Bio-inspired controller achieving forward speed modulation with a 3D bipedal walker

Van der Noot et al.

Group 04
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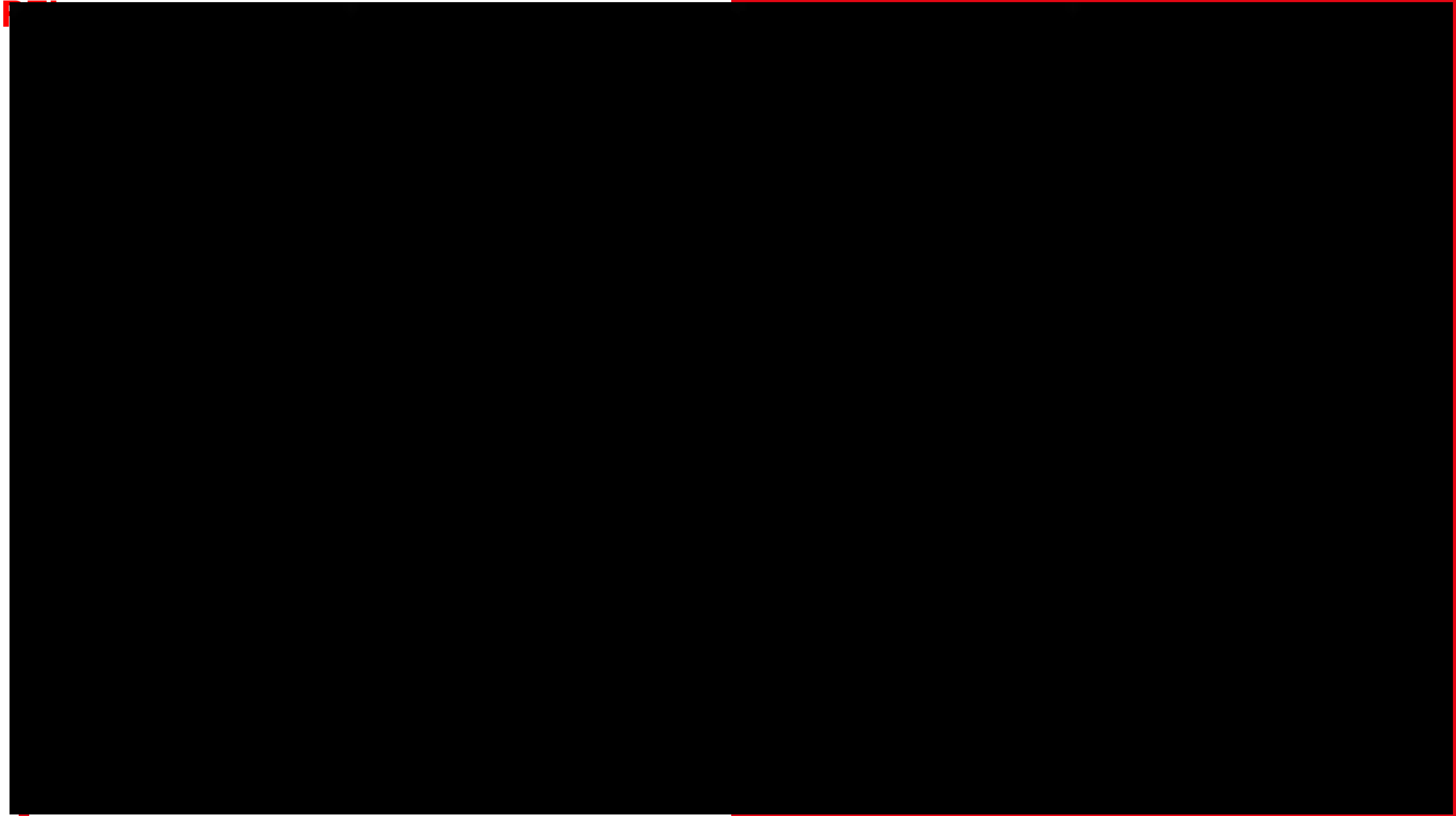


https://www.youtube.com/watch?v=xvsswU4ikqw

Introduction

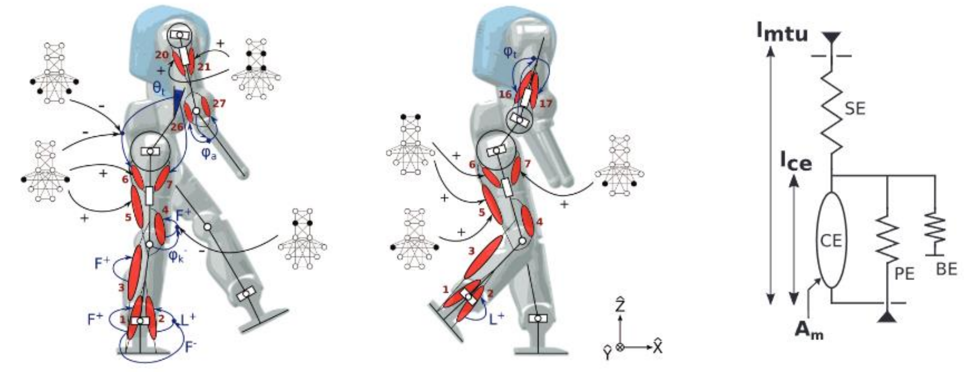
- Keywords:
  - Bipedal Locomotion, COMAN robot
  - Walking gait
  - Use of CPG and Virtual reflexes with virtual muscles
  - Minimizes metabolic energy
  - Design method: tuned with particle swarm optimization

- Main idea :
  - Use of CPG and Virtual reflexes to create human like walking gait with different speed while trying to minimize metabolic energy consumption

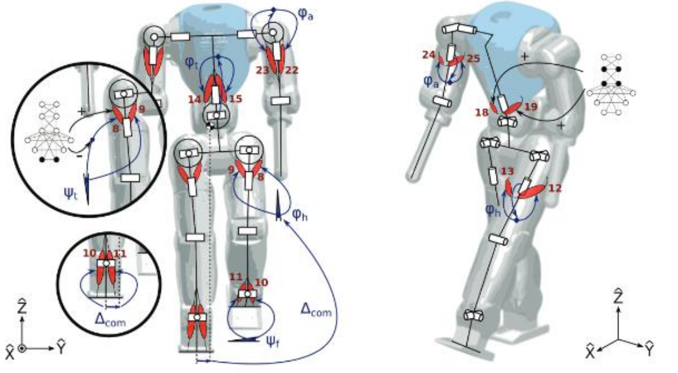
Key aspects

- COMAN robot, biped walking
- Control : Torque control
- Design methods : Particle swarm optimization of 11 keys parameters
- Gaits : Walking with different speed (0.4 m/s up to 0.9 m/s)
- Sensors : Position encoders, torque sensors, IMU, six-axis force/torque sensors.

Neuromuscular model



(a) Sagittal muscles (arm and stance leg) (b) Sagittal muscles (torso and swing leg) (c) Hill muscle model



(d) Lateral muscles (arm, torso, and leg) (e) Transverse muscles (arm, torso, and leg)

Sagittal leg	1	SOL
	2	TA
	3	GAS
	4	VAS
	5	HAM
	6	GLU
	7	HFL
Lateral leg	8	HAB
	9	HAD
	10	EVE
	11	INV
Transverse leg	12	HER
	13	HIR
Torso	14	BTR
	15	BTL
	16	BET
	17	BFL
	18	BRR
	19	BRL
Arms	20	SET
	21	SFL
	22	SAB
	23	SAD
	24	SER
	25	SIR
	26	EET
	27	EFL

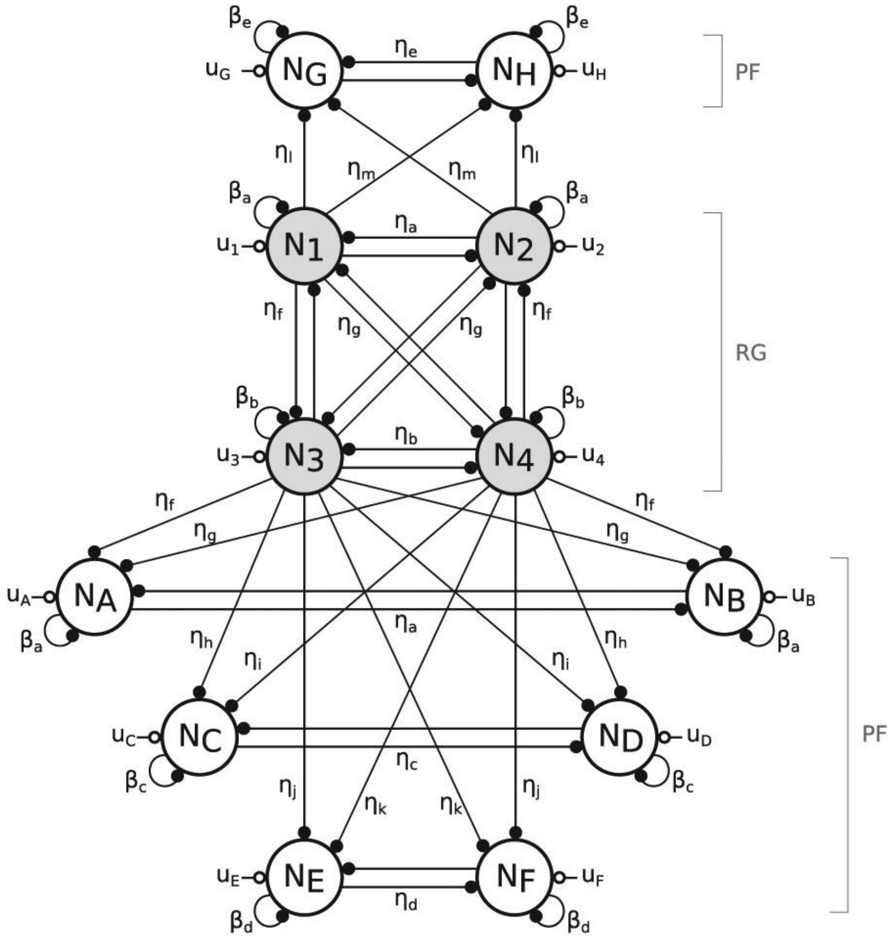
- Hill muscle model : Each muscle tendon unit (MTU) consists of:
  - Contractile element (CE)
  - Series elastic element (SE).
  - Two additional passive elements :
    - Parallel elastic element (PE)
    - Buffer elasticity element (BE)
- Bi-articular muscles : single muscle provides two torque contributions with two different lever arms.
- Musculoskeletal model provides joint torques through virtual muscle forces and attachment points.
- Control each MTU through input signals (muscle activations) related to neural inputs (stimulations),

Central Pattern Generator

- Fully connected Matsuoka neurons
- Rythm generator neurons (RG) generate main frequency and phasing of the gait cycle
- Pattern formation neurons (PF) generate signals shaping the patterns of the muscle stimulation

Main advantages:

- Stable limit cycle
- Low computational cost
- Easy to integrate with sensory feedback signals



Matsuoka Neurons evolution

- Gains will need to be optimized
- Each neuron is captured by the firing rate xi

$$\dot{x}_i = \frac{1}{\tau}\left(-x_i - \beta_j\, v_i - \sum \eta_k\, [x_l]^+ + u_i\right)$$

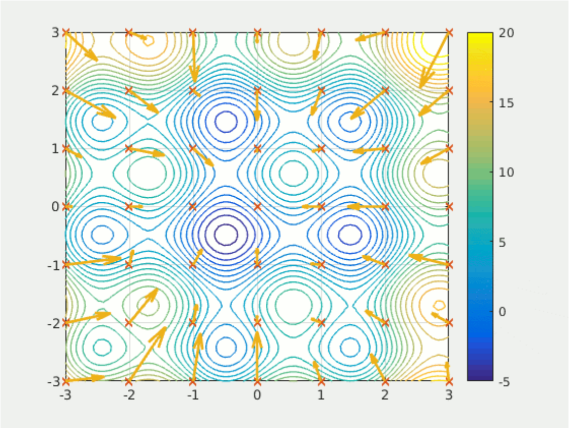
- τ: Time constant affecting the rhythm frequency.
- β : Self-inhibition strength, ensuring the neuron cannot sustain continuous firing.
- η_k: Connection strength from other neurons (x_k),enabling mutual inhibition.
- $[x_k]^+$: Positive component of x_k (non-negative).
- u_i: External input controlling the neuron's output (modulates amplitude or phase).

- And by its self-inhibition

$$\dot{v}_i = \frac{1}{\gamma_j\, \tau}\left(-v_i + [x_i]^+\right)$$

- γ: Scales the time constant for self-inhibition dynamics.
- v_i: Ensures the neuron cannot fire continuously without pauses.

Optimization

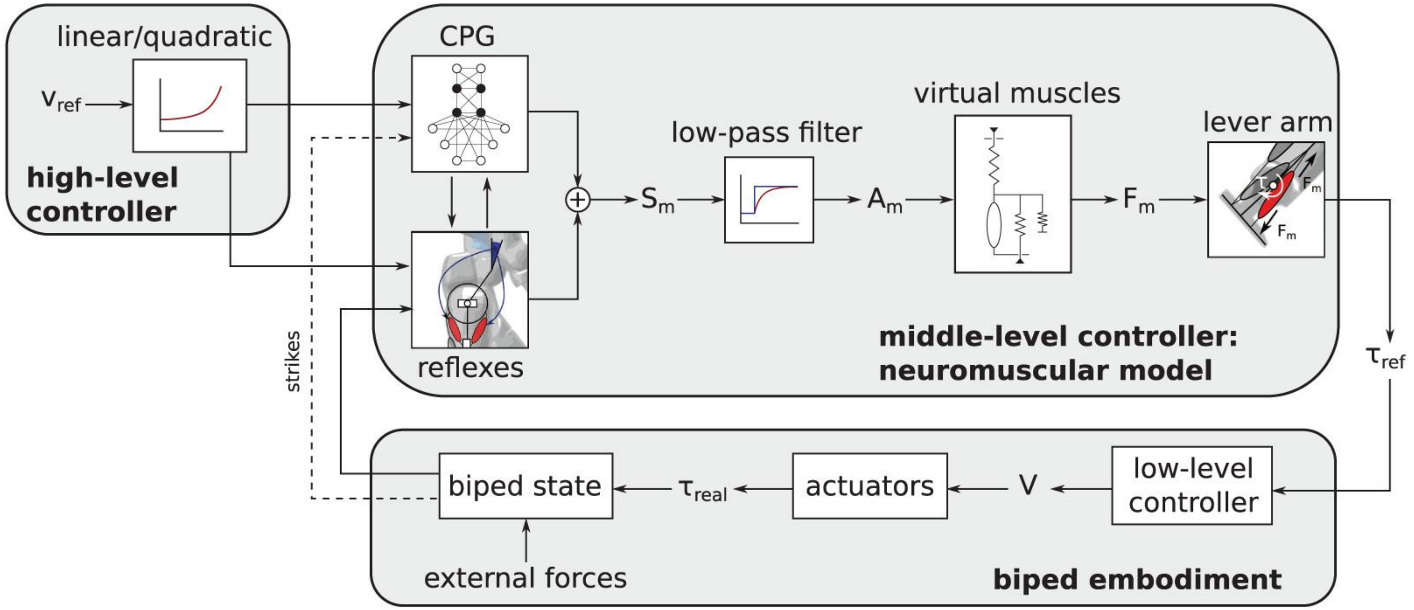


https://en.wikipedia.org/wiki/Particle_swarm_optimization#/media/File:ParticleSwarmArrowsAnimation.gif

- Particle swarm optimization
- Each set tested with a biped walking during a maximal time of 60 s.
- Different stages with different reward function proportional to the distance, the walked time, the speed before trying to minimize the equivalent metabolic energy.
- Corresponding objective function : $f = 100\, e^{-\alpha\,(x-x^*)^2}$
- Mean error between CPG predicted strike times and actual ones, shorter distance between strike foot position of a leg and the line passing through the last two strike positions of the other.
- To promote emergence of solutions with good foot clearance with respect to the ground :
  - trapezoidal shapes below the swing foot

Full controller

- 3 level controller
- Gets reference speed function as input
- Neuromuscular model outputs reference torques
- Low level controller drives the actuators



Simulation

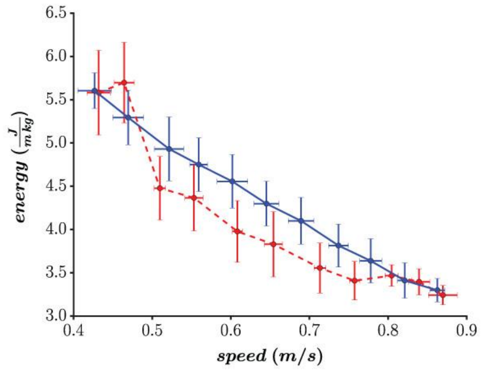
- COMAN robotic platform in a simulation environment Robotran
- Only used sensors available on the real robot
- To comply with a realistic noisy environment, a uniform noise with a maximum amplitude of 0.4 Nm was added to the actual torque measured in the simulation environment

Experiments

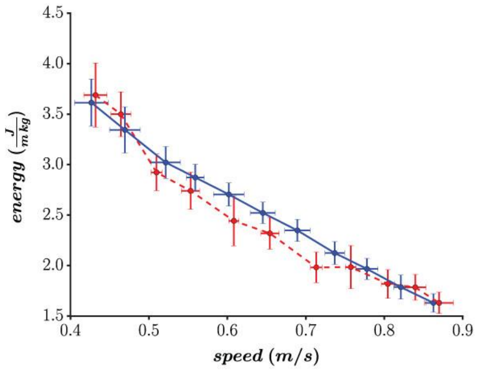
- Different experiments were conducted in the simulation
- Single speed and adaptive controllers

Experiment 1

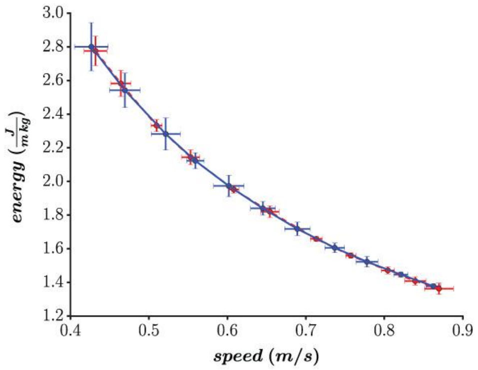
- Gait features changing as a function of speed



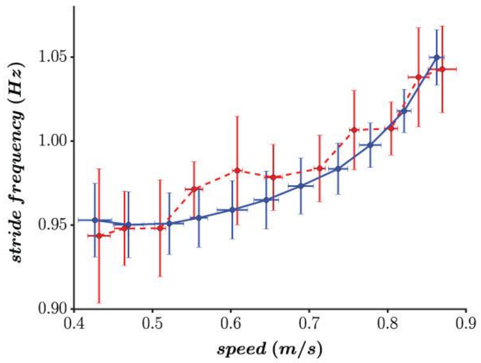
(a) Energy sagittal muscles



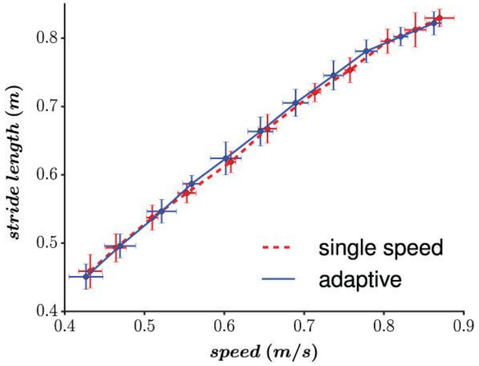
(b) Energy lateral muscles



(c) Energy transverse muscles



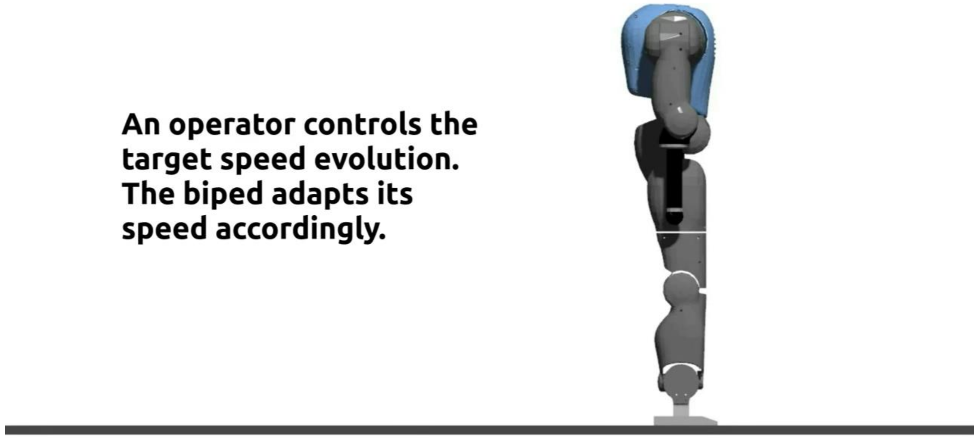
(d) Stride frequency



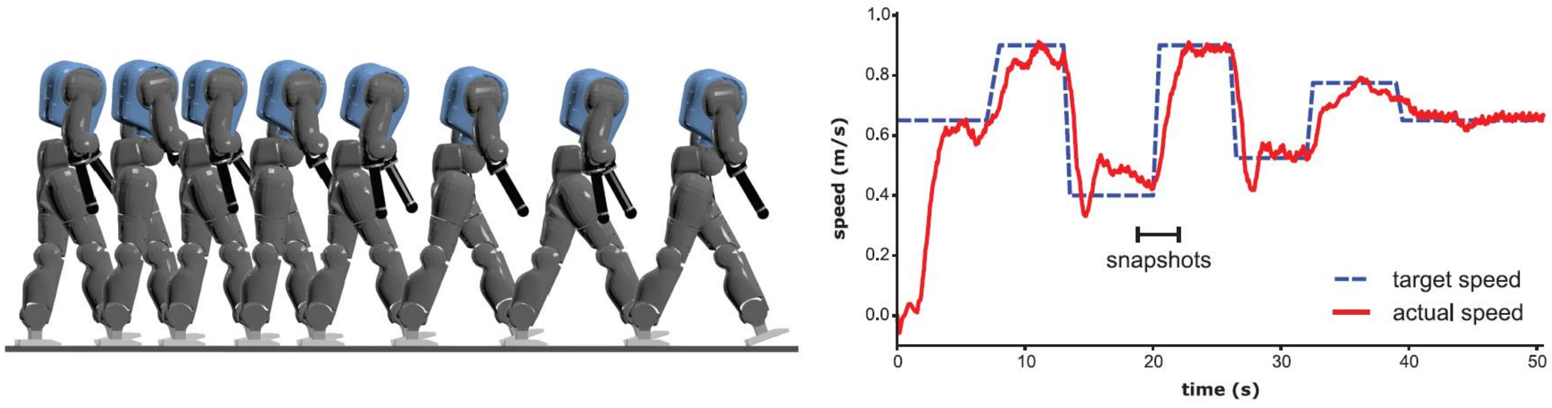
(e) Stride length

Experiment 3

An operator controls the target speed evolution. The biped adapts its speed accordingly.



- Single controller for the whole speed range

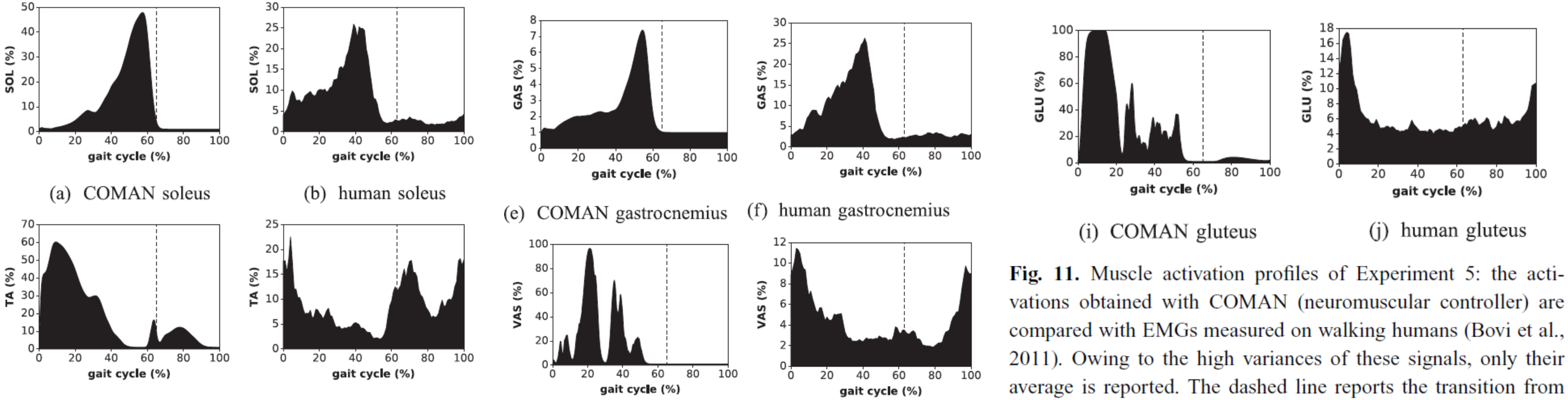


(a) Forward speed modulation (b) Target speed tracking

Fig. 8. (a) Snapshots of an experiment where the robot forward speed is modulated. (b) Tracking of the target speed v_{ref} (dashed line), where the robot actual forward speed (solid line) is post-processed with a running average of 1 s. The time interval during which the snapshots of (a) are taken is also displayed. A video of the corresponding experiment is provided in Extension 2.

Experiment 5

- Steady-state gaits comparisons

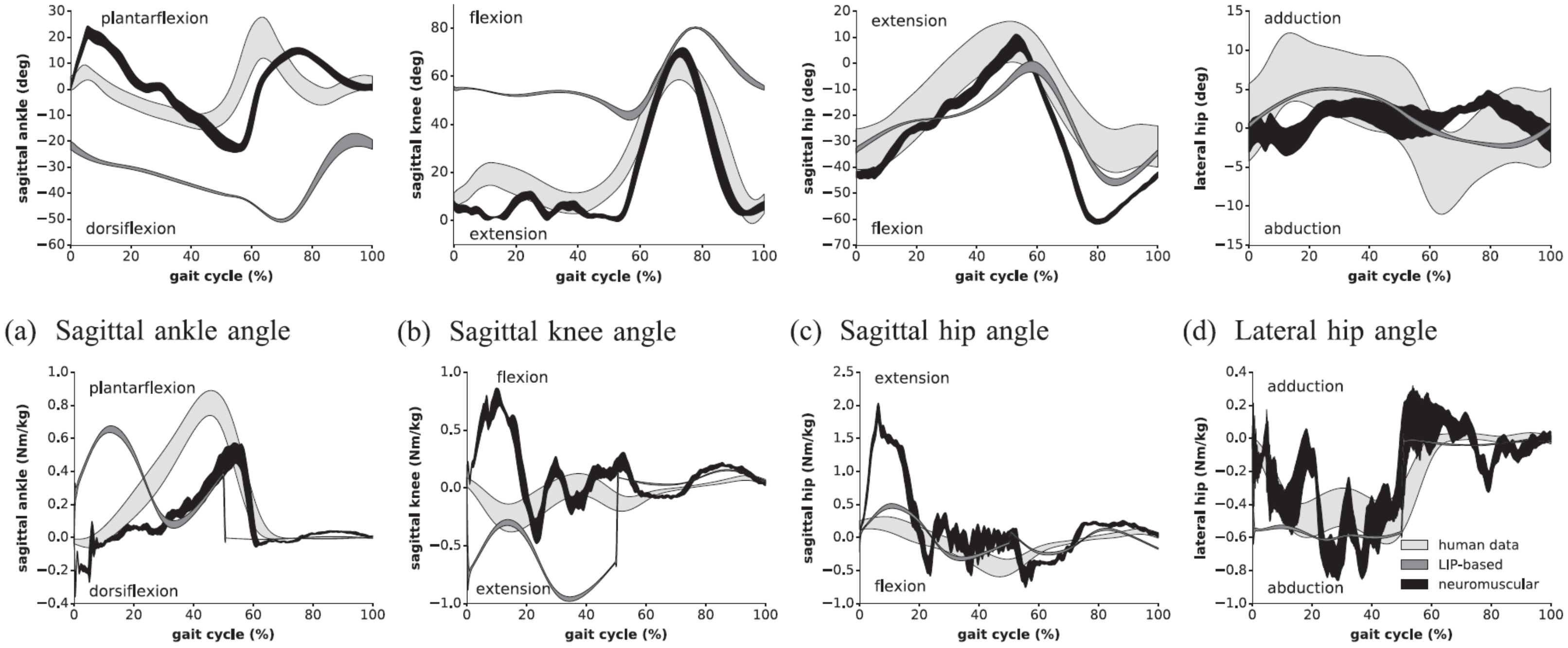


(a) COMAN soleus (b) human soleus (c) COMAN tibialis anterior (d) human tibialis anterior (e) COMAN gastrocnemius (f) human gastrocnemius (g) COMAN vastus (h) human vastus (i) COMAN gluteus (j) human gluteus

Fig. 11. Muscle activation profiles of Experiment 5: the activations obtained with COMAN (neuromuscular controller) are compared with EMGs measured on walking humans (Bovi et al., 2011). Owing to the high variances of these signals, only their average is reported. The dashed line reports the transition from stance to swing.

Experiment 5

- Steady-state gaits comparisons



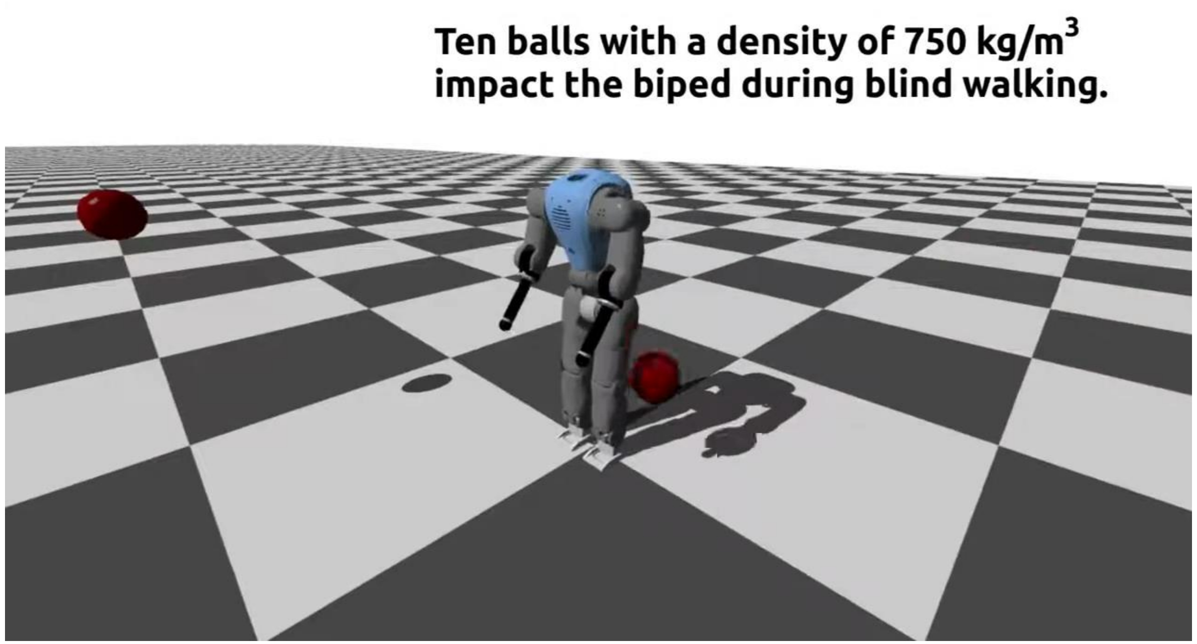
(a) Sagittal ankle angle (b) Sagittal knee angle (c) Sagittal hip angle (d) Lateral hip angle

(e) Sagittal ankle torque (f) Sagittal knee torque (g) Sagittal hip torque (h) Lateral hip torque

Fig. 9. Kinematic and dynamic profiles of Experiment 5: the human data from Bovi et al. (2011) (natural speed) is compared with our neuromuscular controller (0.75 m/s) and with the LIP-based controller (0.31 m/s) from Faraji et al. (2014b). The averages of the different measures are displayed over one gait cycle (starting at right foot strike), augmented by their standard deviations (shaded areas).

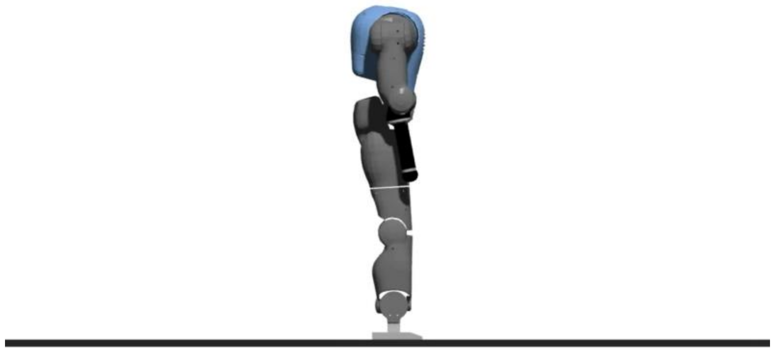
Experiment 6

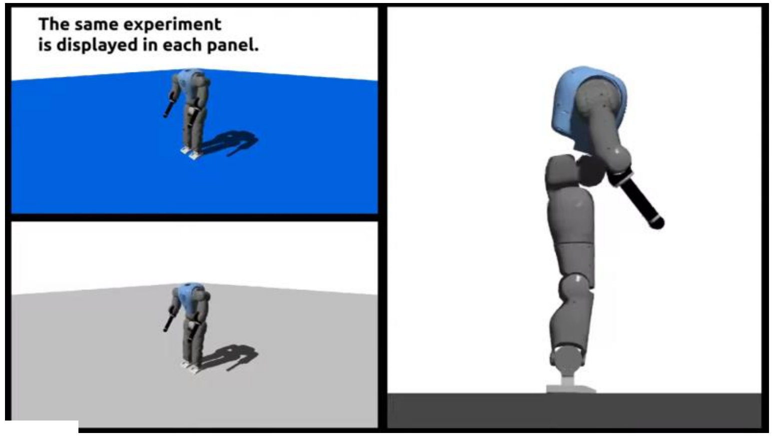
- Resisting pushes



Experiments 7, 8 and 9

- Natural adaptation to stairs, slopes and irregular grounds



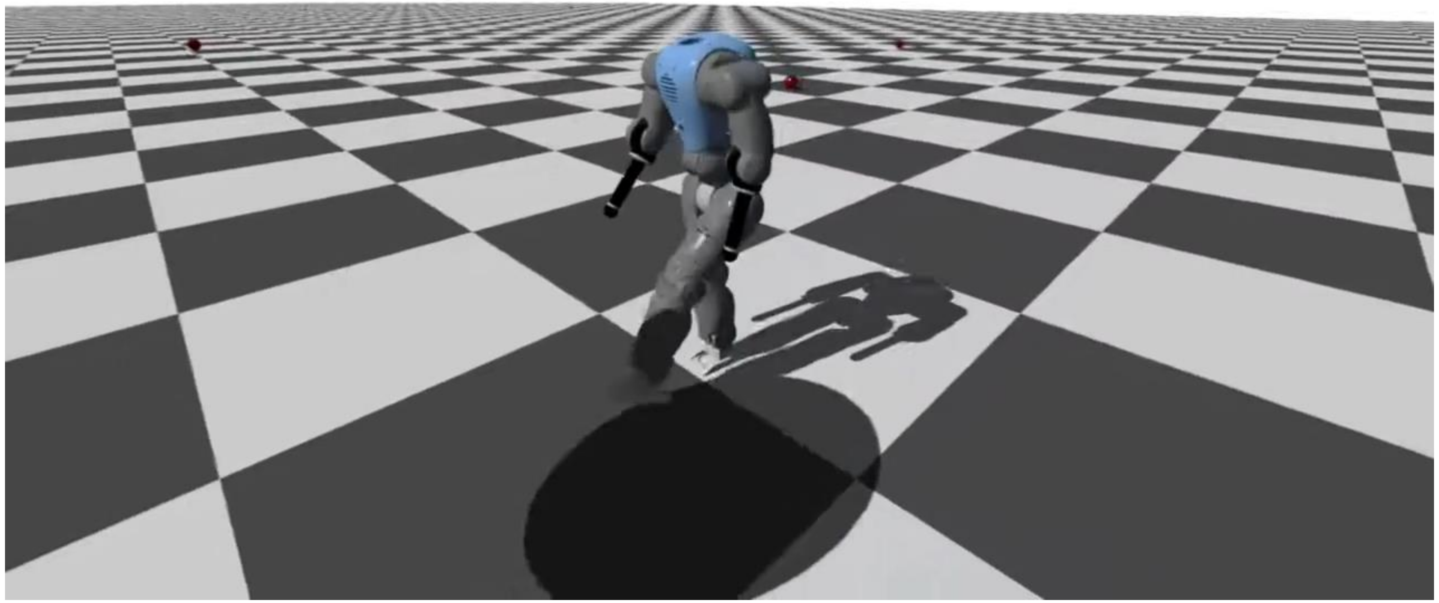


Pros & Cons

Pros	Cons
Human-like Gait	Simplified foot Dynamic
Adaptability and Modulation	Hips rotation differs from human
Simplified Control	Specific to COMAN configuration
Generalized Design	No real life Implementation
Alignment with Biological Principles	High level approximation
Computationally efficient	

Possible exam question

- What is the Hill muscle model and how is it implemented in the controller model?
  - Slide 5
- What are the 3 stages of the full controller ?
  - Slide 9



End

Questions?