Kinematic planning and dynamic control for bipeds

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Motivation

- We propose the architecture capable for the online synthesis of kinematic trajectories of the whole body movements
- We propose an approach for low level control for the bipedal walk, driven by kinematic reference trajectories

Natural looking movements and reactive behavior in real-time

Computer Graphics:

Kinematics animation

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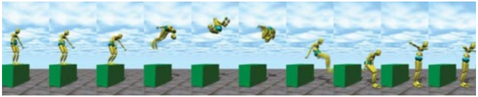
Dynamical systems

+ Physical constraints

(e.g. [Hodgins et al., 1995; Grzeszczuk et al.; 1998; Shao et al., 2005; Terzopoulos, 2009])



[R.Fattal, D. Lischinski, Eurographics, 2006]

Robotics:

Stable autonomous control for physical model

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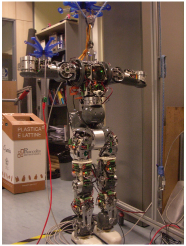
Deformation towards learned kinematic trajectory



Overview of the talk

1. Kinematic primitives and style-preserving motion synthesis

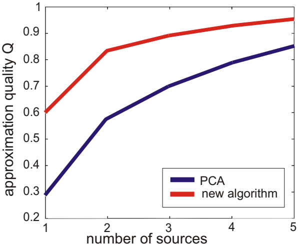
2. **Dynamic control of physical model of humanoid**

Anechoic mixture model

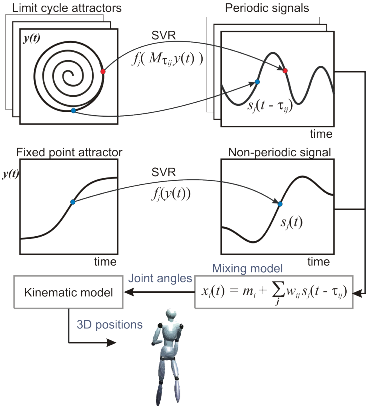
- Learning of movement primitives from motion capture data [Gleicher, 1989; Bodenheimer & Rose, 1997; Arikan et al., 2003; Safanova et al., 2004; Boulić et al. 2005; Shapiro et al, 2004].
- Trajectories approximated by *anechoic mixture model*:

$$\underbrace{\xi_i(t)}_{angles} = m_i + \sum_j w_{ij} \underbrace{\sigma_j\left(t - \tau_{ij}\right)}_{sources}$$

[Omlor & Giese, Neurocomputing, 2007; NIPS, 2006]



Kinematic primitives [Giese et al., 2009; Mukovskiy et al., 2008]



- Source signals generated online by dynamical systems (dynamic primitives). [e.g.: Ijspeert, Nakanishi, Schaal, 2002.]
- Mapping of the solutions of the dynamic primitives onto source signals by support vector regression.

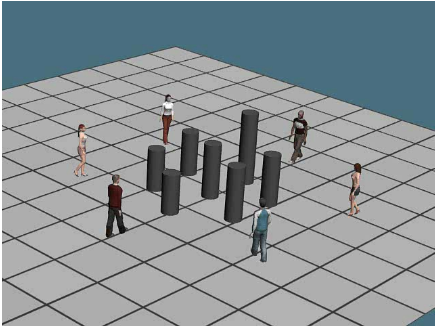
Online motion synthesis

The interpolation between two movement styles (a) and (b), e.g. neutral and emotional walking, can be characterized by the equations

$$m_i(t) = \lambda(t)\, m_i^a + (1-\lambda(t))\, m_i^b$$

$$w_{ij}(t) = \lambda(t)\, w_{ij}^a + (1-\lambda(t))\, w_{ij}^b$$

$\lambda(t)$ specifies the movement style.



The temporal change of the heading direction φ_i of the character i):

$$\frac{d\varphi_i}{dt} = \underbrace{h^{\mathrm{goal}}(\varphi_i, \mathbf{p}_i, \mathbf{p}_i^{\mathrm{goal}})}_{\text{goal-finding term}} + \underbrace{\sum_j h^{\mathrm{avoid}}(\varphi_i, \mathbf{p}_i, \mathbf{p}_j)}_{\text{instantaneous obstacle avoidance}} + \underbrace{\sum_j h^{\mathrm{pcoll}}(\varphi_i, \varphi_j, \mathbf{p}_i, \mathbf{p}_j)}_{\text{predictive obstacle avoidance}}$$

[Giese et al., 2009; Mukovskiy et al., 2009; Park et al., 2008]

Online motion synthesis

Control of step frequency and step phase:

$$\dot{\phi} = \omega_0 \mathbf{1} - m_d (\mathbf{L}^d G(\phi + \phi^0) + \mathbf{c}) - k \mathbf{L}^\phi \phi$$

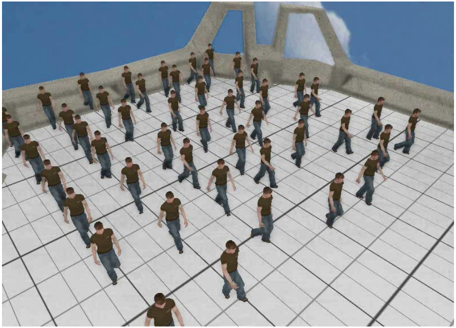
Control of step length:

$$\dot{\mathbf{z}} = \boldsymbol{\omega} g(\boldsymbol{\phi} + \boldsymbol{\phi}^0)(1 - m_z(\mathbf{L}^z \mathbf{z} + \mathbf{c}))$$

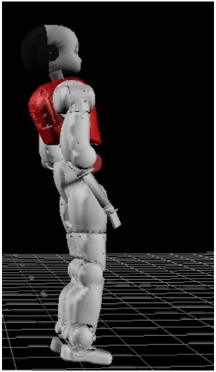
ϕ_i, z_i - gait phases and positions of characters, $\dot{z}_i(t) = \dot{\phi}_i g(\phi_i)$, $G(\phi_i) = \int_0^{\phi_i} g(\phi) d\phi$.

Contraction theory provides the proof of exponential stability of such hierarchically coupled system.

[Giese et al., 2009; Mukovskiy et al., 2010, 2011, 2012]

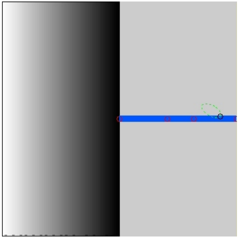


Goal directed movements

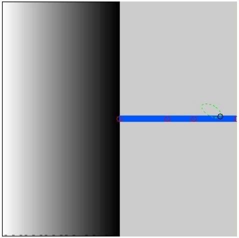


Problem: Excessive number of DoFs allows redundancy in the joints angle space during reaching with the same final configuration of end-effector.

Style-preserving



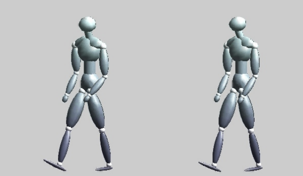
Not style-preserving



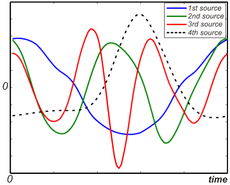
Solution: We learn the augmented style-goal space with dimensionality reduction technique.
We use LWLR to learn the mapping from this space onto **W**.

Reaching-grasping during walking

The two examples of controlled experiments of goal grasping during walking. The goal relative timing in respect to the gait-phase and its position are controlled by VR setup.



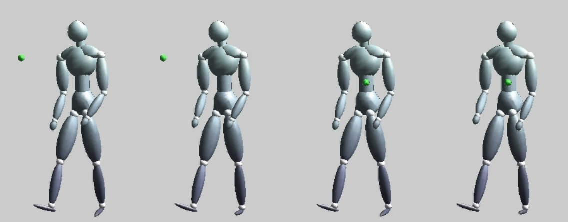
The shift-invariant sources for single step walking-and-grasping.
The bump-like source is black dotted line.



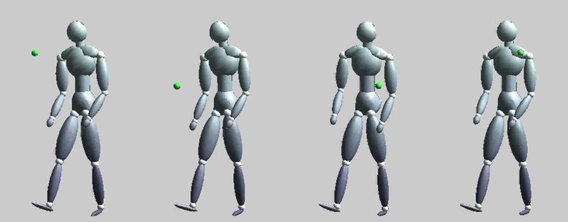
- 3 periodic signals contribute to the all body angles with fixed delays.
- Non-periodic signal (bump-like source) has variable delays.

Reaching-grasping during walking

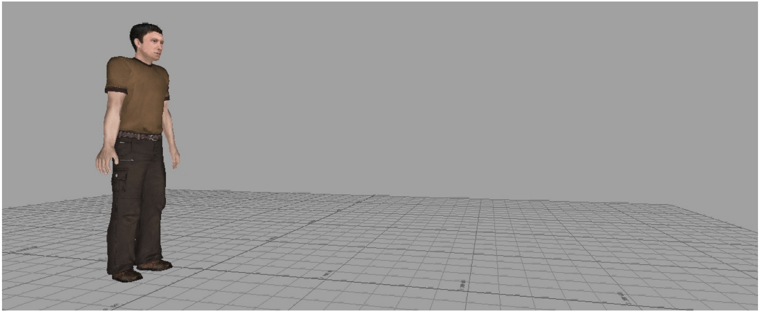
Autonomously controlled grasping of targets at different positions and timings.

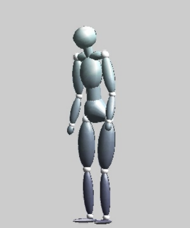


Reaching-grasping for moving targets.



Draw-opening task (with W.Land, T.Schack, Uni. Bielefeld)



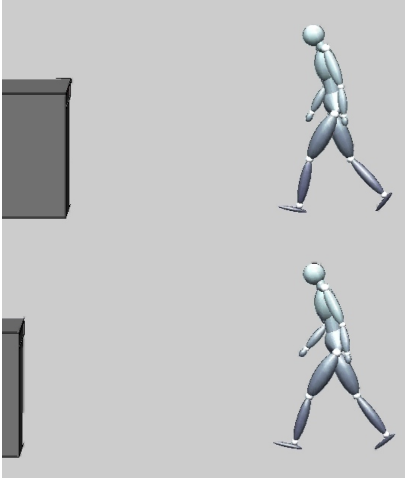


Data set: 3-step sequences:
1) normal walking step;
2) step with the reaching towards the drawer handle;
3) drawer-opening and object grasping.

Draw-opening task: autonomous controller

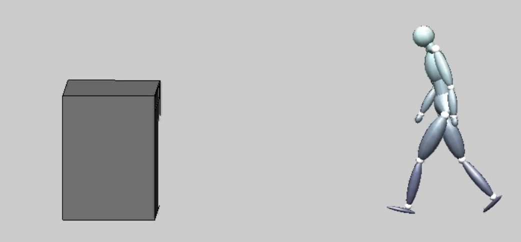
Synthesis:

– the steps lengths are inferred for default target distance
– for the step 1, the weights depend on this step size only
– for steps 2 and 3 the weights depend on the step length of step 2 and timing of steps 2+3



Draw-opening task

Online perturbation scenario.



Autonomous repetition of Step 1 or/and Step 2 if goal is too far away.

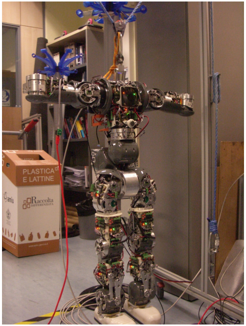
1. **Kinematic primitives and Style-preserving motion synthesis**

2. **Dynamic control of physical model of humanoid**

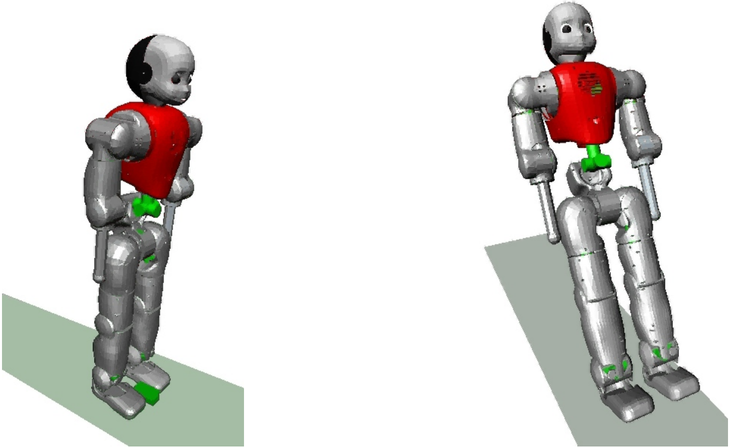
Our approach

- design stable gait with simple event-based switching controller
- deform the gait style dependent on learned motion primitives

CoMan robot, IIT, Genova



Active compliance implemented in the joint space.

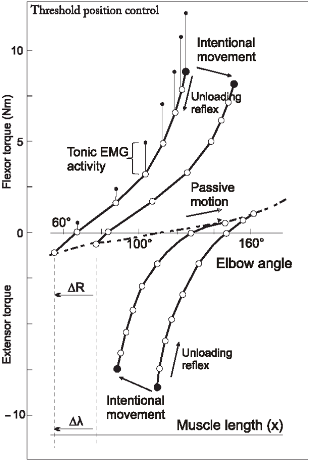


M. Mosadeghzad, G.A. Medrano-Cerda, J.A. Saglia, N.G. Tsagarakis, D.G. Caldwell (2012) "Comparison of Various Active Impedance Control Approaches, Modeling, Implementation, Passivity, Stability and Trade-offs," IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM 2012 , pp. 342-348, July 11-14 2012, Kaohsiung, Taiwan.

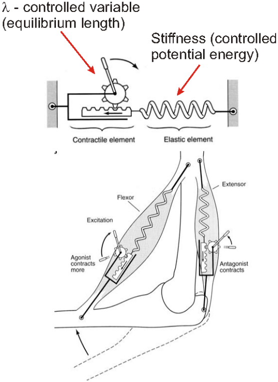
H. Dallali, et al., (2013) "A Dynamic Simulator for the Compliant Humanoid Robot, COMAN," To Appear in ICRA Wokrshop

on Developments of Simulation Tools for Robotics & Biomechanics, Karlsruhe, Germany, May 10, 2013. H. Dallali, et al., (2013)

Equilibrium-point hypothesis (λ-model)

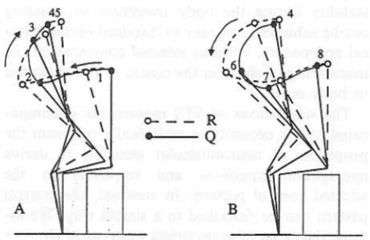


Asatryan D.G., Feldman A.G. (1965) "Functional tuning of the nervous system with control of movements or maintenance of a steady posture: Part I." Biophys. 1965, 10, pp.925-935.



Feldman A.G., Orlovsky G.N. (1972) "The influence of different descending systems on the tonic stretch reflex in the cat." Exper. Neurology, 37(3), pp. 481-494.
Feldman A.G. (1986) "Once more on the equilibrium-point hypothesis (λ-model) for motor control." J. of Motor Behav., 18(1), pp.17-54.

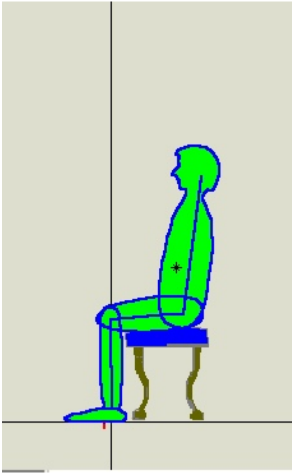
Direct optimization in multi-joint threshold control.



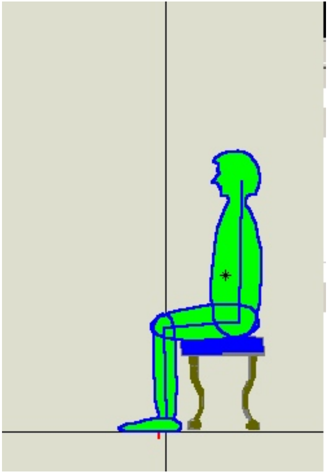
Simulation of sit-to-stand movements (left panel) with reversal (right panel). The referent and actual body configurations (1–8) are shown at time 0.4, 1.0, 1.4, 1.8, 2.43, 2.6, 3.0, and 3.5 s after the onset of movement, respectively. The total movement time is ~4 s.

Feldman A.G., Goussev V., Sangole A., Levin M.F. (2007) "Threshold position control and the principle of minimal interaction in motor control." In: P.Cisek et al. (Eds.) Progress in Brain Research, Vol.165, Ch.17. Pp.267-281. [link]

Simulations. [Feldman et al. 2007]



Sit-to-full stance.

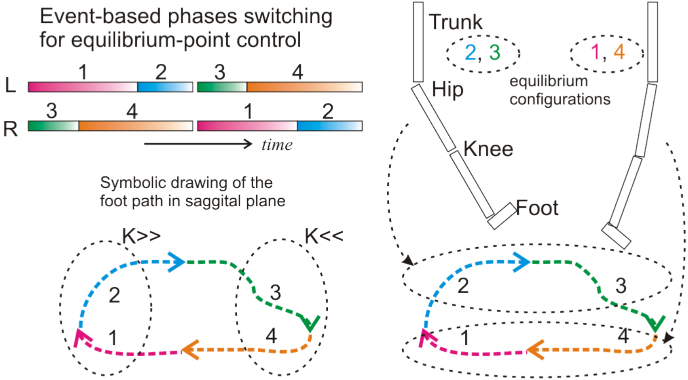


Sit-to-mid stance.

Intermittent equilibrium-point control

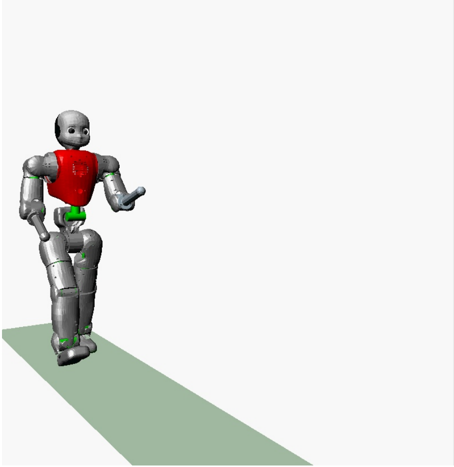
$$F(t) = -\left[K_{ep}(q(t) - q_{ep}) + C\dot{q}(t)\right]$$

where $F(t)$ - resulting force, $q(t), \dot{q}(t)$ - joint angle amplitude and velocity. K_{ep} - time-varying stiffness, C - constant damping term.

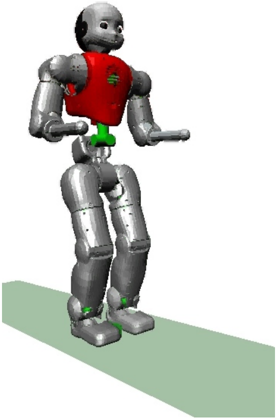


Event-based switching dynamic controller for walking

Normal walk



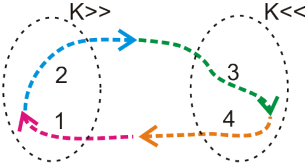
Dynamic balancing



Intermittent E.P. control parameters for the different phases of CoMan model with feet.

P - equilibrium angle (rad),
K - joint stiffness (kgm^2s^{-2}),
damping $C = 11kgm^2s^{-1}$ (Hips/Knees).

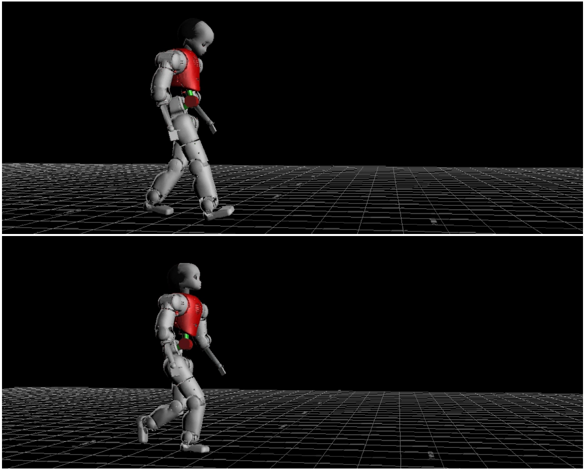
Joint/Phase	1	2	3	4
Hips P	-0.2	1.2	1.2	-0.07
Hips K	100	100	40	80
Knees P	0	-1.2	0	-0.13
Knees K	70	90	70	90
Feet P	0.3	-0.25	0.1	0.2
Feet K	30	30	30	40



If trunk's center of mass is inside feet support interval: legs do 1 & 4 (dependent on which foot is ahead);
Else: legs do 1 & 3, or 2 & 4 (dependent on which foot is ahead and which is on the ground).

Retargeting of the gaits with emotional styles to the skeleton of CoMan robot

Sad and Happy walks.



Deformation of control signal by leaned kinematics.

Total force:

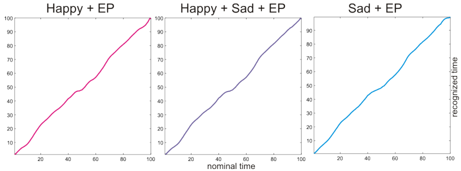
$$F(t) = -\left[K_{ep}(q(t) - q_{ep}(t)) + \underbrace{K_0(q(t) - q_{real}(t)) + C(\dot{q}(t) - \dot{q}_{real}(t))}_{driven \quad terms}\right]$$

$q(t), \dot{q}(t)$ - joint angle amplitude and velocity.

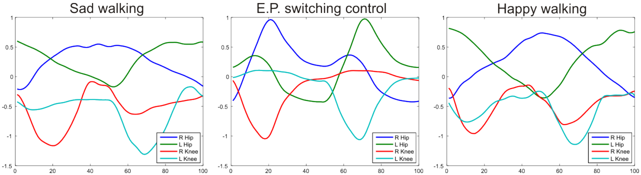
The coupling between high level kinematics and low level E.P. switching control.

$$F(t) = -\left[K_{ep}(q(t) - q_{ep}(t)) + K_0(q(t) - q_{real}(t)) + C(\dot{q}(t) - \dot{q}_{real}(t))\right]$$

Simple linear RBF network infers the phases of the gait cycle, based on hips and knees joints angles and angular velocities:

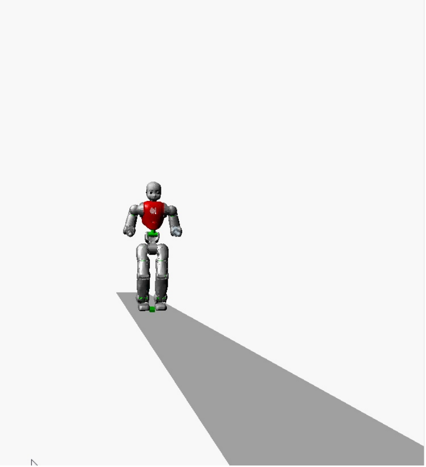


Hips and knees joint angles for different walkers (single gait cycle):

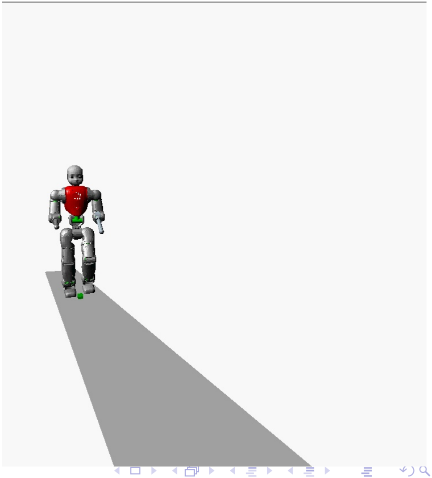


The coupling between high level kinematics and low level E.P. switching control for CoMan model with feet.

Sad walk



Happy walk



Summary

- Flexible realtime synthesis of the kinematics of complex behaviors based on dynamical systems architecture
- Event-based switching force controller based on equilibrium-point control to generate stable basic walk
- The force control can be combined with the kinematic level control for the realization of the stable gaits with different styles

Outlook:

- Implementation of more efficient switching impedance parameters, learned by applying optimization methods.
- Increasing robustness.

Acknowledgments

Thank you for your attention!

- Drawer reaching-and-opening task (in collaboration with W.Land, T.Schack, Uni. Bielefeld, Germany).
- Low-level active compliance control for CoMan (in collaboration with N.Tsagarakis, H.Dalali, Advanced Robotics, IIT, Genova, Italy).
- Contraction theory (in collaboration with J.-J. Slotine, NLS Lab, M.I.T., MA, USA).

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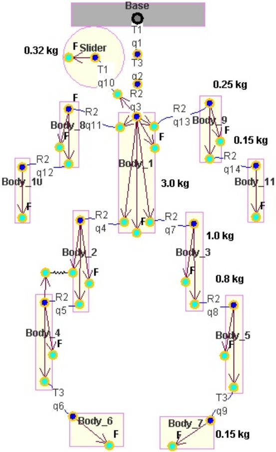
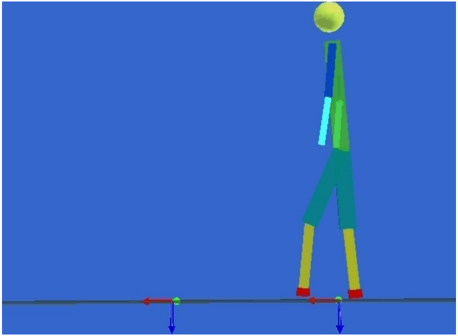
Suppliments

Equilibrium-point control for planar walker

The simplistic dynamic biped walking with intermittent equilibrium-point control.





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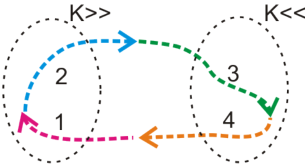
Joint/Phase	1	2	3	4
Hips P	0.05	1.2	1.2	-0.02
Hips K	120	120	40	40
Knees P	0	-0.8	0	-0.1
Knees K	100	100	60	60



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The coupling between kinematics and low level equilibrium-point control for planar walker

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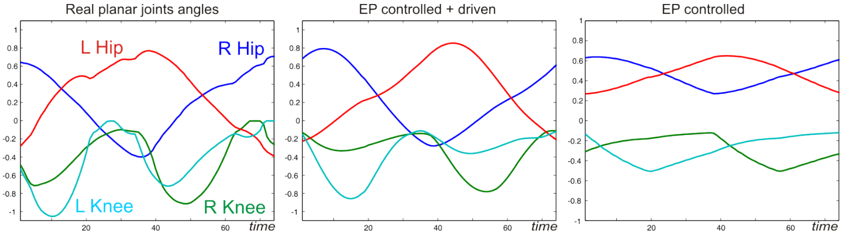

The coupling between kinematics and low level equilibrium-point control for planar walker

EP control driven by sad and happy gait patterns.