Variable Impedance Robots for Efficient, Robust Bipedal Locomotion

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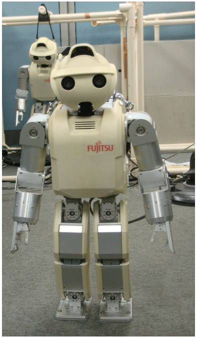
November 26, 2012

Variable Impedance?

1. What & Why
2. How
3. Work at UoE

What & Why

The Spectrum of Robotic Compliance



Fujitsu's HOAP-3

Rigid Joints

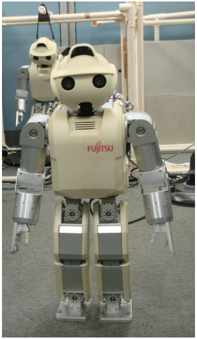
- Behaviourally Flexible
- Energy Inefficient

Cornell biped

Passive Dynamic

- Behaviourally Inflexible
- Energy Efficient

The Spectrum of Robotic Compliance



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Rigid Joints

- Behaviourally Flexible
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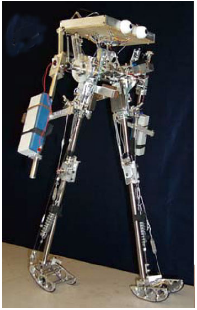
Pratt 2008

Series Elastic

- More behaviours
- Efficiency varies



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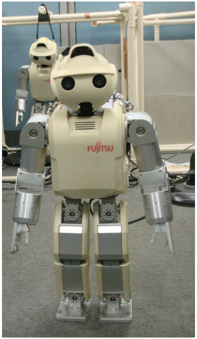
The Spectrum of Robotic Compliance



Fujitsu's HOAP-3

Rigid Joints

- Behaviourally Flexible
- Energy Inefficient

Ott 2010

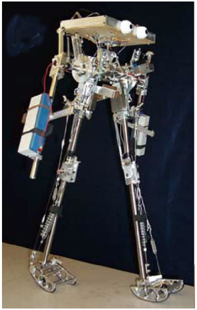
Torque controlled

- Simulate compliance
- No energy storage etc.

Pratt 2008

Series Elastic

- More behaviours
- Efficiency varies



Cornell biped

Passive Dynamic

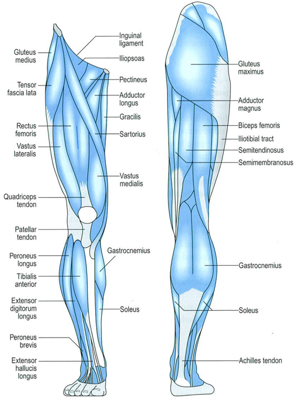
- Behaviourally Inflexible
- Energy Efficient

Variable Impedance

Variable Impedance bipeds aim to achieve the benefits of passive dynamic walkers in terms of efficiency, without the resulting loss of behavioural flexibility.

Human Walking Mechanics

- Walking is a bouncing gait. And people are bouncy.



Whittle 2007

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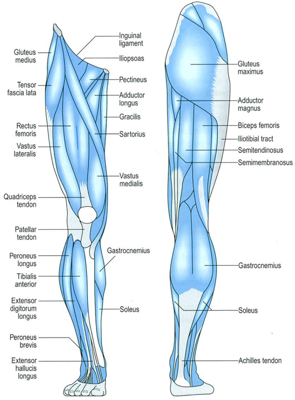
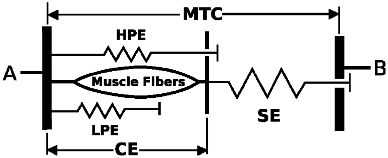


Whittle 2007



Eilenberg 2010

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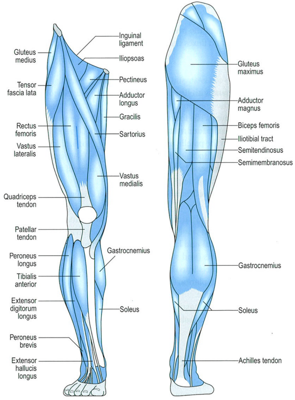
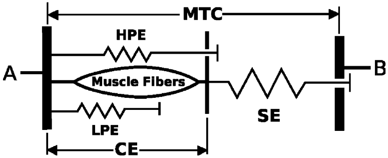
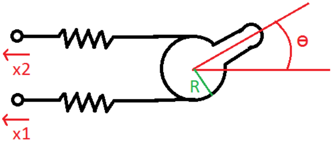


Whittle 2007



Eilenberg 2010



- We can change the stiffness and damping of our joints

Human Walking Dynamics

- Walking makes use of natural dynamics. It is a "controlled fall"
- Studies of human walking kinetics show that a significant amount of work is done by the environment on the body
- Energy efficiency can be improved if energy can be stored and reused or, where necessary, dissipated without driving actuators.

		Power (W kg^{-1})
Summed	Postive	0.72 ± 0.13
	Negative	0.37 ± 0.06
Hip	Positive	0.28 ± 007
	Negative	0.03 ± 0.03
Knee	Positive	0.12 ± 0.06
	Negative	0.20 ± 0.06
Ankle	Positive	0.32 ± 0.08
	Negative	0.14 ± 0.04

Table: Average mechanical power over full gait cycle in human walking. From Umberger 2007

Learning from Humans

We want to mimic (or exceed) human abilities, but this does not require that we necessarily mimic human mechanisms

Recap: Why we would like adaptable compliance

Energy Efficiency

- Significant amount of 'negative power' in the joints during walking

Robustness to disturbances

- Inherently built in to system

Adaptability

- Tailor impedance to task requirements

But!

- Introducing series compliance can introduce unwanted oscillations

- Sometimes we want to dissipate energy from the system

→ Variable Damping

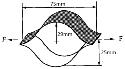
How? Approaches to Variable Impedance

Variable Impedance is a big field...

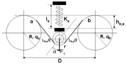
There are many, many published methods for achieving variable compliance

Variable Stiffness Designs (Some of them...)

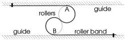
Verrelst2005



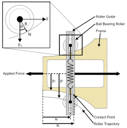
Laurin-Kovitz1991



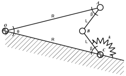
Tonietti2005



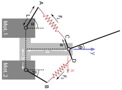
English1999



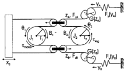
Migliore2005



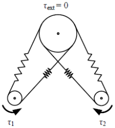
Schiavi2008



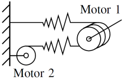
Mitrovic 2010



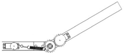
Hurst2004



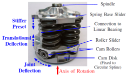
Petit 2010



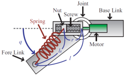
Eiberger 2010



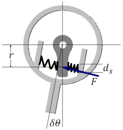
Van Ham 2007



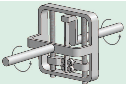
Wolf 2008



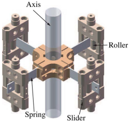
Uemura 2010



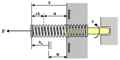
Jafari2010



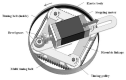
Morita1997



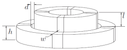
Choi 2011



Hollander 2005



Umedachi 2006



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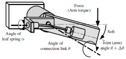


Seki 2006

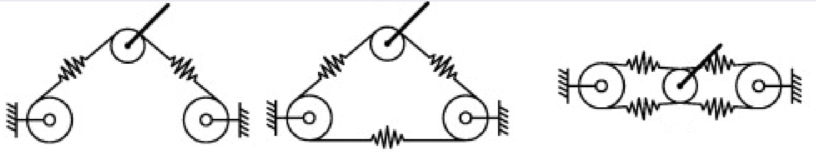
Categories of Variable Compliance Mechanisms

Antagonistic Two or more compliant actuators working in opposition

Series A single compliant element in series with the output link

Antagonistic Mechanisms

Several possible antagonistic layouts



Tagliamonte 2012

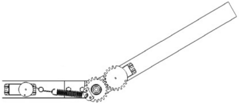
- Normally pretension based
  - Easy to show that in order to be able to adjust stiffness, non-linear springs must be used

Pros and Cons of Antagonistic Mechanisms

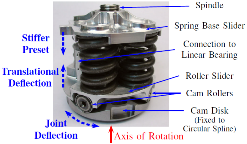
- Almost all antagonistic mechanisms rely on pretension
  - Uses energy to increase/hold stiffness
  - Energy storage capability reduces as stiffness increases
  - Maximum torque decreases as stiffness increases
- But generally quite simple to implement
  - Only tricky bit is the non-linear springs

Series Mechanisms

- Can be pretension based
  - E.g. MACCEPA, DLR VS-joint



Van Ham 2007



Wolf 2008

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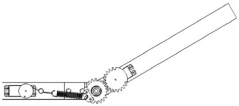
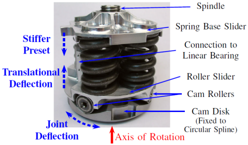
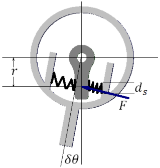


Van Ham 2007

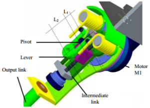


Wolf 2008

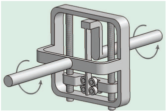
- Or non-pretension based
  - E.g. AwAS, AwAS-II, MIA



Jafari2010



Jafari 2011



Morita1997

Characteristics of Series Variable Compliance Mechanisms

Vary greatly between mechanisms

- In general, series mechanisms tend to
  - Be more complex to construct
  - Have a smaller elastic deformation range
- Pretension based mechanisms
  - Significant energy cost of changing/holding stiffness
  - Full energy storage capability not available at all stiffnesses
- Non-pretension based mechanisms
  - Little energy required to change/hold stiffness
  - Full energy storage capability available at all stiffnesses

General Design Considerations for Variable Stiffness Mechanisms

When selecting a variable compliance mechanisms, we must consider:

- Torque/Deflection curve
- Stiffness/Deflection curve
- Stiffness range
- Deflection range
- Energy storage vs. stiffness
- Maximum torque vs. stiffess
- Energy cost of changing/holding stiffness

Variable Damping

There are fewer options for variable damping, but still at least four possible methods

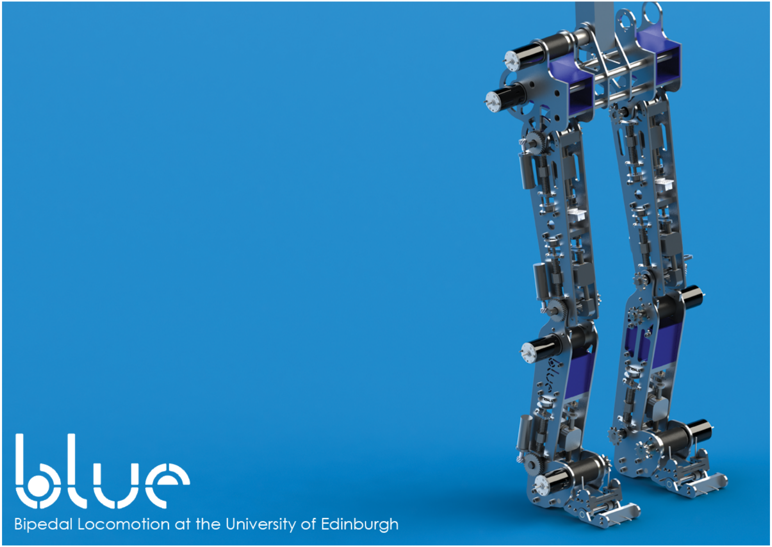
Methods for Variable Damping

Adding physical damping in parallel with a series elastic actuator allows oscillations to be damped without requiring energy to be transferred through the compliant element.

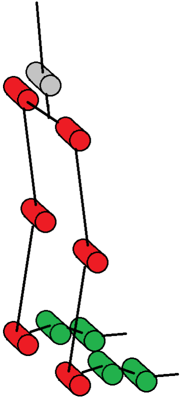
Methods for variable damping:

- Magnetorheological damping
  - As used in prosthetic knees
- Frictional Damping
  - PWM modulation of friction brake
- Variable hydraulic damping
  - Vary the channel size in a fluid damper
- Motor braking
  - Shorting together the terminals of a motor causes it to brake
  - PWM modulations of this to vary damping

Work at UoE


blue
Bipedal Locomotion at the University of Edinburgh

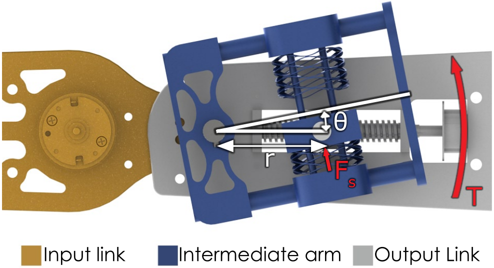
High Level Mechanical Design



Kinematic layout
Red = Position & Impedance control;
Green = Passive
Grey = Position control

- Sagittal plane biped
- 6 joints with position/stiffness/damping control
  - Stiffness controlled longitudinal foot arch
  - Passive toe
  - Position controlled torso joint
- $\frac{3}{4}$ size of adult male

Variable Stiffness Mechanism: MAwAS



$$F_s = rK_s \sin\theta \quad (1)$$

$$T = \frac{r^2 K_s}{2} \sin(2\theta) \quad (2)$$

$$K = \frac{dT}{d\theta} = r^2 K_s \cos(2\theta) \quad (3)$$

T = Joint Torque

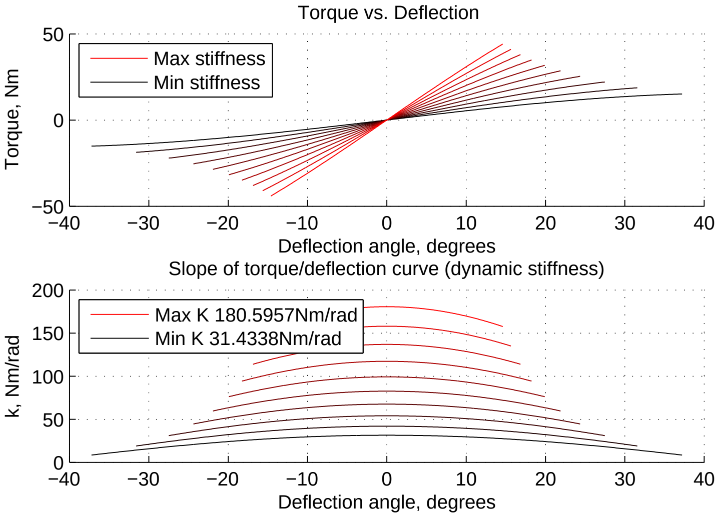
F_s = Spring Force

θ = Deflection from equilibrium

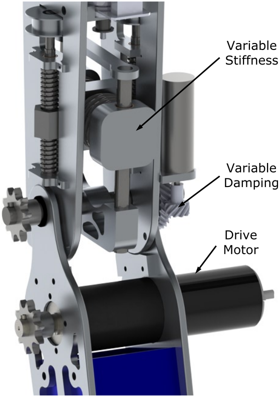
r = Stiffness Setting

K_s = Spring Constant

Torque and Stiffness Curves



Variable Damping: PWM Motor Braking



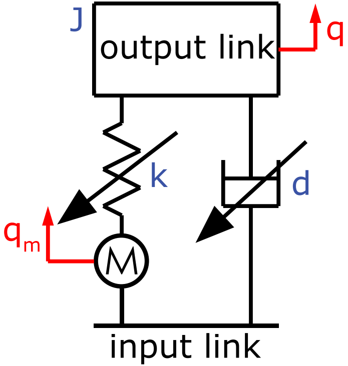
- Third motor in parallel with main drive motor and MAwAS mechanism
  - Shorting together the terminals of this motor applies damping torque
  - Very little energy is used to modulate the damping
- Maximum damping coefficient:[a]

$$d = \frac{n^2 \kappa_\tau \kappa_{\dot{q}}}{R_e}$$

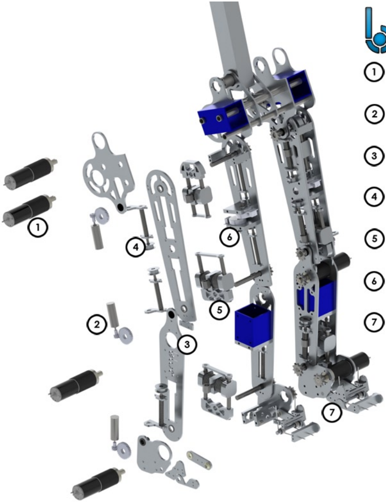
  - n:1 is the gear ratio
  - κ_τ and $\kappa_{\dot{q}}$: motor torque and speed constants
  - R_e is the equivalent resistance of the motor

[a] See Radulescu 2012

Joint Dynamics

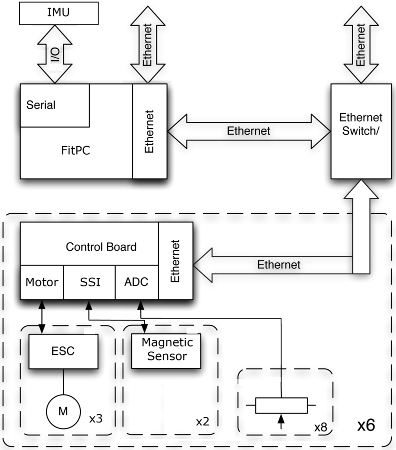


BLUE



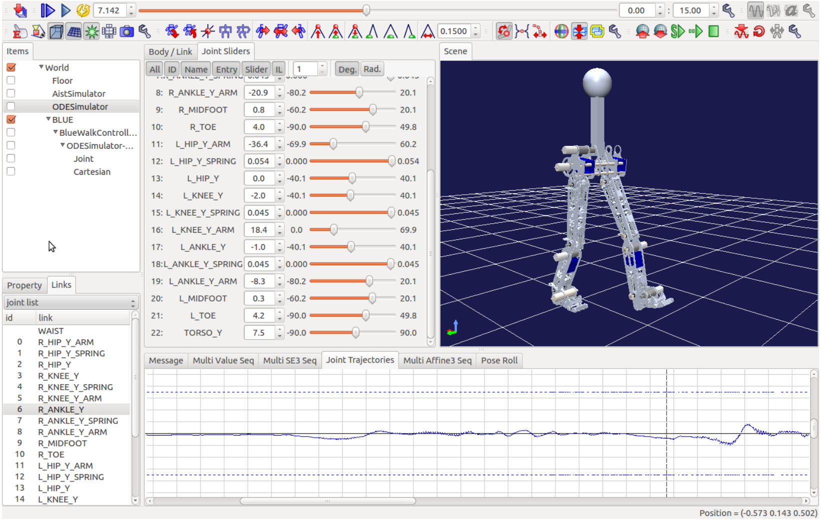
1. **Drive Motors**
   150W Maxon DC Brushed
2. **Variable Damping**
   PWM motor braking
3. **Waterjet cut chassis**
4. **Leadscrews**
   For stiffness adjustment
5. **Variable Stiffness**
   Through MAwAS mechanism
6. **Stiffness adjustment motors**
   50W Maxon EC flat
7. **Three part compliant foot**
   For energy storage and robustness to disturbances

Electronics and Low Level Control



- Onboard ethernet network
  - Very fast comms
  - Broadcast capability
- One control board per major joint
  - ATMEL microcontroller
  - Reads all joint sensors, digitally filters
  - PID loops and controls motor drivers
  - Failsafes

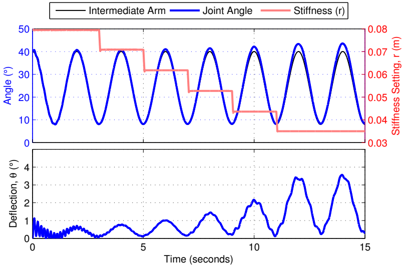
Simulation in Choreonoid



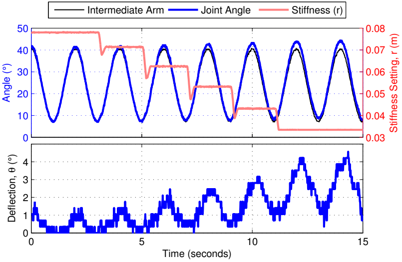
Video

I will now play a video of BLUE

Squatting

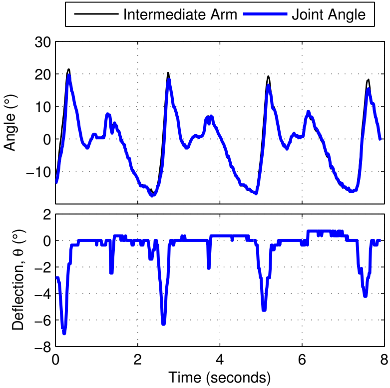


Simulation

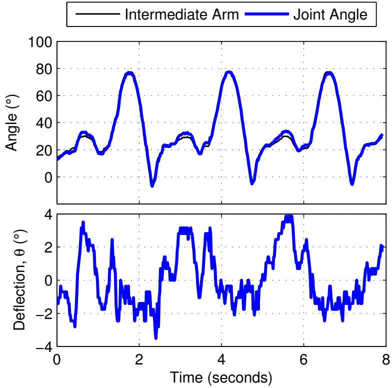


Hardware

Walking on the Hardware

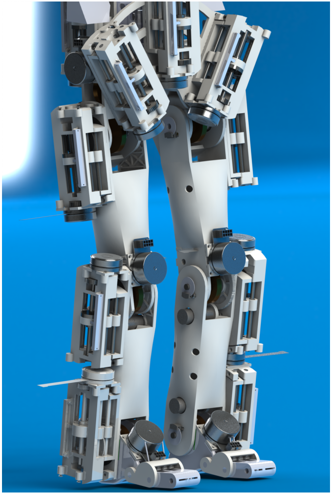


Ankle



Knee

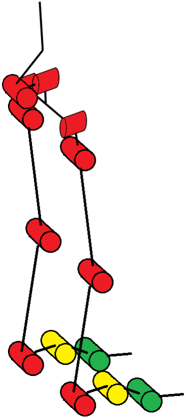
miniBLUE



miniBLUE design ideas:

- Lighter and smaller
- Non-backdriveable equilibrium position setting
- Wider compliant range
- More D.O.F - not just sagittal plane
- 3D printing
  - Reduce workshop time
  - More complex shapes - not a 'flatpack robot'
- Use modular unit for variable stiffness

High Level Mechanical Design



Kinematic layout
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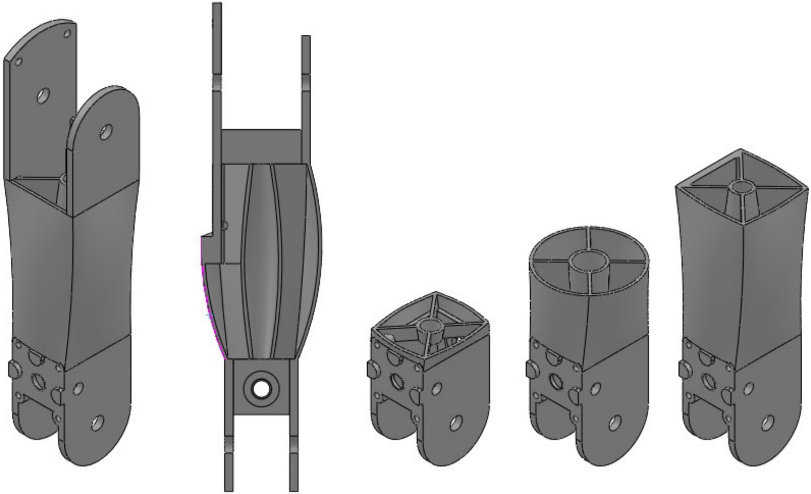
Green = Passive
Grey = Position control

- 10 active DOF
  - 2 DOF torso
  - 2 DOF hip
  - 1 DOF knee
  - 1 DOF ankle
- Similar foot design to BLUE
- $\frac{1}{2}$ scale
  - Hip rotation height 465mm

3D printing



Other Work with Variable Impedance at the UoE

- Optimal ball throwing on a two link MACCEPA arm
  - D. Braun, M. Howard and S. Vijayakumar "Optimal Variable Stiffness Control: Formulation and Application to Explosive Movement Tasks", Autonomous Robots, 2012
- Variable impedance brachiation
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Questions

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