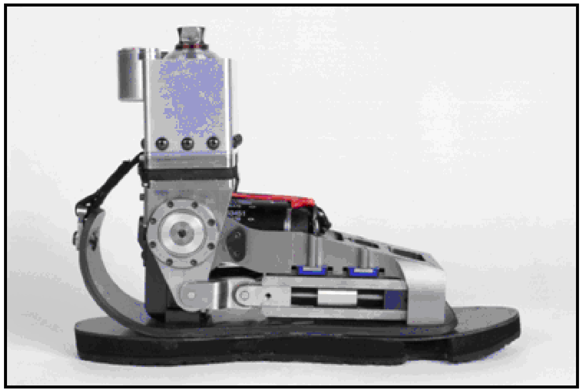


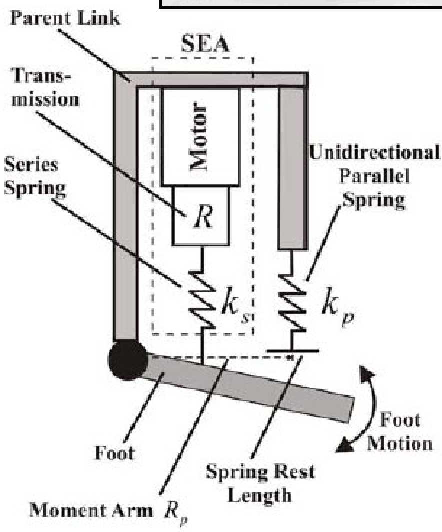
- 1 : Heel - Strike
- 2 : Foot - Flat
- 3 : Heel - Off
- 4 : Toe - Off

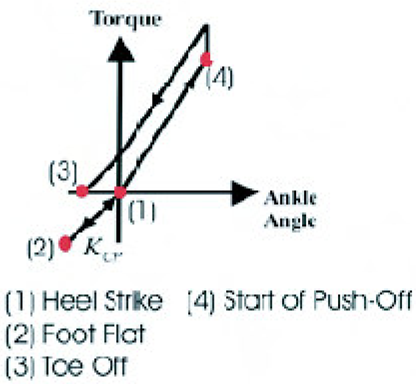
- CP = Controlled Plantar-flexion
- CD = Controlled Dorsi-flexion
- PP = Powered Plantar-flexion

Mimicking the human ankle: devices of Herr and Sugar

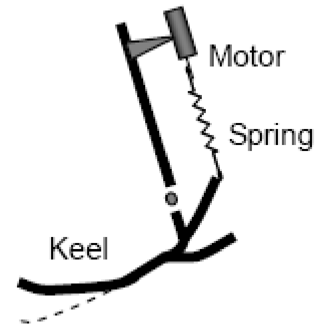
H. Herr (MIT)

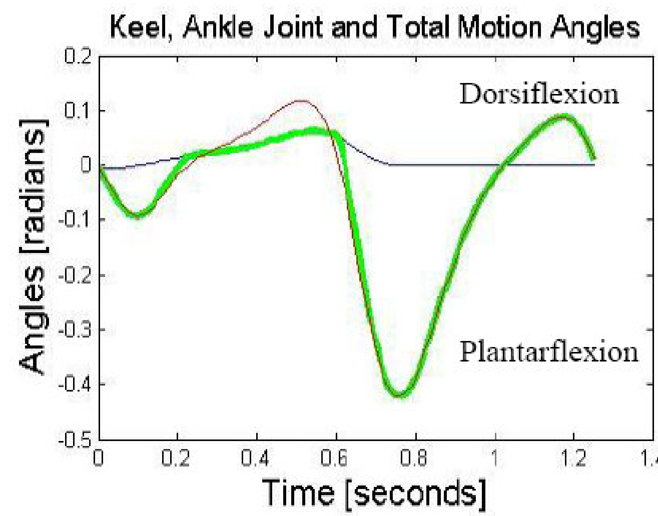


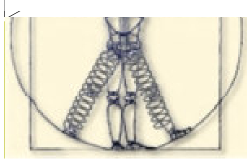


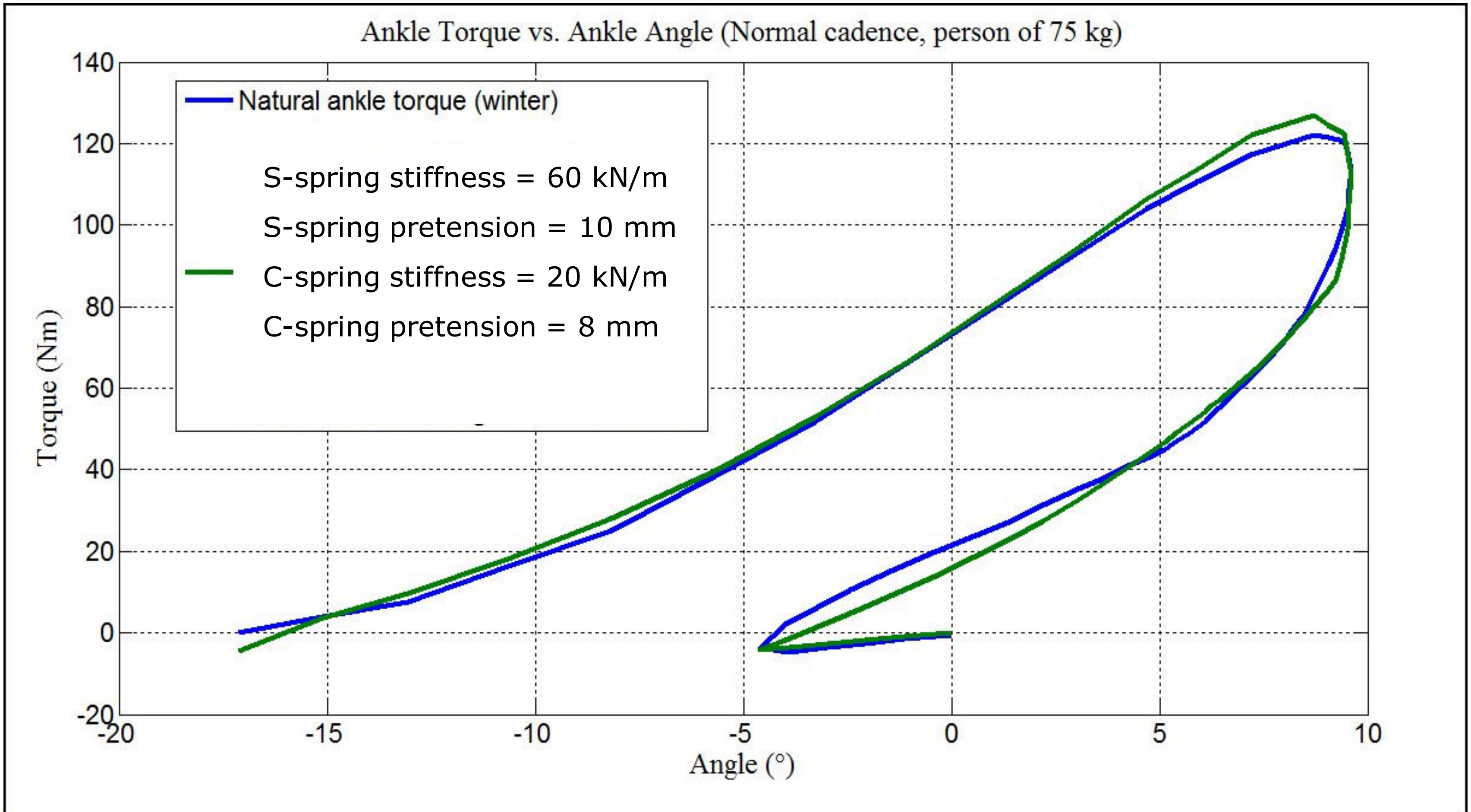


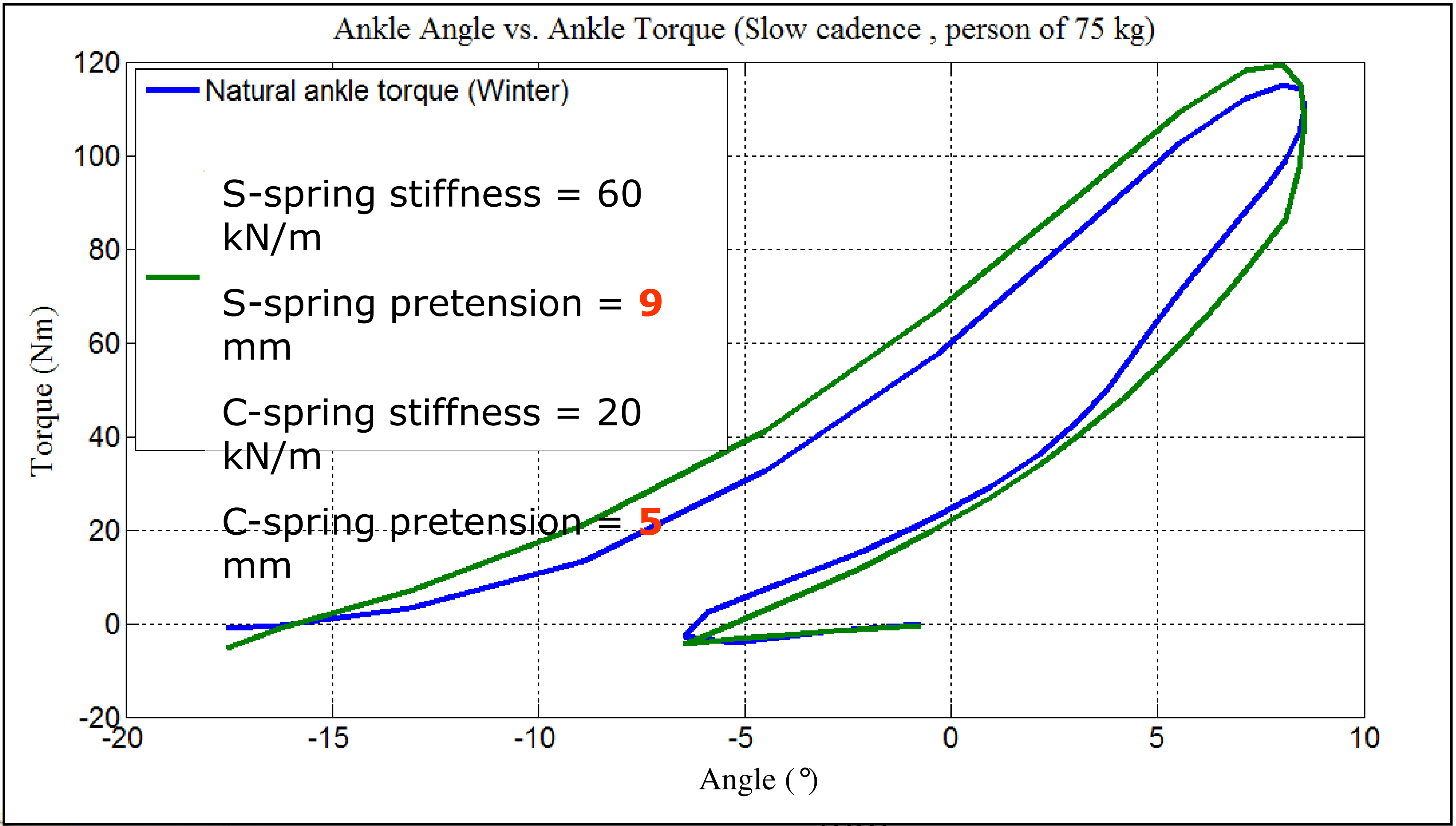
T. Sugar (Arizona State University)

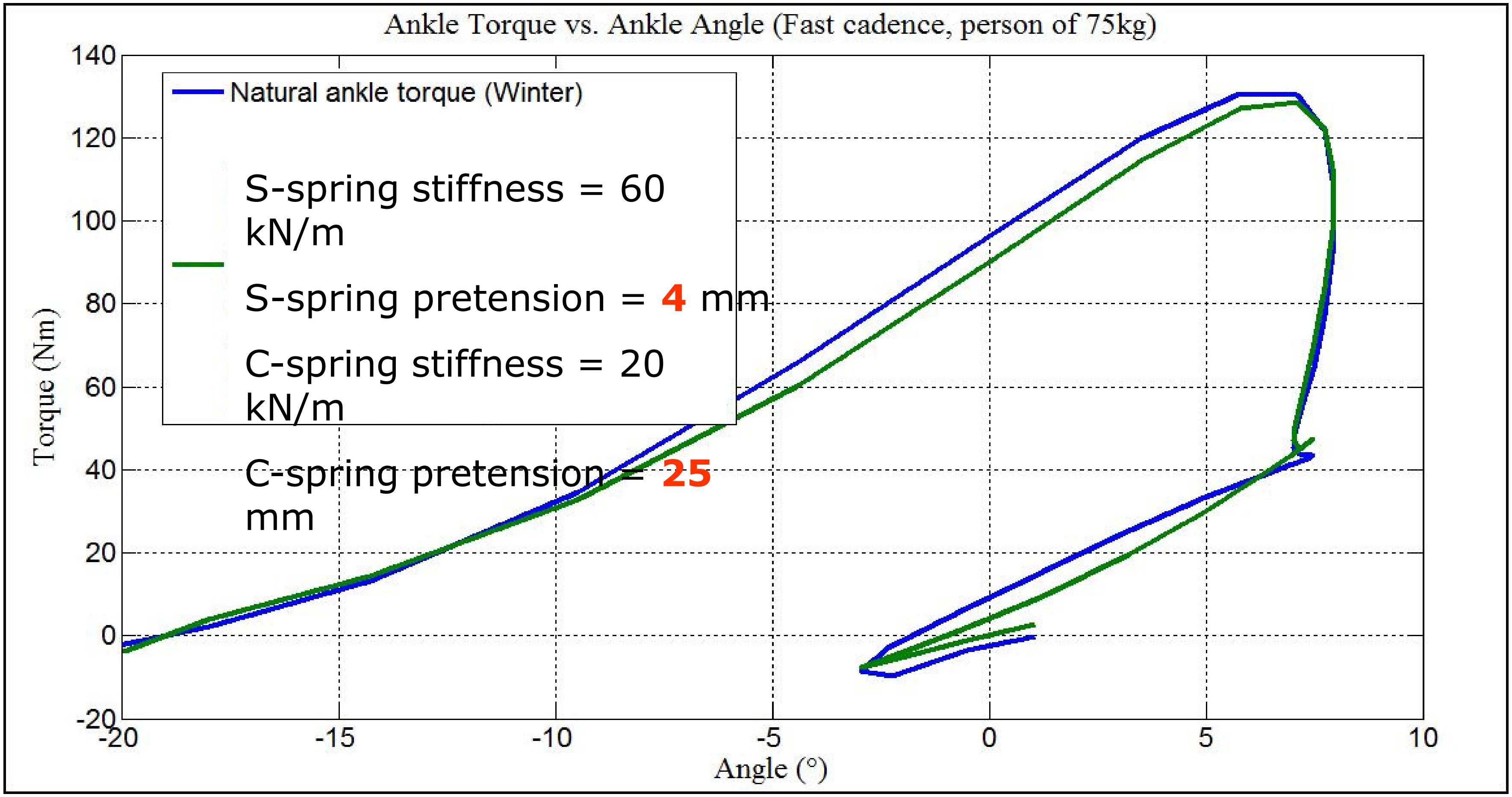







Ankle Torque vs. Ankle Angle (Normal cadence, person of 75 kg)
Natural ankle torque (winter)
S-spring stiffness = 60 kN/m
S-spring pretension = 10 mm
C-spring stiffness = 20 kN/m
C-spring pretension = 8 mm
Torque (Nm)
140
120
100
80
60
40
20
0
-20
-20
-15
-10
-5
0
5
10
Angle (°)


Ankle Angle vs. Ankle Torque (Slow cadence , person of 75 kg)
Natural ankle torque (Winter)
S-spring stiffness = 60 kN/m
S-spring pretension = 9 mm
C-spring stiffness = 20 kN/m
C-spring pretension = 5 mm
Torque (Nm)
Angle (°)
120
100
80
60
40
20
0
-20
-15
-10
-5
0
5
10



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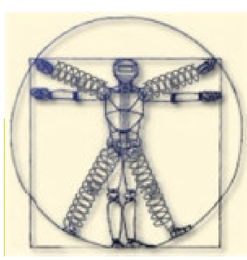
Promising performance output for different step speeds

- Lithium ion-polymer battery : 200 Wh/kg
- Maxon RE40 150 W brushed DC-motor
- 22,19 J/step for normal cadence

cadence	slow	normal	fast
Required battery weight (in g) for 1,5h/day walking	177	282	463
run time (in h) with 1,5kg battery pack	13	8	5

- cfr. SPARKy : 21 J/step 8h



Conclusions

- Variable impedance actuators are able to reduce peek torque and peek power
- Variable impedance actuators allow to adapt to changing torque characteristics by adapting the compliance
- Negative work can be stored in a variable impedance actuator, and energy consumption can be reduced
- Impact is no problem
- These characteristics of variable impedance actuators are important in the development of efficient humanoid robots