Compliant Actuation Technologies for Emerging Humanoids

Nikos Tsagarakis

Humanoid & Human Centred Mechatronics Lab
Dept. of Advanced Robotics
Istituto Italiano di Tecnologia

Outline

- Classical robotics actuation
  - Pros and cons
- Compliant actuators
  - Series elastic actuators (SEA)
  - CompAct unit and compliant humanoid COMAN
  - Variable stiffness actuation (VSAs)
- Variable damping actuation
  - the Variable physical damping actuator VPDA
  - CompAct manipulator

Robot soccer state

- relative slow motions
- absence of fast/high power motions
- always in static balancing
- physical game is missing
  - body to body physical interaction
  - dynamic balancing against strong disturbances
  - impacts with ground and other bodies can damage the robots

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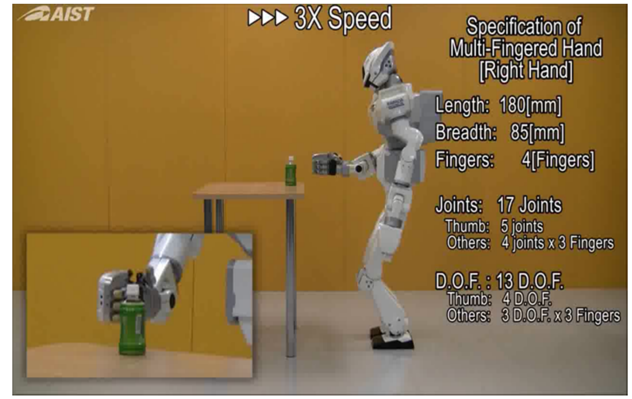
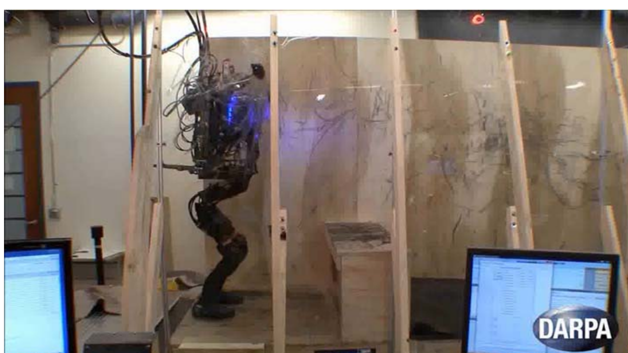
Humanoid SoA





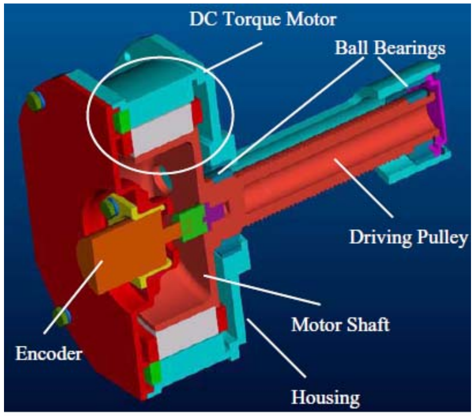
Robotics actuation (motorized)

- Direct drive actuation
- Geared actuators
  - Motor + reduction gearheads
  - Motor + low-friction cable /belt drive transmissions

Direct drive actuation

a high quality servomotor directly connected to the load

- Pros
  - the torque output can be accurately controlled through motor current regulation
  - robust against impacts
- Cons
  - servomotors operate inefficiently at low speeds and high torques
  - the power of direct drive servomotors is selected to be much higher than the actual useful power output
  - they are typically too large and heavy



Frisoli et al, 2005

Geared drives

Motor + reduction gearheads

a servomotor combined with a gearhead

- Pros
  - motor operates in a more efficient spot (high speed/low torque) while driving a low speed/high torque trajectory
  - for low reduction ratio, current control can then be still applied to the geared actuator to control force output

Geared drives

Motor + reduction gearheads

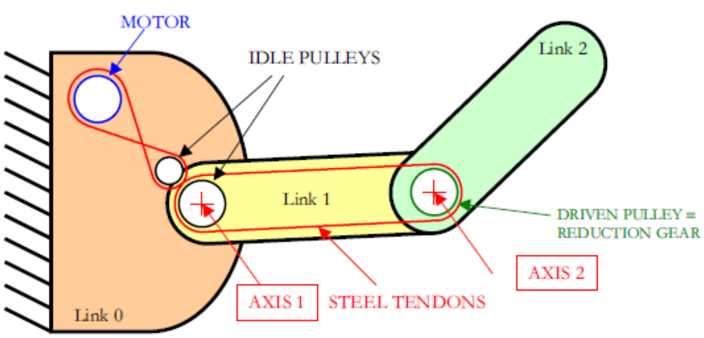
- Cons
  - introduces significant friction
    - friction can become essentially high in some types of non-backdriveable gears
  - increases the reflected inertia at the output of the gearbox
    - large output mechanical impedance
  - non-linear, non-continuous dynamics such as stiction and backlash
  - force control through current regulation is unsuitable as it will result in extremely poor force fidelity
  - weak under impacts

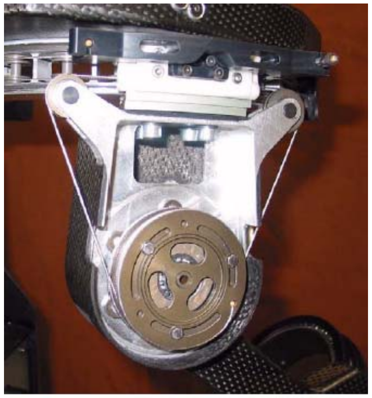
Geared drives

Motor + low-friction cable /belt drive transmissions

a servomotor combined with a cable drive transmission

- Pros
  - cable drive transmissions, have low stiction and low backlash.
  - can be approximated by linear dynamics allowing to model the transmission and compensate for its effects
- Cons
  - only low to moderate ratios can be implemented
  - high rations requiring large pulleys and multi-stages which need large space
  - More complex assembly with many pulleys requiring the fixation and pretension of cables





Frisoli et al, 2005

Humanoid actuation

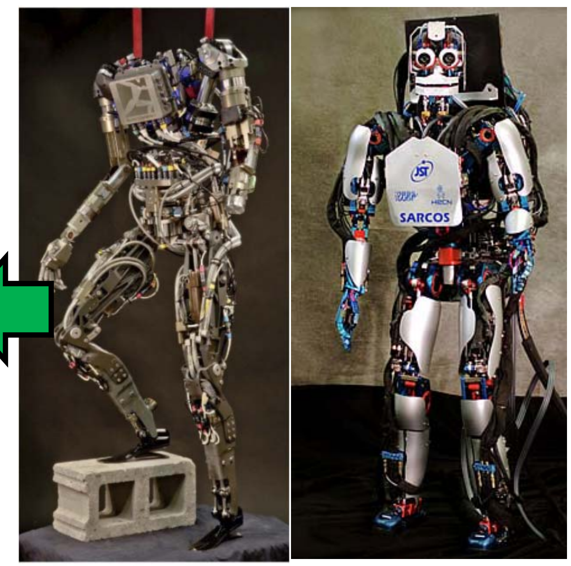
- **Features**
  - DC brush or brushless motors combined with planetary or harmonic drive gears
    - relative high gearing position control groups (>100:1)
    - limited back-drivability
    - stiff Position / velocity servo loops
  - minimum passive compliance (mostly from tendons)
  - no direct joint torque sensing
- **Advantages**
  - high disturbance rejection
  - accuracy and repeatability

Humanoid actuation

Electrical

Stiff actuation for accuracy
+
Active compliance regulation

Hydraulic



The need of compliance

- Robots coperating / interacting (purposely or accidentally) with their environment have different requirements than the current stiff robotic systems
  - Accuracy and repeatability 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 ?

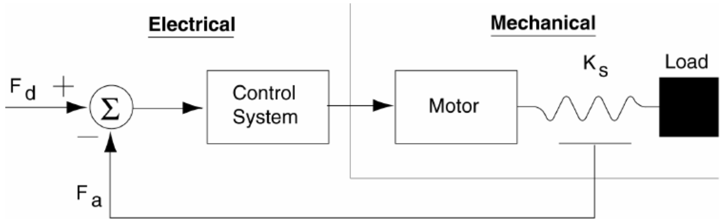
Stiff body/actuation for accuracy
+
Active/Controlled impedance
to satisfy new requirements

Intrinsic body compliance
+
Control to satisfy performance indexes

1. **lower impact forces, improves robustness**
2. **passive adaptability to interaction**
3. peak power generation
4. **energy efficiency**

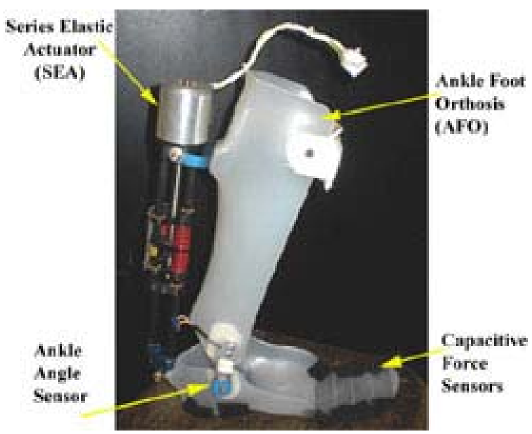
Series elastic actuation (SEA)

- **Fixed series elasticity**
  - passively adaptable
  - lower impact forces
  - inherently safer, more tolerant to disturbances
  - can be combined with active stiffness regulation

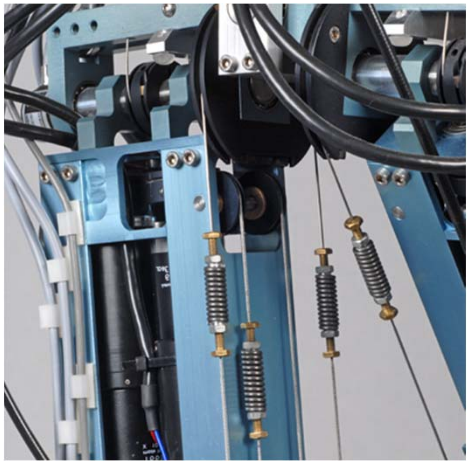


  - preset passive mechanical compliance
  - performance is compromised

Pratt et al, 1995



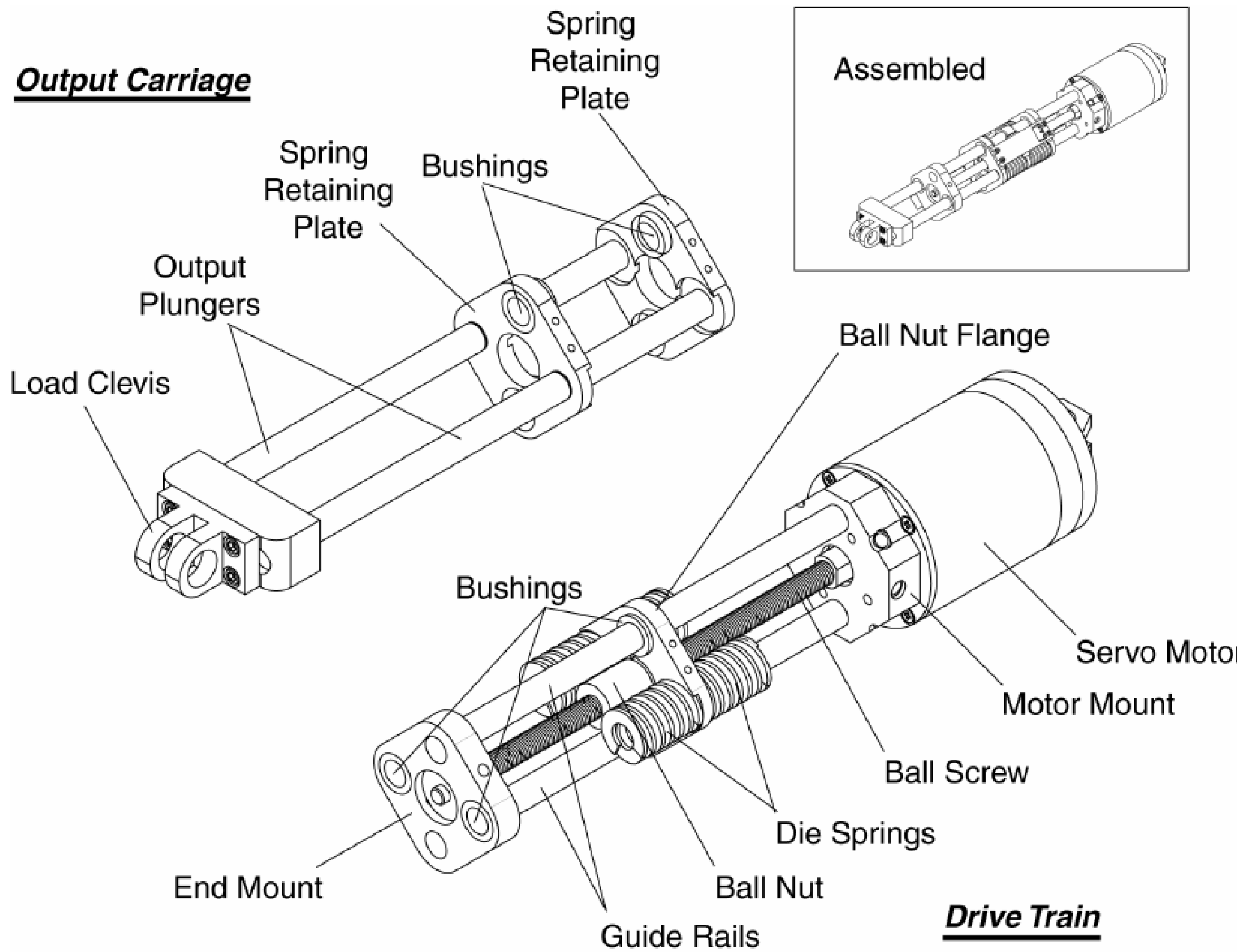
Herr et al, 2004



Wisse et al, 2007

Series elastic actuator

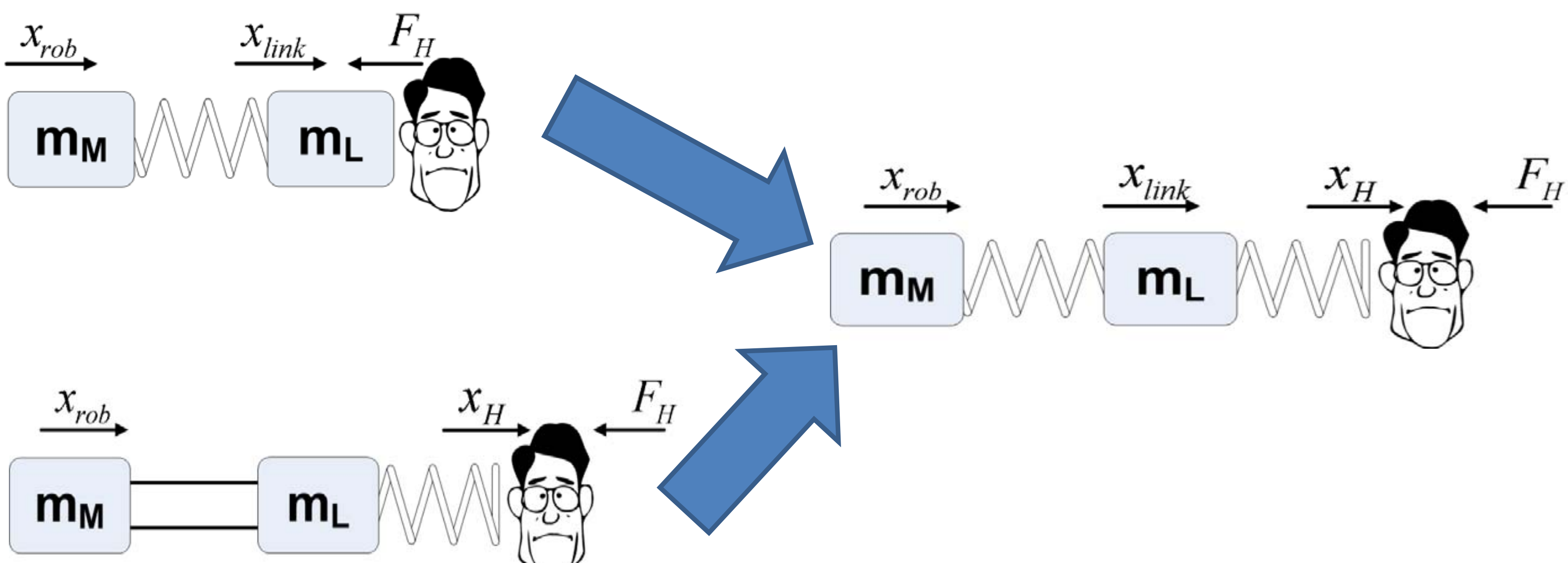
Pratt et al, 95



Intrinsic passive compliance
Effect on the impact forces

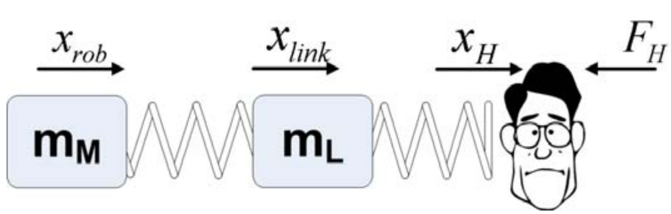
Compliance can been introduced:

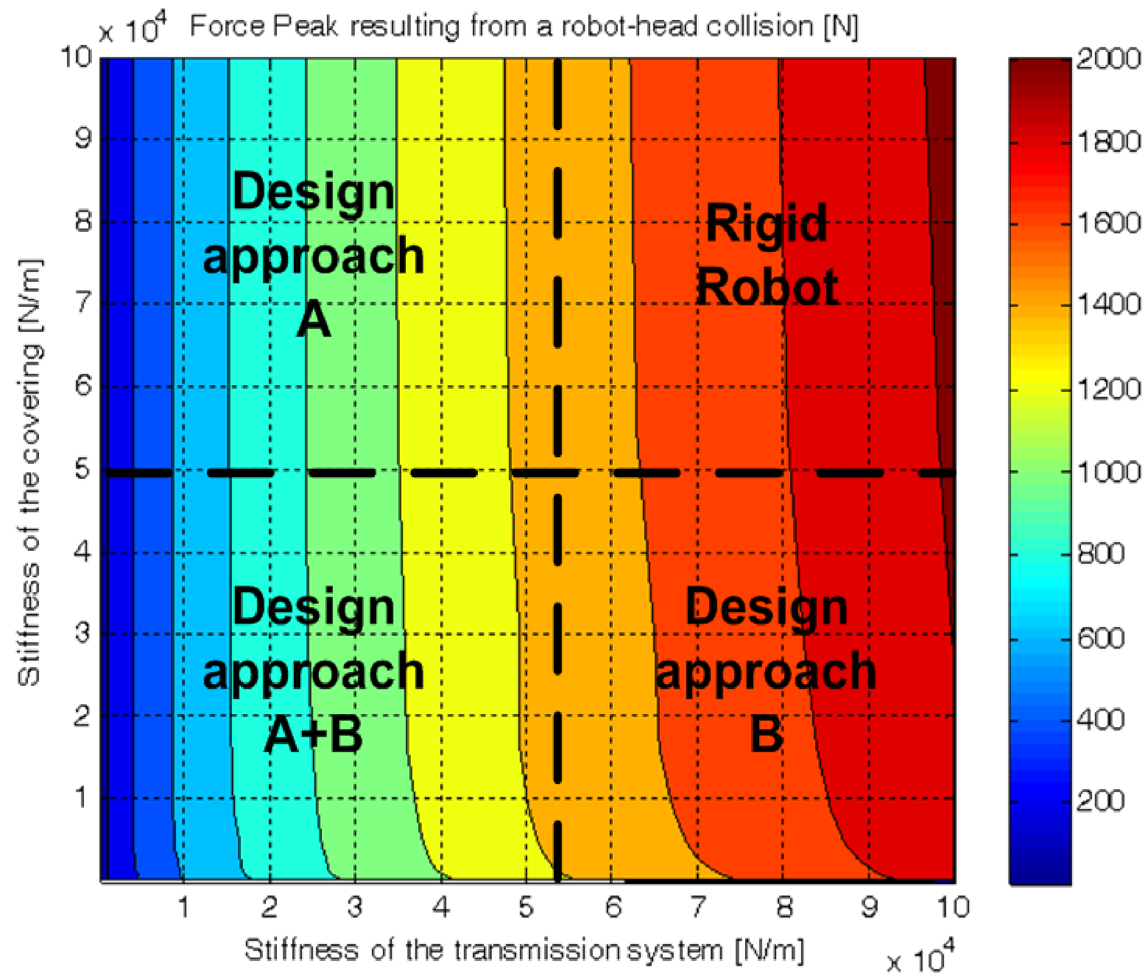
- A: between the actuator and the link
- B: around the link/structure (soft cover)
- C: A and B



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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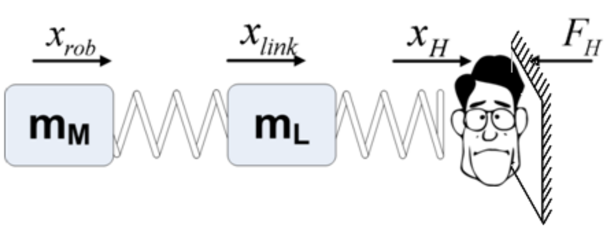
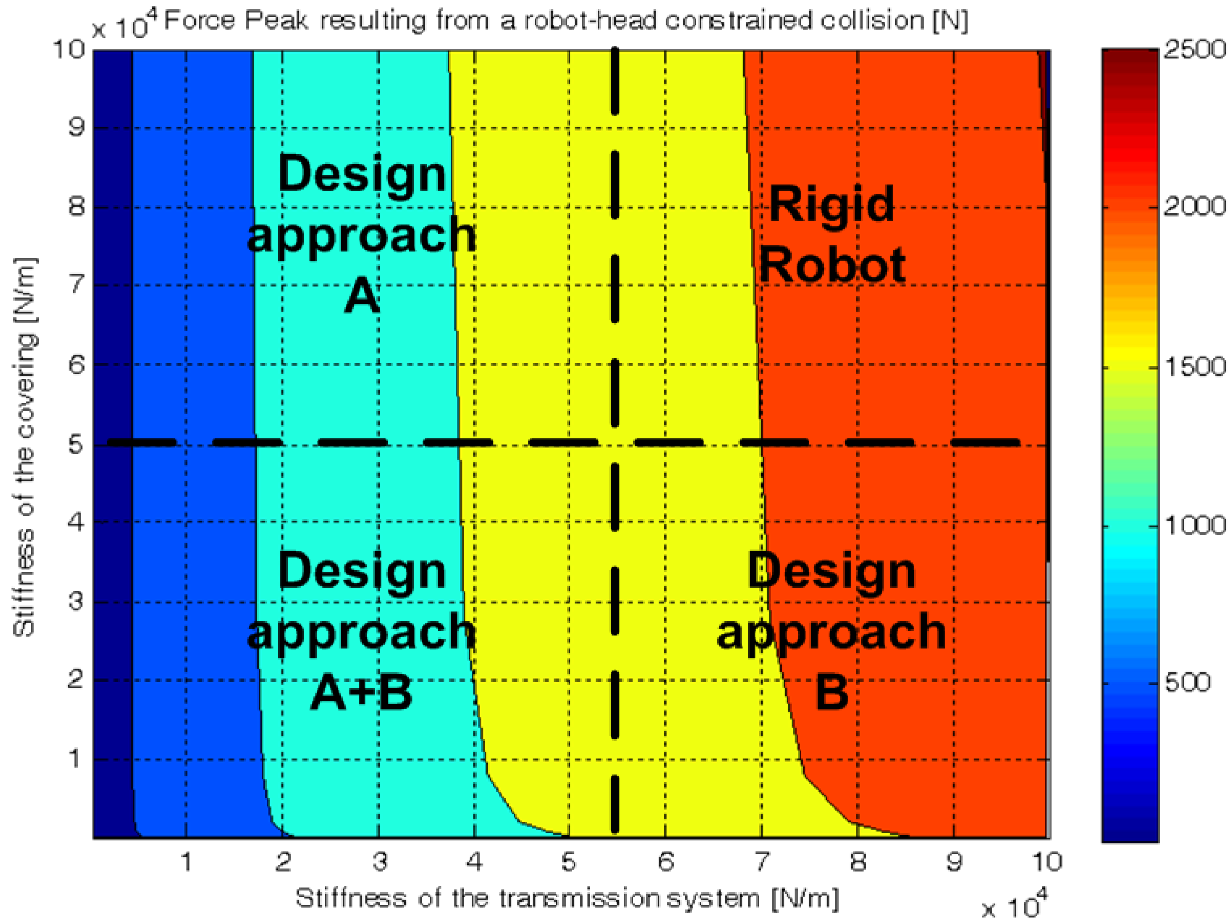




The AMARSI project

- 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)

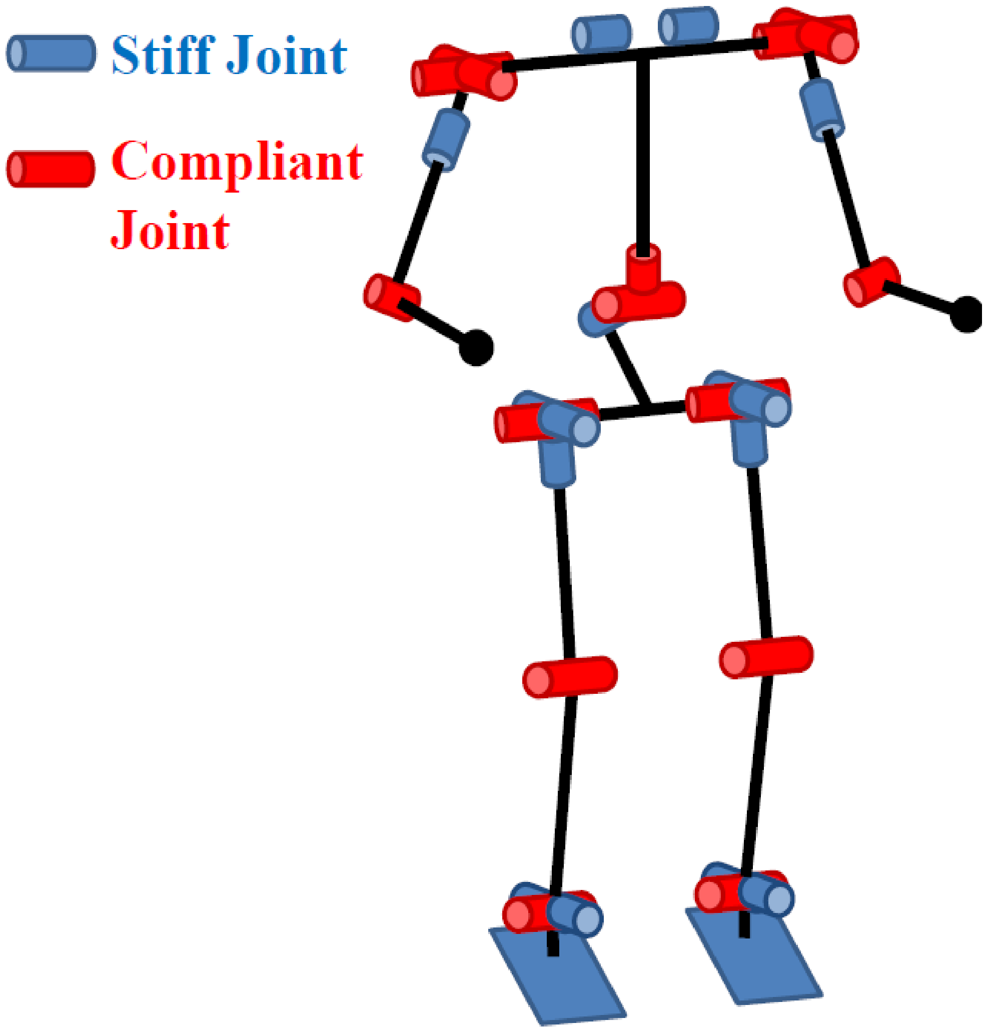
- a full humanoid robot
- 25 major degrees of freedom (arms/legs and torso excluding hands and neck/head)
- intrinsic passive compliance
- joint torque sensing/active compliance

COMAN overview

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

Tsagarakis et al, ICRA 2013

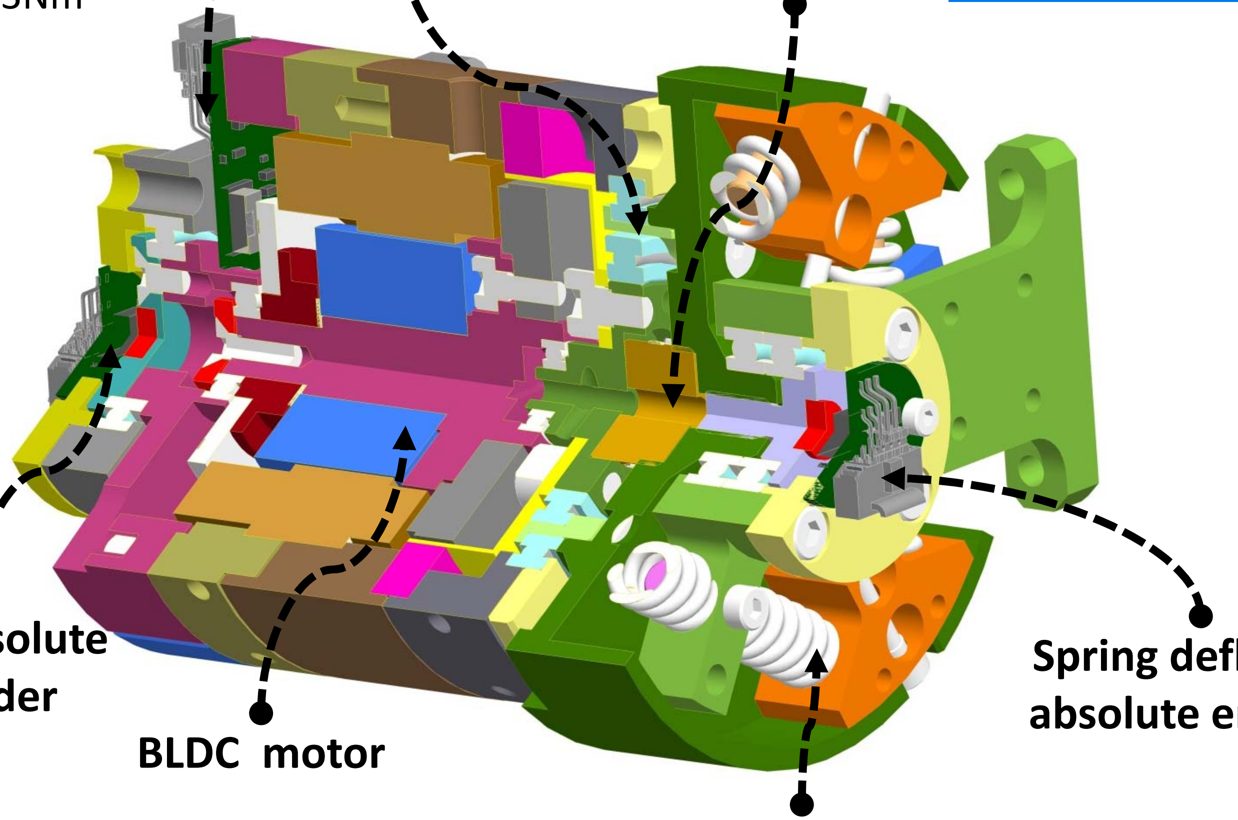
COMAN kinematics



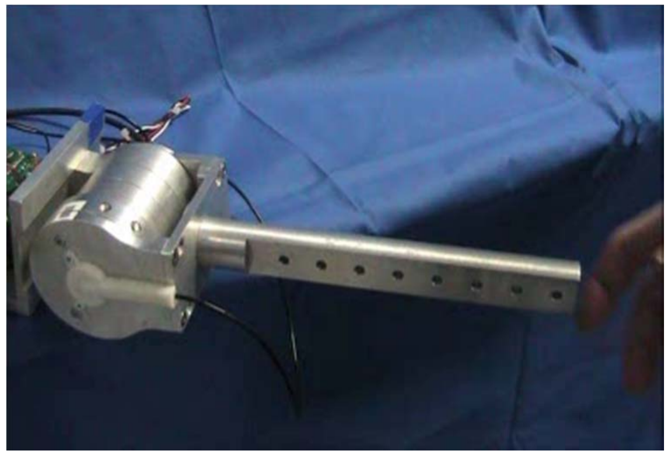
Joint	Number of DOF
Ankle	2
Knee	1
Hip	3
Waist	3
Shoulder	3
Elbow	1
Neck	2

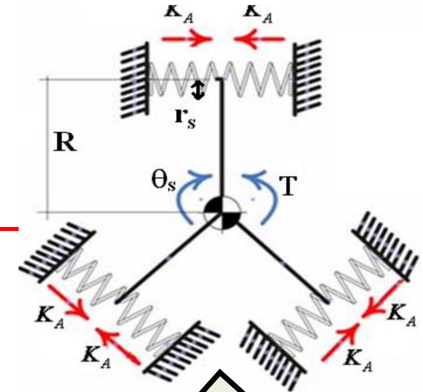
Compliant joint: CompAct unit

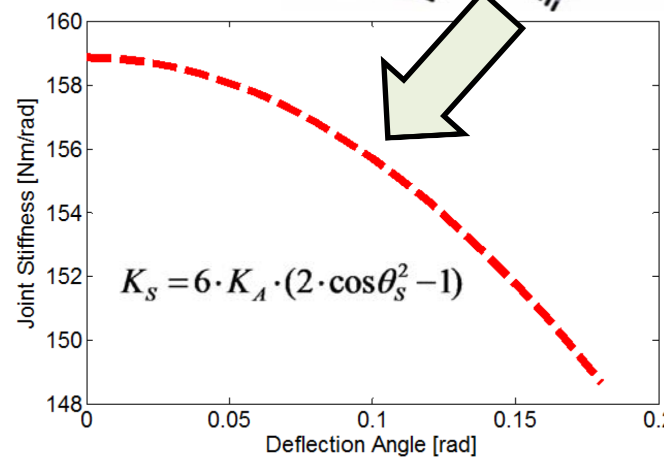
- **Motor**
  - Kollmorgen RBE1211
  - rate power :152W
  - peak power:470W
  - continues torque : 0.23Nm
  - peak torque: 0.8Nm
- **Reduction drive**
  - CSD17 (100:1)
  - peak torque : 55Nm
  - series elastic module

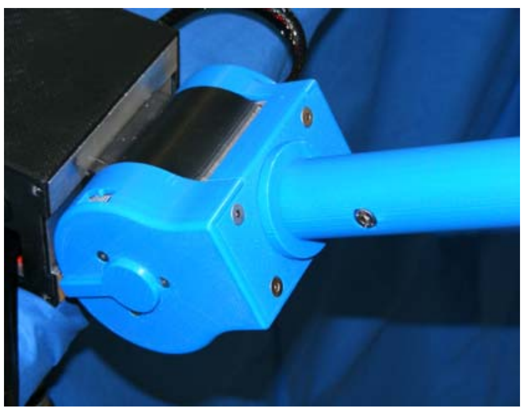


The CompAct actuator

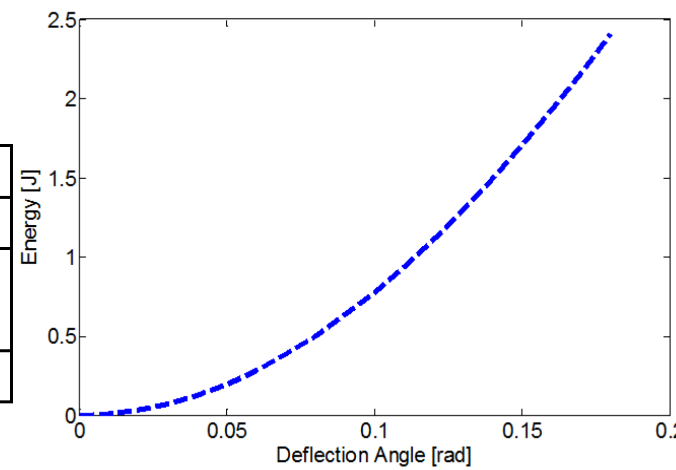




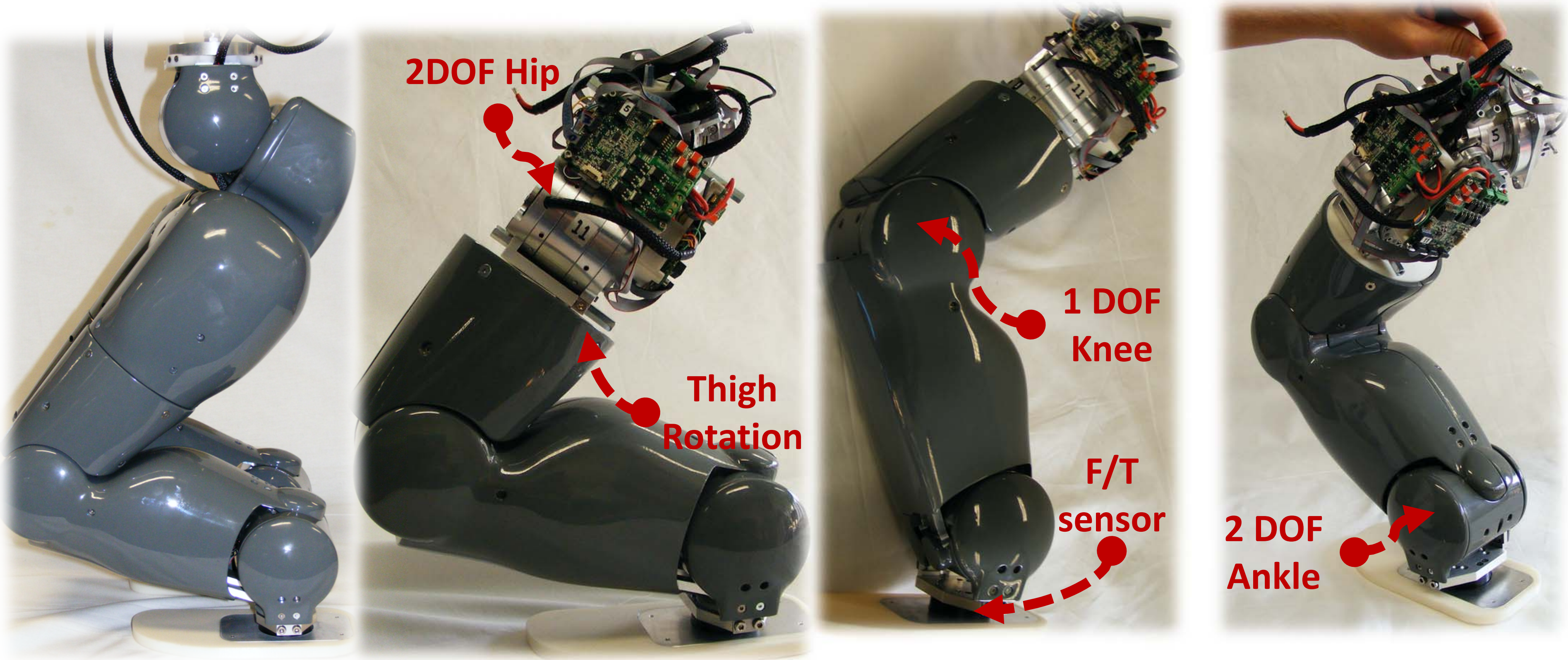


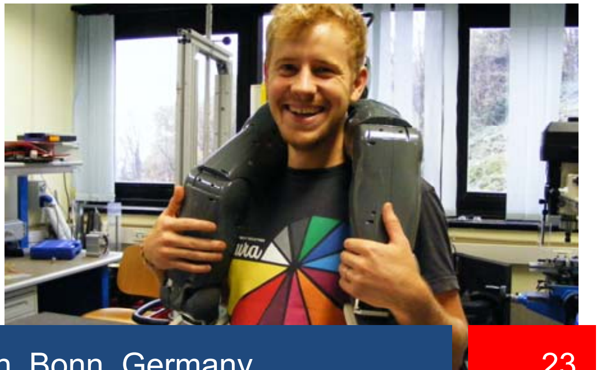


Diameter	70mm
Length	80mm
Max rotary passive deflection	+/-0.2rad
Weight	0.52Kg



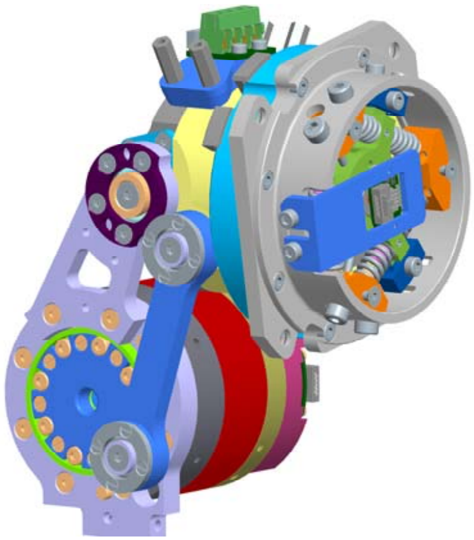
COMAN lower body

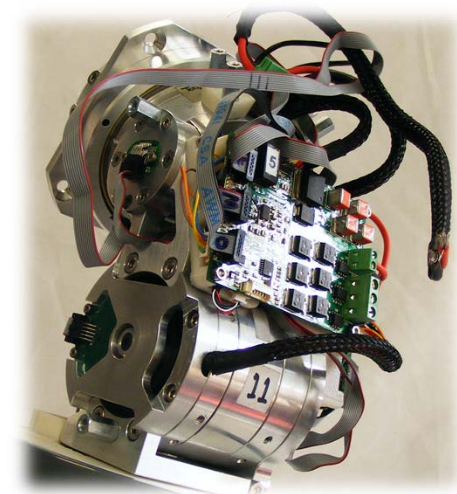




Hip design and specs

- serial mechanism
- passive compliance for hip pitch and roll
- gear ratio 100:1

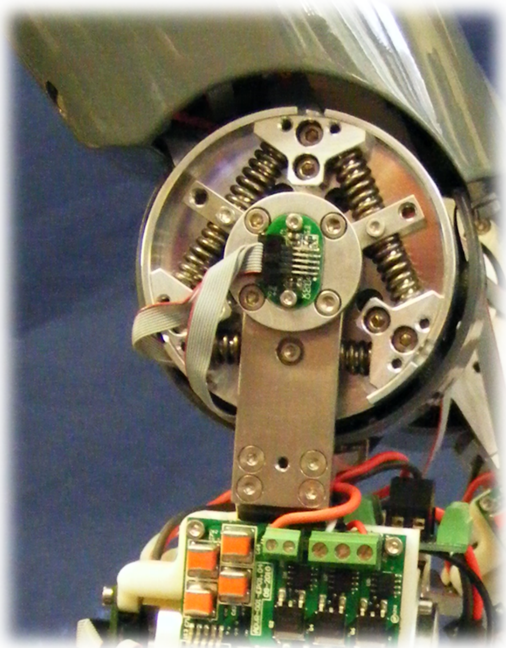


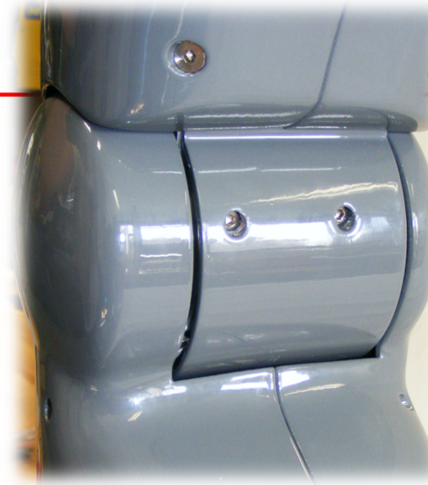


Joint	New Hip	
	Motion Range **(°)**	Peak Torque (Nm)
Flex/Ext	+110, -45	**55** (6.2rad/s at 36V, 9.0rad/s at 48V)
Abd/Add	-60, +20	**55** (6.2rad/s at 36V, 9.0rad/s at 48V)
Rotation	+50, -50	**55** (6.2rad/s at 36V, 9.0rad/s at 48V)

Knee design and specs

- series elastic actuated
- gear ratio 100:1

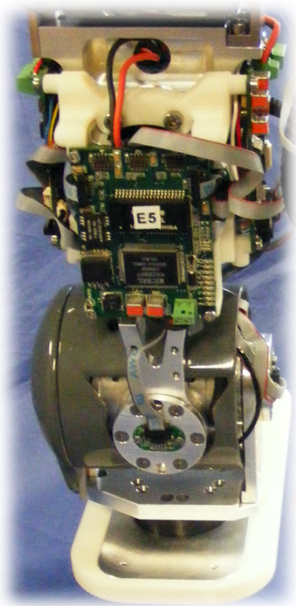




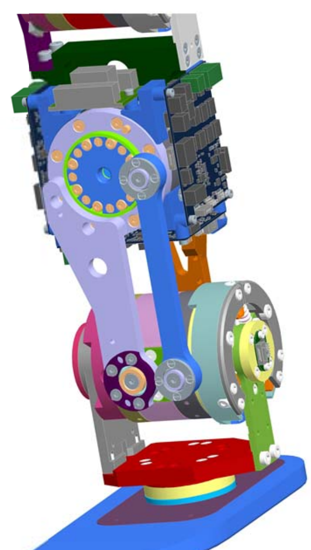
Joint	knee	
	Motion Range (°)	Torque (Nm)
Flex/Ext	-120, +10	**55** (6.2rad/s at 36V, 9.0rad/s at 48V)

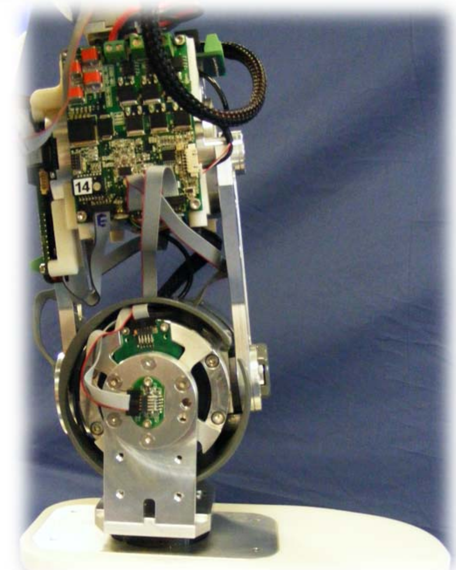
Ankle design and specs

- serial mechanism
- passive compliance for hip pitch and roll
- gear ratio 100:1



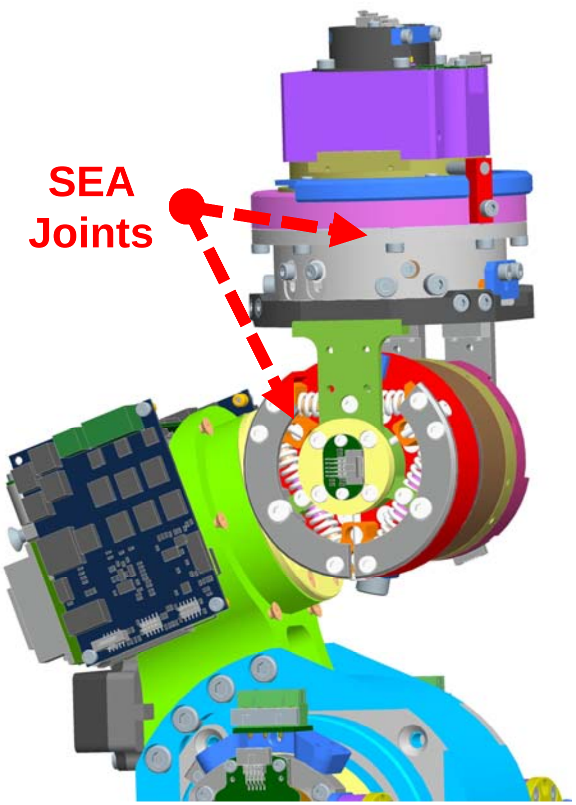
Joint	Ankle	
	Motion Range (°)	Torque (Nm)
Flex/Ext	+70, +50	**55** (6.2rad/s at 36V, 9.0rad/s at 48V)
Abd/Add	-35, +35	**55** (6.2rad/s at 36V, 9.0rad/s at 48V)

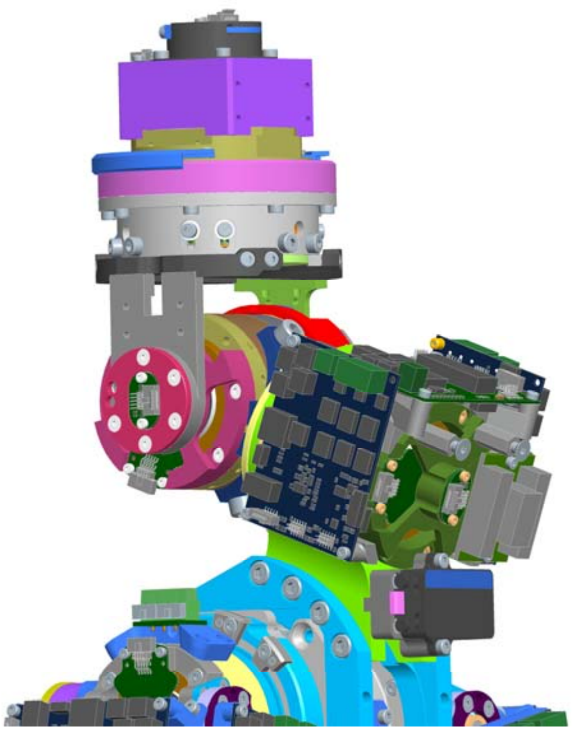


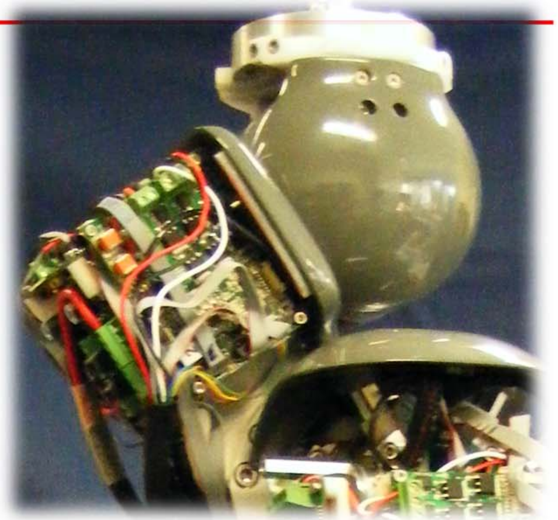


COMAN torso joint

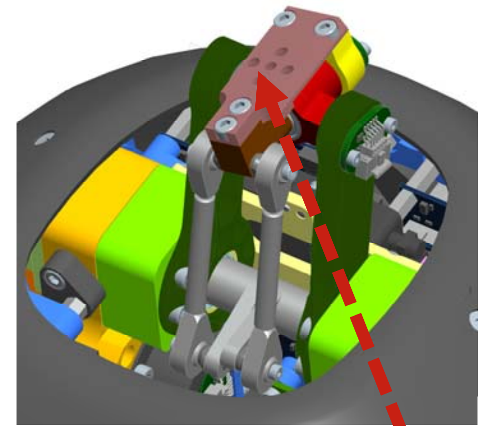
- 3DOF serial mechanism
- passive compliance for pitch and yaw motions







Upper torso and neck

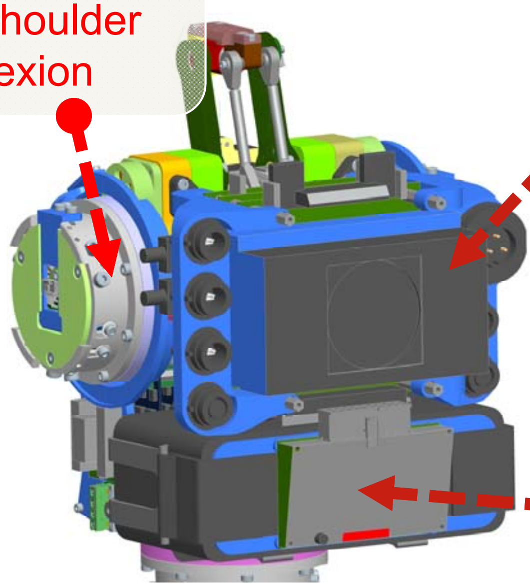


Neck module

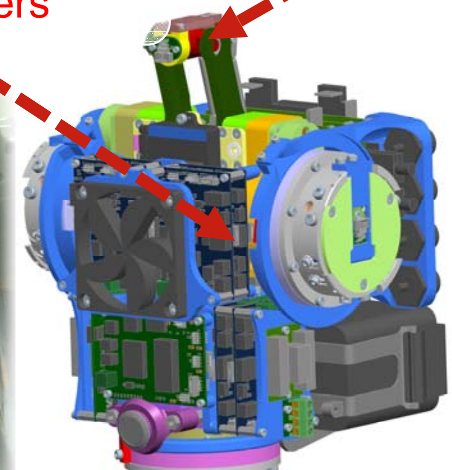
Compliant Shoulder flexion

PC104 controller

Shoulder and neck motor controllers

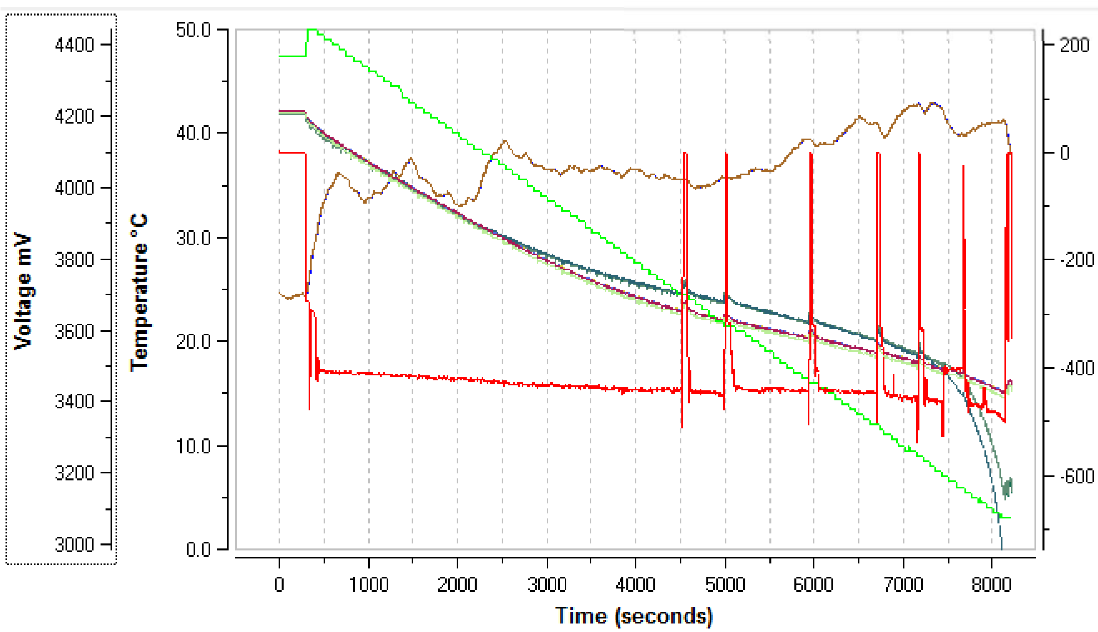


Battery pack and BMS system



Battery pack and BMS system

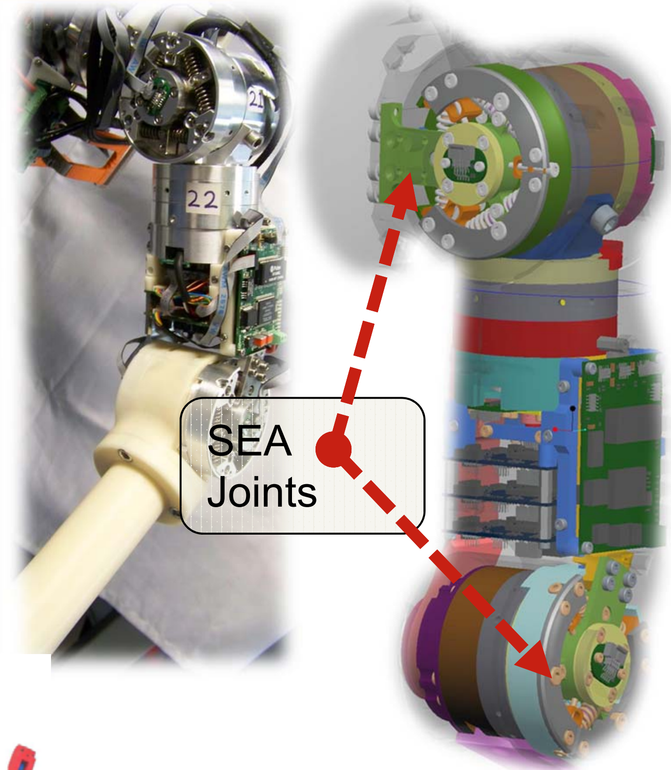
- Lithium polymer
- weight 1.7Kg
- nominal voltage 23-29V
- capacity 10Ah

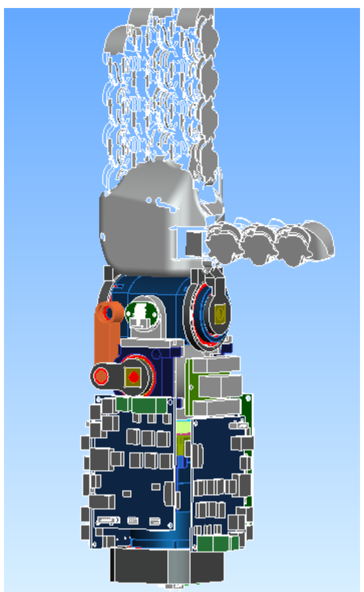


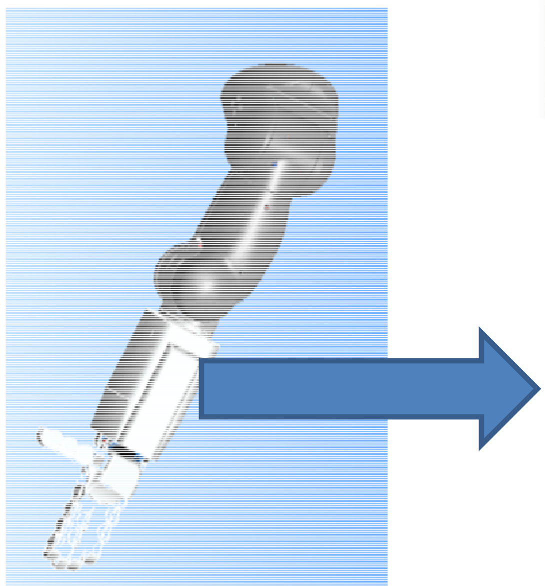
..more than two hours of light-duty squatting

COMAN arm

- 3DOF serial shoulder mechanism
- 1DOF elbow
- passive compliance
  - shoulder (flex/ext and abd/add) motions
  - elbow flex/ext
- Wrist/hand will be integrated soon







Catalano et al, 2012

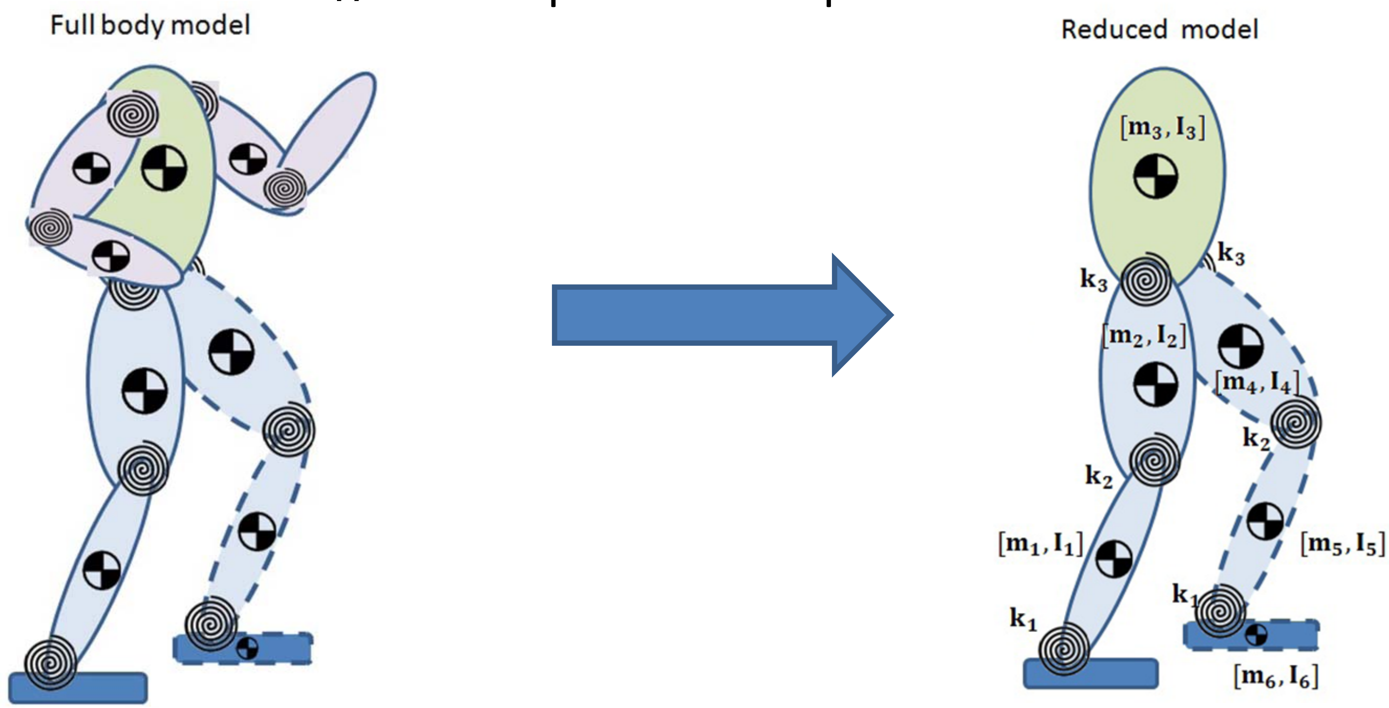
How to tune the intrinsic elasticity?

- Where to place the compliance?
- How to select the joint compliance level?
- the tuning of the series passive elasticity still remains an experimental trial and error process and very little information on the methodologies used is available

- Can we tune compliance using a more systematic method?
  - optimise for bandwidth constraints

Selecting COMAN's leg compliance

- multi-dof mass-spring system
- highly nonlinear varying system
  - mass matrix changes
  - additional nonlinearities may exist in the drive elasticity
- resonances change and depend on the posture



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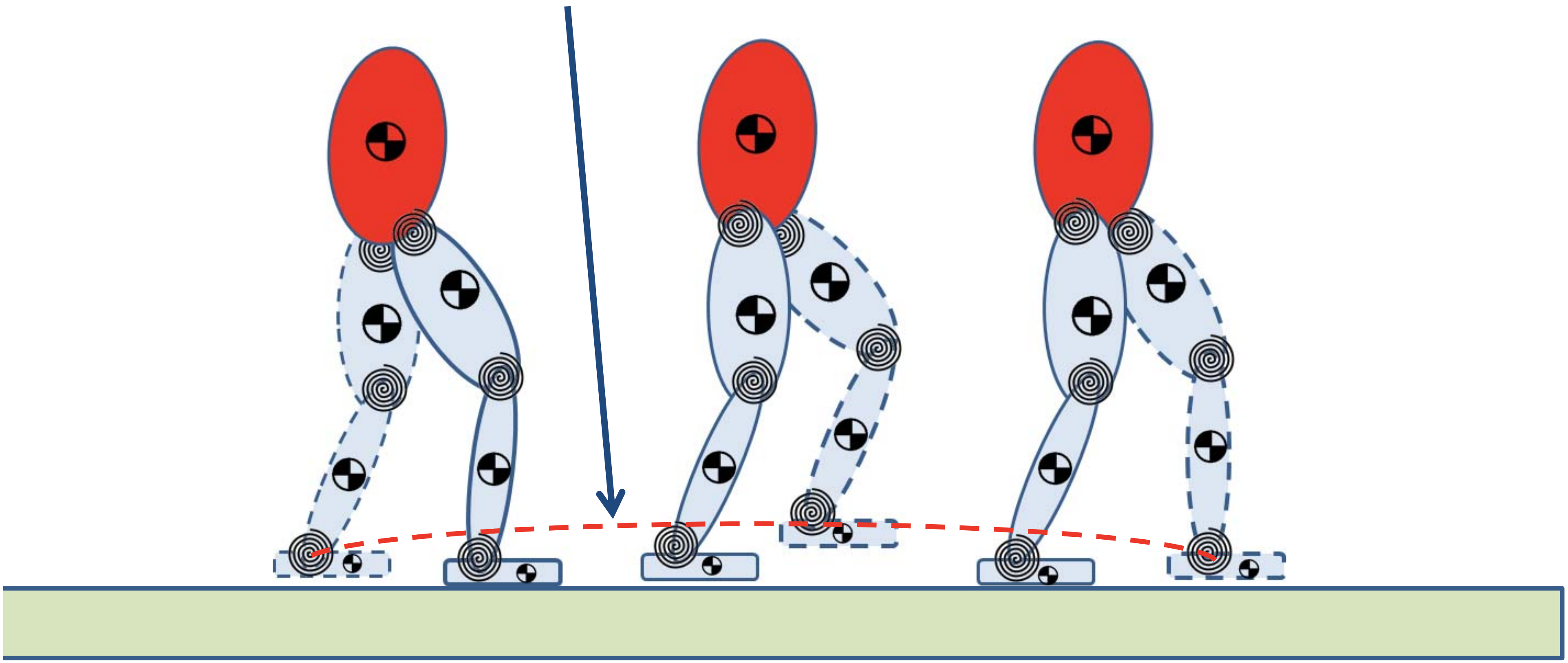
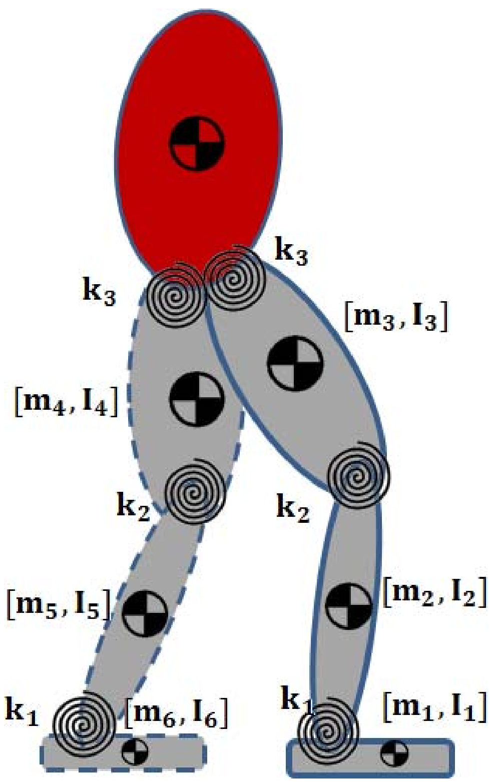
Selecting COMAN’s leg compliance

Twenty posture configuration points of the single support phase were considered



Selecting COMAN's leg compliance



$$\Delta(q)\begin{bmatrix}\ddot{q}\\ \ddot{\theta}\end{bmatrix}+\Gamma(q,\dot{q})\begin{bmatrix}\dot{q}\\ \dot{\theta}\end{bmatrix}+\begin{bmatrix}g(q)-K(\theta-q)\\ K(\theta-q)\end{bmatrix}=\begin{bmatrix}\tau_e\\ \tau_m\end{bmatrix}$$

$$\Theta = \begin{bmatrix} q^T & \theta^T \end{bmatrix}^T \quad G(q) = \begin{bmatrix} g(q)^T & 0 \end{bmatrix}^T$$

$$\Delta(q)\ddot{\Theta} + \Gamma(q,\dot{q})\dot{\Theta} + S\Theta + G(q) = \tau \qquad S = \begin{bmatrix} K & -K \\ -K & K \end{bmatrix}$$

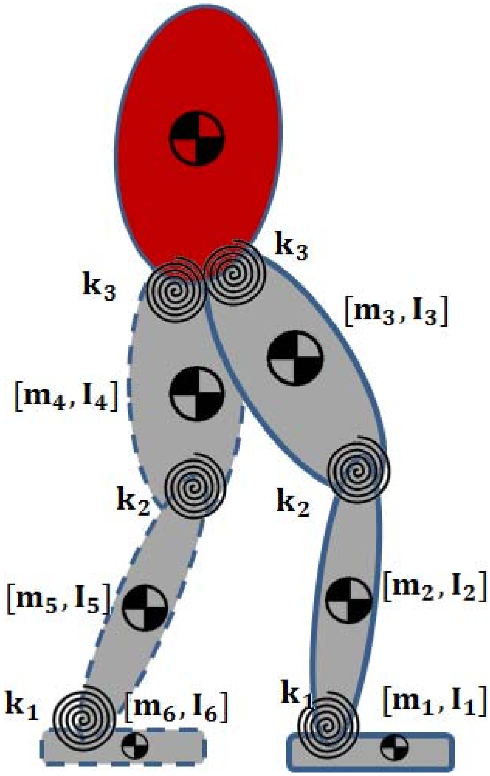
$$\phi = \Theta - \Theta_e$$

$$\Delta(q_e)\ddot{\phi} + S_g\phi = \tau$$

$$S_g = \begin{bmatrix} K & -K \\ -K & K \end{bmatrix} + \nabla G(q_e)$$

$$\nabla G(q_e) = \begin{bmatrix} \nabla g(q_e) & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}$$

Selecting COMAN's leg compliance



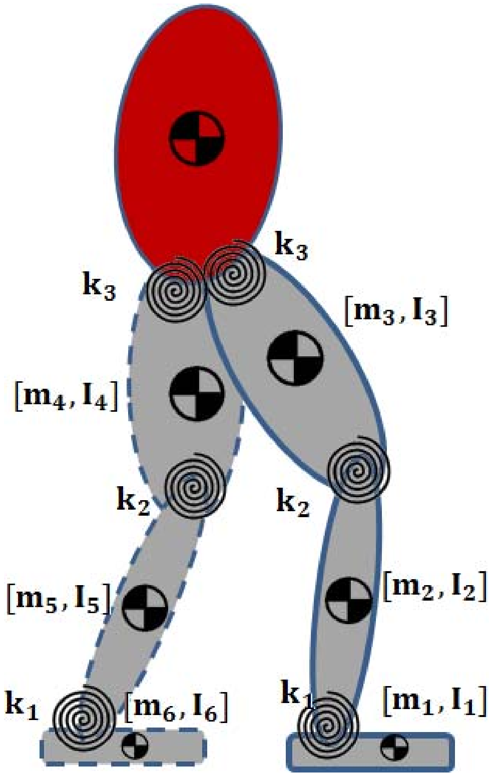
$$S_{gm} = \begin{bmatrix} K + \nabla g(q_e) & -K \\ -K & K + K_m \end{bmatrix}$$

$$\Delta(q_e)\ddot{\phi} + S_{gm}\phi = \tau \qquad M\ddot{x} + Kx = f$$

$$A = \Delta(q_e)^{-1} S_{gm}$$

$$f_i = \frac{1}{2\pi}\sqrt{\lambda_i}, i = 1, 2 \ldots N$$

Optimal joint stiffness selection



constrained optimization problem

- maximize the joint passive deflection for a given joint torque vector
- subject to constraints
  - natural frequencies constraints
  - stiffness constraints

$$min\left(\frac{2}{\tau_i^2\left(\frac{1}{k_a}+\frac{1}{k_k}+\frac{1}{k_h}\right)}\right)$$

$$f_{ir} : f_{ir} > \frac{\alpha_i}{2\pi}\omega_b, \alpha_i > 1, i = 1, 2, ..., n$$

$$k_{min} < k_i < k_{max}$$

$$k_{min} = \frac{\tau_{max}}{\theta_{smax}}$$

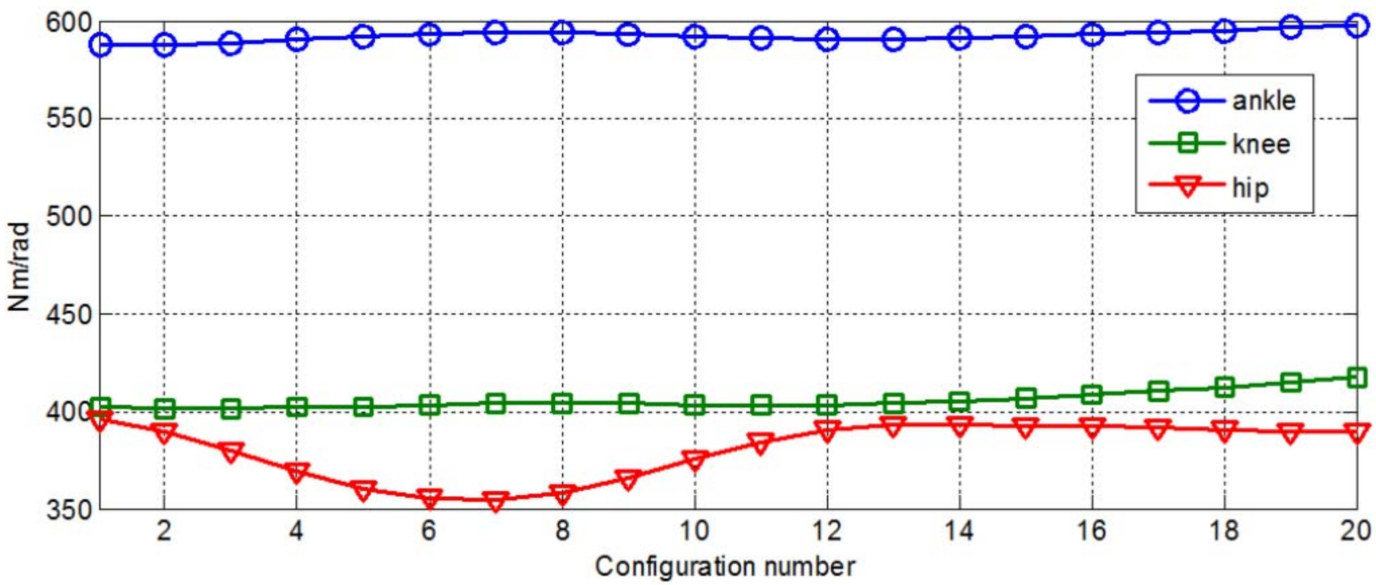
$$k_{max} = 800\frac{Nm}{rad}$$

Tsagarakis et al, ICRA 2013

Optimal joint stiffness selection

- constraints were chosen for two lowest resonant frequencies
- first and second natural frequencies inequalities constraints:

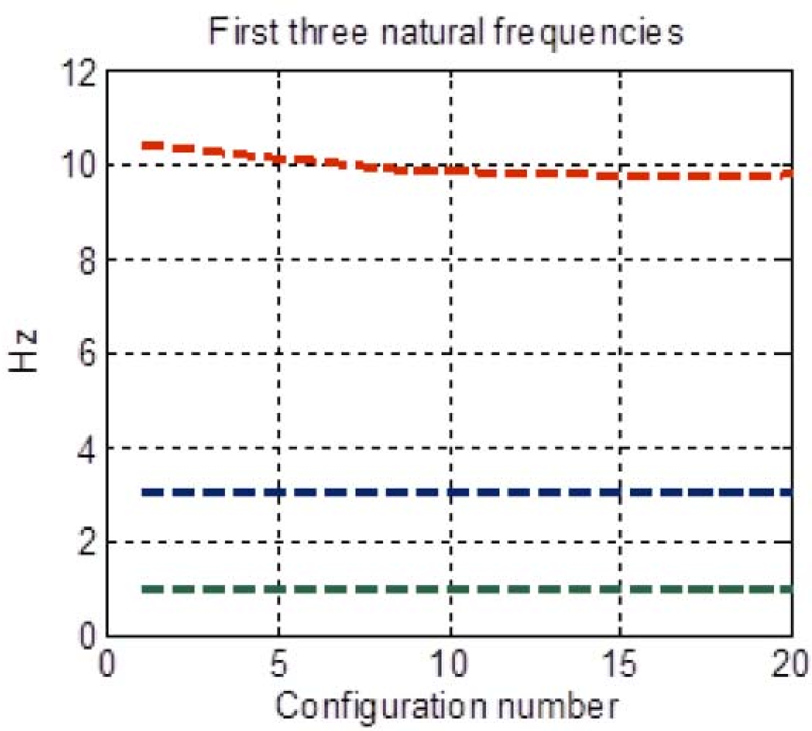
$$(f_1 > 1.0Hz)\ (f_2 > 3.0Hz)$$

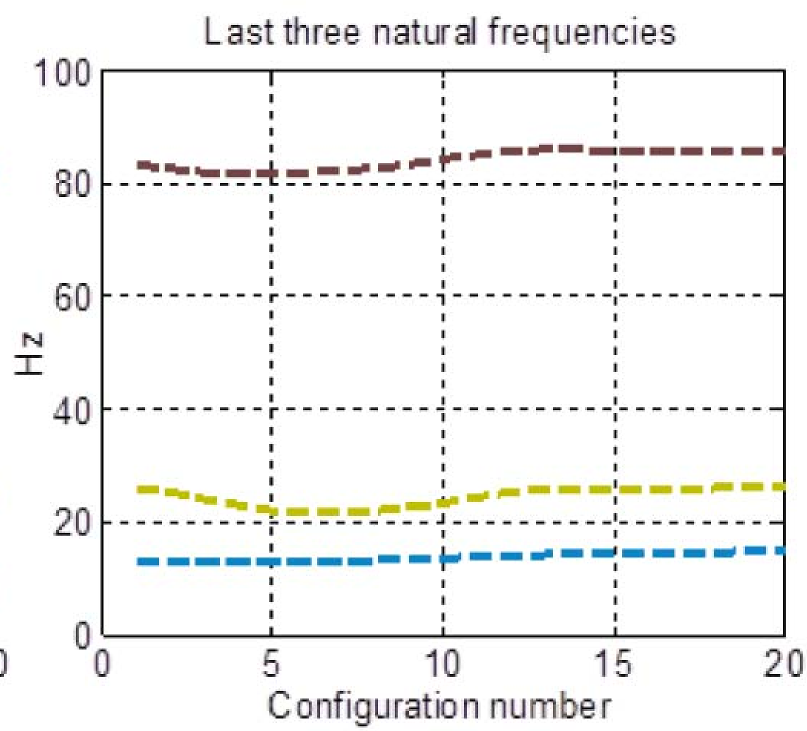


$$(k_a, k_k, k_h) = (597, 417, 396)Nm/rad.$$

Optimal joint stiffness selection

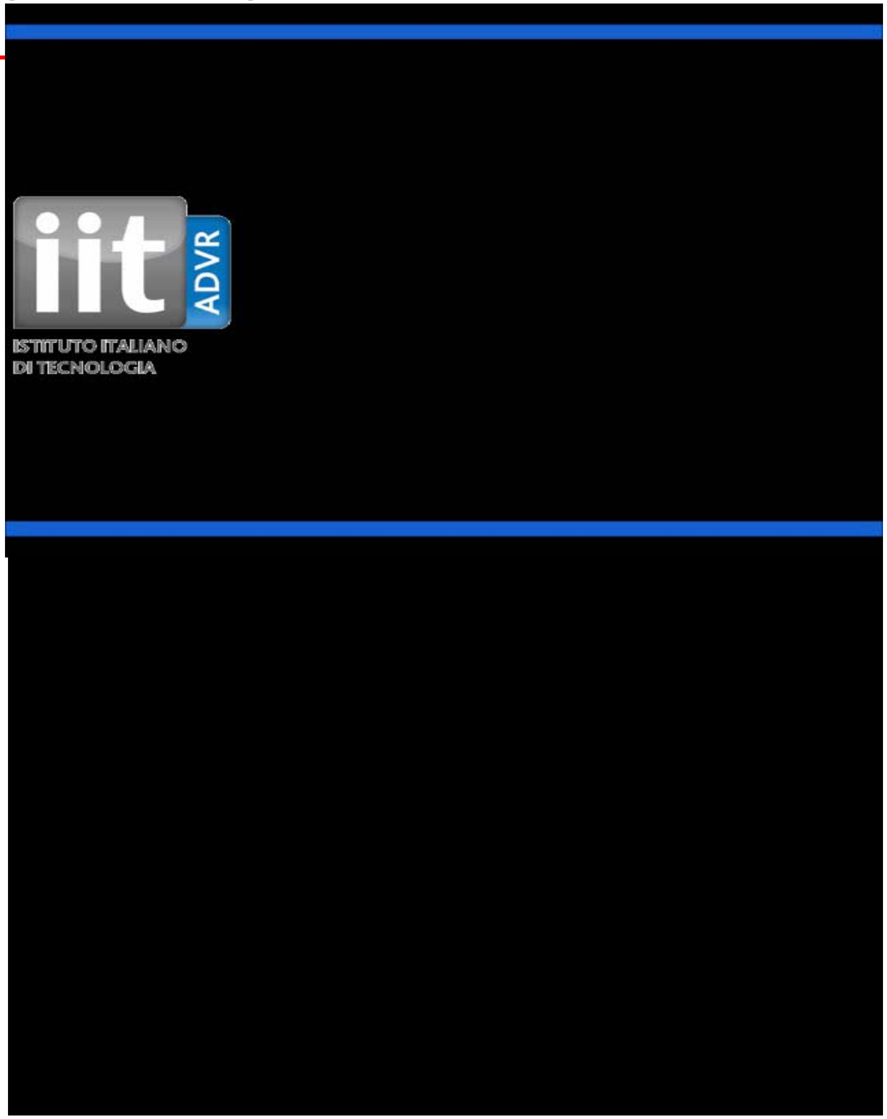
- the resultant natural frequencies given a configuration and the selected optimal joint stiffness matrix

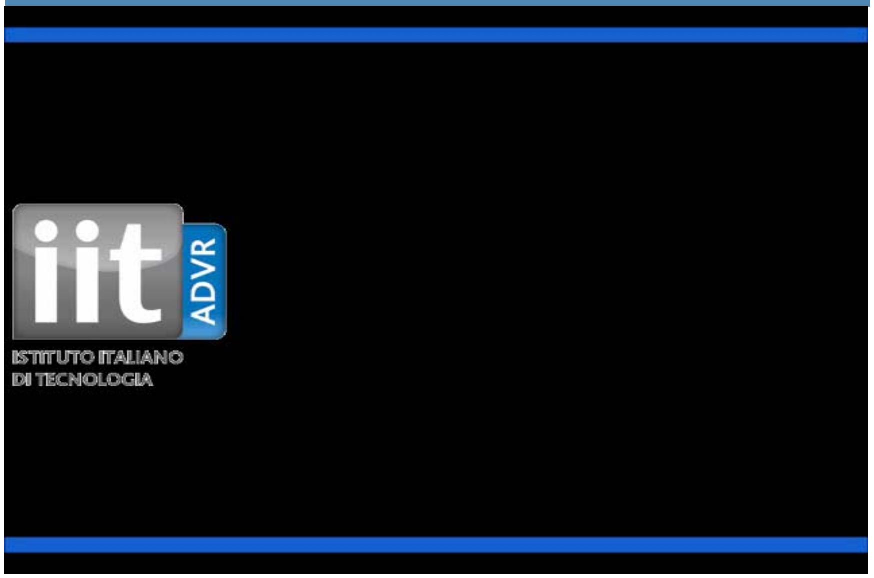




Whole body torque/impedance regulation

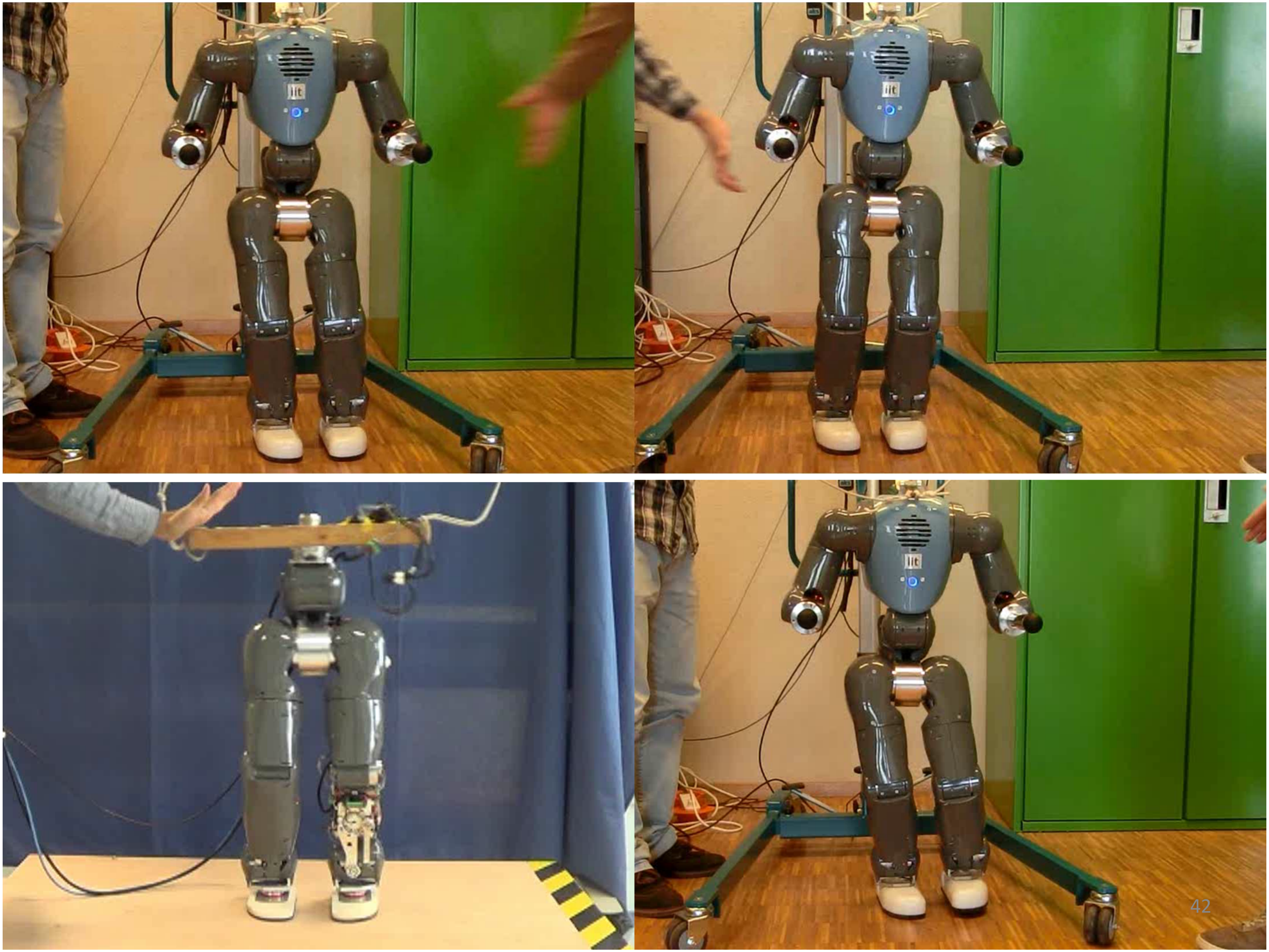
COMAN lower body early tests



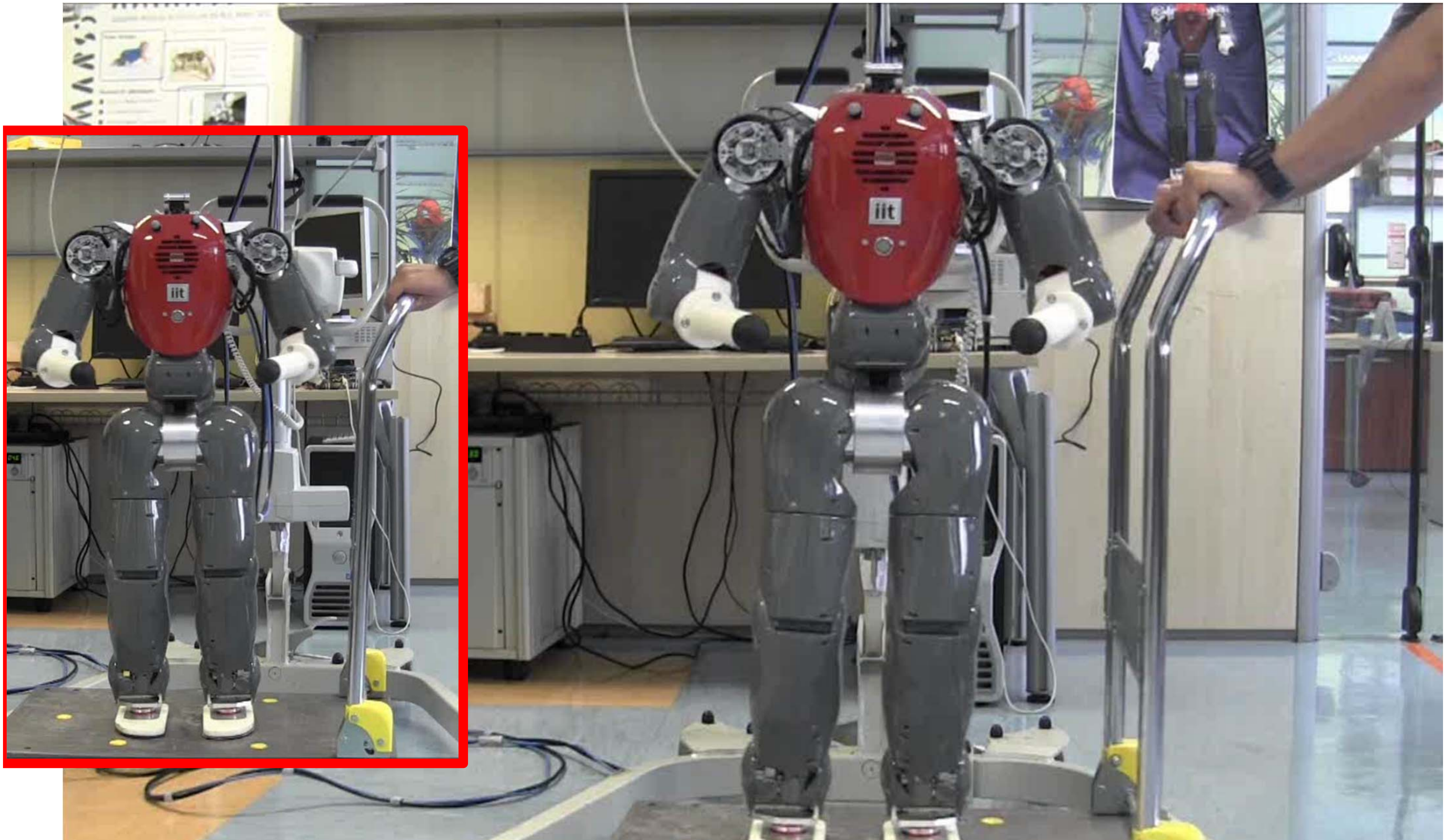


Zhibin Li et al, ICRA 2012

Zhibin Li et al, Humanoids 2012



Stabilization on mobile platform



…and some recent work with COMAN

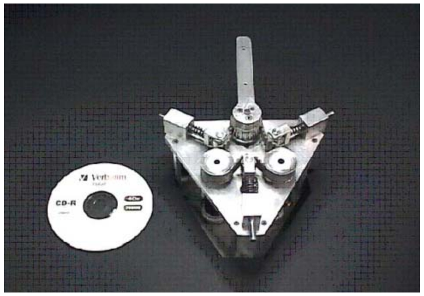
Zhibin Li et al, IROS 2013

Fixed and variable compliance

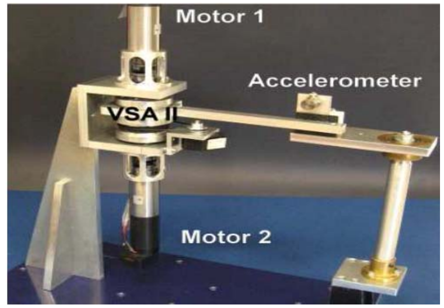
- **Fixed series elasticity (SEA)**
  - passively adaptable
  - inherently safer
  - makes the robot more tolerant to impacts
  - does not need additonal actuation
  - can be combined with active stiffness regulation
  - preset passive mechanical compliance
  - performance is compromised

- **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

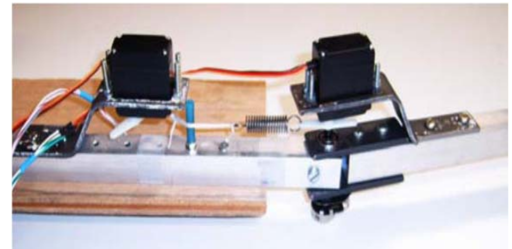
VSAs prototypes



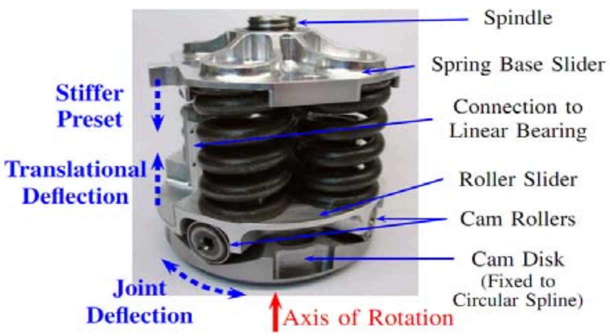
VSA: G. Tonietti *et al.* (2005)



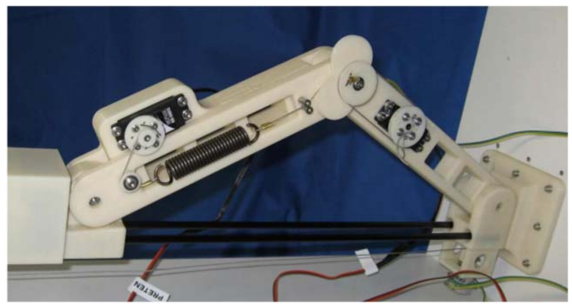
VSA-II: R. Schiavi *et al.* (2008)



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

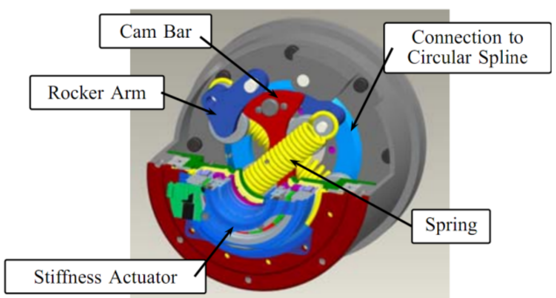


VS-Joint: S. Wolf et al. (2008)

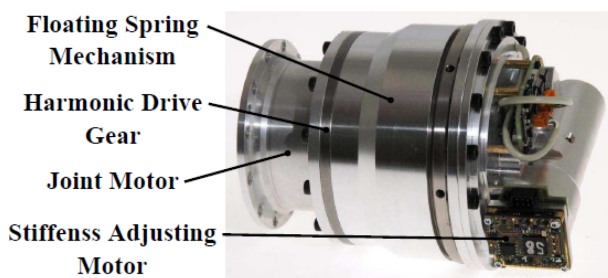


MACCEPA 2.0: B. Vanderborght et al. (2009)

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



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



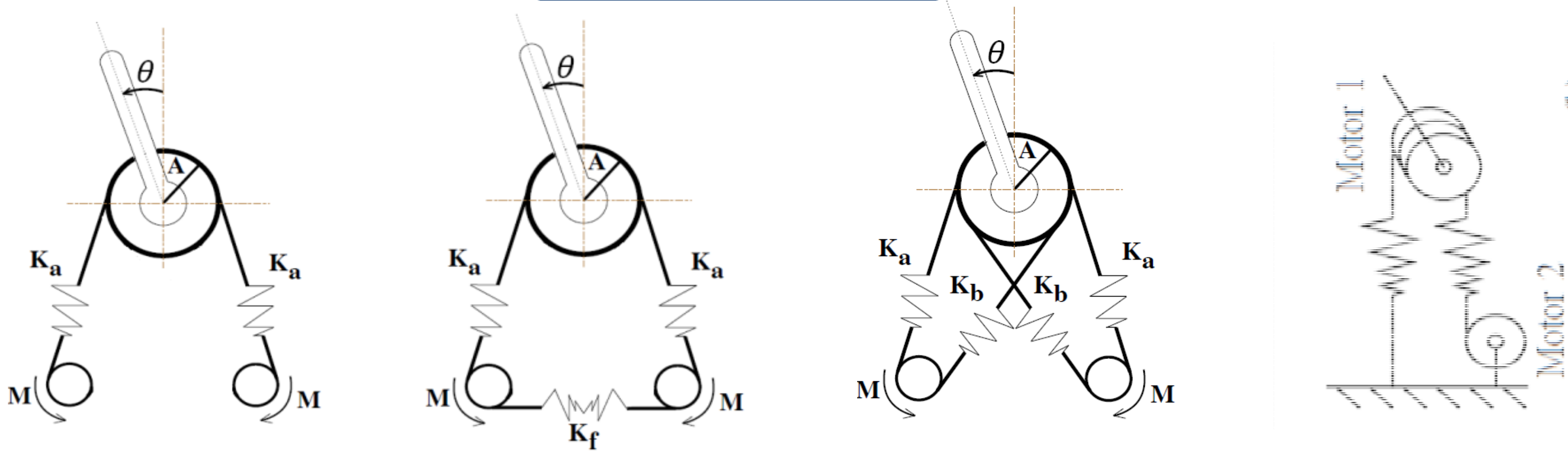
FSJ: Wolf et al. ICRA 2011

VSA Cube: Catalano et al. ICRA 2011

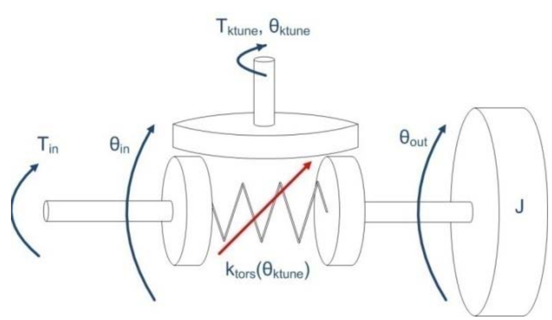
Variable Stiffness Actuators (VSAs)

Main configurations

Antagonistic



Serial

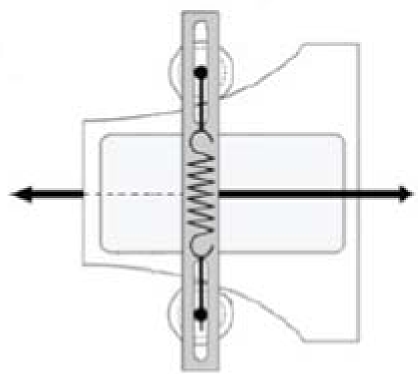


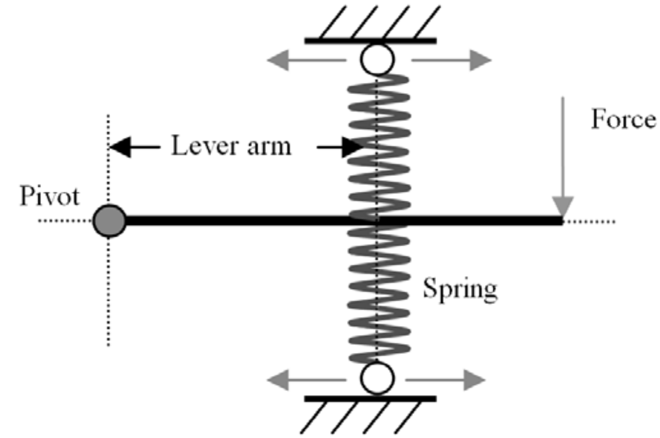
Variable Stiffness Actuators (VSAs)

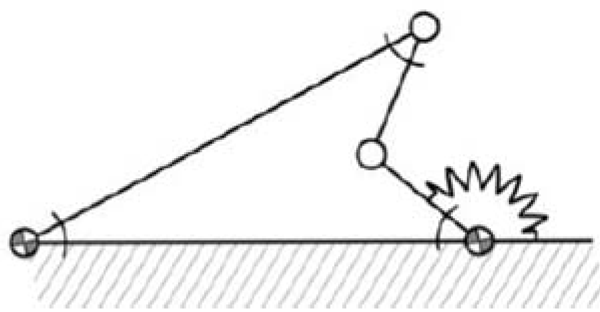
Stiffness regulation principles

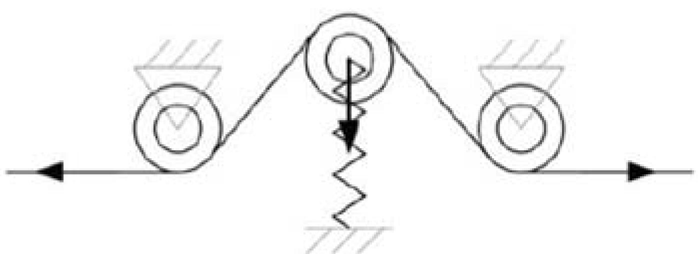
- Spring preloading
  - Stiffness is altered by changing the pretension of the nonlinear spring.
- Variable transmission
  - Stiffness is regulation is achieved by changing the transmission ratio between the output link
- Modification of spring properties
  - The physical structure of the spring is mechanically modified

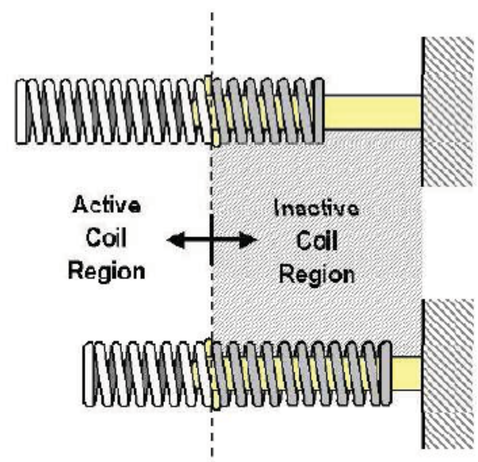
Mechanisms for generating nonlinear spring forces





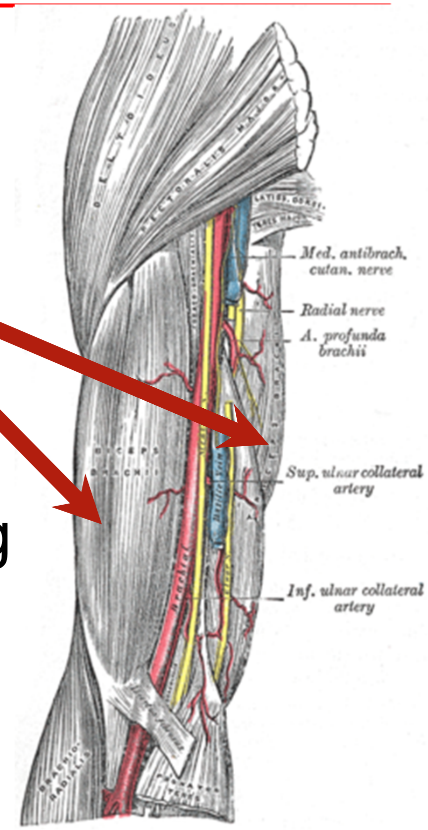






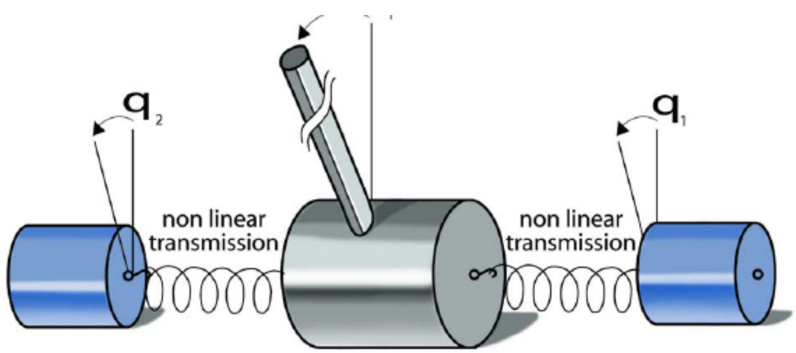
Simple antagonistic arrangement

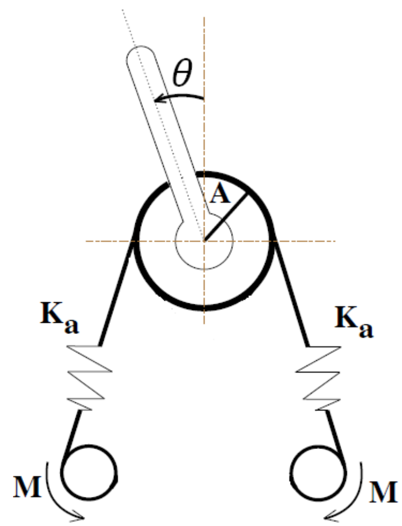
- Bio-inspired configuration
- In the human body, each joint is actuated by - *at least* – two muscles



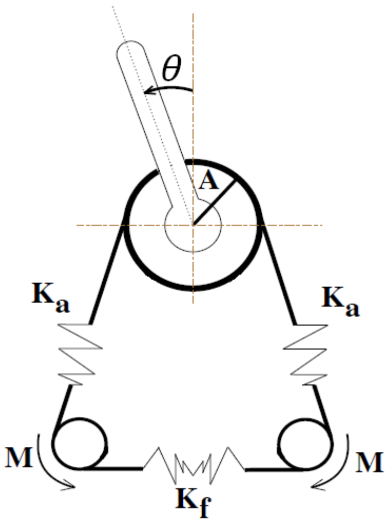
Conventional mechatronic realization

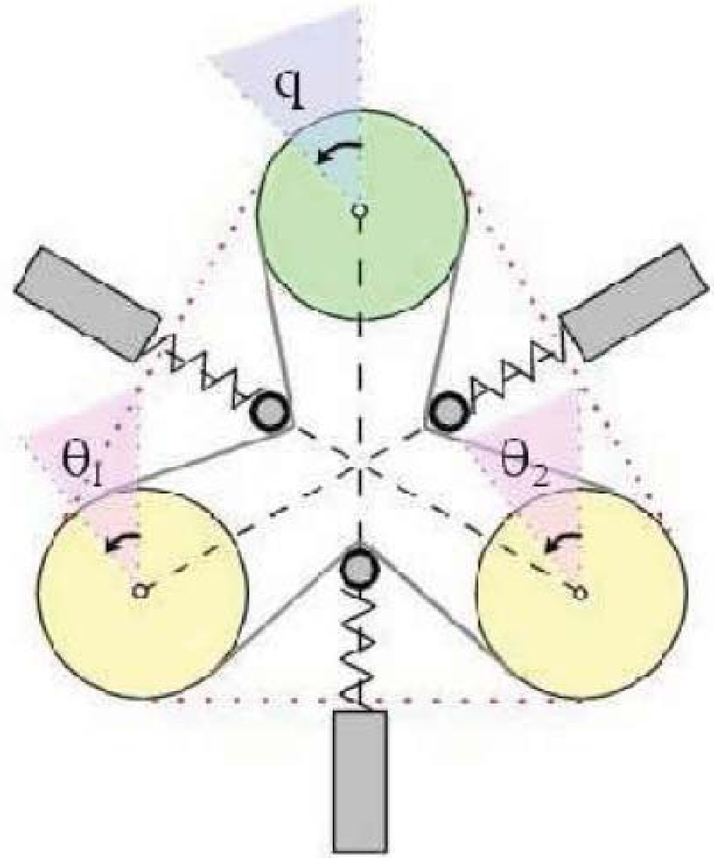
- Two actuators with a single direction coupling
- A pair of elastic elements





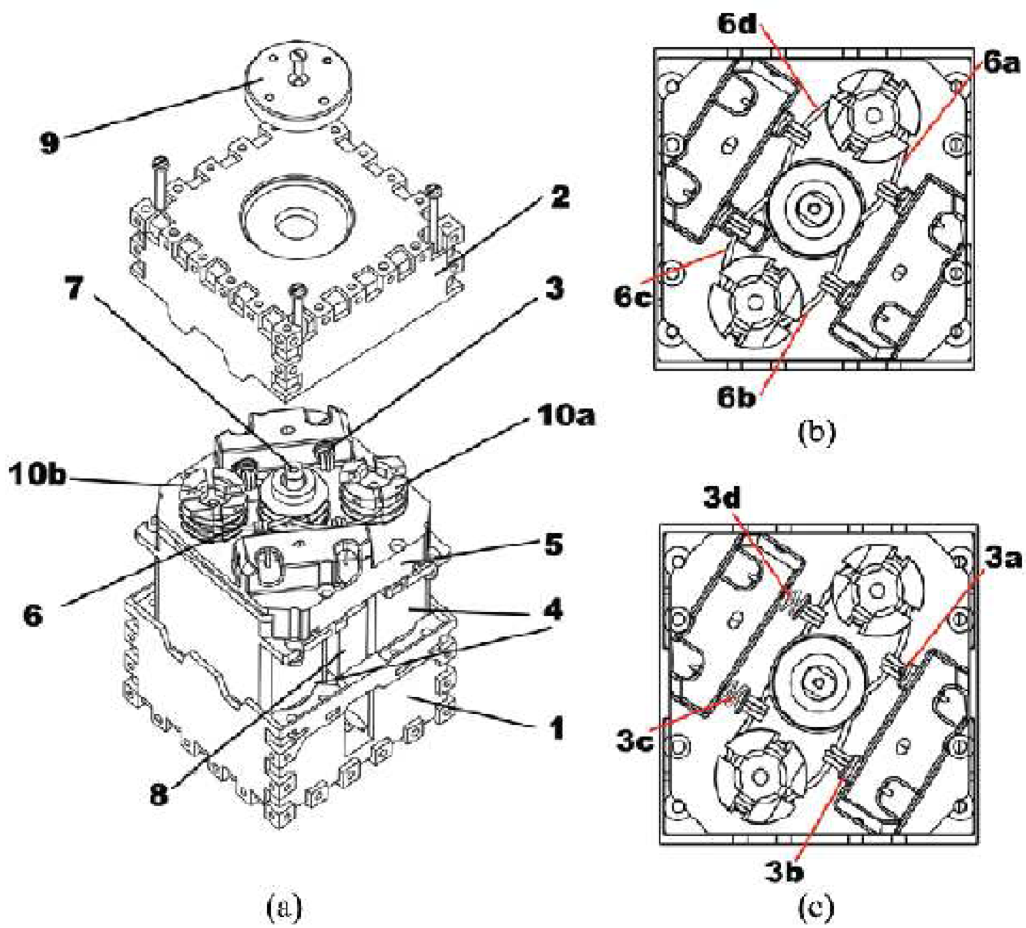
Cross – coupled antagonsitic scheme

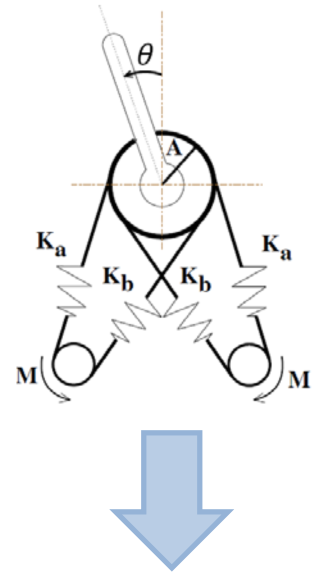




Tonietti, Bicchi, ICRA 2005

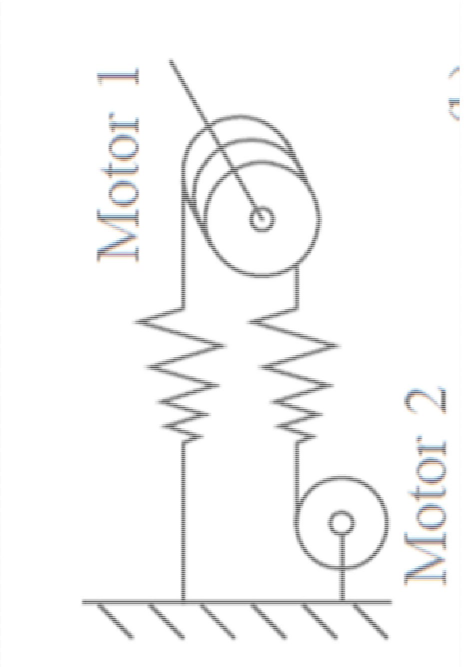
Cross – coupled and bilateral antagonsitic schemes

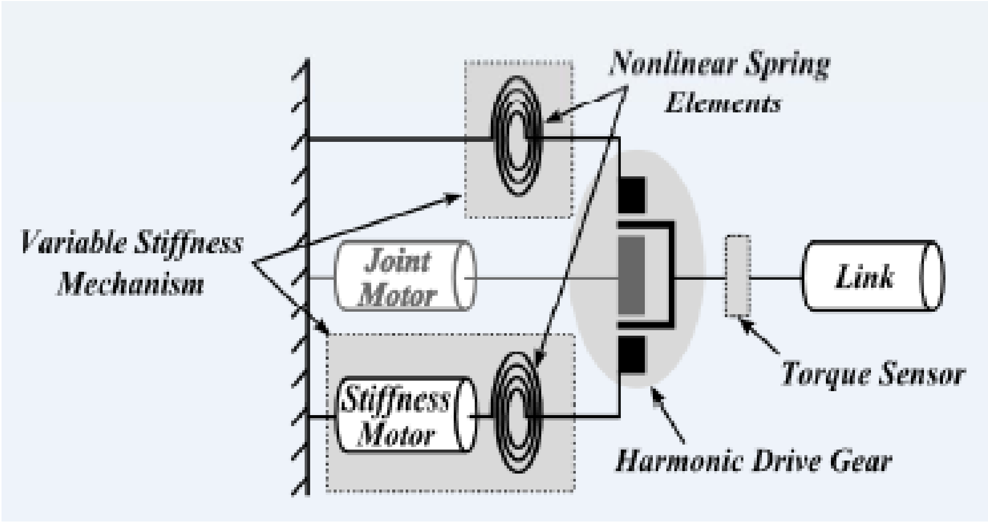


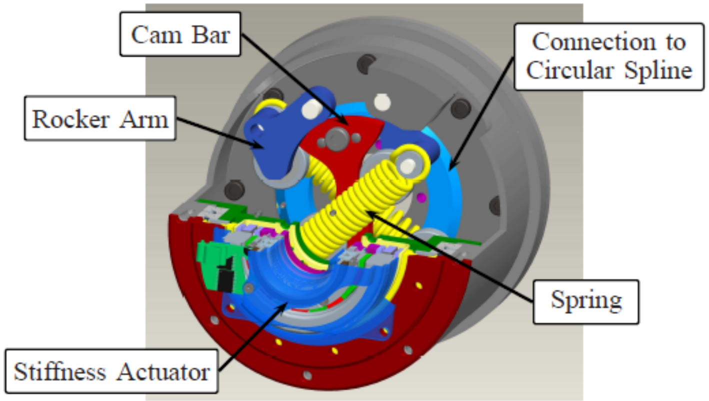


VSA Cube: Catalano et al. ICRA 2011

Quasi Antagonistic Joint Mechanism



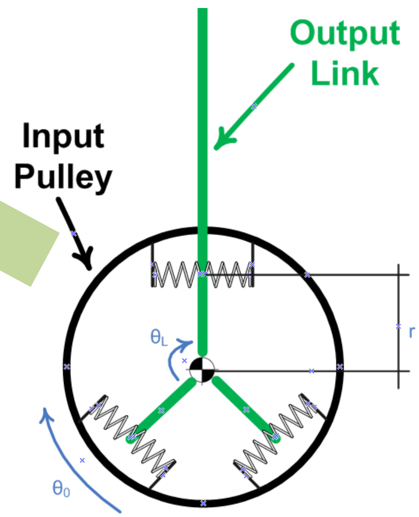




O. Eiberger et al. ICRA 2010
Alin Albu-Schäffer et al, RA Mag., 2008

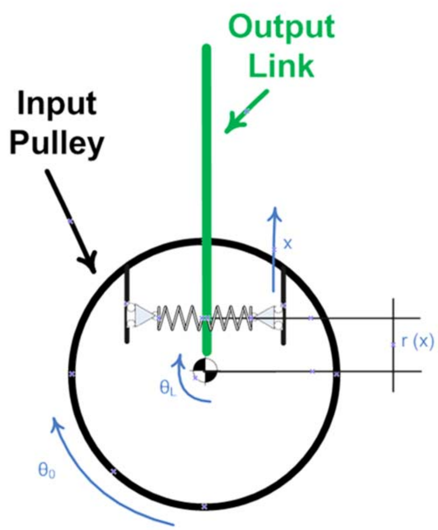
From CompAct to CompAct-VSA

Fixed stiffness joint



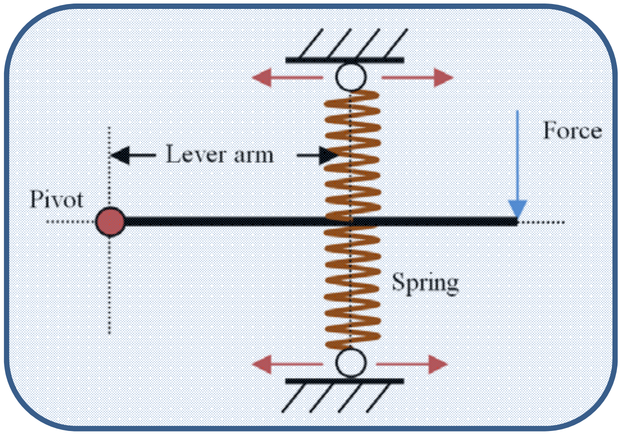
$$K_T = 6 \cdot K_S \cdot f(r^2)$$

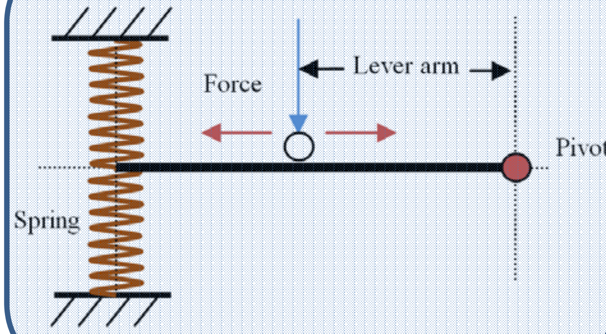
Variable stiffness joint

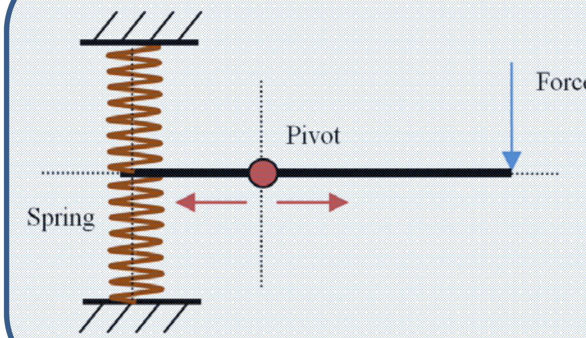


Lever arm principle

Variable spring position







- Positions of the pivot and force point are fixed. Position of the spring is adjustable.
- The bigger is the lever arm, the stiffer is the link.
- The minimum stiffness is zerAwAS: A. Jafari *et al.*, IROS 2010

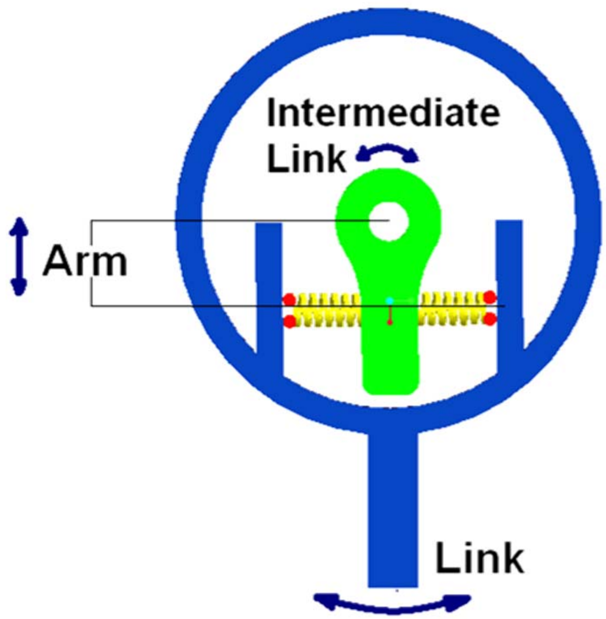
•o. The maximum stiffness depends on the length of the lever and the stiffness of the

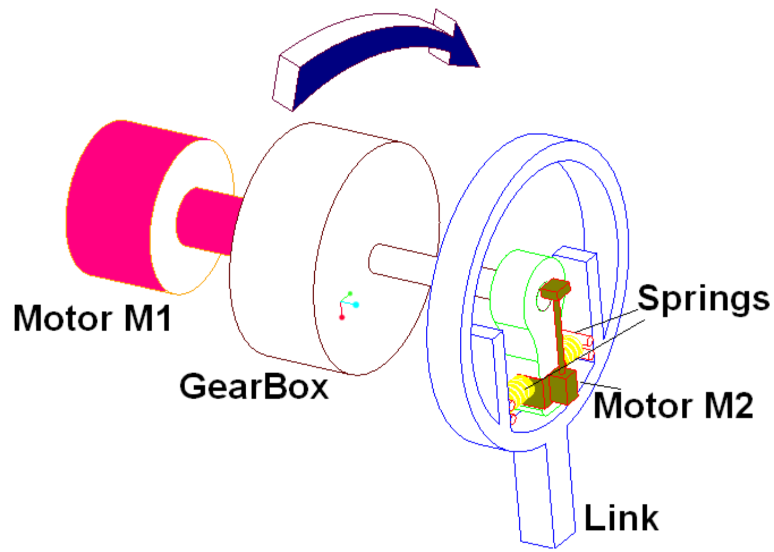
Hybrid actuator: Byeong-Sang Kim et al., ICRA 2010

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

AwAS:Principle of operation

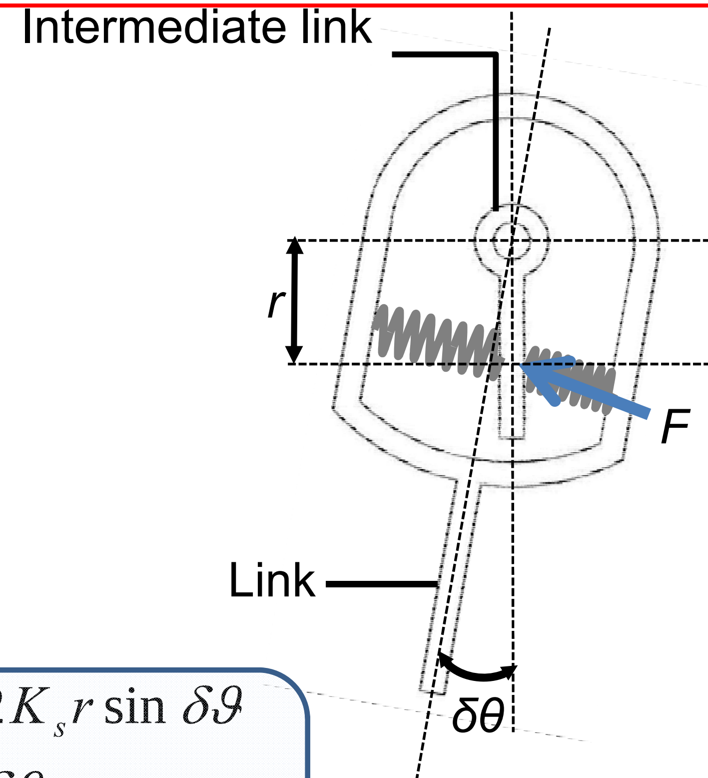
- Intermediate link is connected the motor M1;
- Springs are located between intermediate link and the link;
- Arm (variable) is the distance from the center of rotation to the attachment point of springs





(AwAS)-Principle of operation

Parameter	Description
r	Arm
$\delta\vartheta$	Angular deflection
Ks	Spring's rate
F	Resultant force of spring
p	Spring's pretension
δX	Spring's deflection
K	Stiffness
T	Overall torque



$$F = K_s(p+\delta x) - K_s(p-\delta x) = 2K_s\delta x = 2K_s r \sin\delta\vartheta$$

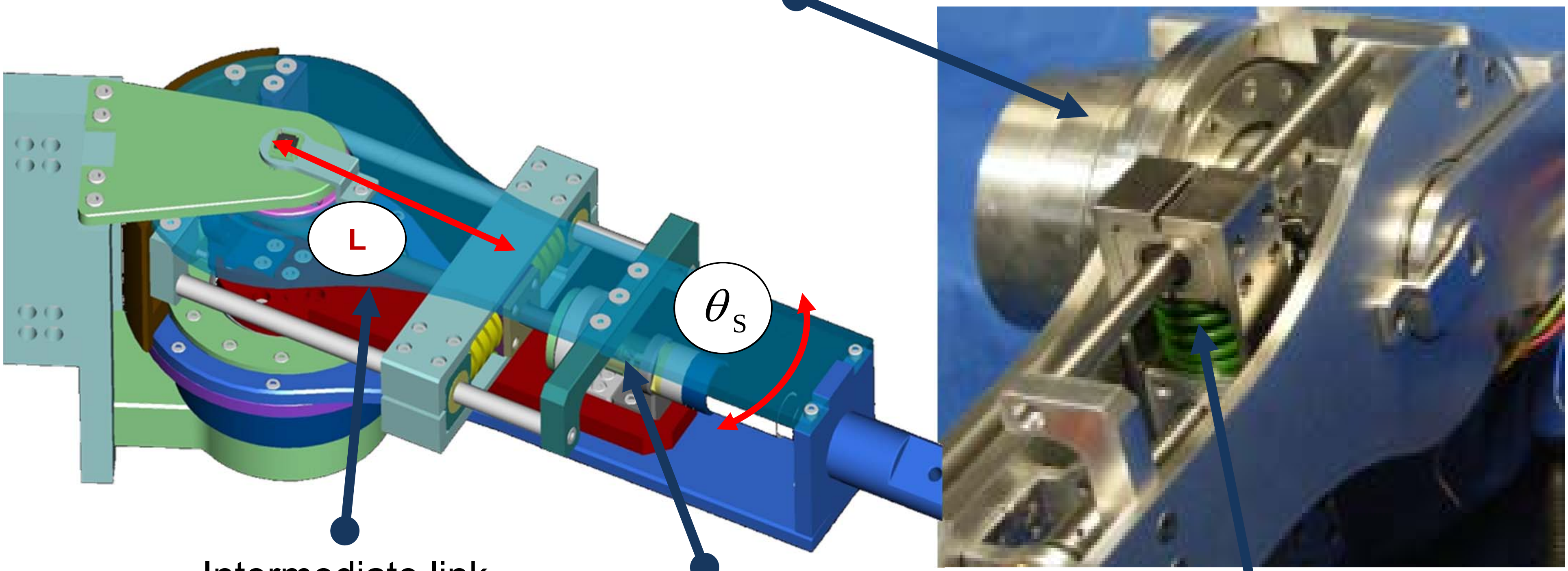
$$T = F\cdot r\cdot\cos\delta\vartheta = 2\cdot K_s\cdot r^2\cdot\sin\delta\vartheta\cdot\cos\delta\vartheta$$

$$K = \frac{dT}{d\theta} = 2\cdot K_s\cdot r^2\cdot(2\cdot\cos^2\delta\vartheta - 1)$$

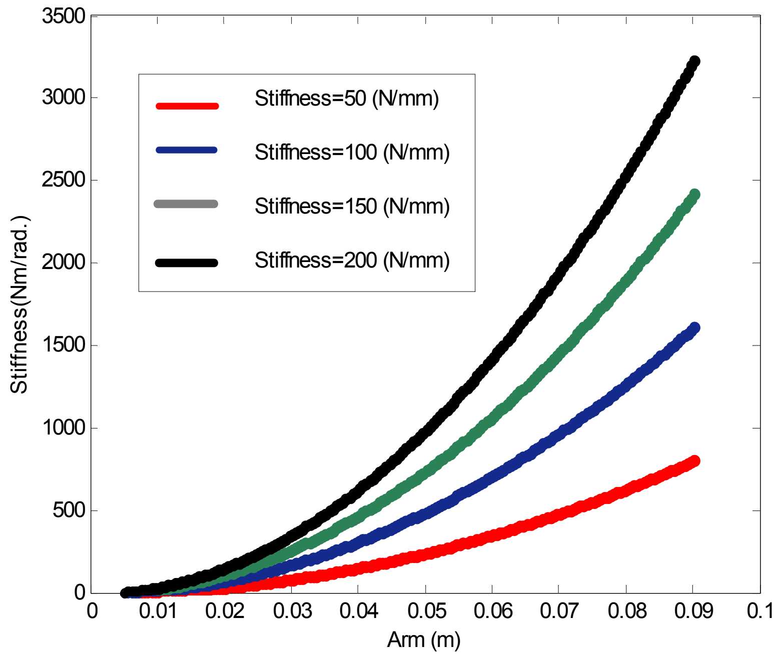
At equilibrium position, force *F* generated by the springs is perpendicular to the displacement needed to change the stiffness.

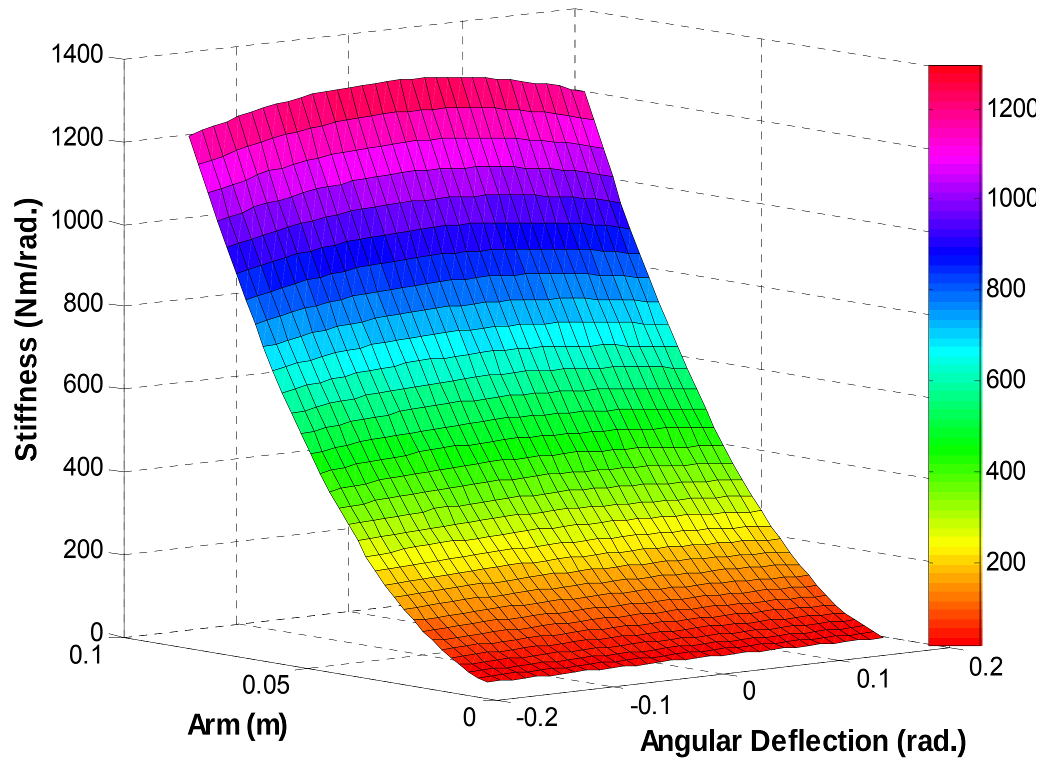
AwAS:Assembly

$$K = 2 \cdot K_S \cdot L^2 \cdot f(\theta_S)$$



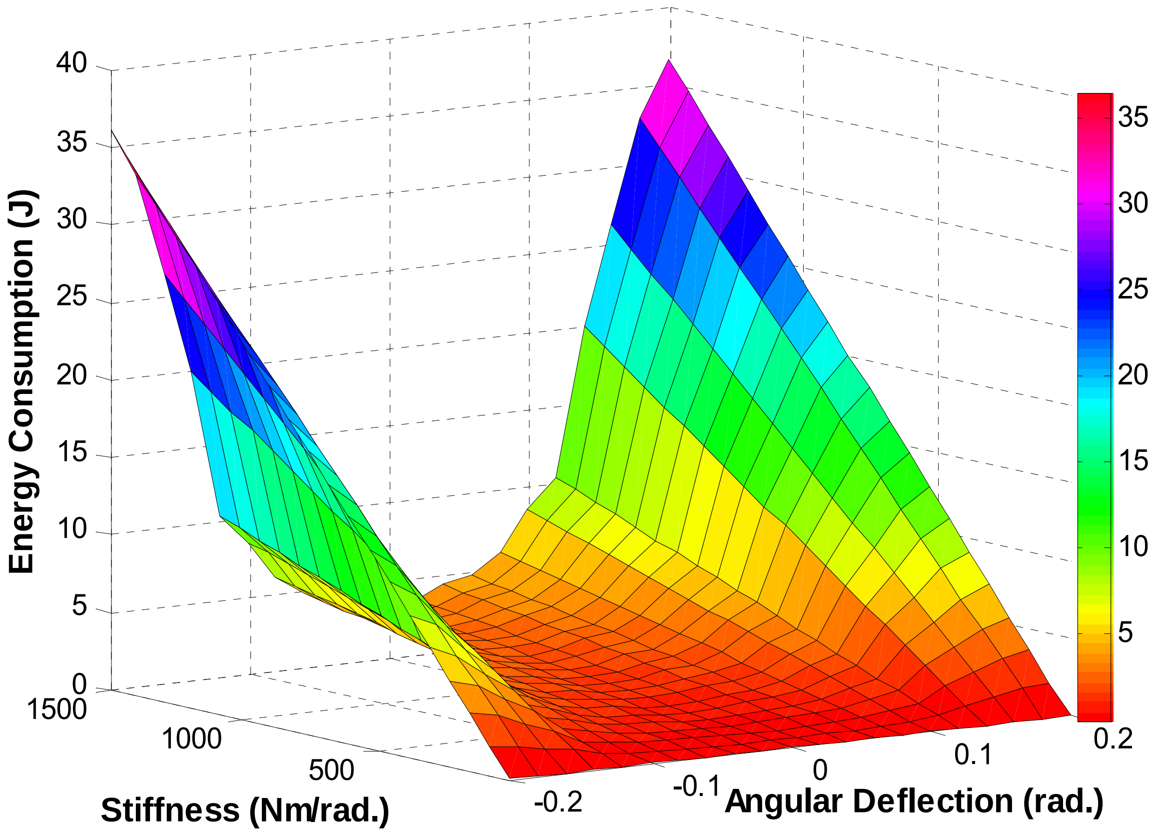
Stiffness regulation





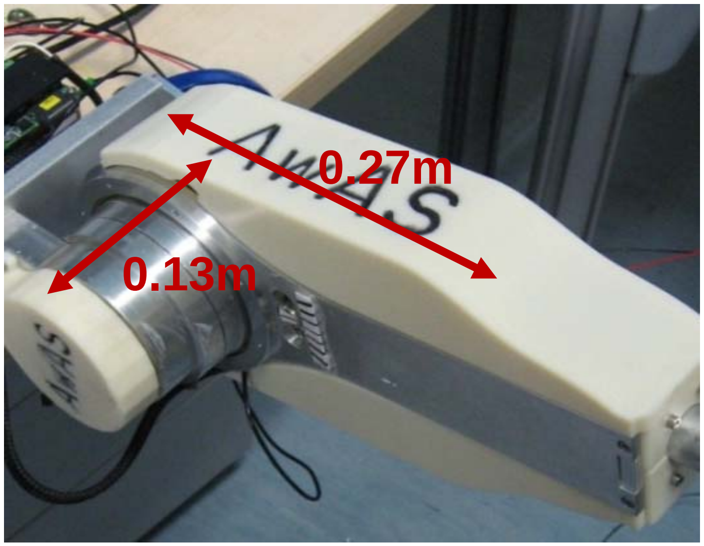
Stiffness of the springs and maximum arm length are 80N/mm and 0.09m, respectively

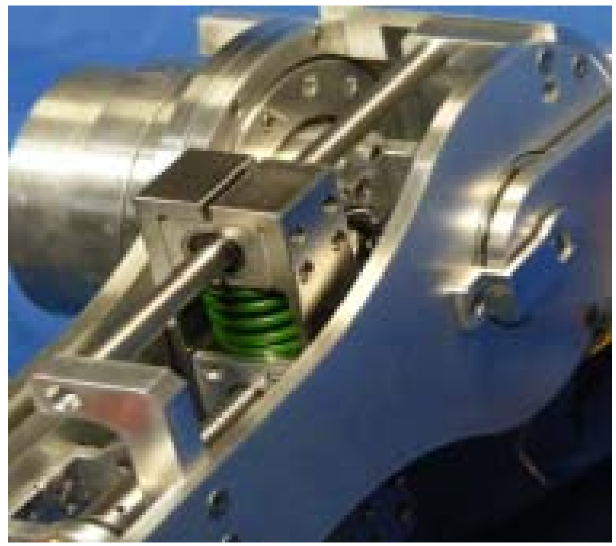
Experimental measures of energy

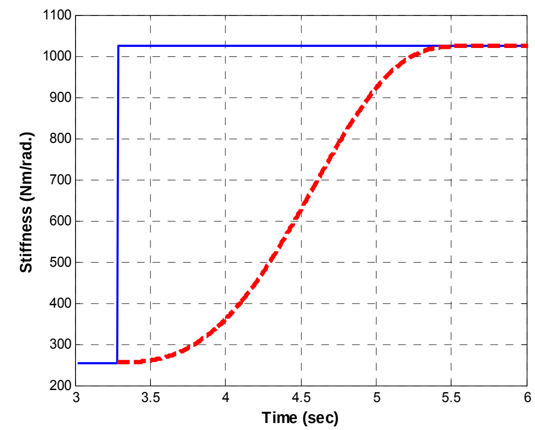


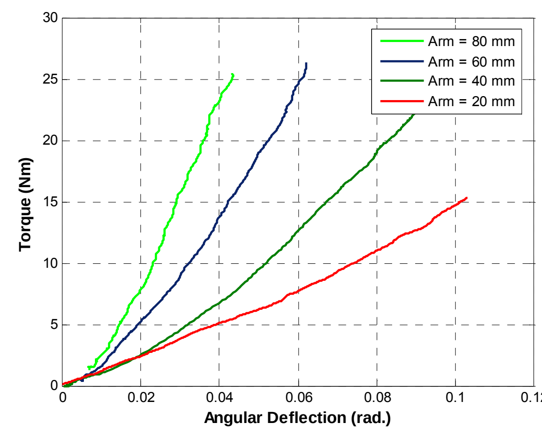
Energy required to change the stiffness

AwAS:Specifications



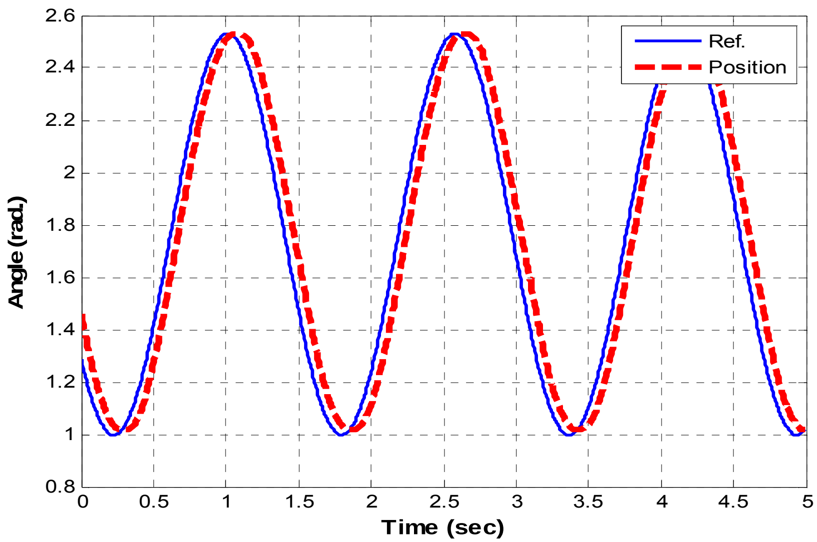


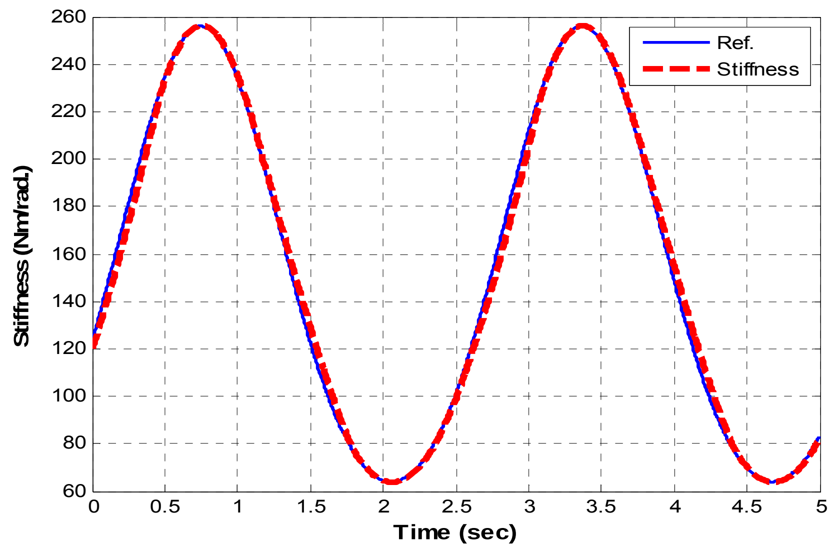




Range of Motion (rad)	Range of Stiffness (Nm/rad)	Passive Angular Deflection (rad)	Max Stiffness regulation speed (Nm/rad sec)	Energy Storage (J)	Output Torque (Nm)	Weight (Kg)
-2,+2	30,1800	-0.2,+0.2 at 640Nm/rad	800	3.5	80	1.4

Tracking position and stiffness



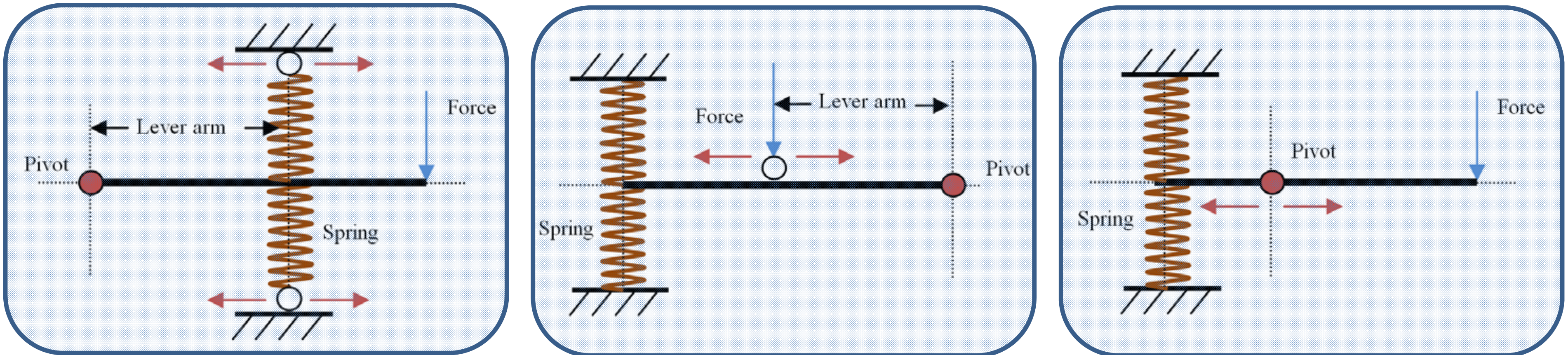


Both motors M1 for position and M2 for stiffness were simultaneously controlled to follow sinusoidal position and stiffness trajectories of different frequencies

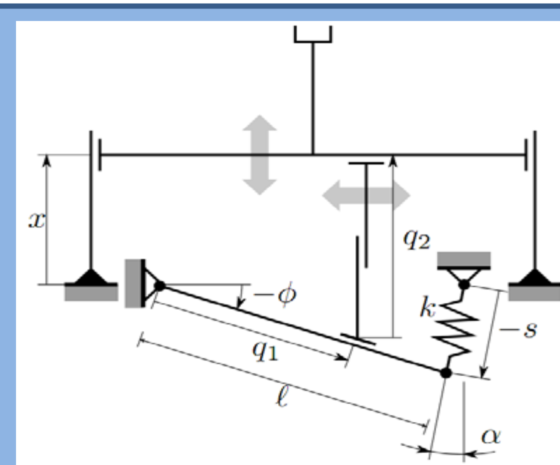
AwAS prototype

Lever arm principle

Variable force application point



- Positions of the pivot and spring are fixed.
- Position of the force point is adjustable.
- The shorter is the lever arm, the stiffer is the link.
- The maximum stiffness is infinite. The minimum stiffness depends on the length of the lever and the stiffness of the springs.

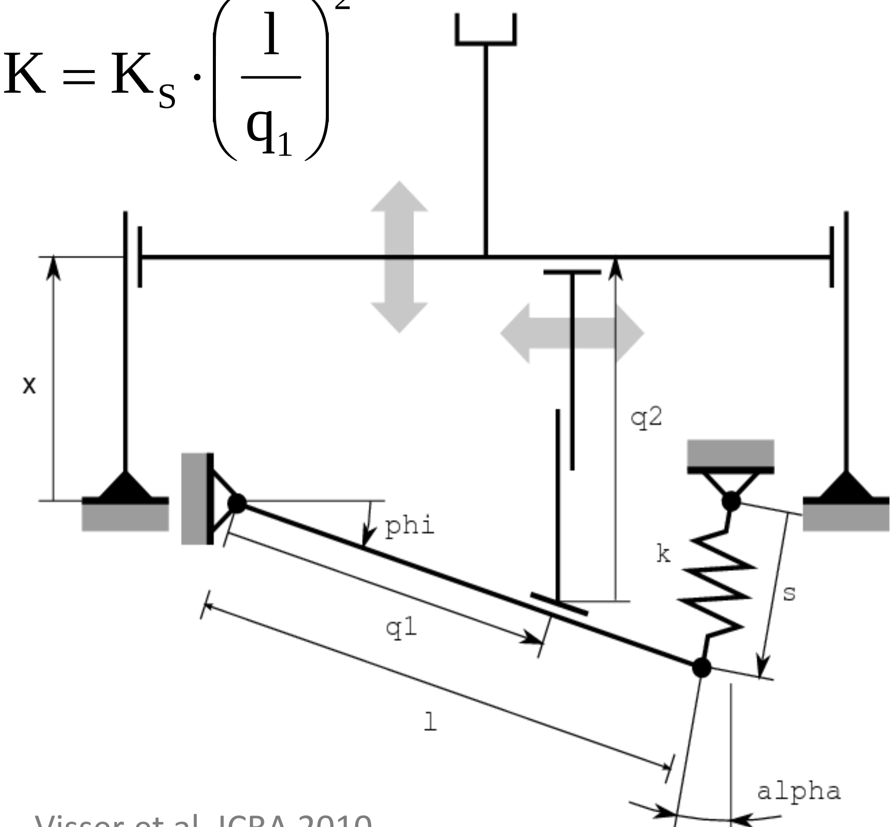


Energy Efficient VSA:
L.C. Visser *et al.*, ICRA 2010

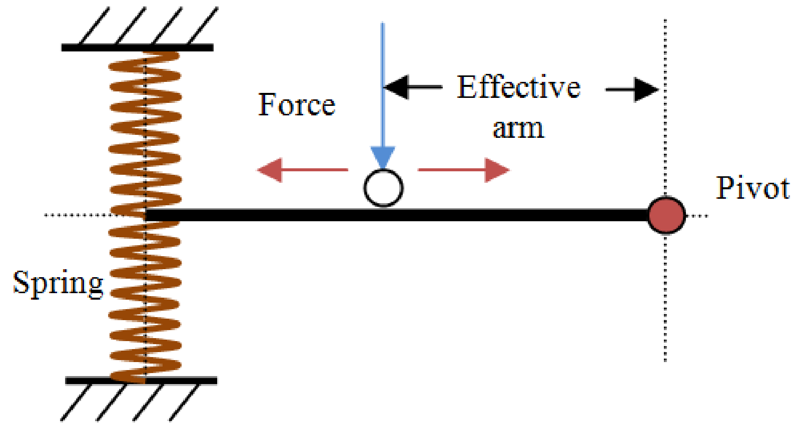
Lever arm principle

Variable force application point

$$K = K_S \cdot \left(\frac{l}{q_1} \right)^2$$

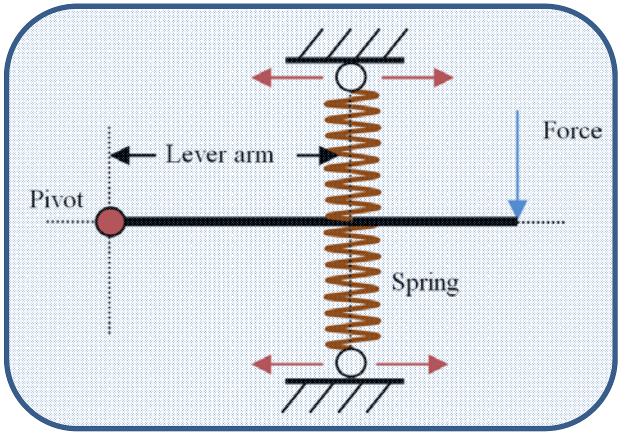


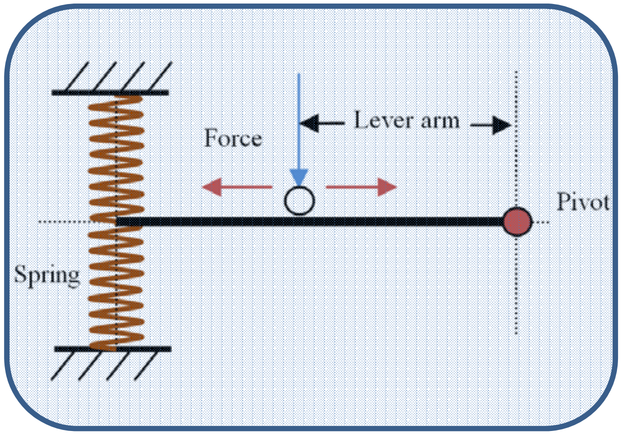
Visser et al, ICRA 2010

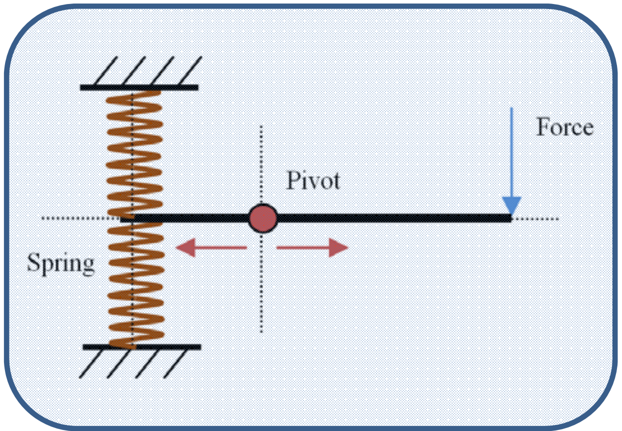


Lever arm principle

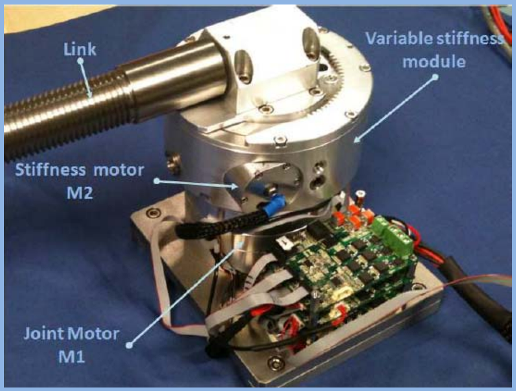
Variable pivot position





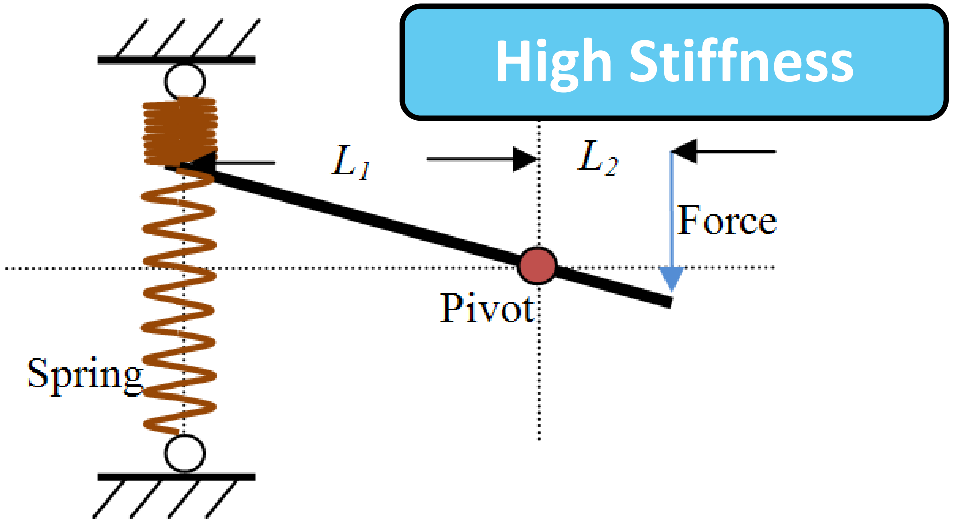


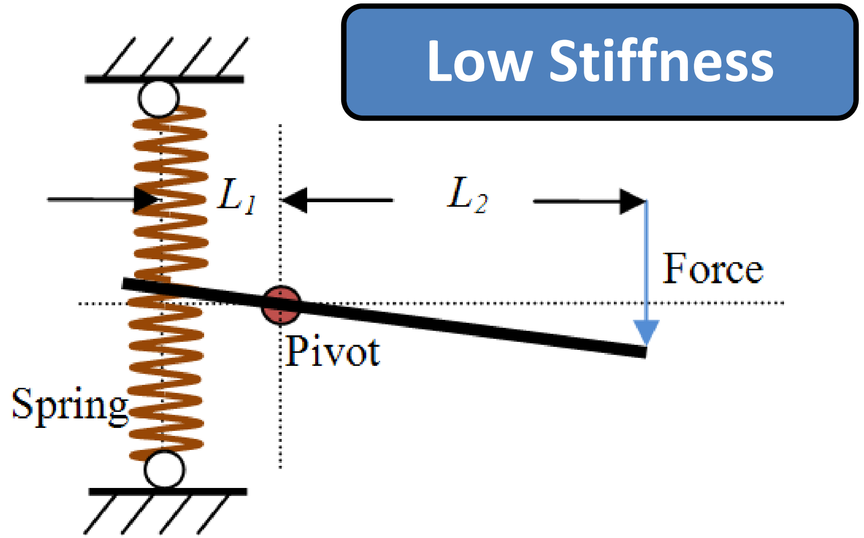
- Positions of the spring and force point are fixed. Position of the pivot is adjustable.
- The closer is the pivot to the force point, the stiffer is the link.
- The minimum stiffness is zero. The maximum stiffness is infinite. This range does not depends on the length of the lever and the stiffness of the springs.



CompAct VSA
Tsagarakis *et al.* , IROS 2011

CompAct-VSA: Lever arm with variable pivot point principle

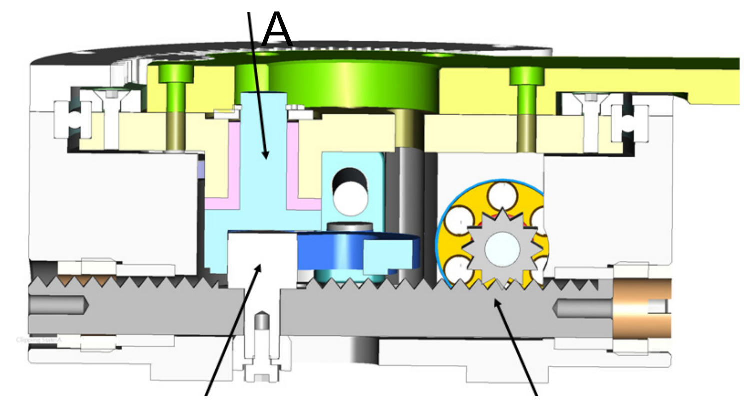


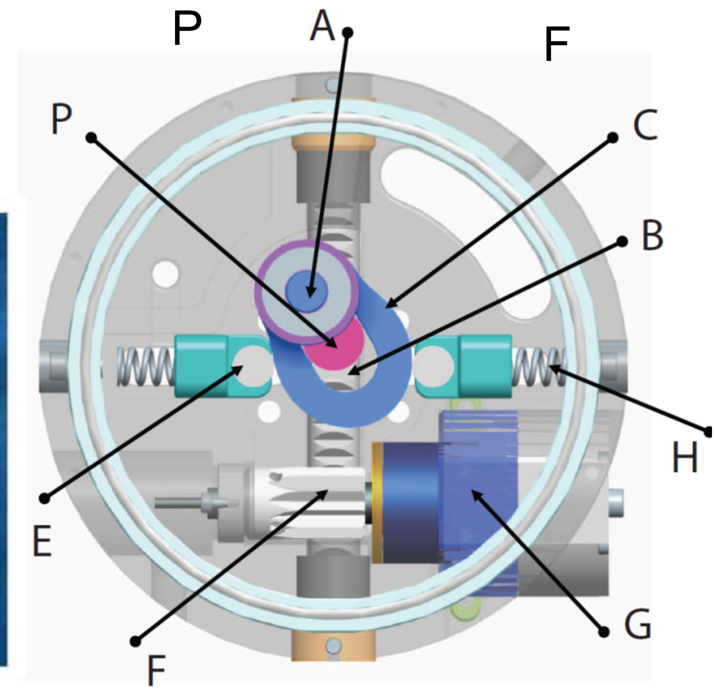


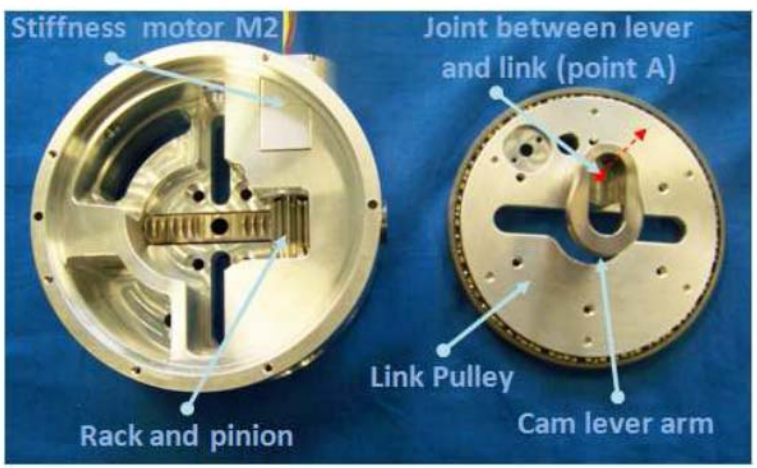
CompAct-VSA: Realization

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 Point

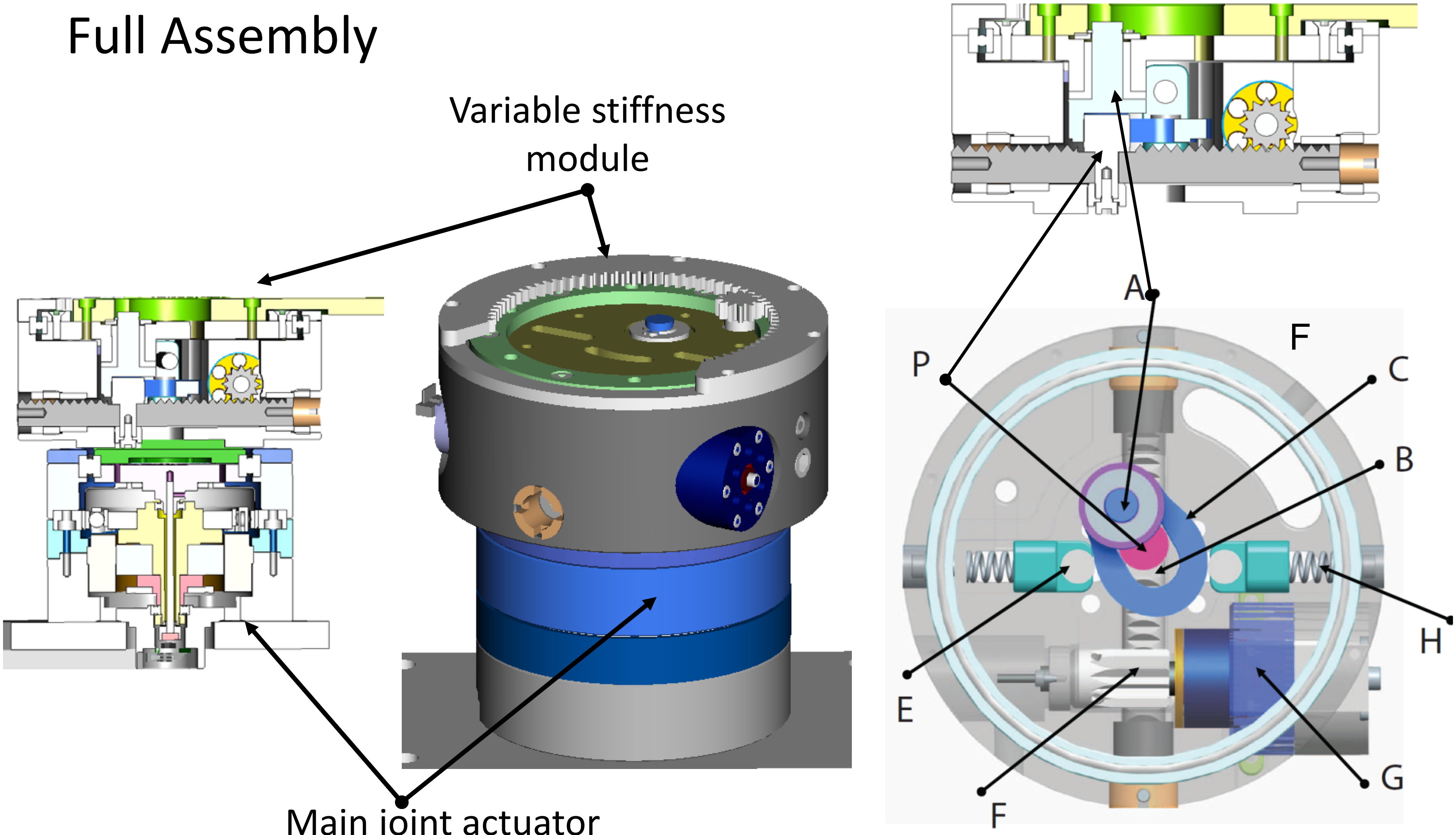






CompAct-VSA: Realization

Full Assembly



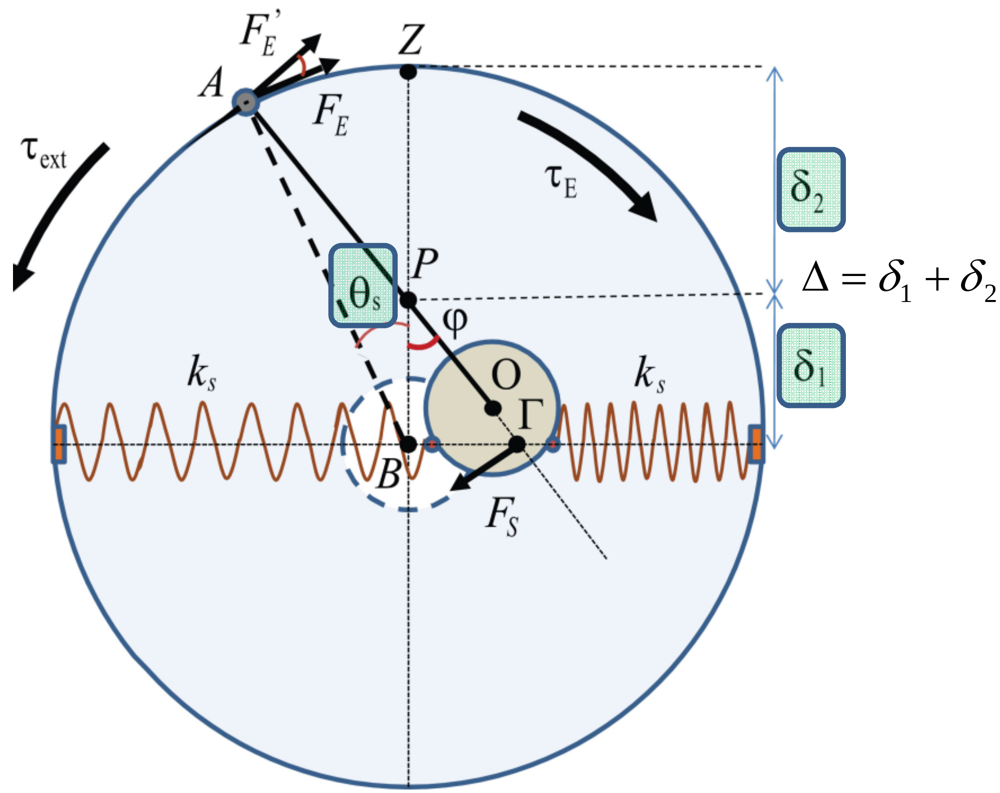
CompAct-VSA: Stiffness model

- Elastic torque $\tau_E = \dfrac{2k_s\delta_1^2\Delta^2\theta_s}{(\Delta-\delta_1)^2}$

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

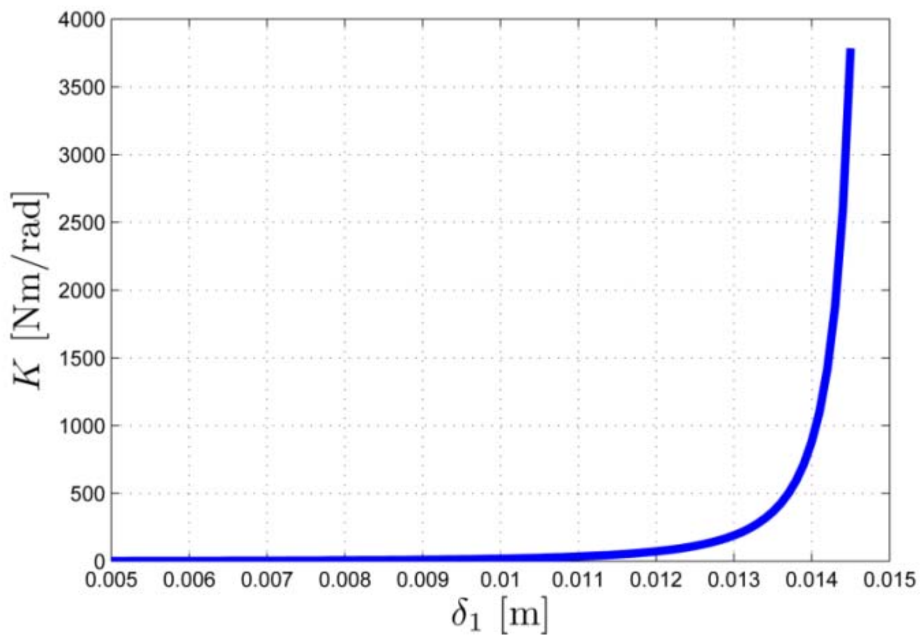
- Torque of the pivot motor

$$\tau_R = \frac{2k_s n^2\theta_2\theta_s^2\Delta^3}{(\Delta-n\theta_2)^3}.$$

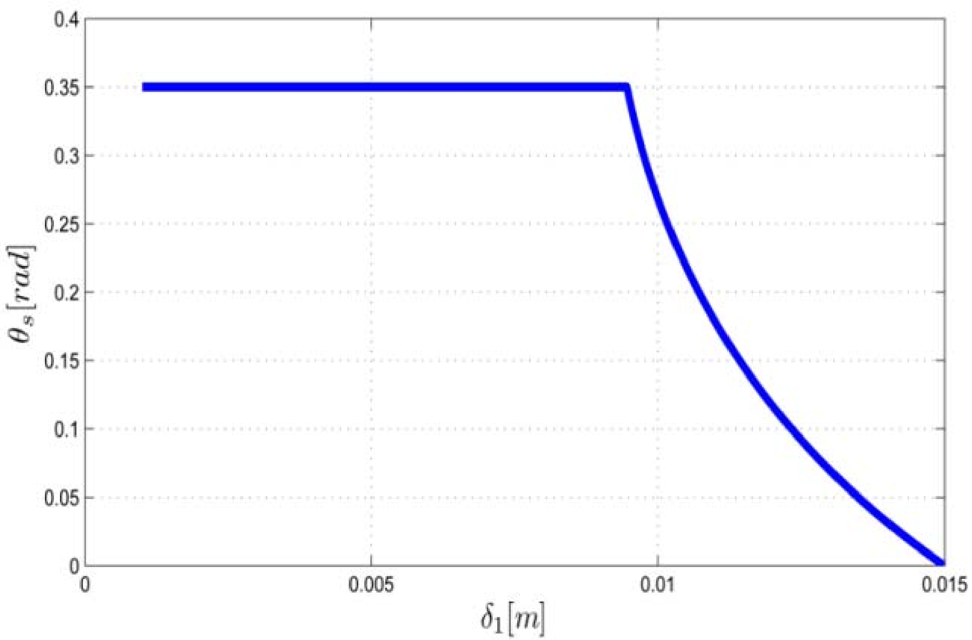


Stiffness & Passive deflection profiles

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



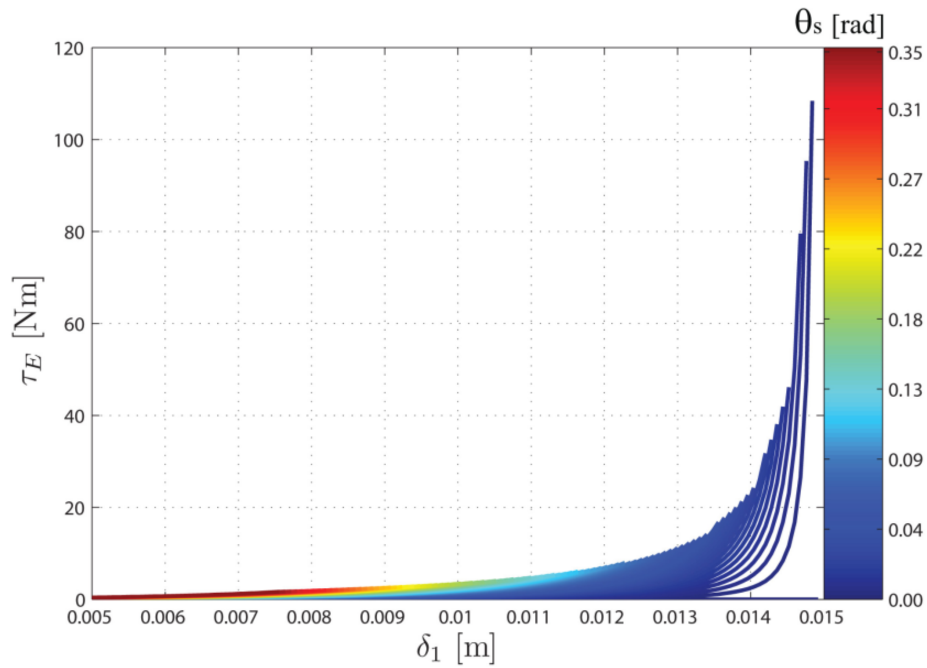
Passive deflection angle range



Elastic and pivot motor torques

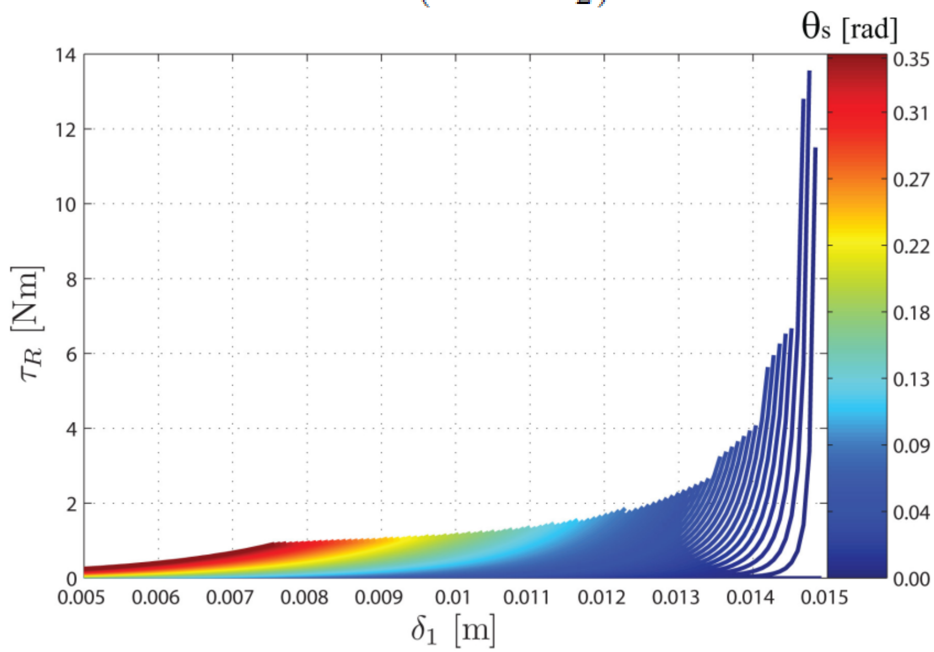
Elastic torque

$$\tau_E = \frac{2k_s\delta_1^2\Delta^2\theta_s}{(\Delta-\delta_1)^2}$$



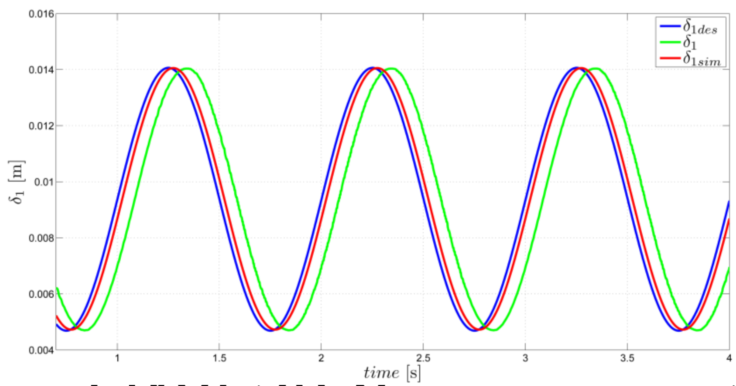
Resistant torque
of the pivot motor

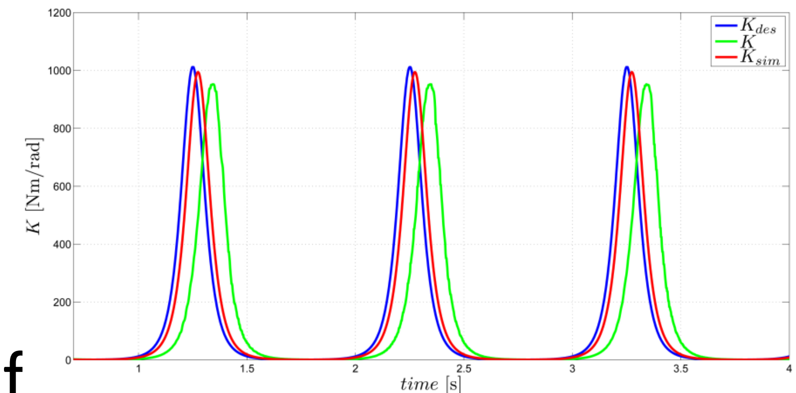
$$\tau_R = \frac{2k_s n^2\theta_2\theta_s^2\Delta^3}{(\Delta-n\theta_2)^3}.$$



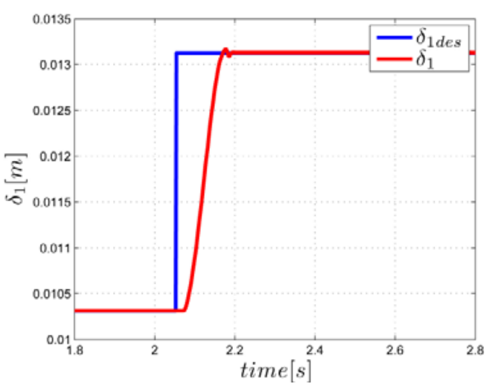
Stiffness response:Experimental results

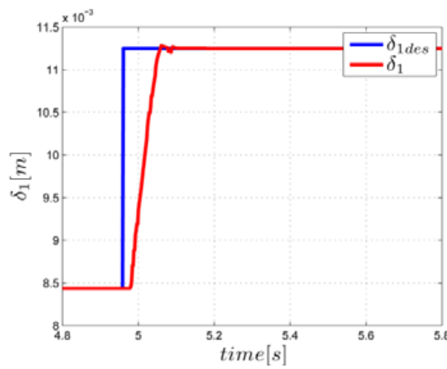
- Pivot Tracking Stiffness Tracking

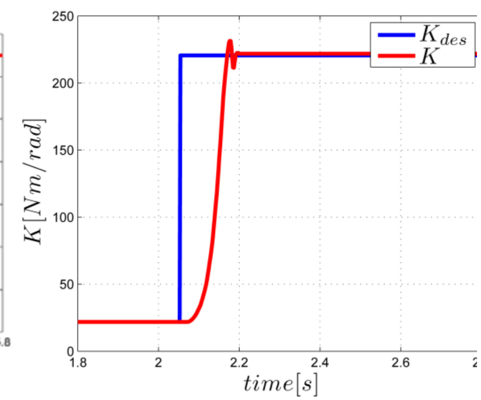


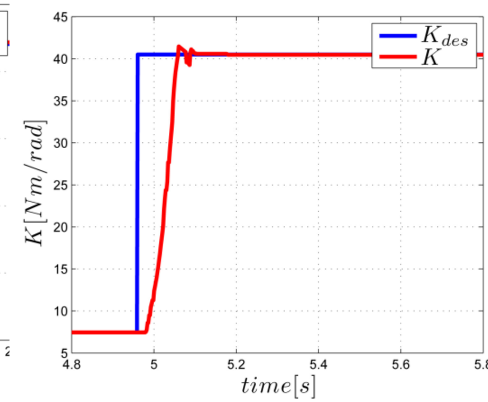


Pivot Step Stiffness Step

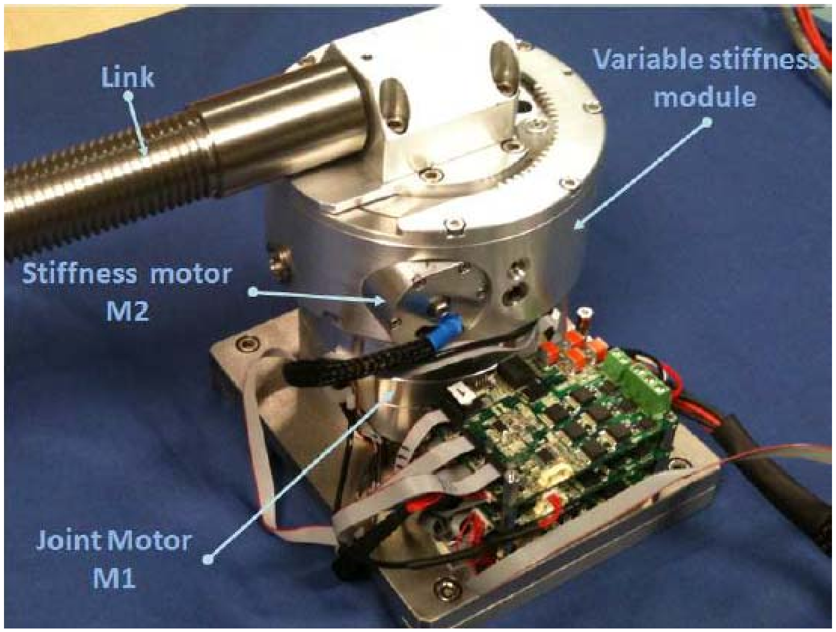








CompAct-VSA: Prototype



Tsagarakis *et al.* , IROS 2011

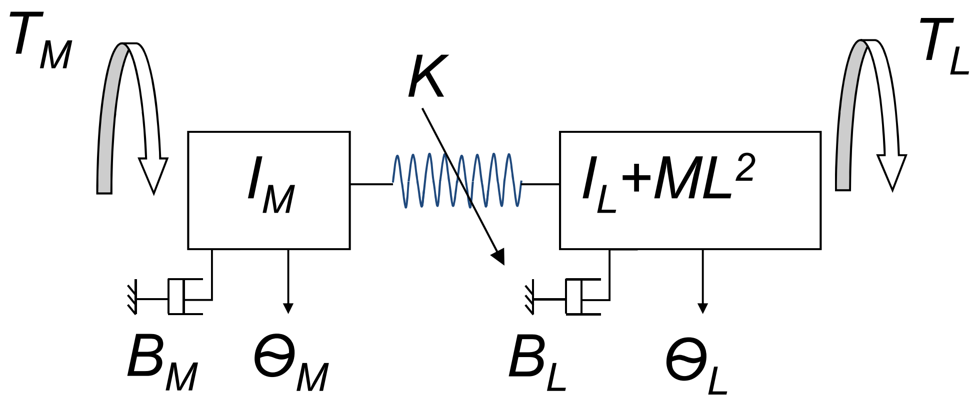
	CompAct-VSA	AwAS -II	AwAS
Range of Motion (deg)	+/-150°	+/- 150°	+/-120°
Range of Stiffness (Nm/rad)	0 ~ rigid	0 ~ rigid	30~130 0
Time to change the stiffness (s)	~0.2sec	~1	3.5
Energy storage (J)	0.35	3.3	3.2
Peak Output Torque (Nm)	117	80	80
Length (m)	0.10	0.18	0.27
Width (m)	0.11	0.14	0.13
Overall Weight (Kg)	1.1	1.4	1.8

CompAct-VSA prototype

Compliance actuation benefits and challenges

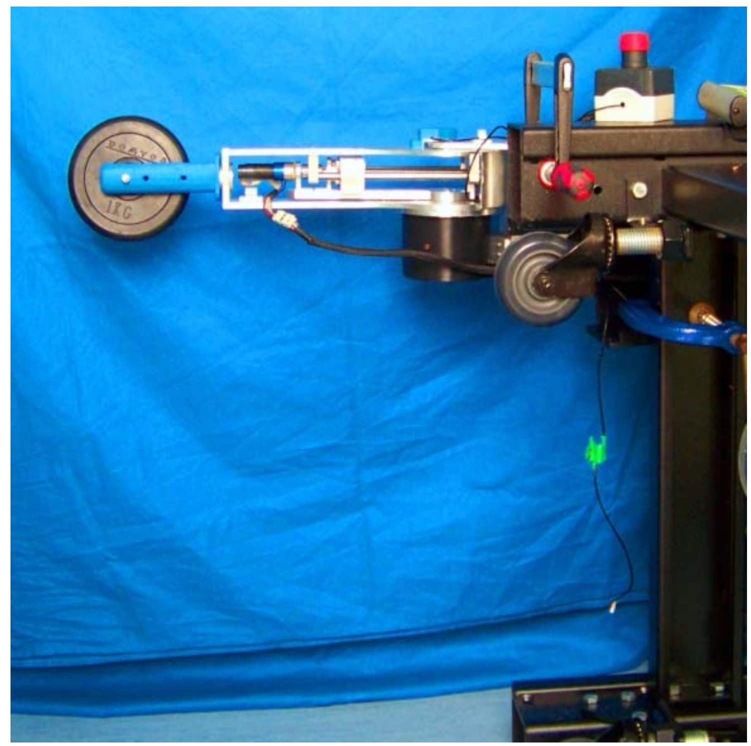
- intrinsic robustness against impacts
- passive adaptability to interaction
- high fidelity force/torque control
- peak power generation
- energy efficiency

Exploiting natural dynamics with AwAS



$$\begin{cases}(I_L + ML^2)\ddot{\theta}_L + B_L\dot{\theta}_L + K(\theta_L - \theta_M) = T_L \\ I_M\ddot{\theta}_M + B_M\dot{\theta}_M + K(\theta_M - \theta_L) = T_M\end{cases}$$

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{(I_L + ML^2)}}$$

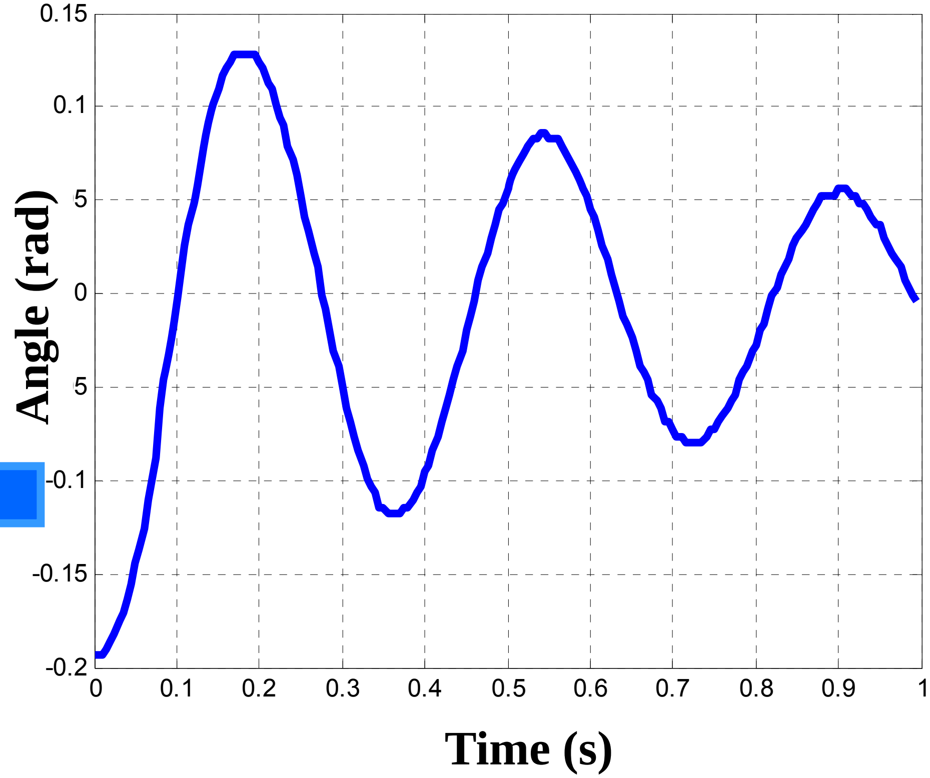


Fixed frequency sinusoidal reference

Desired link trajectory: $\theta_L = A\sin(2\pi f t)$ [fixed frequency]

Parameter	Value
I_M	0.35 (Kgm^2)
I_L	0.1 (Kgm^2)
M	1 (Kg)
L	0.34 (m)
f	2.5 (Hz)
A	0.2 (rad)

$$K = 4\pi^2 f_n^{\,2}(I_L + ML^2) = 51.8 Nm/rad$$



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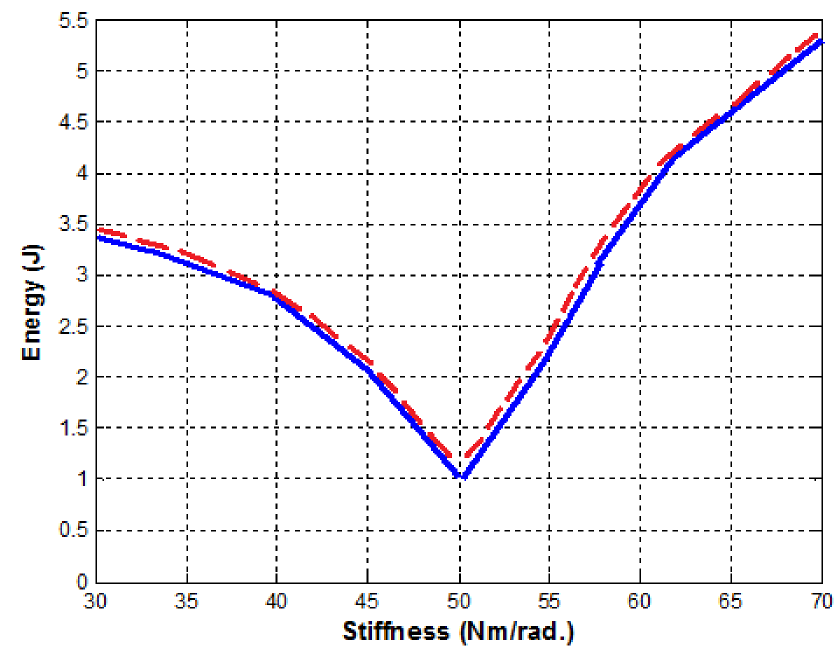


Energy (J)

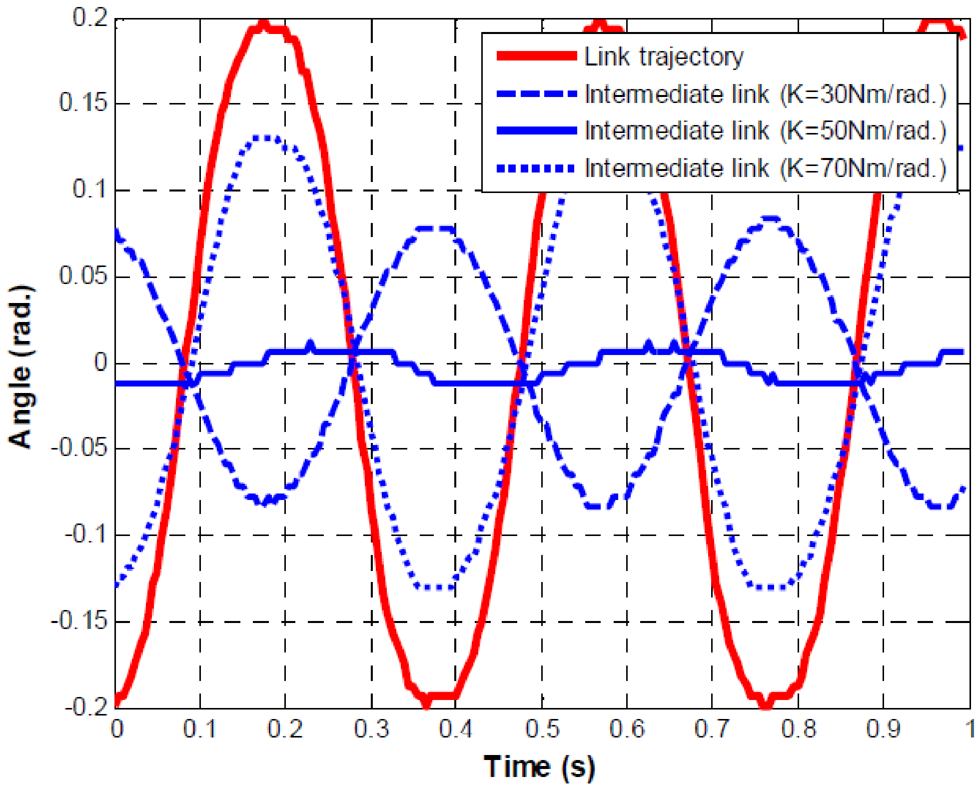
Stiffness(Nm/rad)

Fixed frequency sinusoidal reference

K=30 [Nm/rad]

K=50 [Nm/rad]

K=70 [Nm/rad]

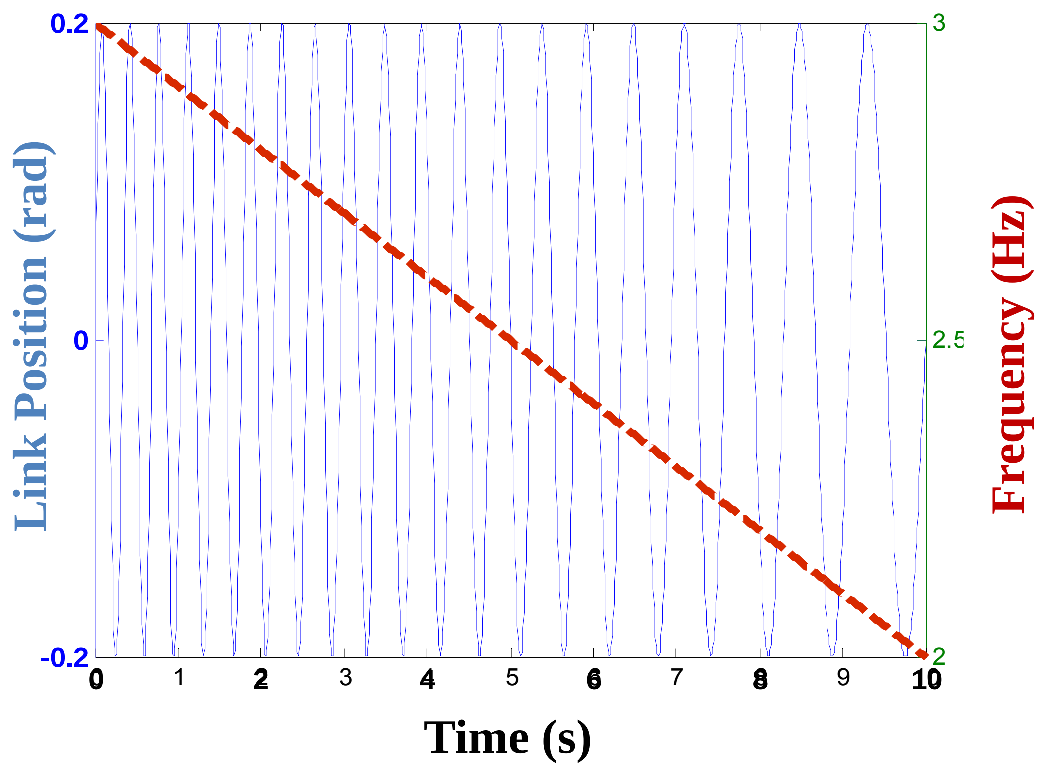


Varying frequency sinusoidal reference

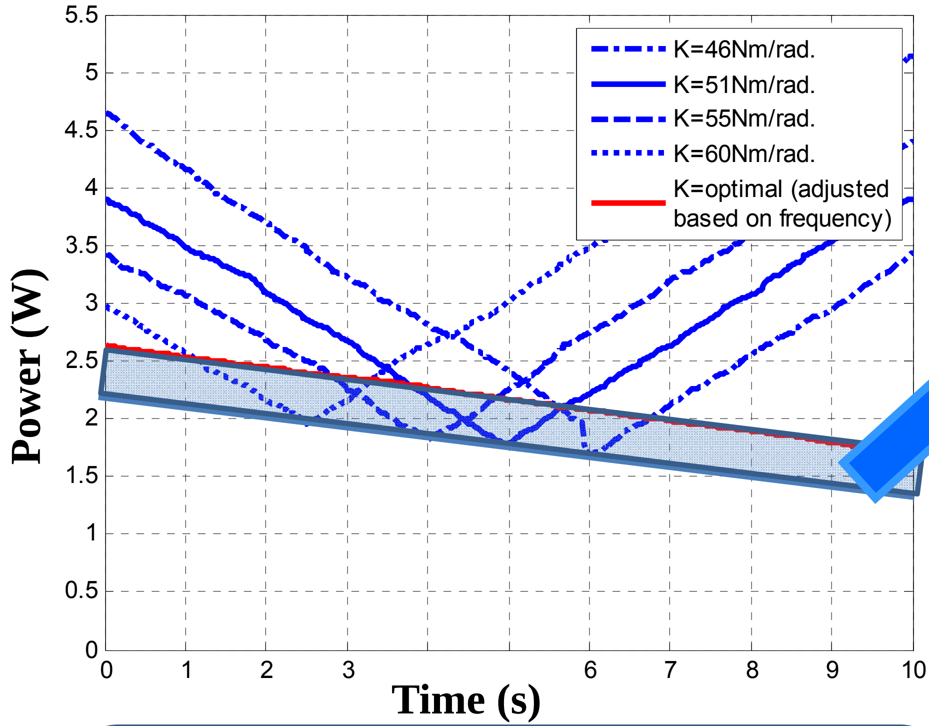
Desired link trajectory: $\theta_L = A\sin(2\pi f t)$ [Variable frequency]

Strategy 1:
Set the stiffness to a fixed optimum value

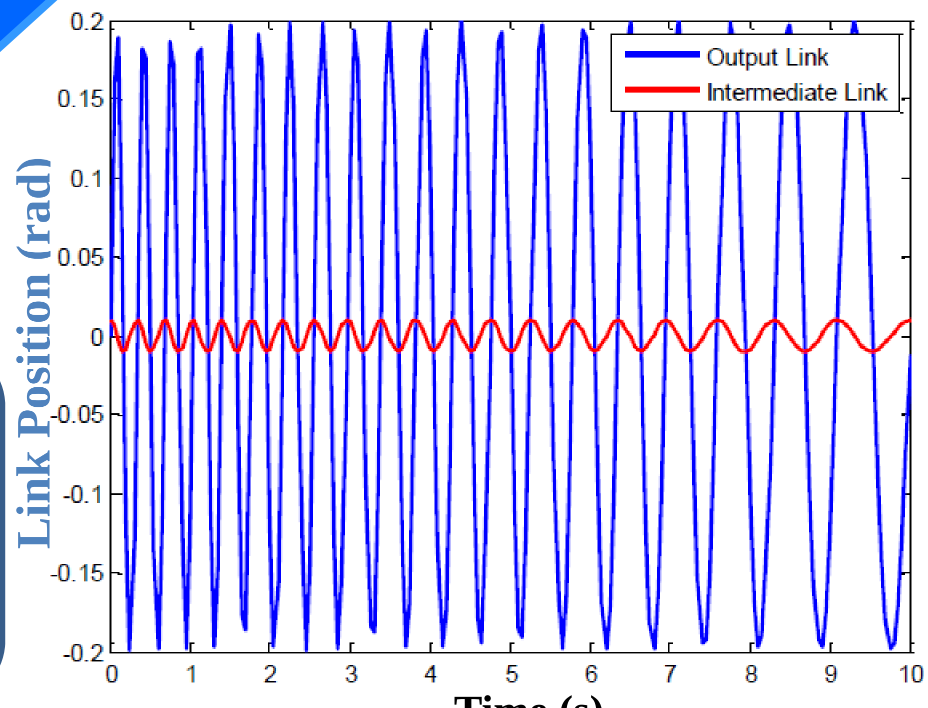
Strategy 2:
Tune the stiffness based on the frequency in real time



Varying frequency sinusoidal reference

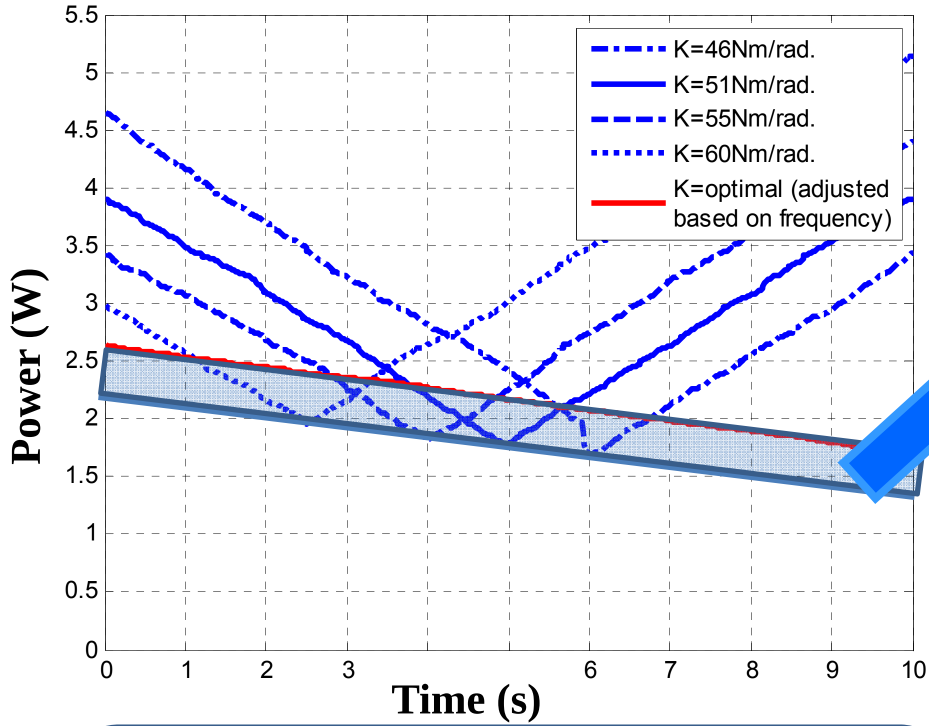


Energy consumption of the stiffness motor



Energy Consumption:
1st Strategy: 28.6J
2nd Strategy: 21.3J
[25% less than first strategy]

Varying frequency sinusoidal reference



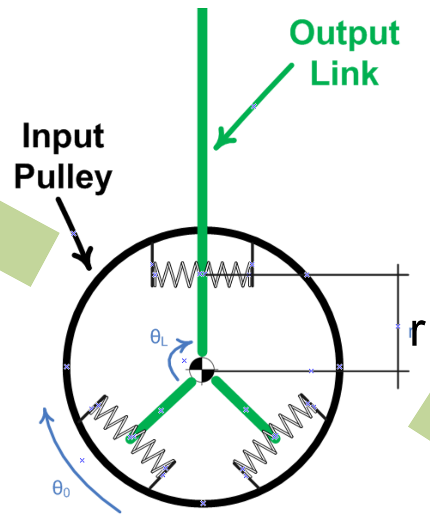
Energy consumption of the stiffness motor

Jafari et al., ICRA 2011

Energy Consumption:
1st Strategy: 28.6J
2nd Strategy: 21.3J
[25% less than first strategy]

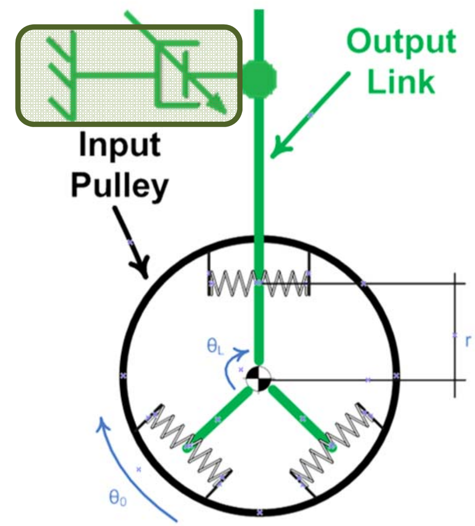
From CompAct to CompAct-VSA

Fixed stiffness joint



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

Variable damper



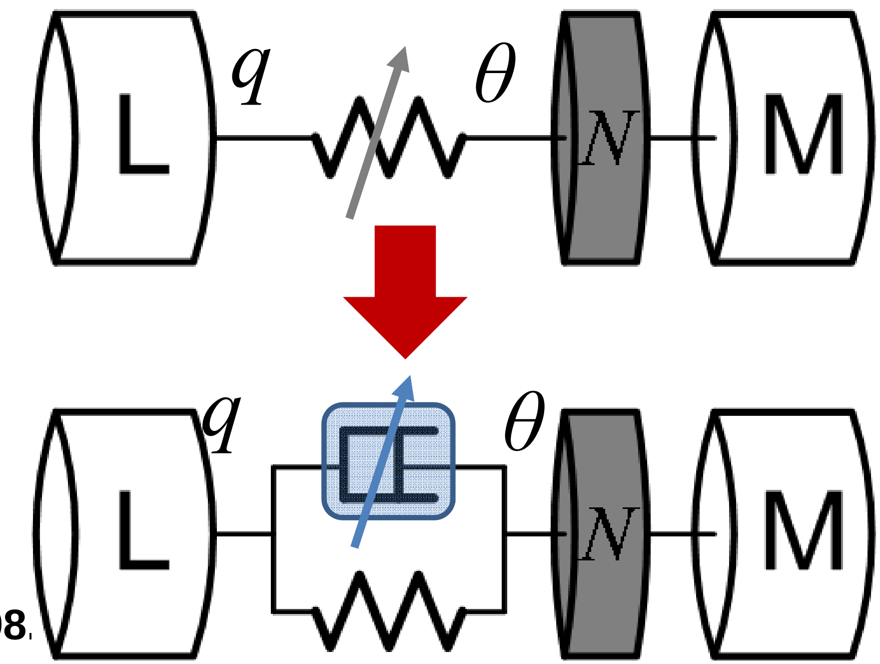
Stiffness and damping regulation in humans

- 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.

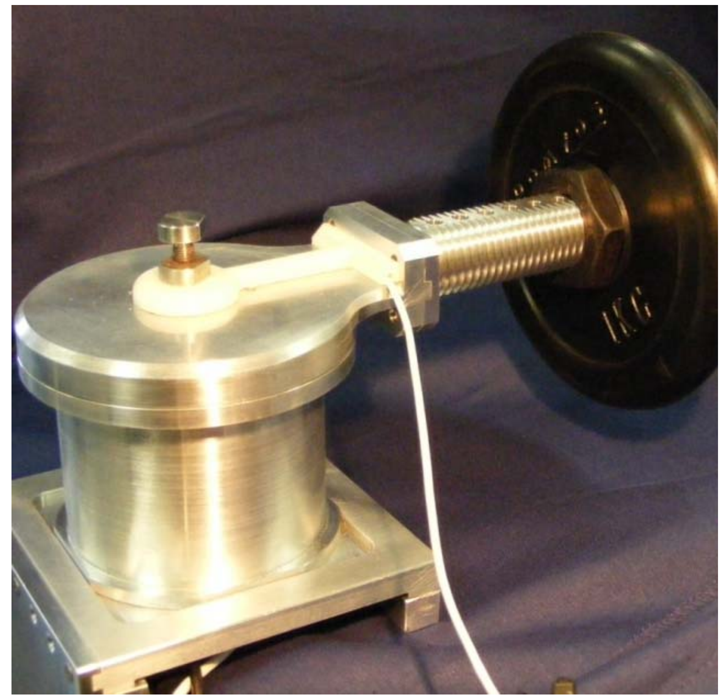
VPDA -Variable physical damping actuator

Motivation

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

Principle & Features

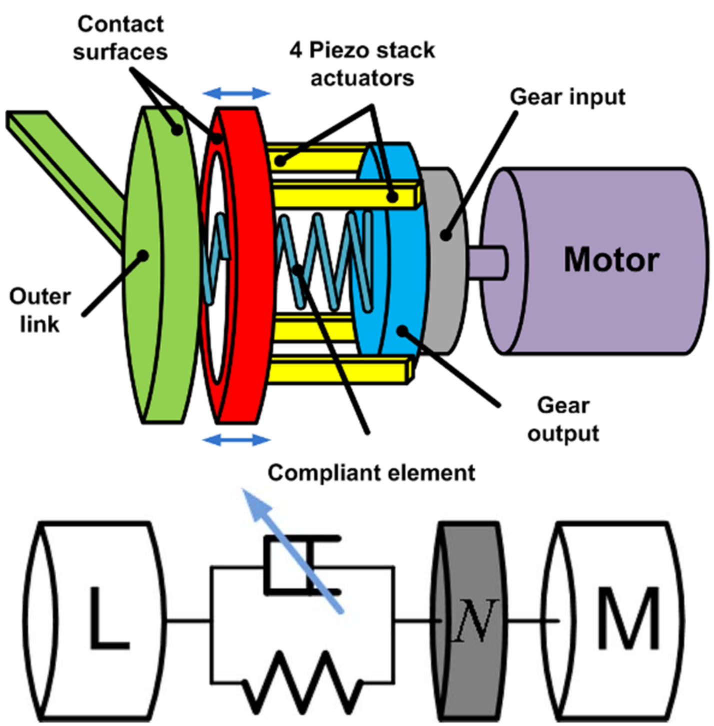
- semi-Active Solution
- introduces “real” physical damping
- piezoelectric actuation

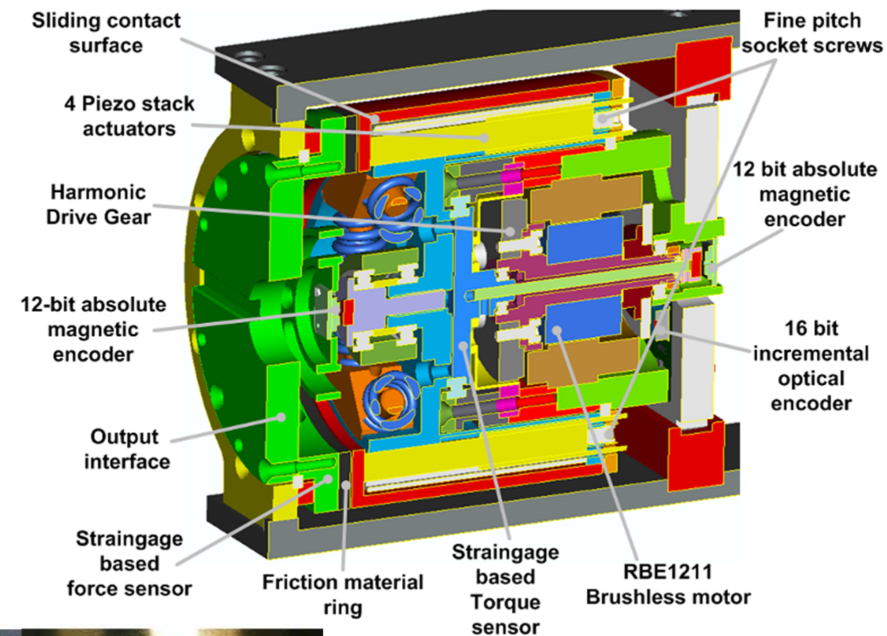


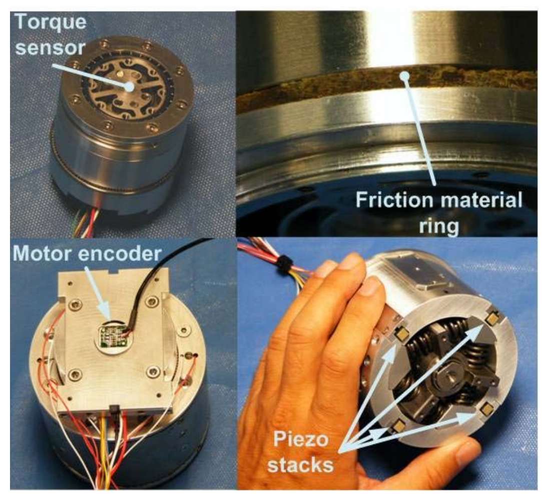
SEA + Variable physical damping actuator

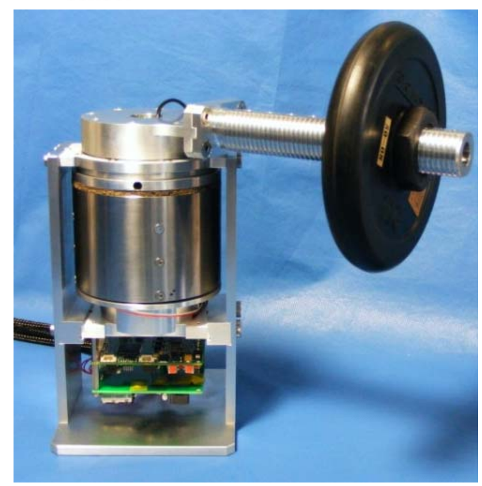
VPDA + **SEA**

Laffranchi et al. ICRA 2010





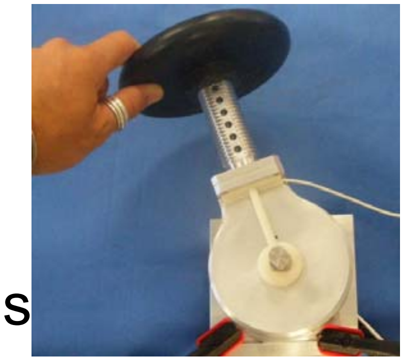


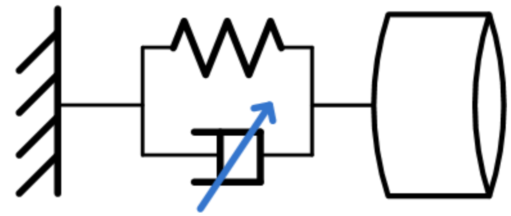


Experimental results

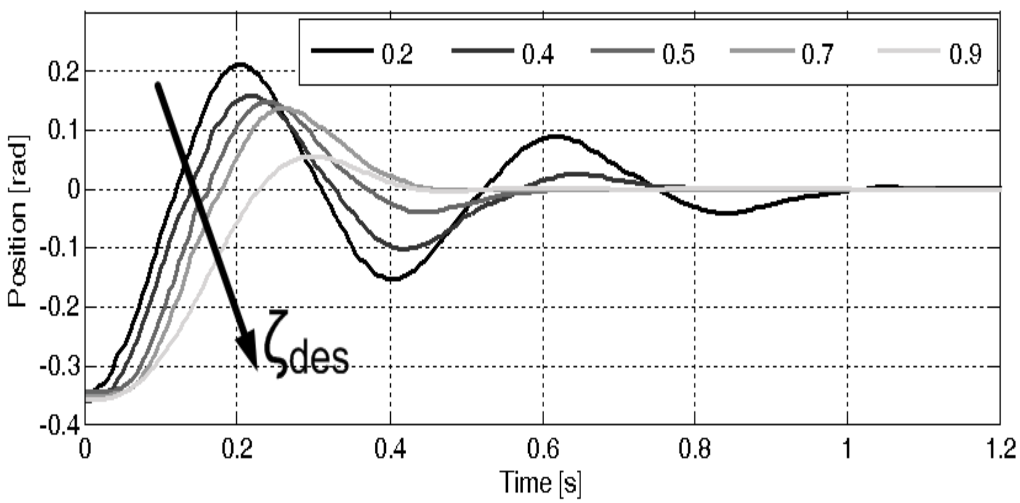
Mass-spring-damper system

- Damping ratio
- Free response to initial conditions

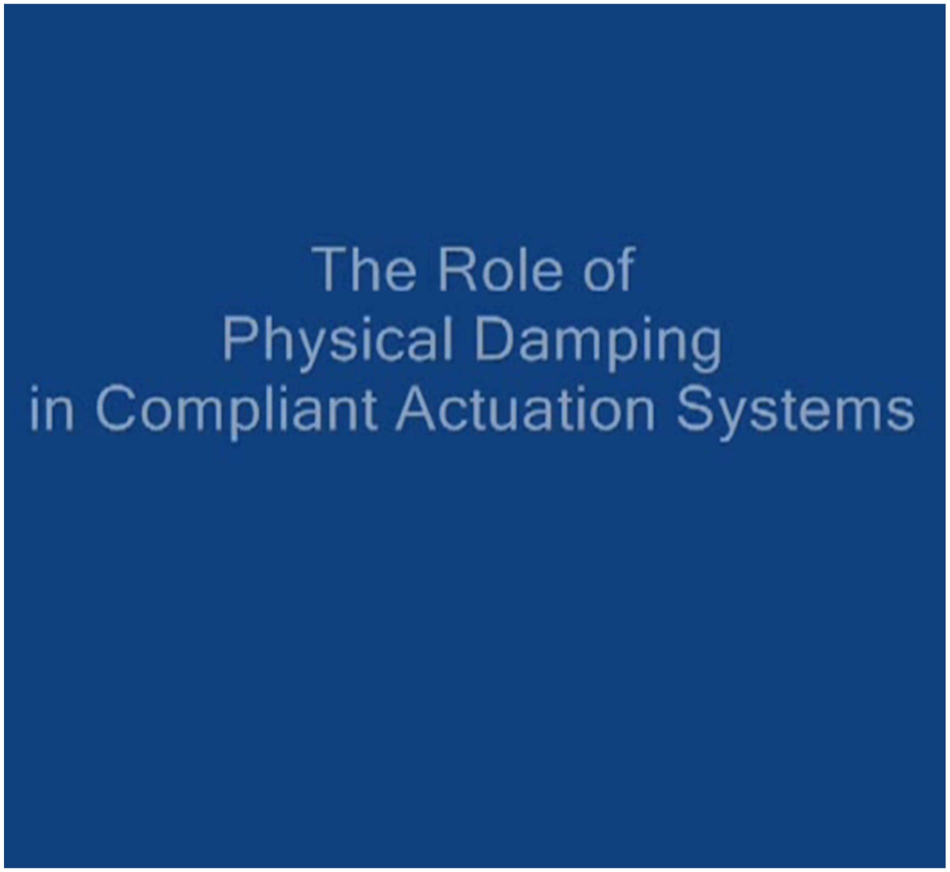




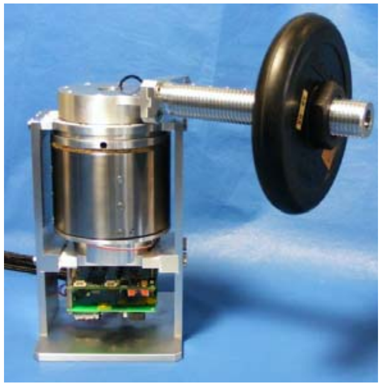
Experimental setup

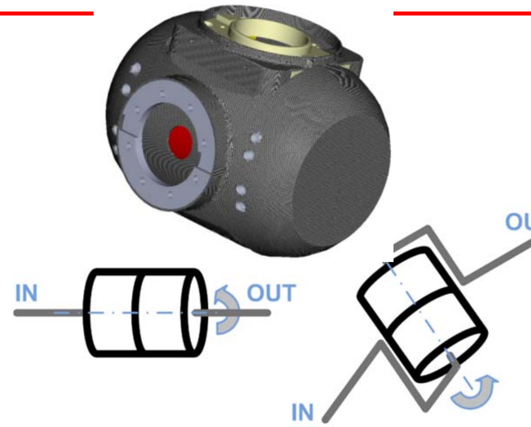


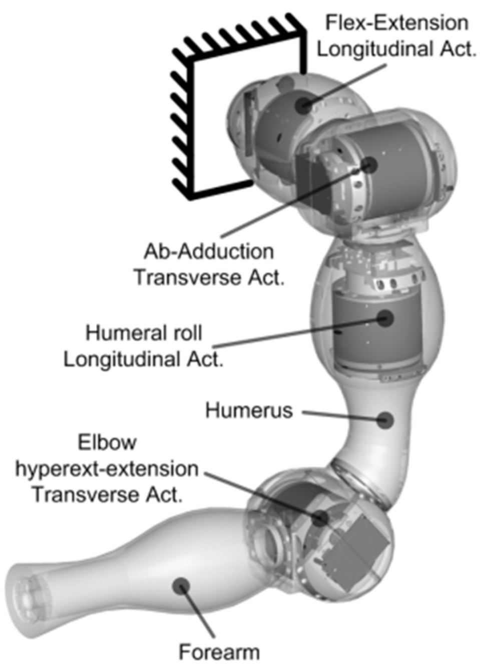
VPDA and Arm prototype

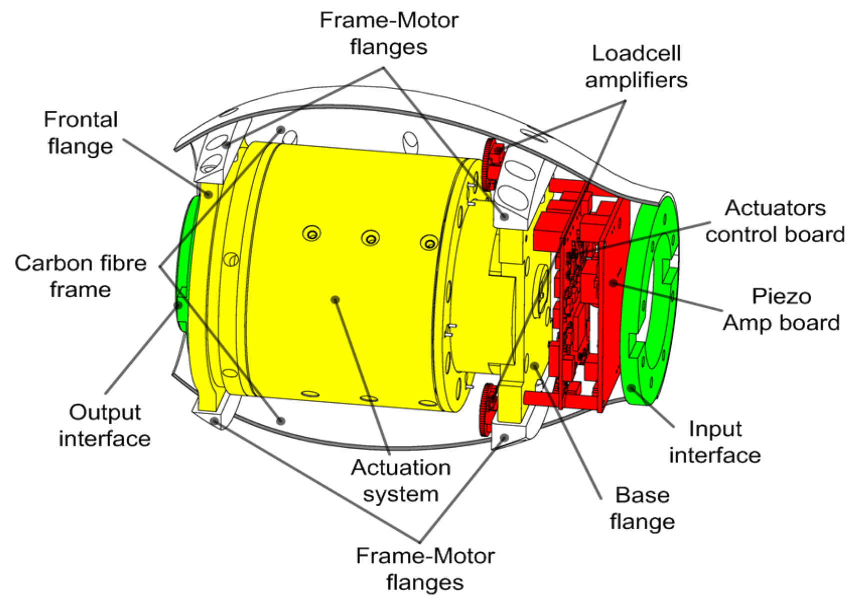


CompAct-VPDA Manipulator

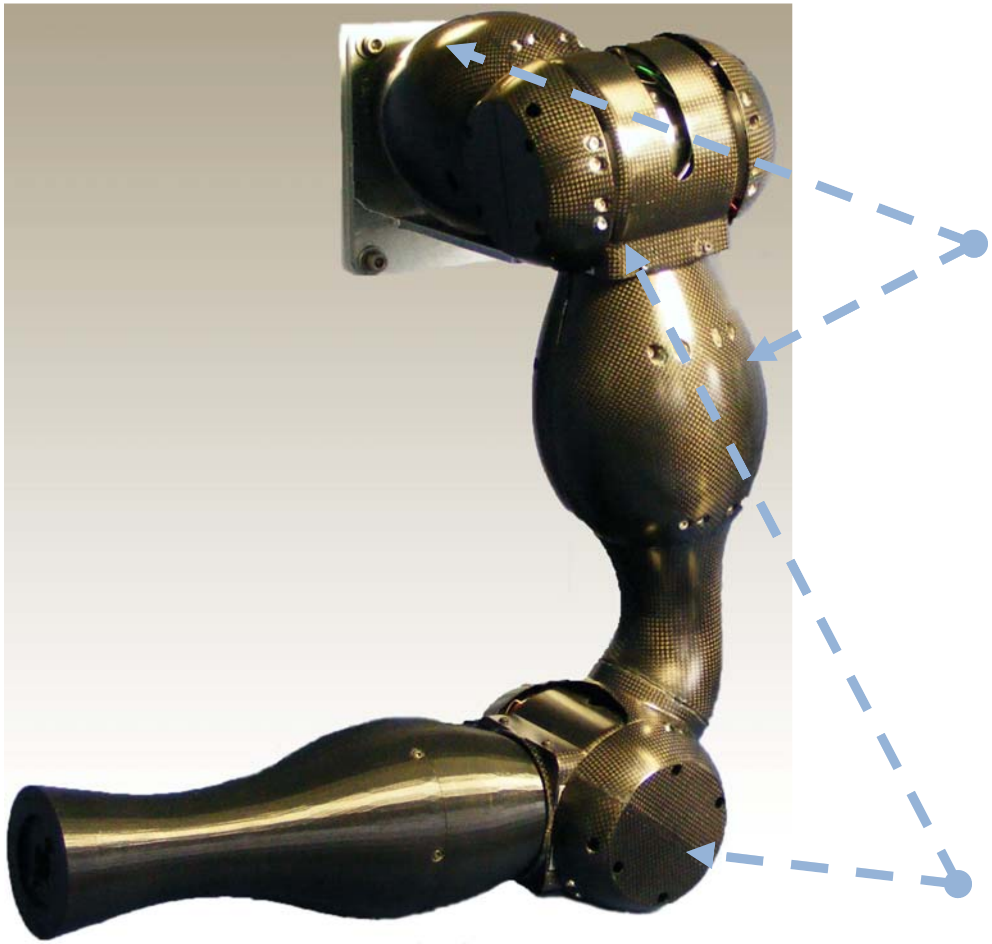




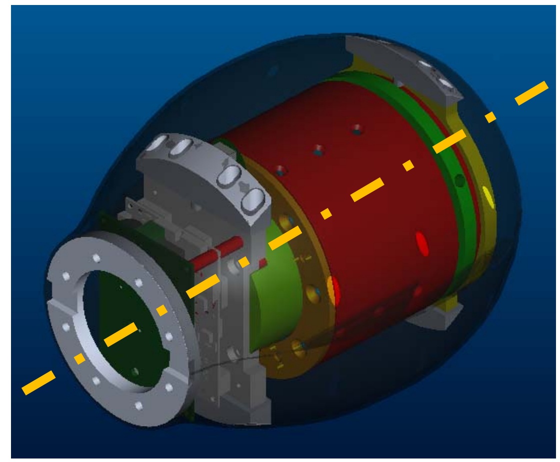




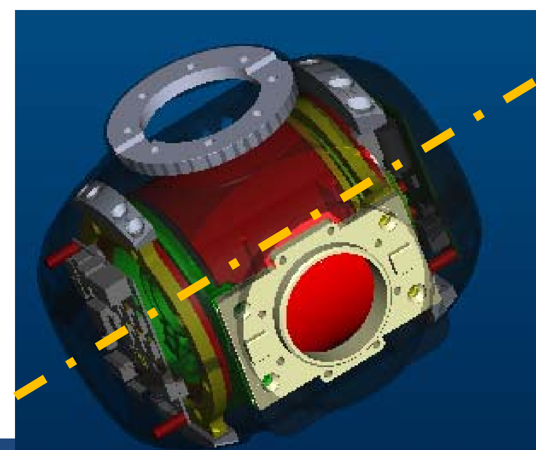
CompAct-VPDA Manipulator



LONGITUDINAL



TRANSVERSE



M. Laffranchi, N.G. Tsagarakis, Darwin G. Caldwell. **CompAct™ Arm: a Compliant Manipulator with Intrinsic Variable Physical Damping.** Robotics: Science and Systems VIII (RSS 2012), Sydney, Australia.

CompAct-VPDA Manipulator

CompAct-VPDA Manipulator