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Soft Actuation for Humanoids

Nikos Tsagarakis

Humanoid & Human Centred Mechatronics Lab

Dept. of Advanced Robotics
Istituto Italiano di Tecnologia

7th Workshop on Humanoid Soccer Robots

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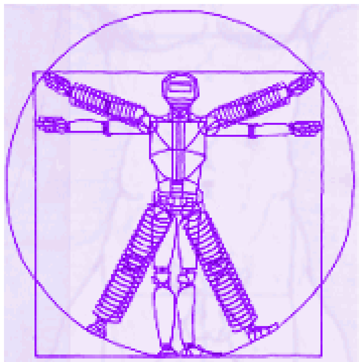

VIACTORS

The goal is to design, realize and evaluate new range of actuator groups exhibiting variable stiffness, variable damping or full impedance regulation principles

AMARSI

The goal of AMARSi is to achieve a qualitative jump toward rich motor behaviour where novel mechanics, control and learning solutions are integrated with each other

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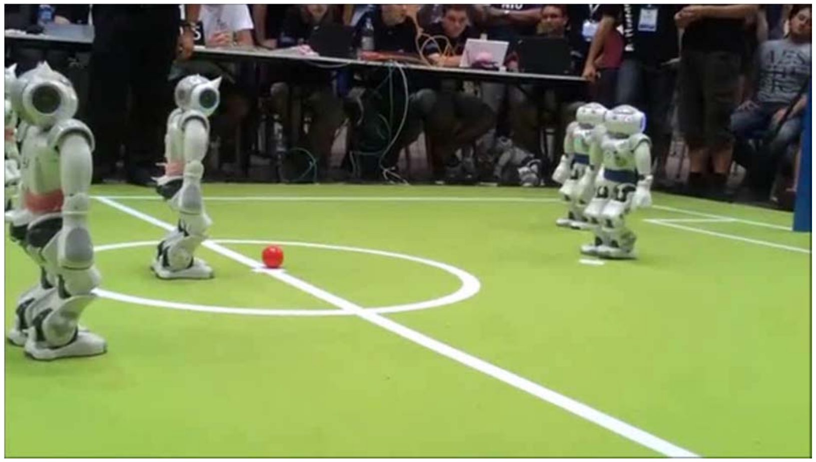
Robot soccer

- whole body physical interaction
- explosive/high power motions
- dynamic balancing against strong disturbances
- impacts with ground and other bodies



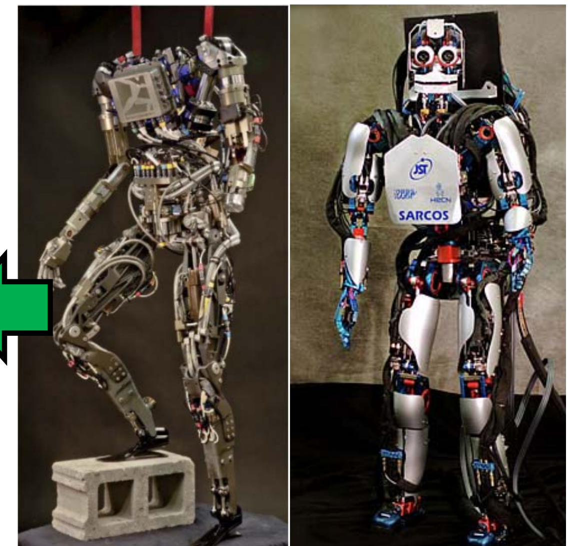
Biological muscle actuation

- two or more muscles for each joint
- soft with tunable stiffness
- robust and highly tolerant to impacts
- can store energy and generate explosive motions
- highly adaptable and stable to load and interaction

Robotic actuation for humanoids

Electrical

Hydraulic



Stiff actuation for accuracy

+

Active compliance regulation

HONDA ASIMO

BOSTON DYNAMICS PETMAN

Predominant robot actuation (electrical motor)

- The actuation principle of most existing motorized robots uses a combination of
  - Planetary or harmonic drive gears and DC brush or brushless motors
  - Relative high gearing position control groups (>100:1)
  - Limited back-drivability
- Minimum passive compliance (mostly from tendons)
- No direct joint torque sensing

The need of compliance

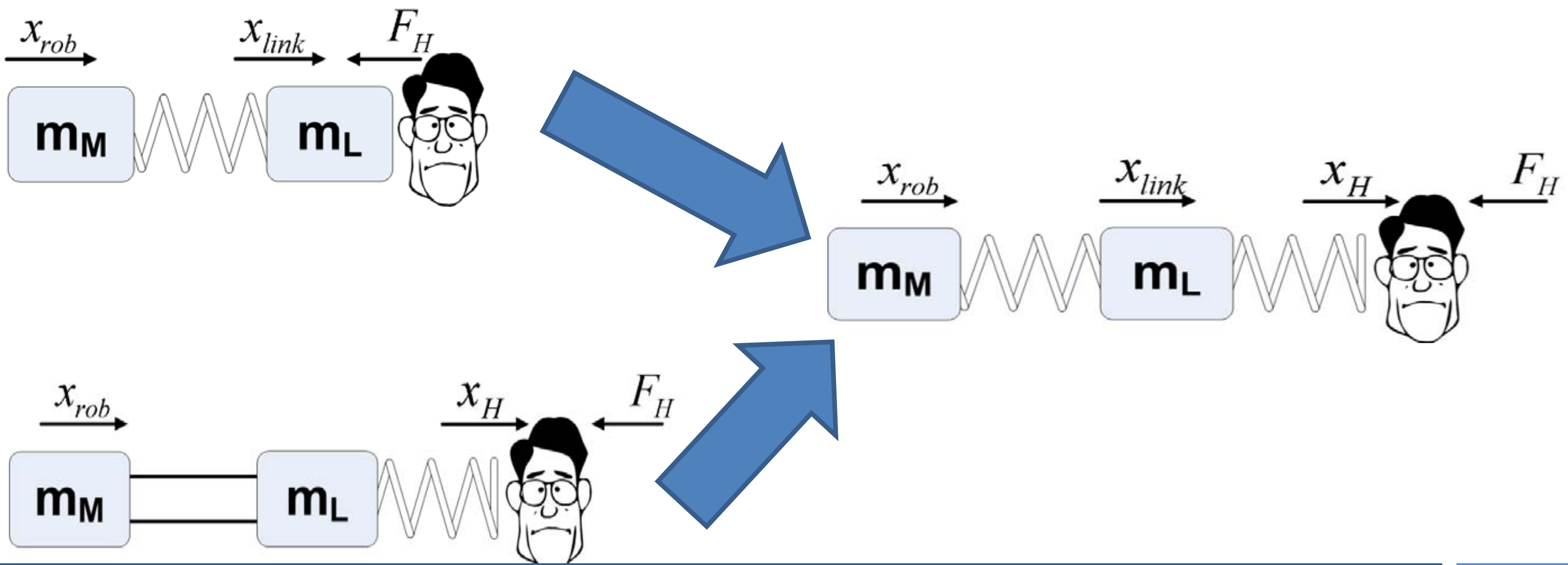
- Robots coperating / interacting (purposely or accidentally) with their environment have different requirements than the current stiff robotic systems
  - Accuracy and speed are necessary but probably not the highest priorities
  - **Adaptability** to interaction (whole body level) , **safety** and **robustness** is at least of equal significance
- How to satisfy the new requirements ?

Stiff body/actuation for accuracy + Active/Controlled impedance to satisfy new requirements	Intrinsic body compliance + Control to satisfy traditional performance indexes

Intrinsic passive compliance
Effect on the impact forces

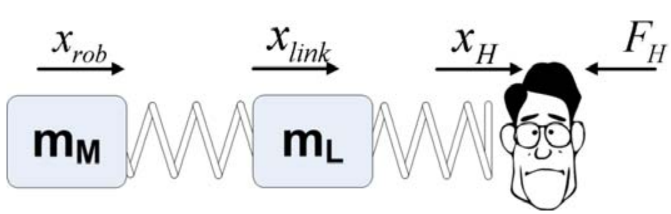
Compliance can been introduced:

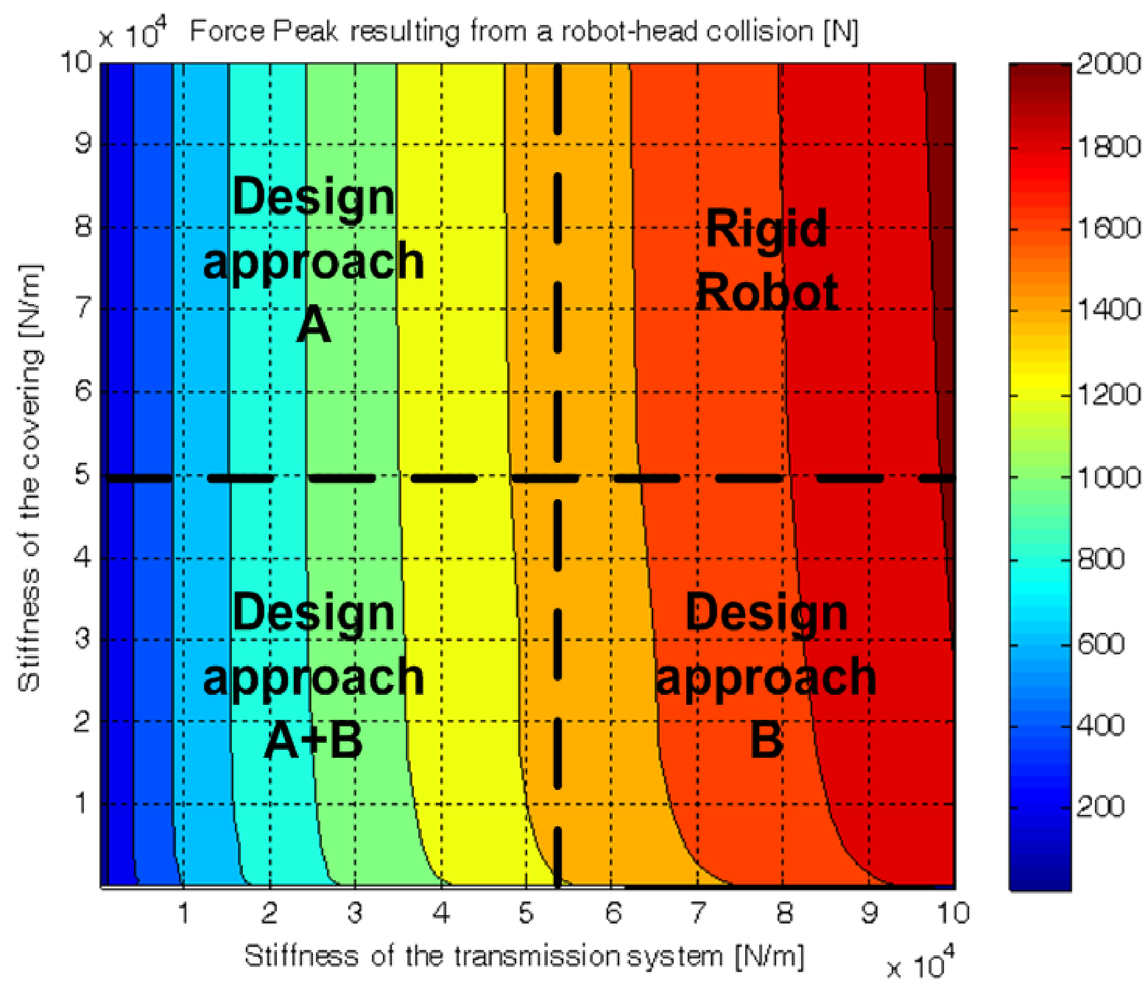
– A: between the actuator and the link
– B: around the link/structure (soft cover)
– C: A and B



Effect of the stiffness to the impact forces: unconstrained case

Parameter	Value
Link reflected mass	1.85 kg
Rotor reflected mass	0.79 kg
External object mass	5 kg
Impact speed	3 m/s





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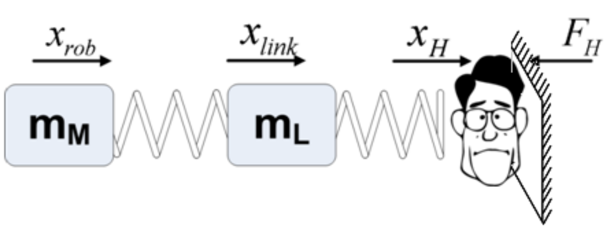

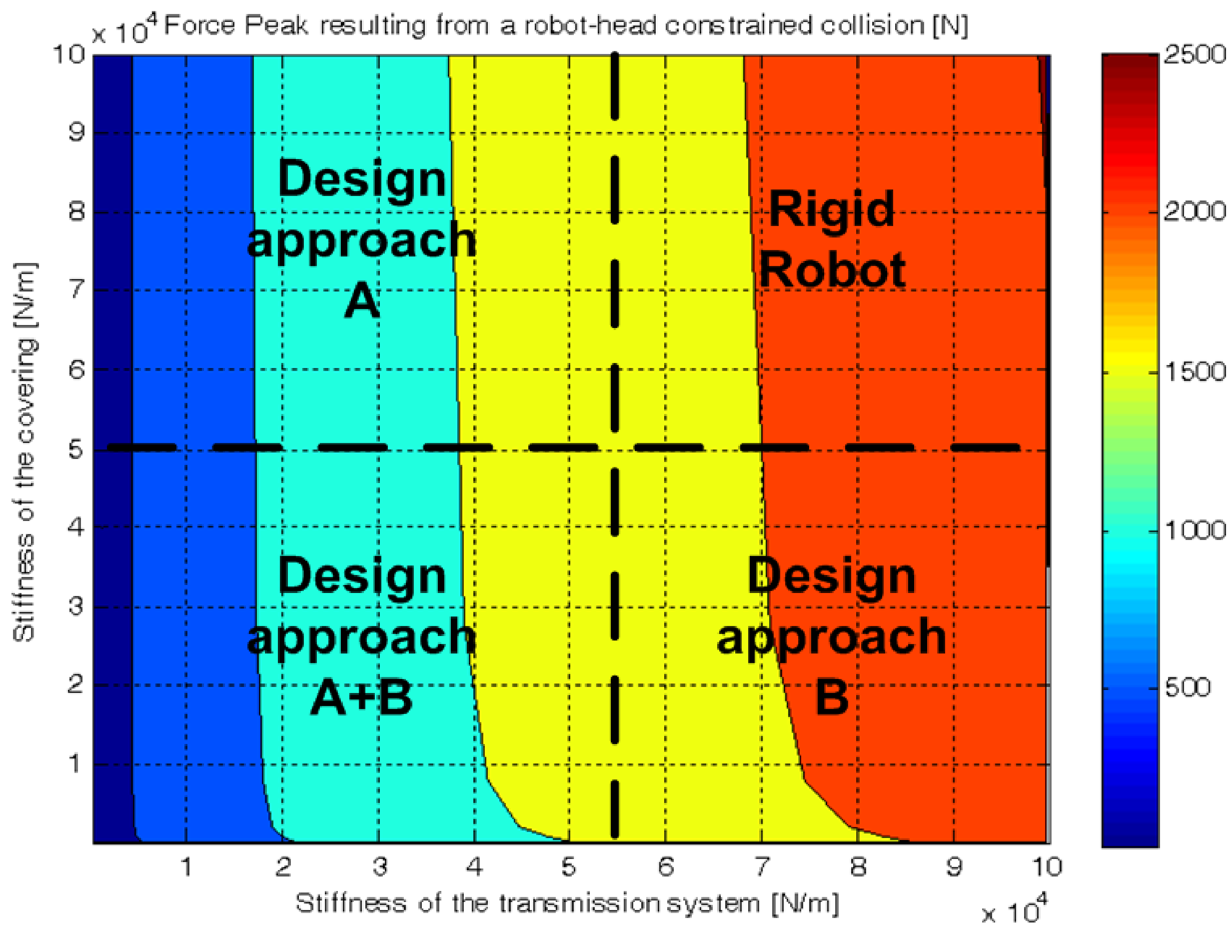

The AMARSI project

- The goal of AMARSi is to make a qualitative jump toward rich motor behaviour where novel mechanical, control and learning solutions are integrated with each other

AMARSI passive COMpliant huMANoid (COMAN)

- a full humanoid robot
- 25 major degrees of freedom (arms/legs and torso excluding hands and neck/head)
- intrinsic passive compliance
- joint torque sensing/active compliance

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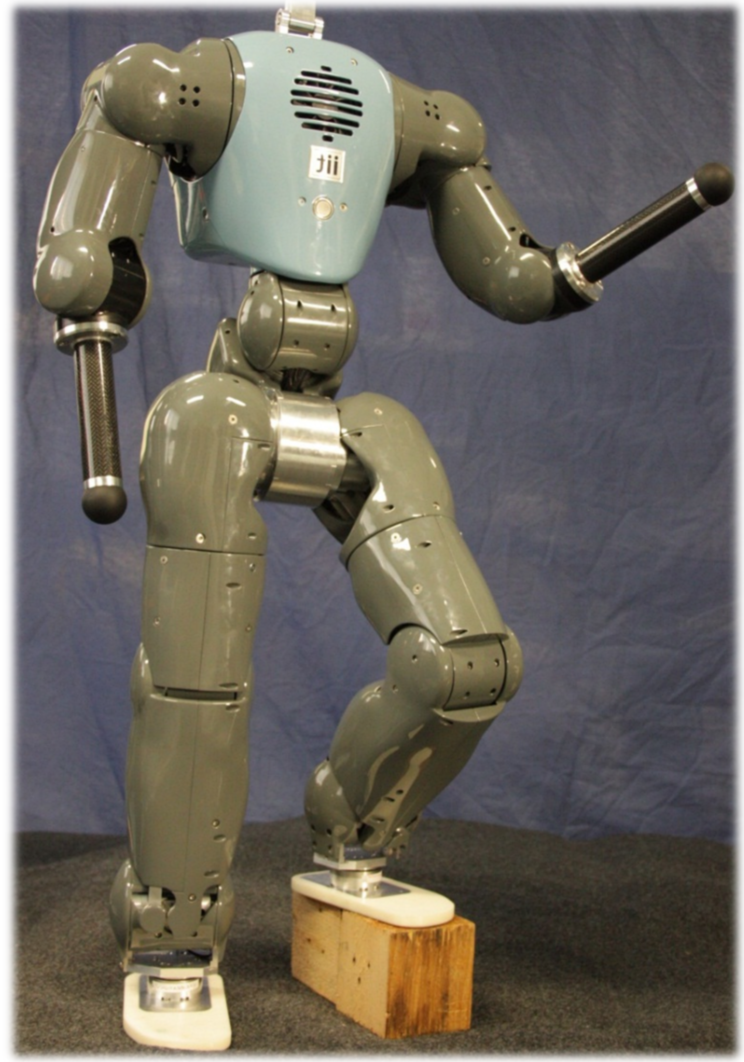
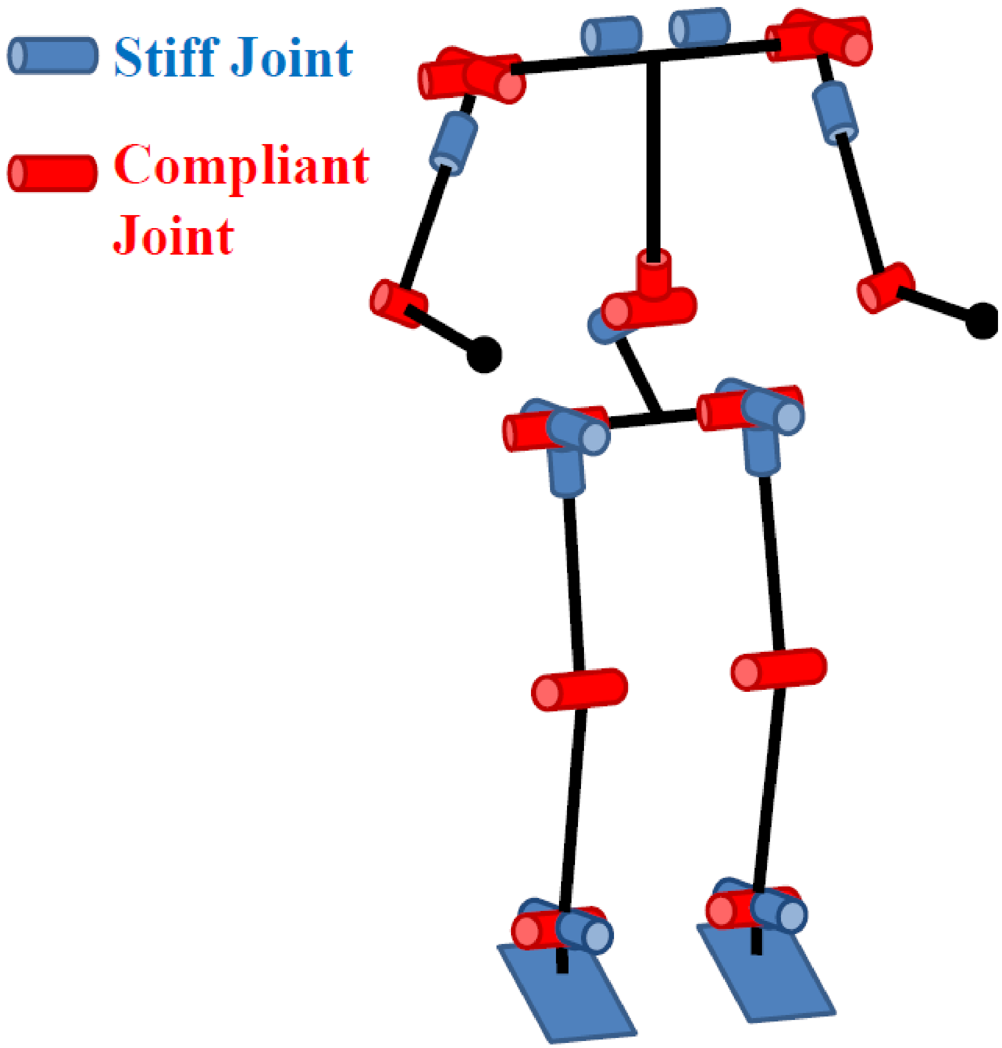
COmpliant HuMANoid COMAN

- **Actuation**
  - moderate to high power
  - passive series compliance
    - legs (ankle/knee and hip sagittal joints)
    - torso (pitch and yaw)
    - arms: (shoulder and elbow)
  - elimination of cable transmissions
- **Sensing**
  - joint torque sensing
  - 2 x 6 DOF F/T sensors
  - IMU at the lower torso
- **Power autonomy**
  - battery
  - power management system
- **On board computation power**
  - 2 x PC104 (1 inside the torso and one in the head)
- **Body housing**
  - internal electrical wiring routing
  - full body covers (no exposed components/wires)

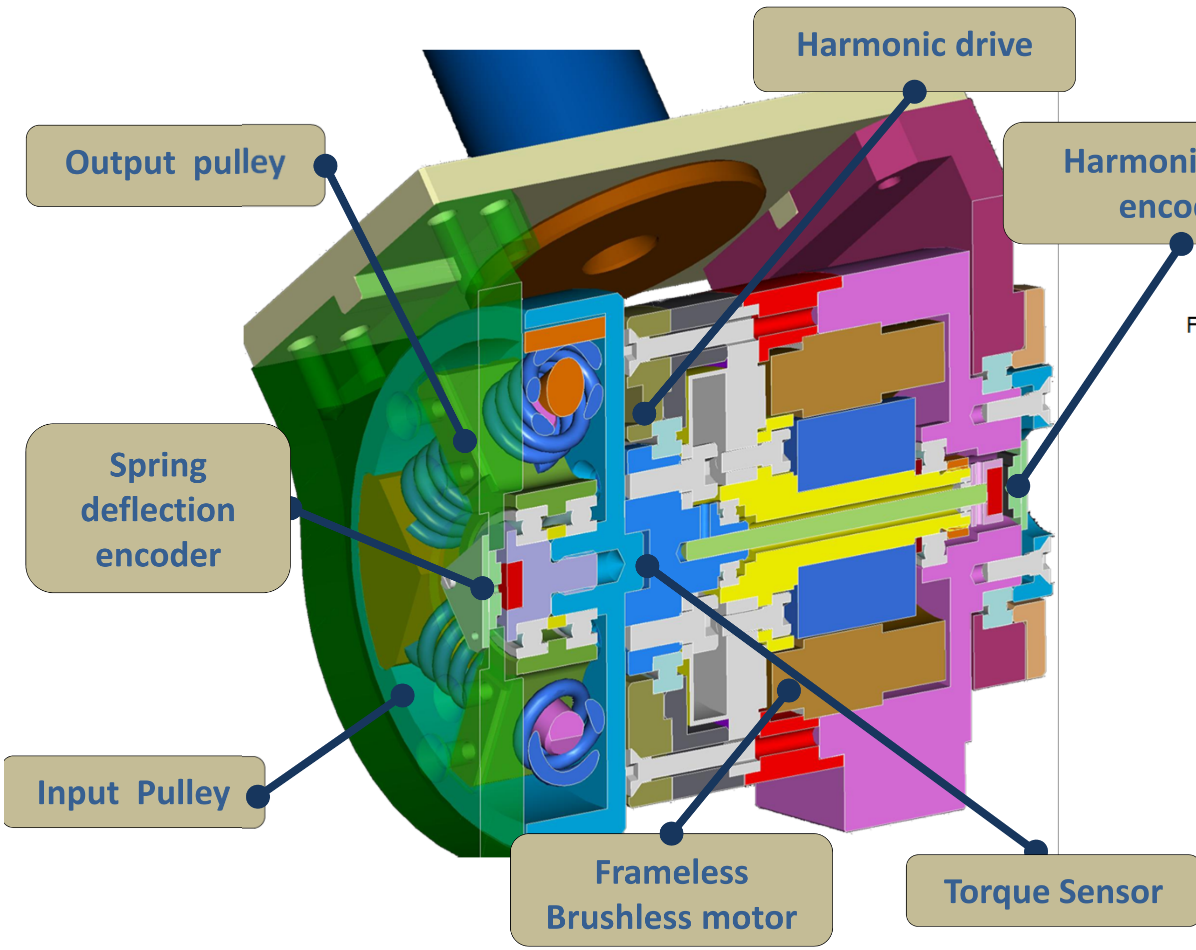


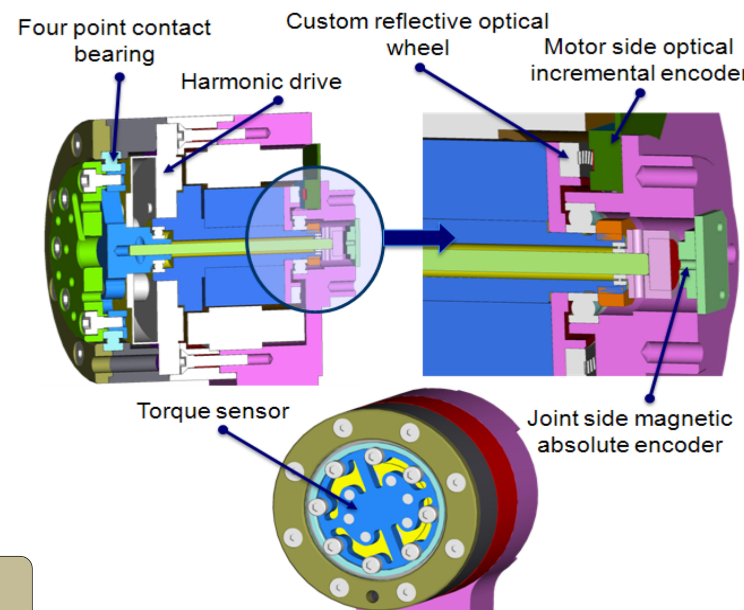
COMAN Kinematics



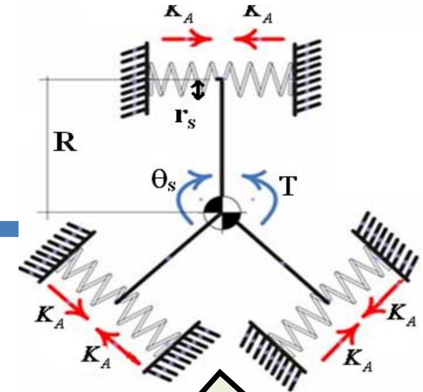
Joint	Number of DOF
Ankle	2
Knee	1
Hip	3
Waist	3
Shoulder	3
Elbow	1
Neck	2

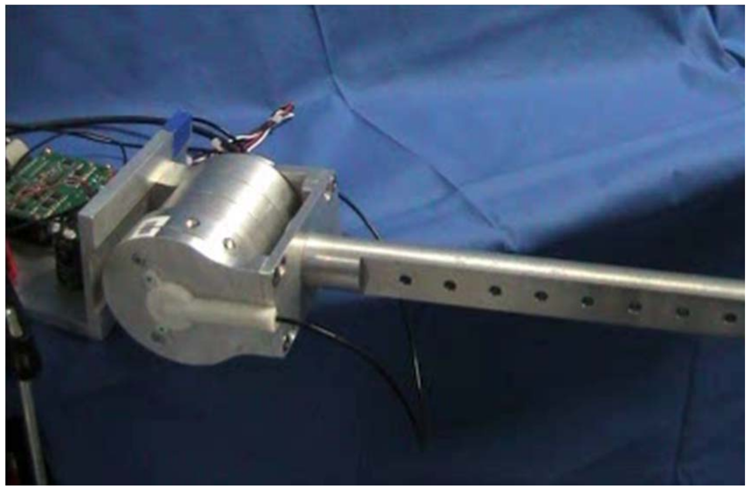
The CompAct actuator

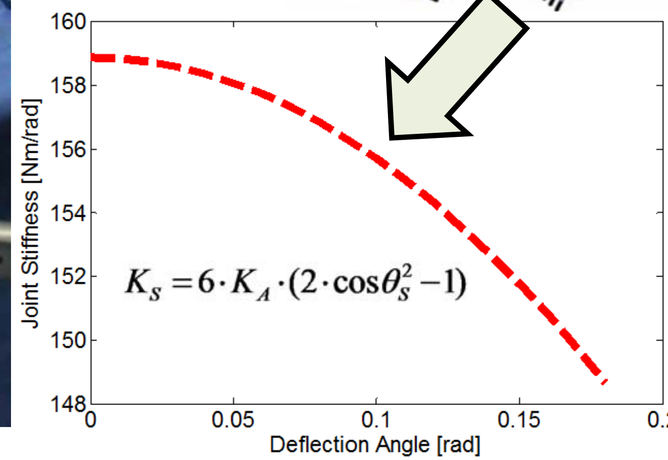


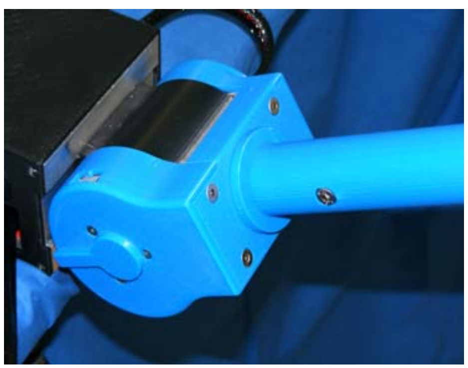


The CompAct actuator

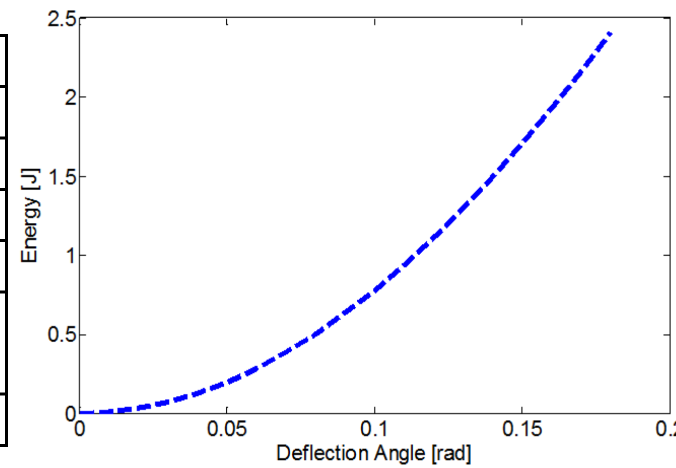




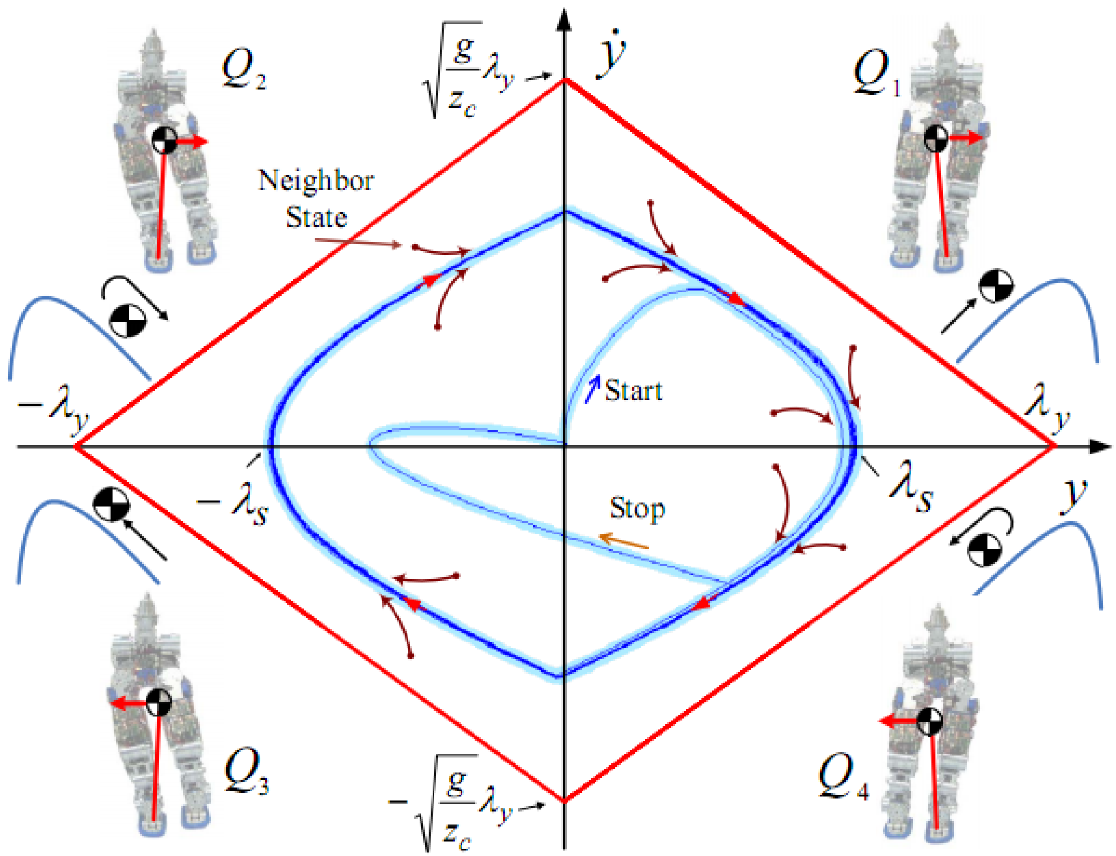




Diameter	70mm
Length	80mm
Power	152W
Gear Ratio	100:1
Peak torque	55Nm
Max rotary passive deflection	+/-0.2rad
Weight	0.52Kg



COM state control gait generator



Zhibin Li, et. al, ICRA 2012

Motivation

- springs reduce the control bandwidth of the actuation system
- spectrum of ZMP signal is higher than that of the COM
- the ZMP method requires a time-based ZMP trajectory planning, which may violate the natural dynamics of the compliant robot system

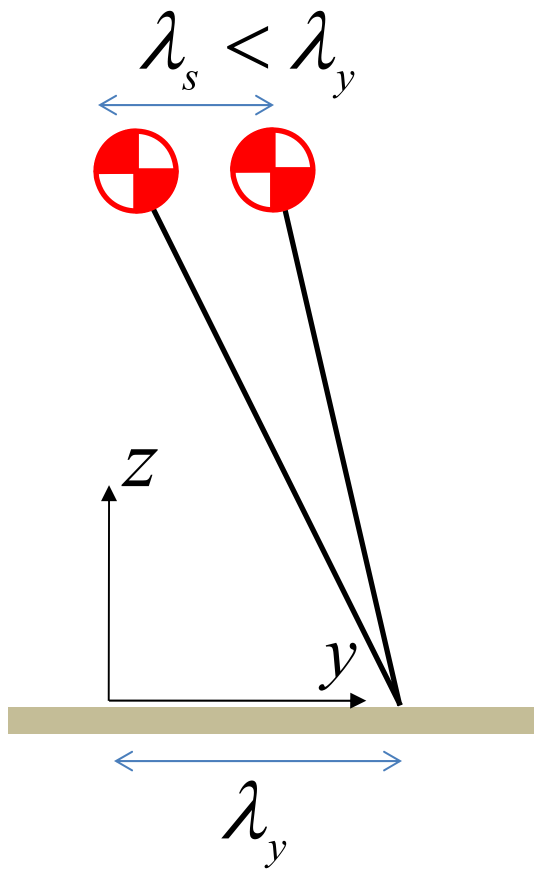
Lateral gait control

- given $\lambda_y, z_c, y \Rightarrow$ desire velocity V_y^{ref} to stop at λ_s

$$V_y^{ref} = \sqrt{2\frac{g}{z_c}\lambda_y(\lambda_s - y) + \frac{g}{z_c}(y^2 - \lambda_s^2)}$$

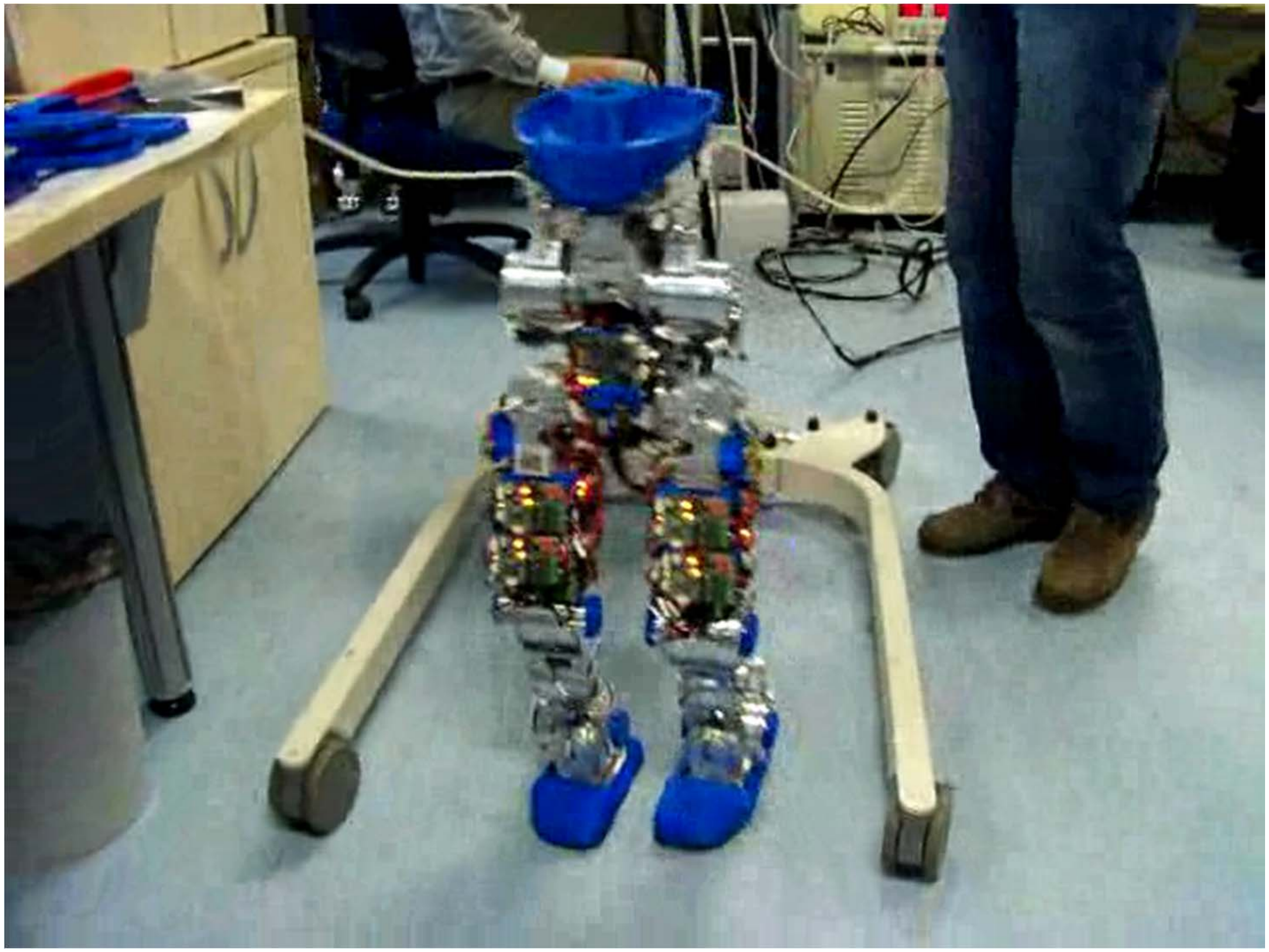
- V_y^{ref} updates online at every control loop
- simple control law

$$u_y = K_{p1}^y(V_y^{ref} - \dot{y})$$

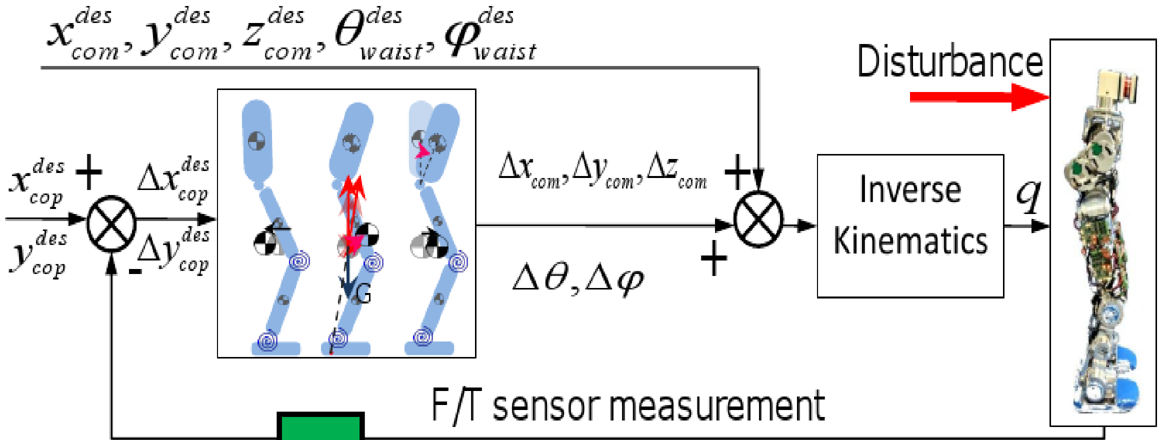


Zhibin Li, et. al, ICRA 2012

COM state control gait generator

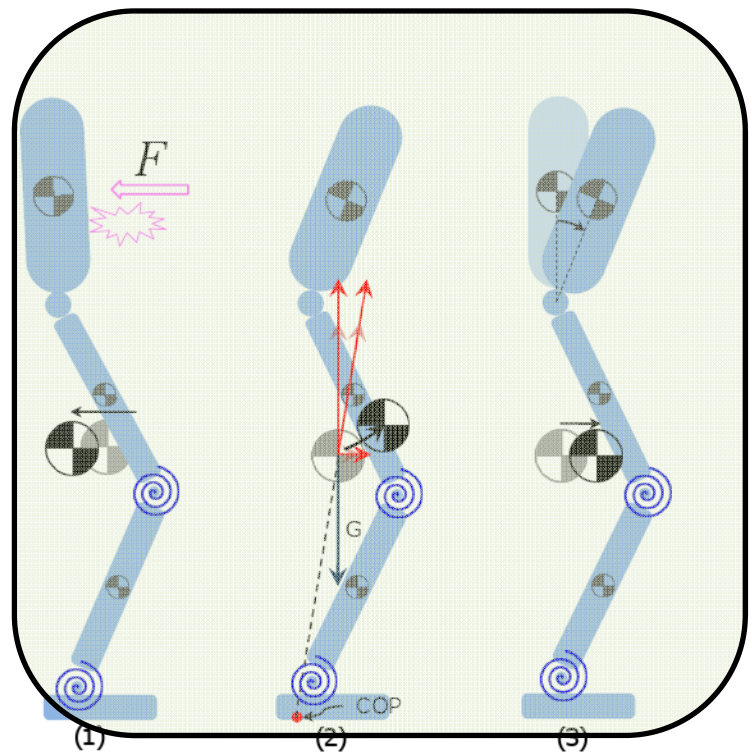


Balancing against push disturbances



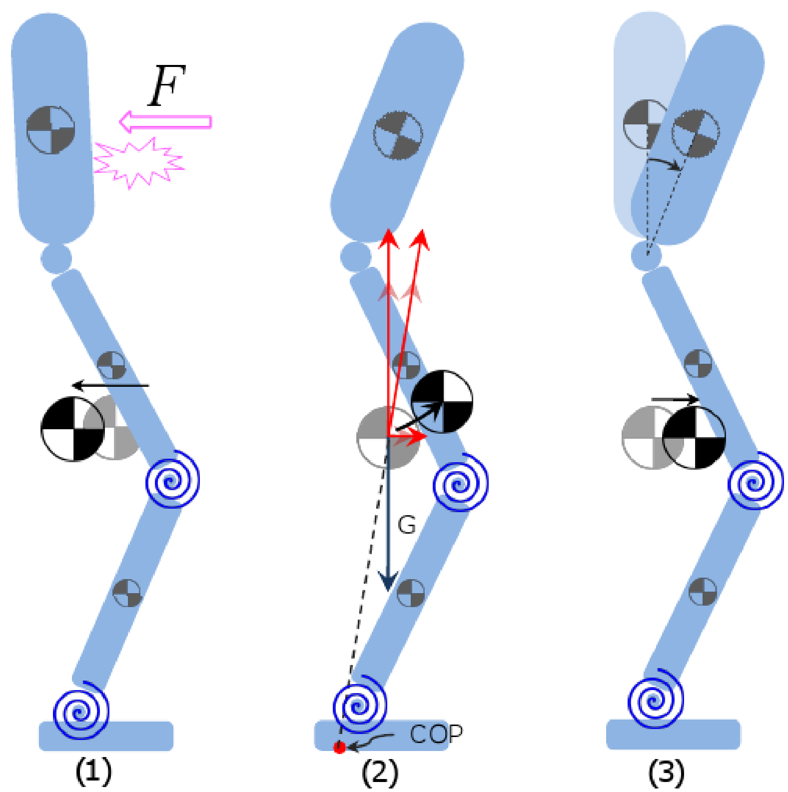
Three actions recovery strategy

- Whole body compliance control
- Body attitude regulation
- Manipulation of GRF

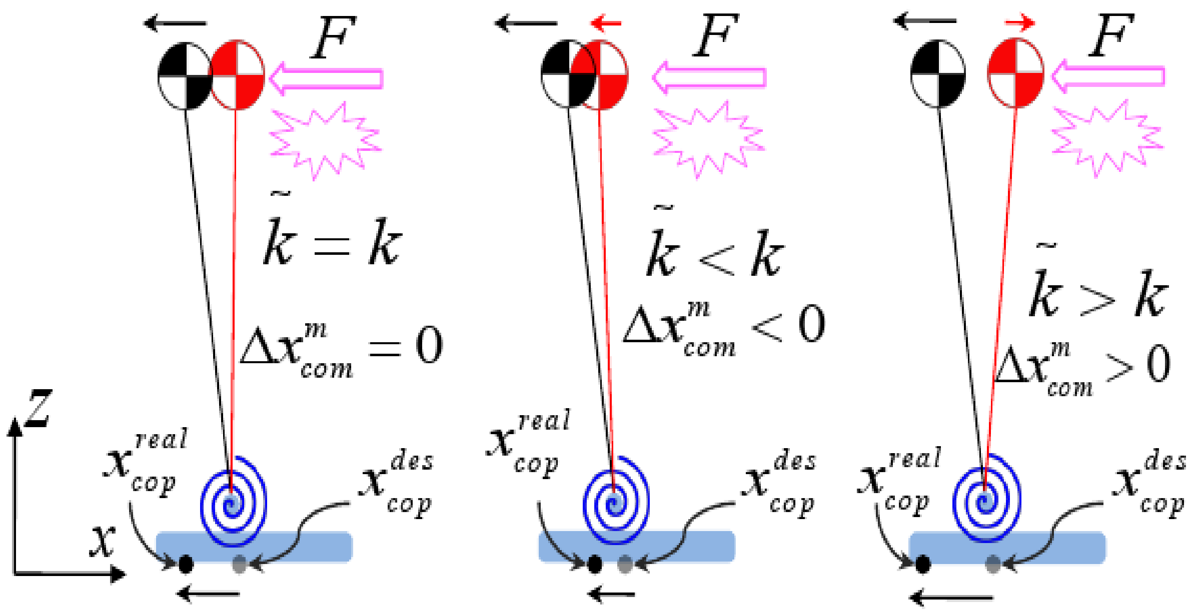


Stabilization strategies

- **Transversal plane compliance control:** to control compliance by modulating the horizontal COM position based on overall COP feedback
- **Body attitude control:** to control body inclination based on the low frequency component of the overall COP feedback
- **Enlargement of horizontal force** by increasing vertical GRF based on overall COP feedback



Transversal plane compliance control



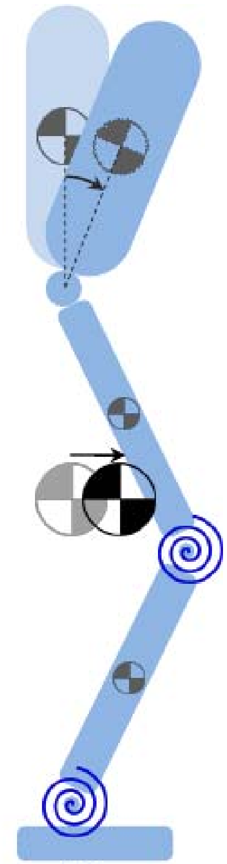
In analogy to admittance schemes

$$\Delta X_{com} = -\frac{\Delta X_{cop}}{Z_{\mathrm{x}}} \qquad \Delta X_{com} = -\frac{\Delta X_{cop}}{Z_{\mathrm{y}}}$$

Body attitude control

- Upper body inclination control is used to shift the upper body mass towards by performing a leaning motion

$$\Delta\theta = \frac{\Delta X_{cop}}{Z_{\theta}} \qquad \Delta\varphi = \frac{\Delta X_{cop}}{Z_{\varphi}}$$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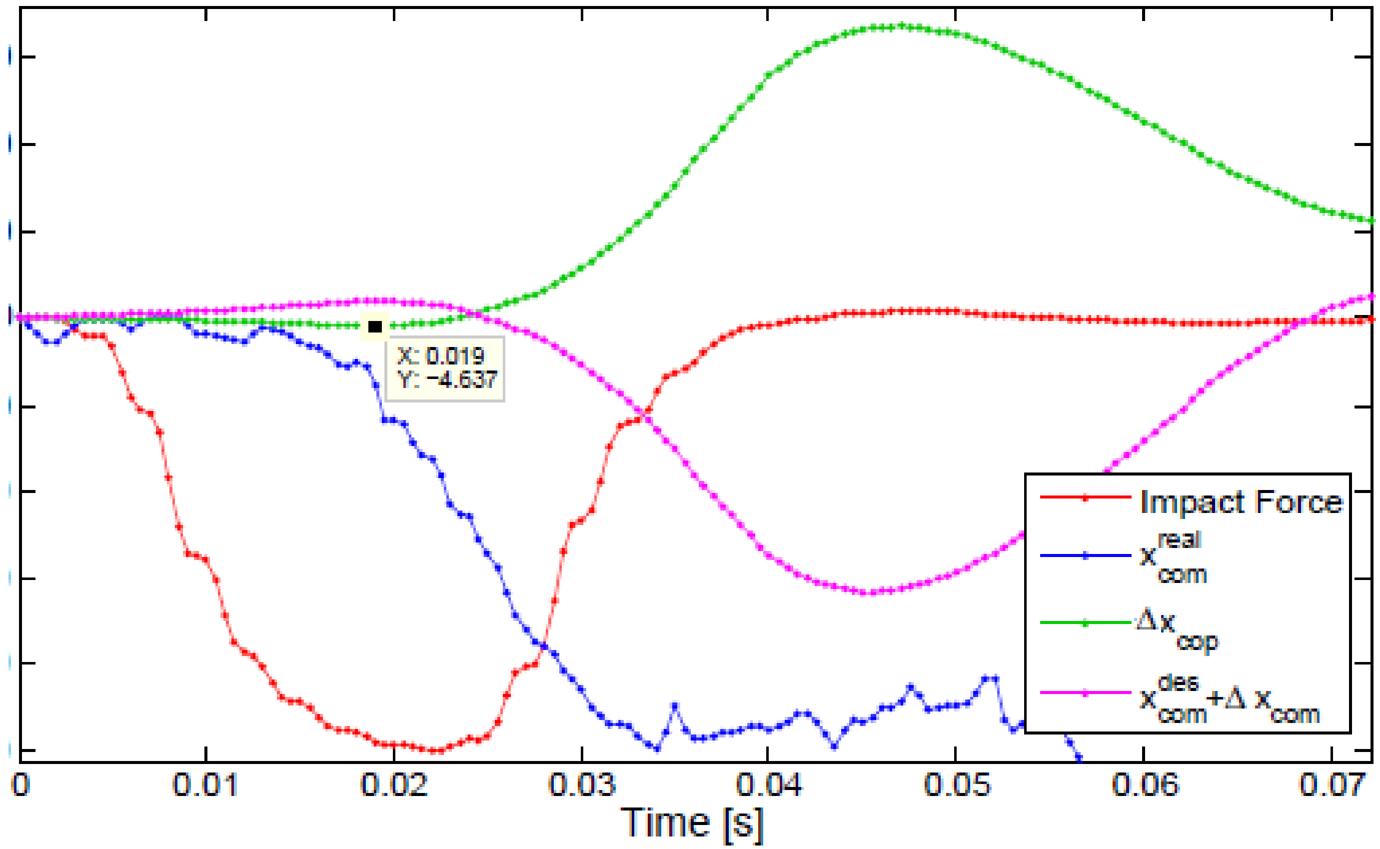
COMAN lower body early tests

Experimental response



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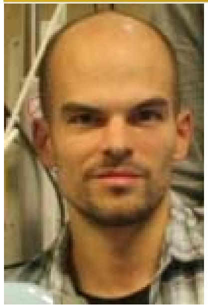
Oral session II: Dynamics and Skills, 13:20-15:00, Friday the 30th
Zhibin Li, N.G. Tsagarakis, D.G. Caldwell, "A Passivity Based Admittance Control for Stabilizing the Compliant Humanoid COMAN",

…and some recent trials with COMAN



Nicolas Perrin

Mohamad Mosadeghzad

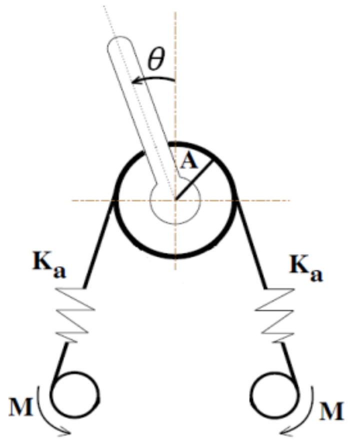
Fixed and variable compliance

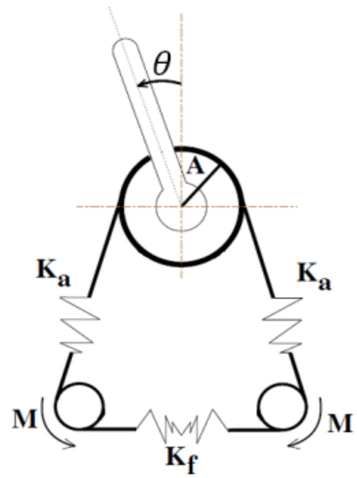
- **Fixed series elasticity (SEA)**
  - passively adaptable
  - inherently safer
  - makes the robot more tolerant to impacts
  - does not need additonal actuation
  - can be combined with active stiffness regulation
  - preset passive mechanical compliance
  - performance is compromised

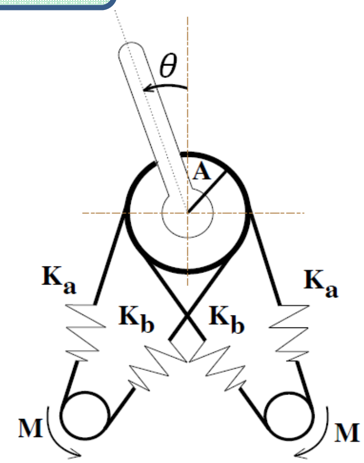
- **Variable impedance actuators**
  - passively adaptable
  - inherently safer
  - makes the robot more tolerant to impacts
  - compliance can be reguled according to task needs
    - accuracy, efficiency or safety
  - performance can be maintained
  - complex, requires additiotal actuators for the impedance tuning
  - application to MDOF systems is not trivial

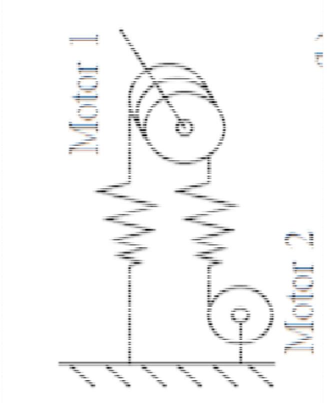
Variable Stiffness Actuators (VSAs)

Antagonistic

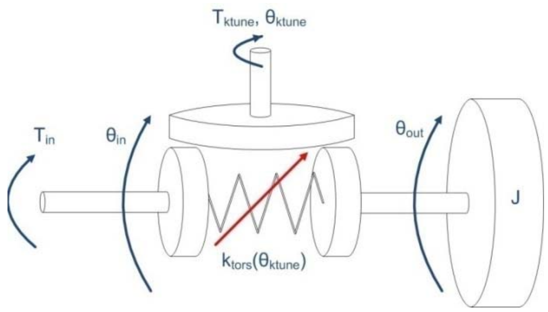




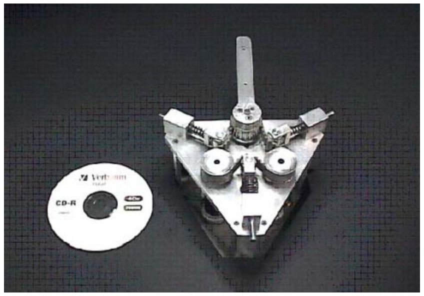




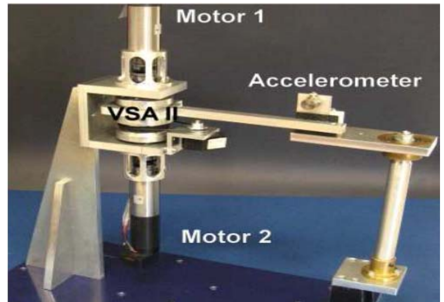
Serial



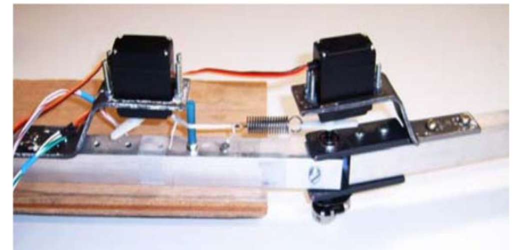
VSAs prototypes



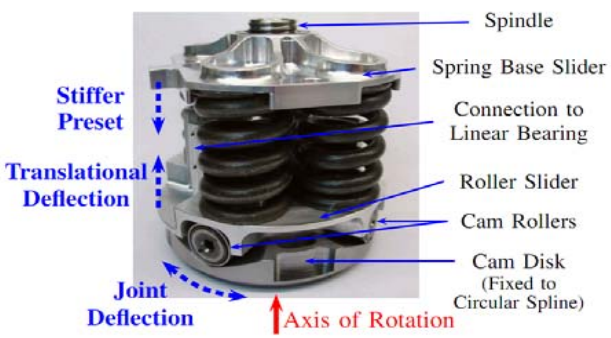
VSA: G. Tonietti *et al.* (2005)



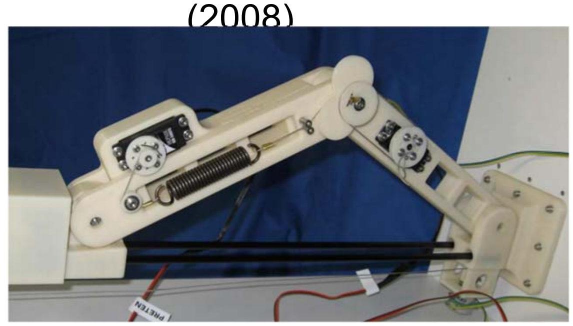
VSA-II: R. Schiavi *et al.* (2008)



MACCEPA: R. Van Ham et al. (2007)

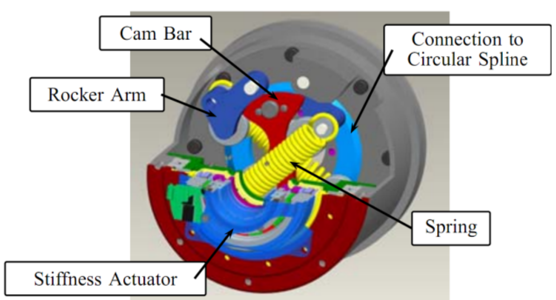


VS-Joint: S. Wolf et al. (2008)

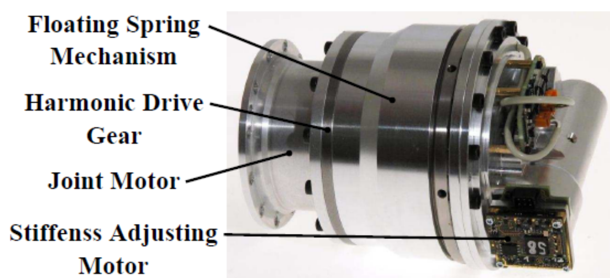


MACCEPA 2.0: B. Vanderborght et al. (2009)

Hybrid VSA:
Byeong-Sang Kim et al. (2010)



QA-Joint: O. Eiberger *et al.* (2010)

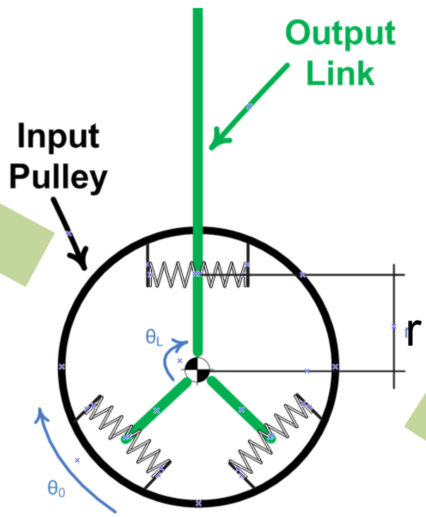


FSJ: Wolf et al. ICRA 2011

VSA Cube: Catalano et al. ICRA 2011

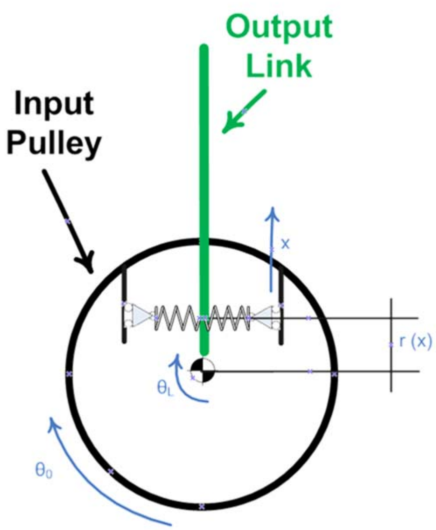
From CompAct to CompAct-VSA

Fixed stiffness joint

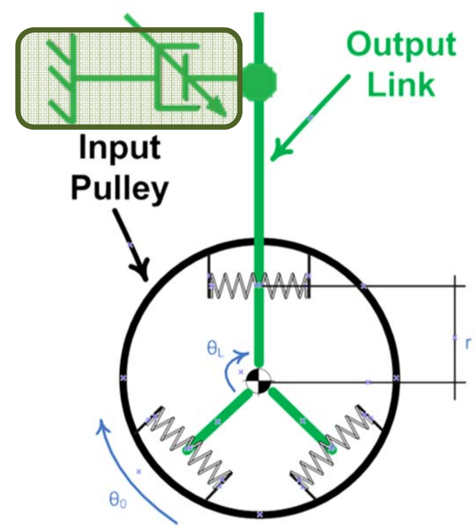


$$K_T = 6 \cdot K_S \cdot f(r^2)$$

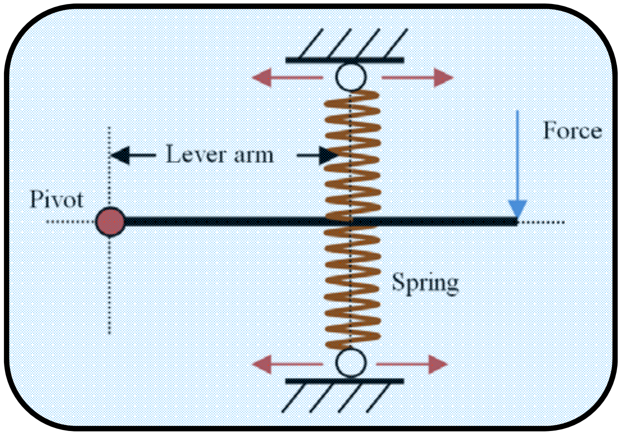
Variable stiffness joint

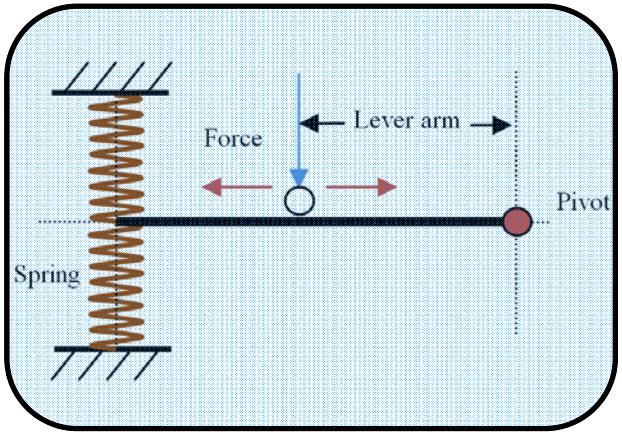


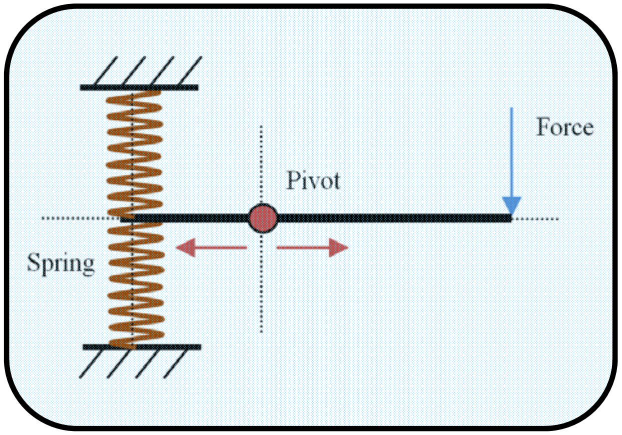
Variable damper

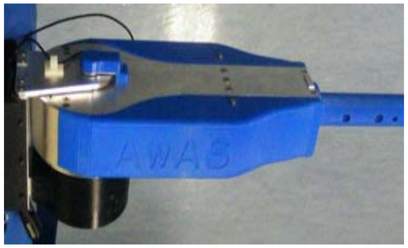


The lever arm principle

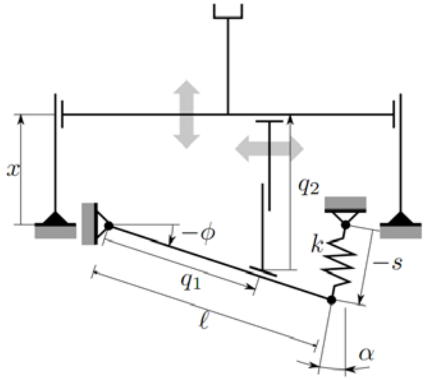




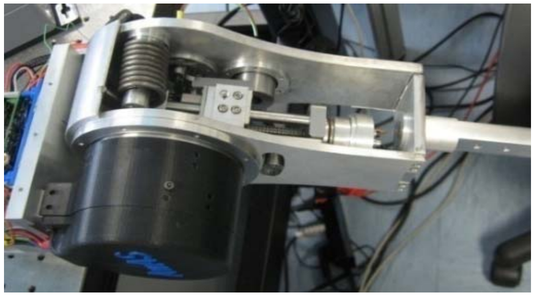




AwAS: A. Jafari *et al*., IROS 2010



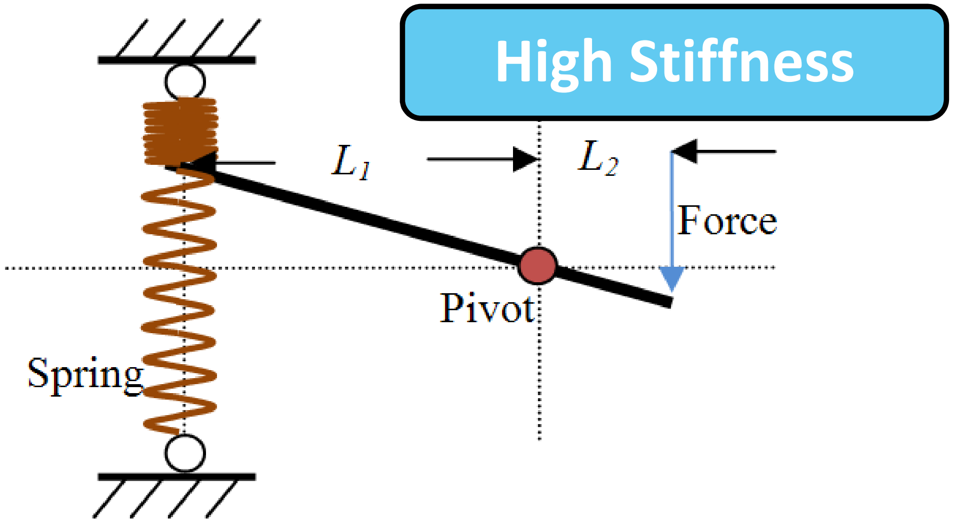
Energy Efficient VSA:
L.C. Visser *et al*., ICRA 2010

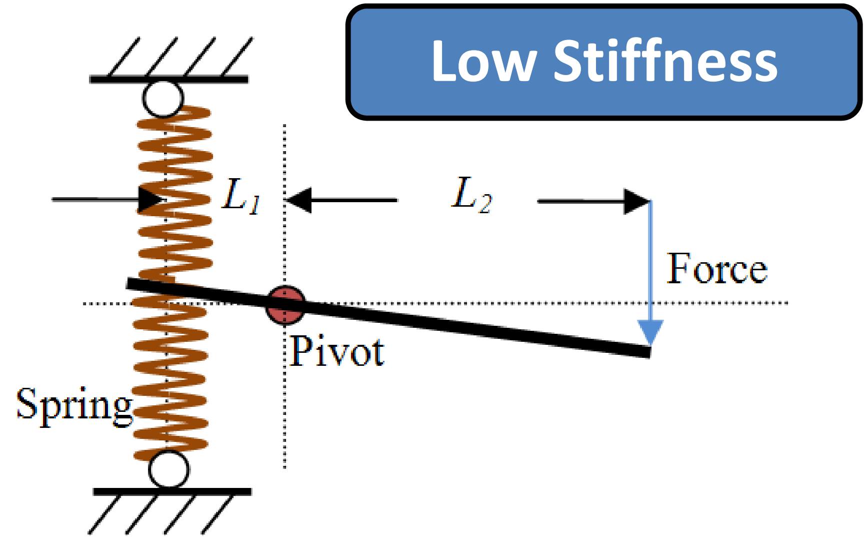


AwAS II
Jafari *et al*. , ICRA 2011,

Hybrid actuator:
Byeong-Sang Kim et al., ICRA 2010

CompAct-VSA: Lever arm with variable pivot point principle

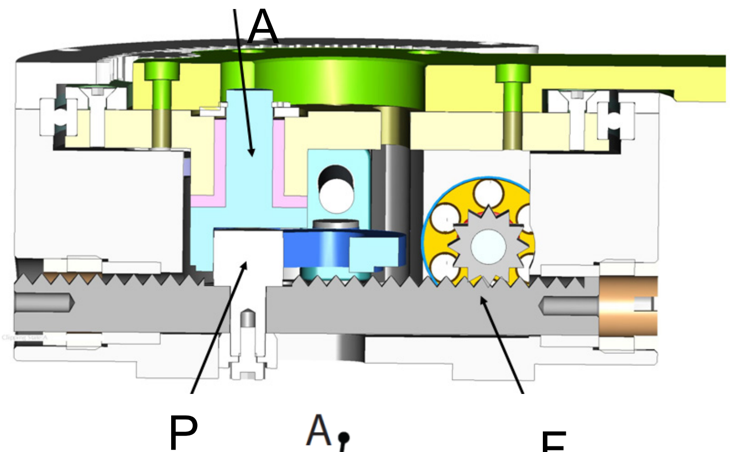


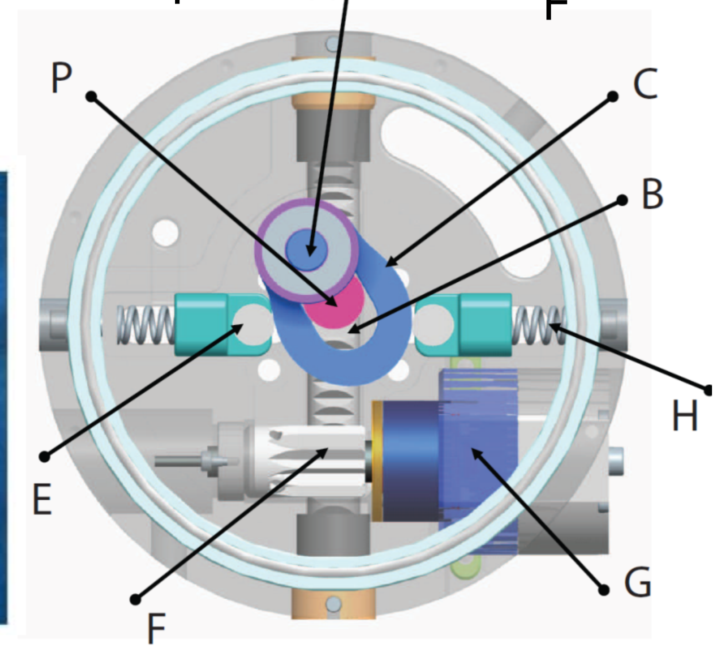


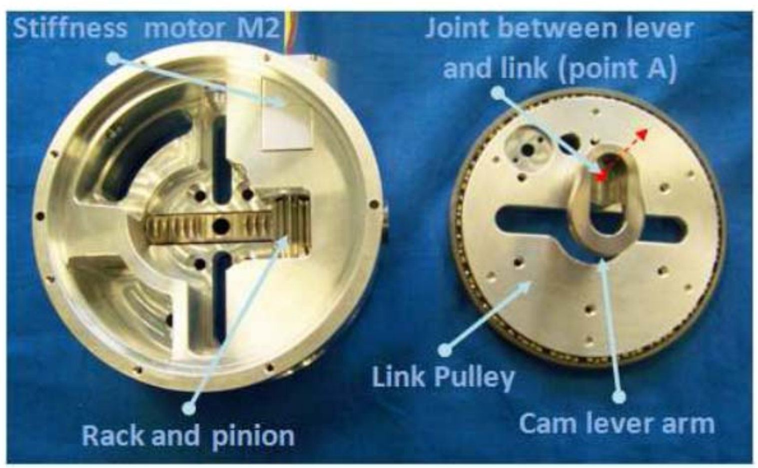
CompAct-VSA: Realization

Variable Stiffness Module

- A) Link/Cam Connection
- B) Joint Axis
- C) Cam Shaped Lever Arm
- E) Cam Roller
- F) Rack/Pinion
- G) Stiffness Motor
- H) Springs
- P) Pivot Poin

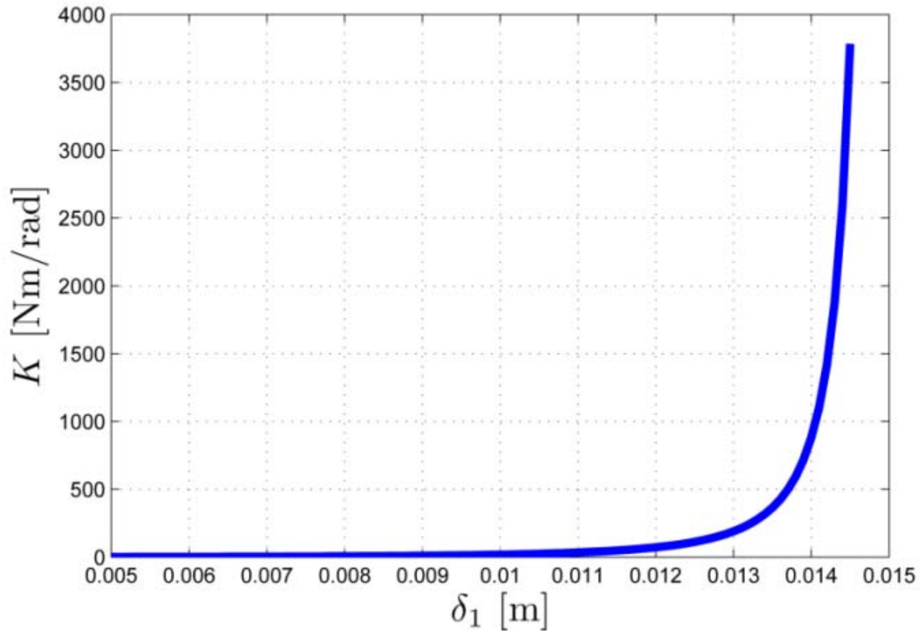




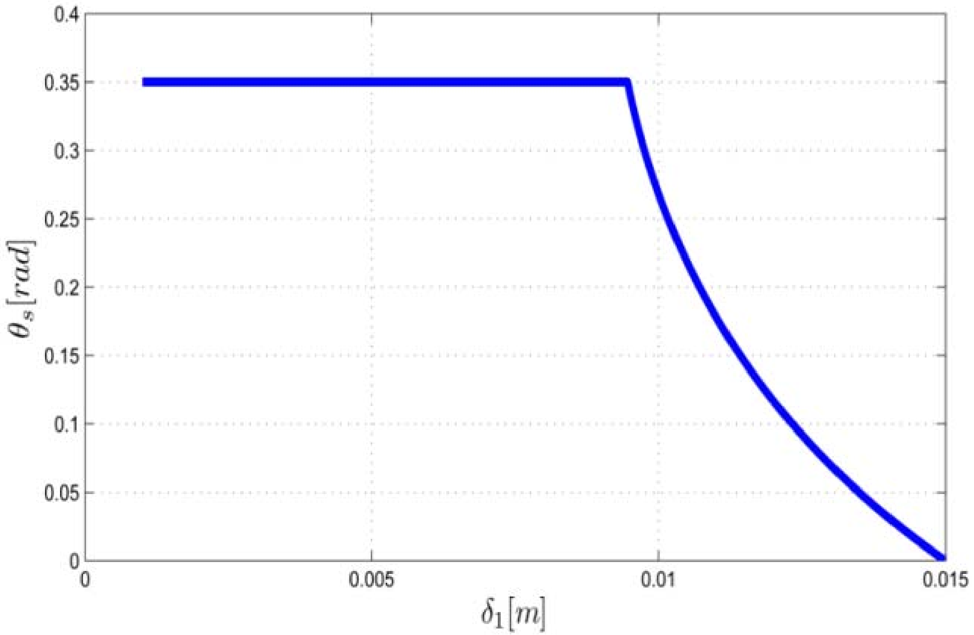


Stiffness & passive deflection profiles

Stiffness $K = \frac{2k_s \delta_1^2 \Delta^2}{(\Delta - \delta_1)^2}.$

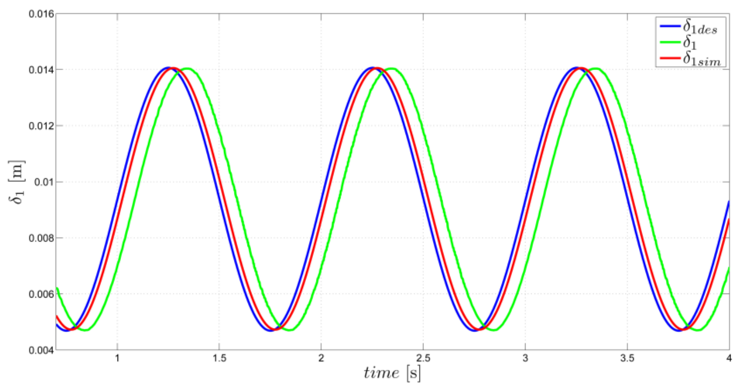


Passive deflection angle range

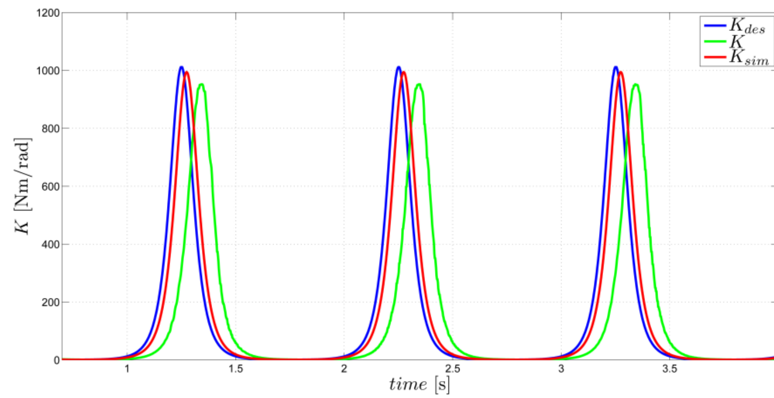


Stiffness response:Experimental results

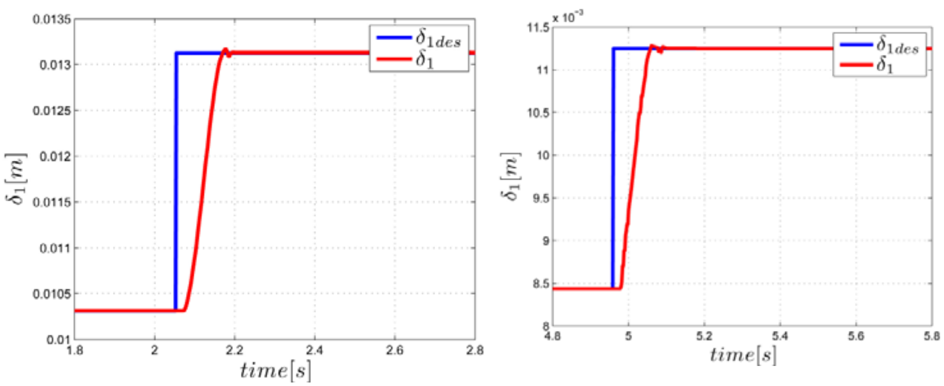
- Pivot Tracking



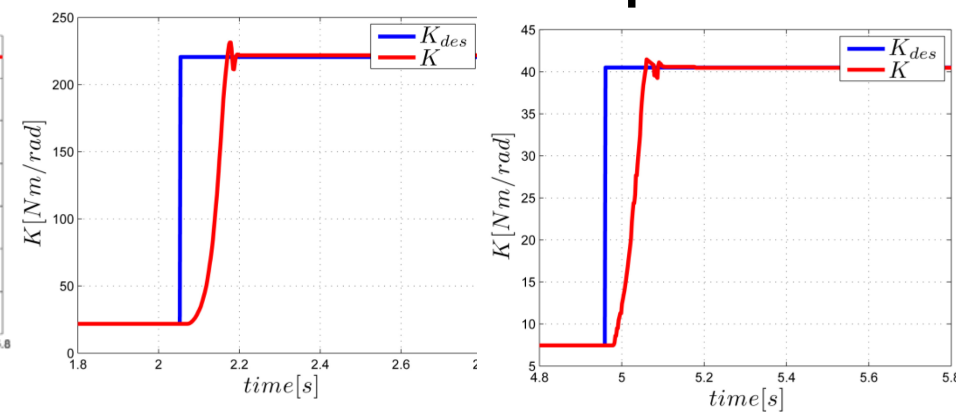
Stiffness Tracking



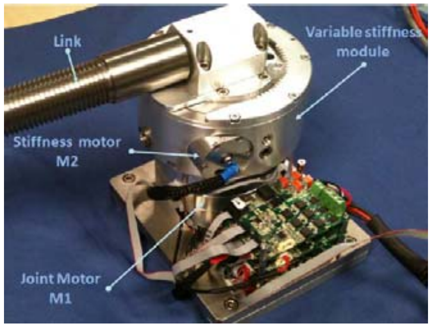
- Pivot Step



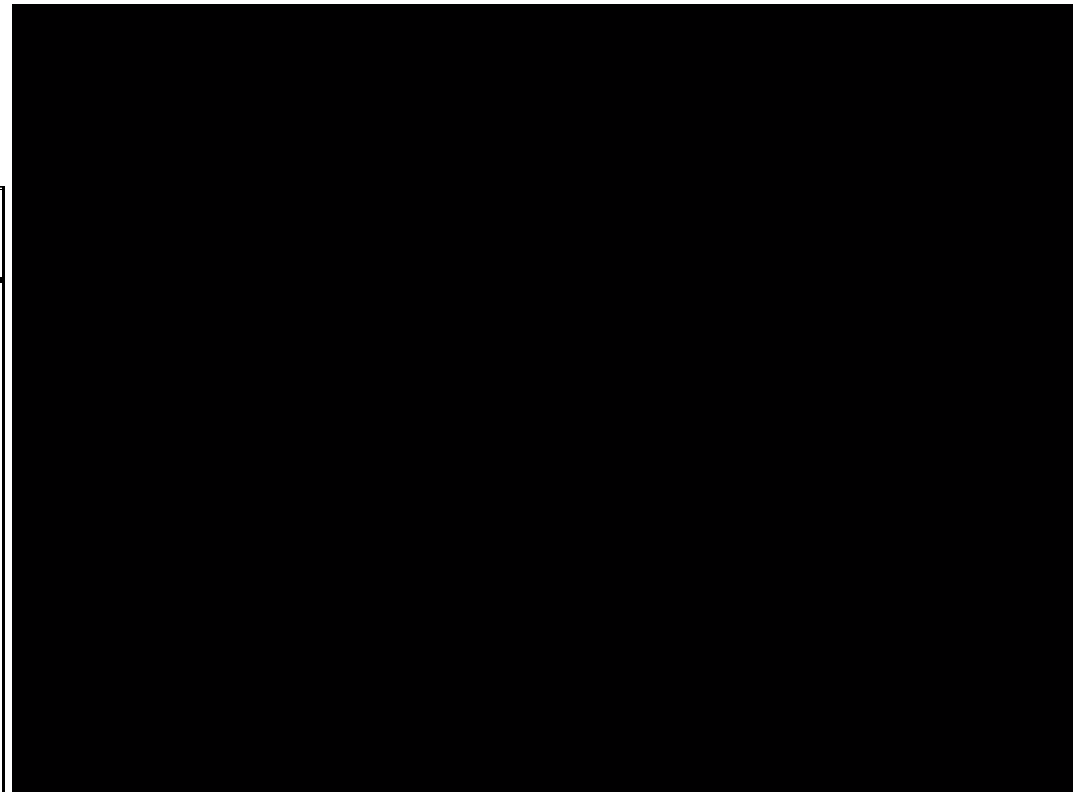
Stiffness Step



CompAct-VSA: Prototype



	CompAct-VSA
Range of Motion (deg)	+/-150°
Range of Stiffness (Nm/rad)	0 ~ rigid
Time to change the stiffness (s)	~0.2sec
Energy storage (J)	1.2
Peak Output Torque (Nm)	117
Length (m)	0.10
Width (m)	0.11
Overall Weight (Kg)	1.4



Stiffness and damping regulation in humans

Suppress oscillations

Humans improve accuracy and motion control by varying the stiffness and damping of the joints to appropriate values

- **Large amplitude oscillations:**
  - muscles co-contraction
  - damping ↑↑
  - stiffness ↑↑
- **Low amplitude oscillations:**
  - intrinsic damping of muscles↑↑
  - low energy expenditure
- **Voluntary motions**
  - damping, stiffness inverse function of velocity

Elbow flex-extension

(Lacquaniti et al, '82)

C = [0.22 – 1.56] [Nms/rad]

ζ = [0.08 – 0.2]

K = [14.8 – 125] [Nm/rad]

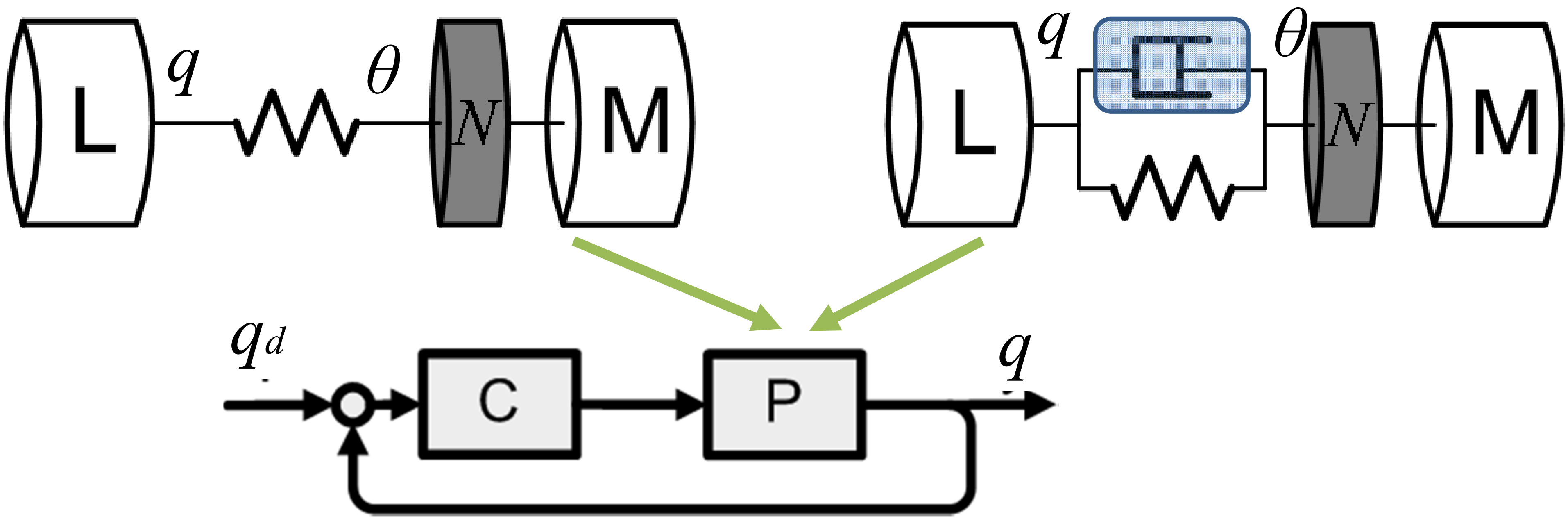
Milner and Cloutier, *Exp. Brain Research* ,1998.

Damping for compliant joints

Compliance:

- Precision
- Bandwidth
- Oscillations

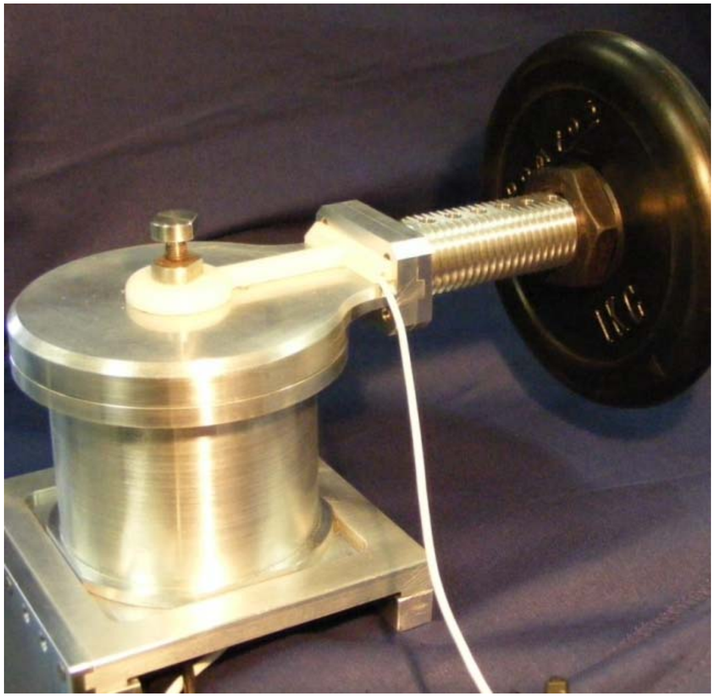
} **CONS**



VPDA -Variable physical damping actuator

Motivation

- facilitates control
  - inherently damps vibrations
  - reduces control effort
  - Intrinsically passive
- improve dynamic performance
- Spring energy management



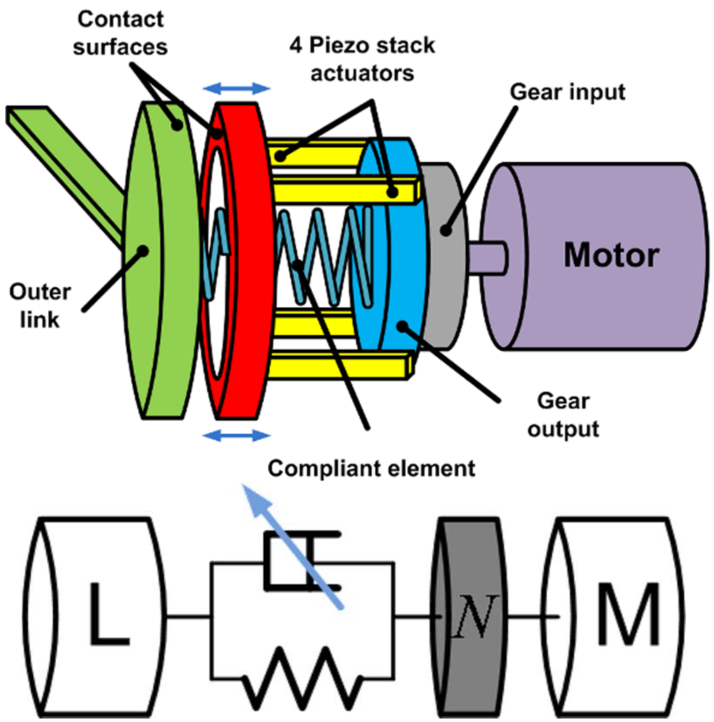
Principle & Features

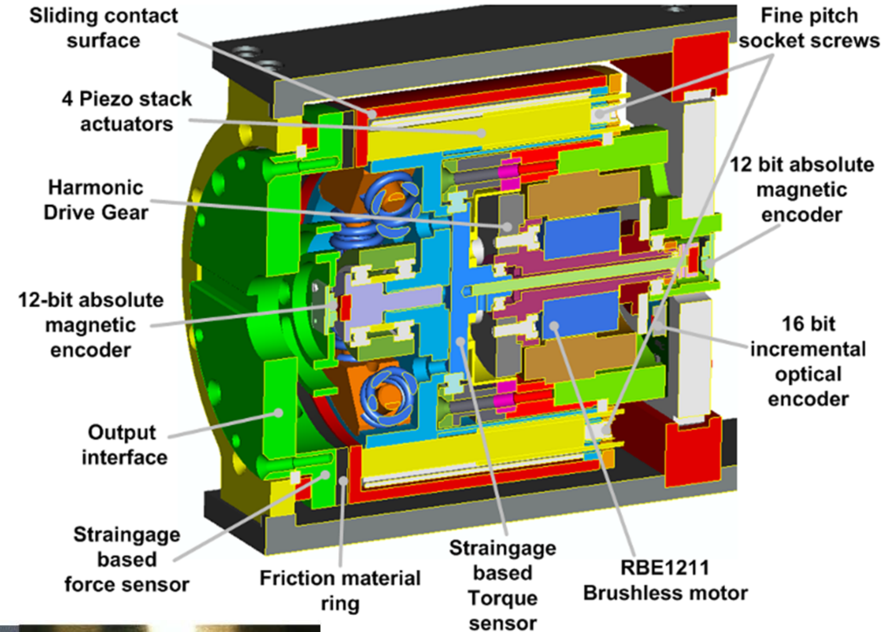
- semi-Active Solution
- introduces “real” physical damping
- piezoelectric actuation

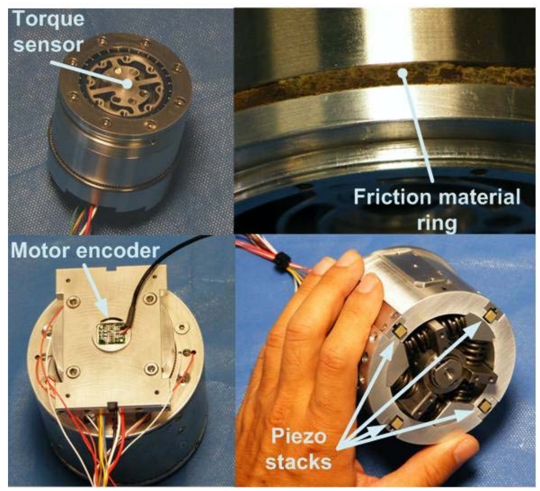
SEA + Variable physical damping actuator

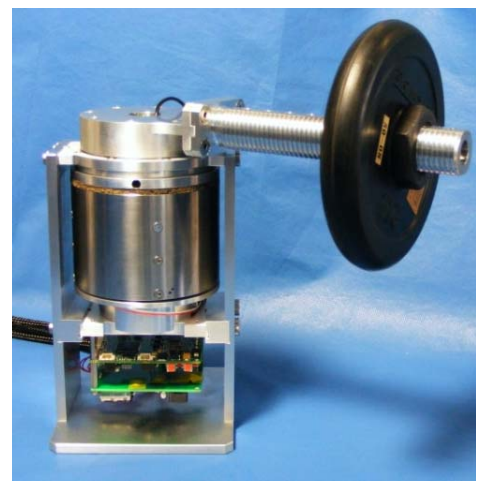
VPDA + **SEA**

Laffranchi et al. ICRA 2010





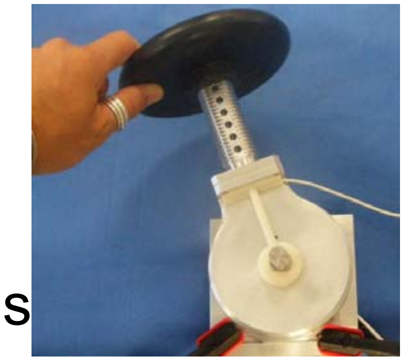


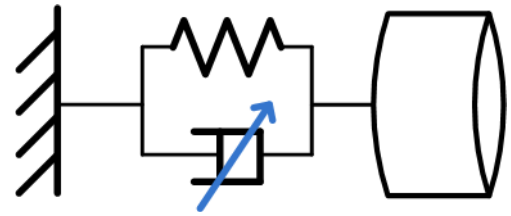


Experimental results

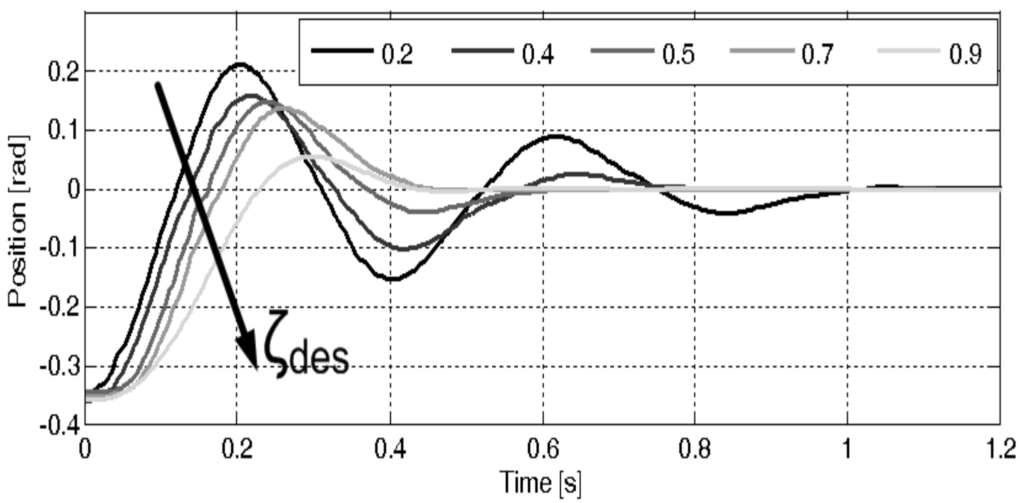
Mass-spring-damper system

- Damping ratio
- Free response to initial conditions

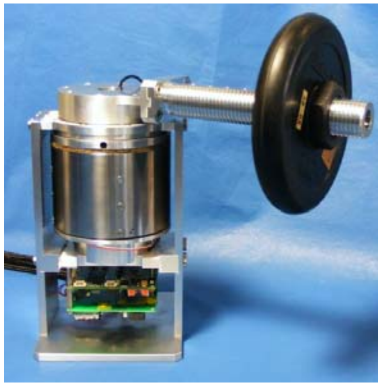


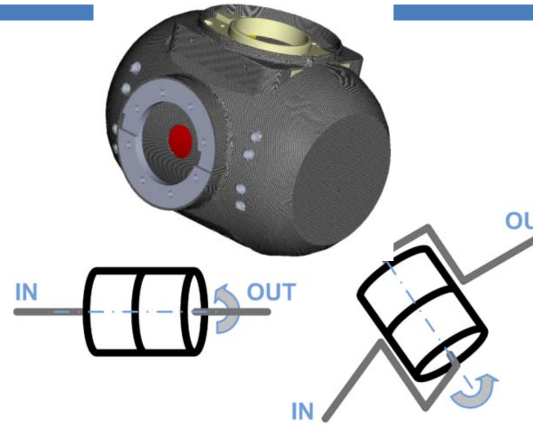


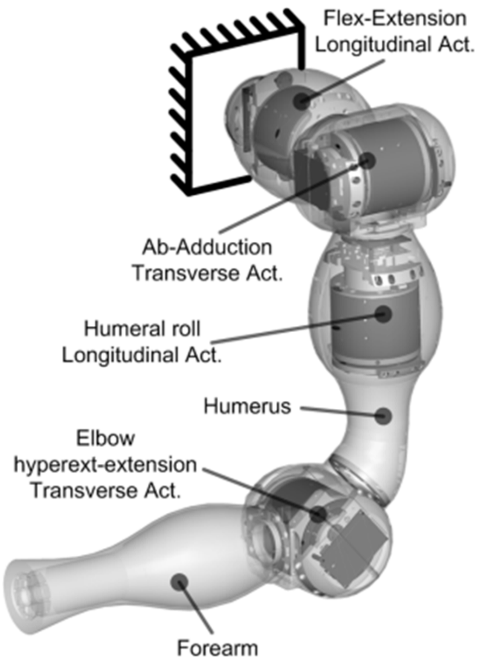
Experimental setup

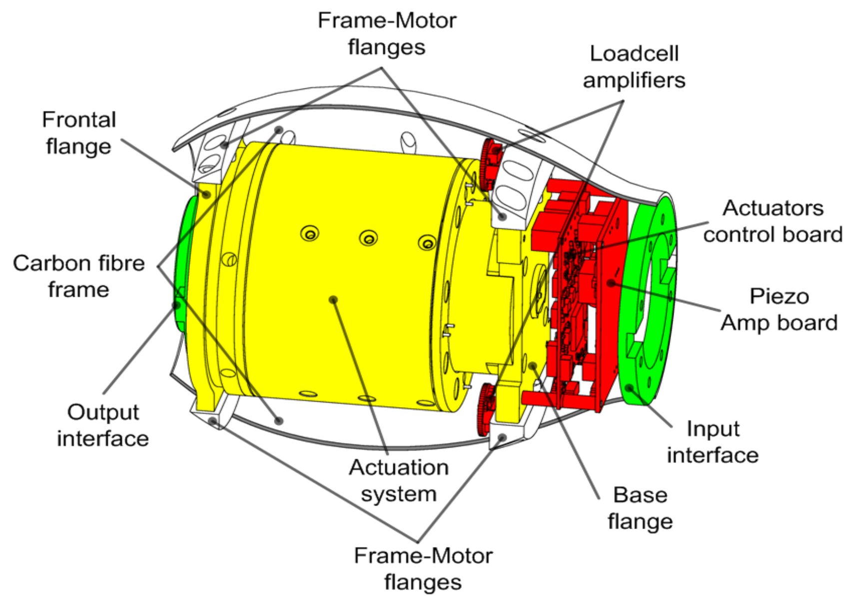


VPDA actuated arm

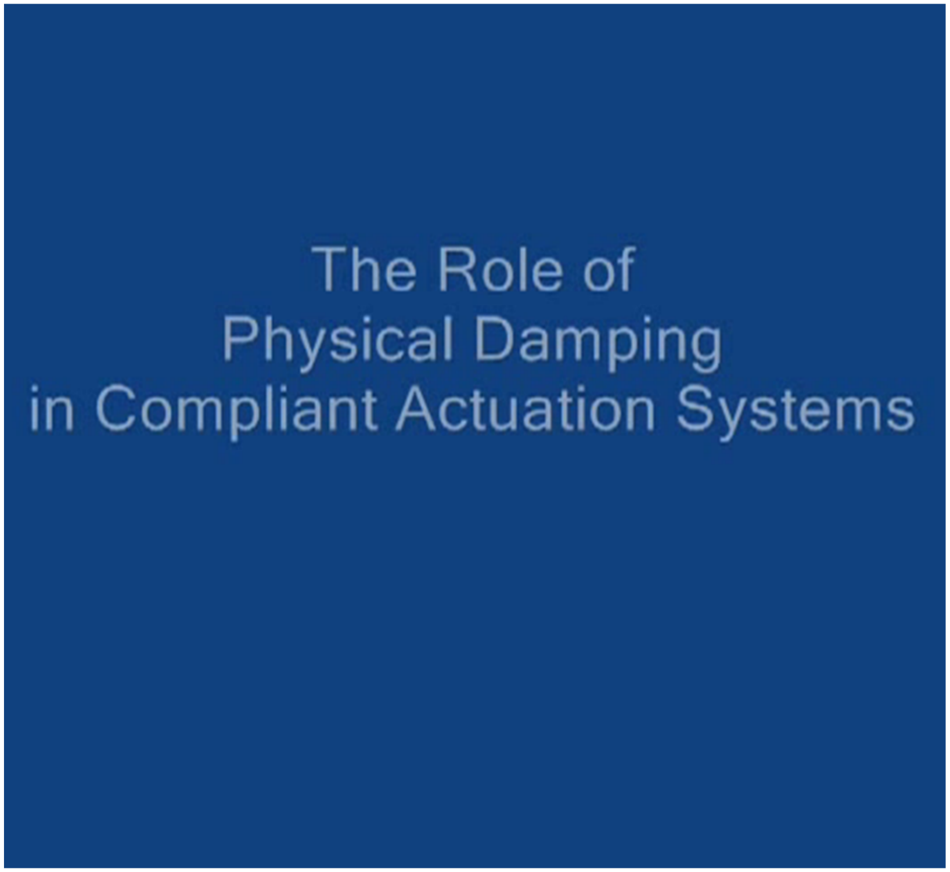








VPDA and Arm prototype



Any questions?