Efficient Bipedal Robots Based on Passive-Dynamic Walkers

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How to stabilize 2 legged walking motion?

Trajectory control approach = precise planning and tracking of joint movements

- \+ versatility (different terrains and tasks)
- \- energy inefficient
- \- complex, and require high-frequency controllers

Asimo Honda robot

Passive walking approach = no actuation, stabilize using passive dynamics

- \+ energy efficient
- \+ simple
- \+ natural gait
- \- non controllable, need a slope to actuate

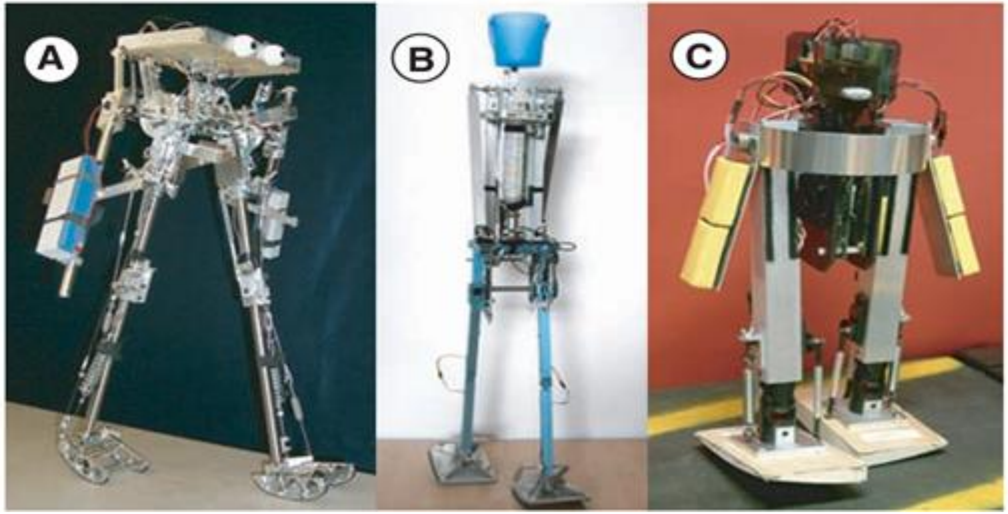
McGeer's passive dynamic walker [4]

Idea: take the best of both worlds

Addition of minimal actuation to passive-based robot designs

➡ Natural human-like gait, energy efficient, and independent of gravitational power

Martijn Wisse, Russ Tedrake, Steve Collins, and Andy Ruina [4]



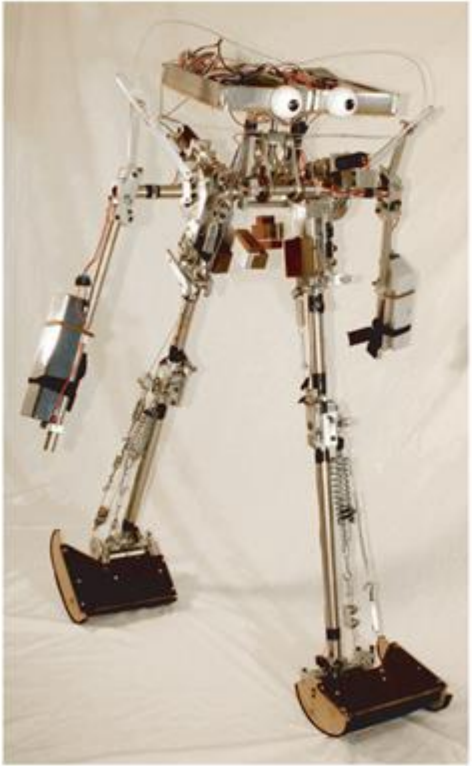
Walkers inspired by passive walkers: **(A)** Cornell biped **(B)** Delft biped **(C)** MIT learning biped [1] [4]

Cornell bipedal walker demo

https://www.youtube.com/watch?v=Y1N-aKK879Q&t=40s&ab_channel=RuinaLab

Cornell bipedal walker - Overview

- Fully autonomous powered bipedal walker
  - 12.7 kg
  - 0.81m legs
- Mechanical design inspired from anthropomorphic geometry and mass distributions
- 5 internal degrees of freedom:
  - 1 hip, 2 actuated ankles, 2 locking knees
- Finite state machine controller:
  - Inputs: 8 switches
  - Outputs: on-off activations of solenoids/motors
  - 20 bits of information per step



Cornell bipedal walker [2]

Cornell bipedal walker - Results

- Achieved steady human-like gait
- Forward velocity of **0.44 m/s** with an average step period of **0.85 seconds**
- Mildly unstable in heading, success rate of 30% of attempts
- Very efficient cost of transport

TABLE I

ESTIMATED SPECIFIC COST OF TRANSPORT, c_{et}, AND MECHANICAL ENERGY EFFICIENCY, c_{mt}, OF SEVERAL LOCOMOTIVE DEVICES*.

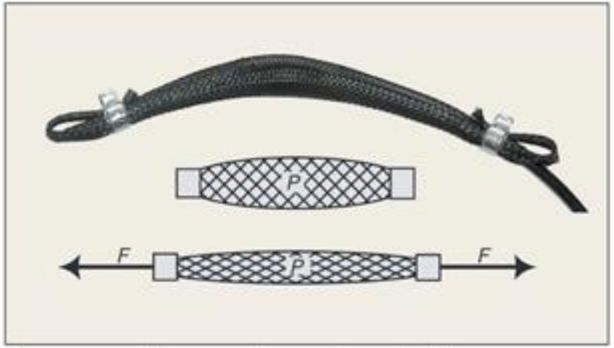
		c_{et}	c_{mt}
Walking Robots:	Honda's Asimo$^{\alpha}$	3.2	1.6
	T.U. Delft's Denise$^{\beta}$	5.3	0.08
	MIT's Spring Flamingo$^{\gamma}$	2.8	0.07
	Our Robot	0.20	0.055
	McGeer's Dynamite$^{\delta}$	-	0.04
Humans$^{\epsilon}$:	Walking$^{\zeta}$	0.2	0.05
Flying Machines:	Modern Helicopter$^{\eta}$	1.6	0.4
	Wright Flyer$^{\theta}$	0.72	0.18
	Boeing 747$^{\iota}$	0.12	0.05
	Modern Glider$^{\kappa}$	-	0.02
Other$^{\lambda}$:	Efficient Auto	0.06	0.015
	Cyclist	0.04	0.01
	Freight Train	0.012	0.003
	Freighter	0.004	0.001

Table of cost of transport of different devices[2]

Introduction video - Delft

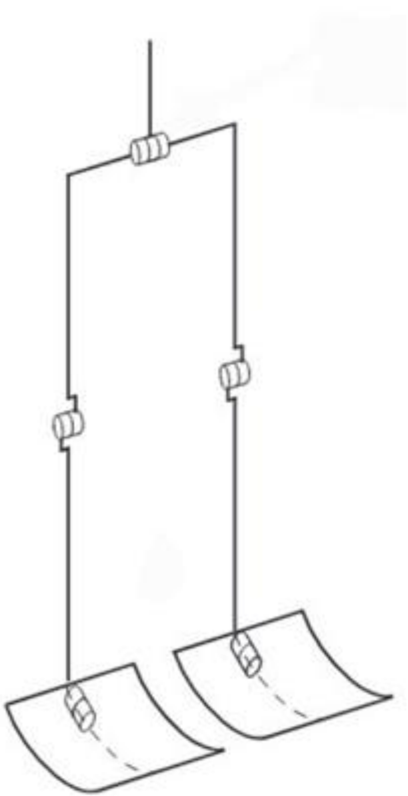
Delft Biped Robot - Mechanical Design

- 5 DOF:
  - 1 hip joint
  - 2 knees joints
  - 2 lateral ankle joints
- Pneumatic hip actuation



McKibben muscle operating principle. [4]

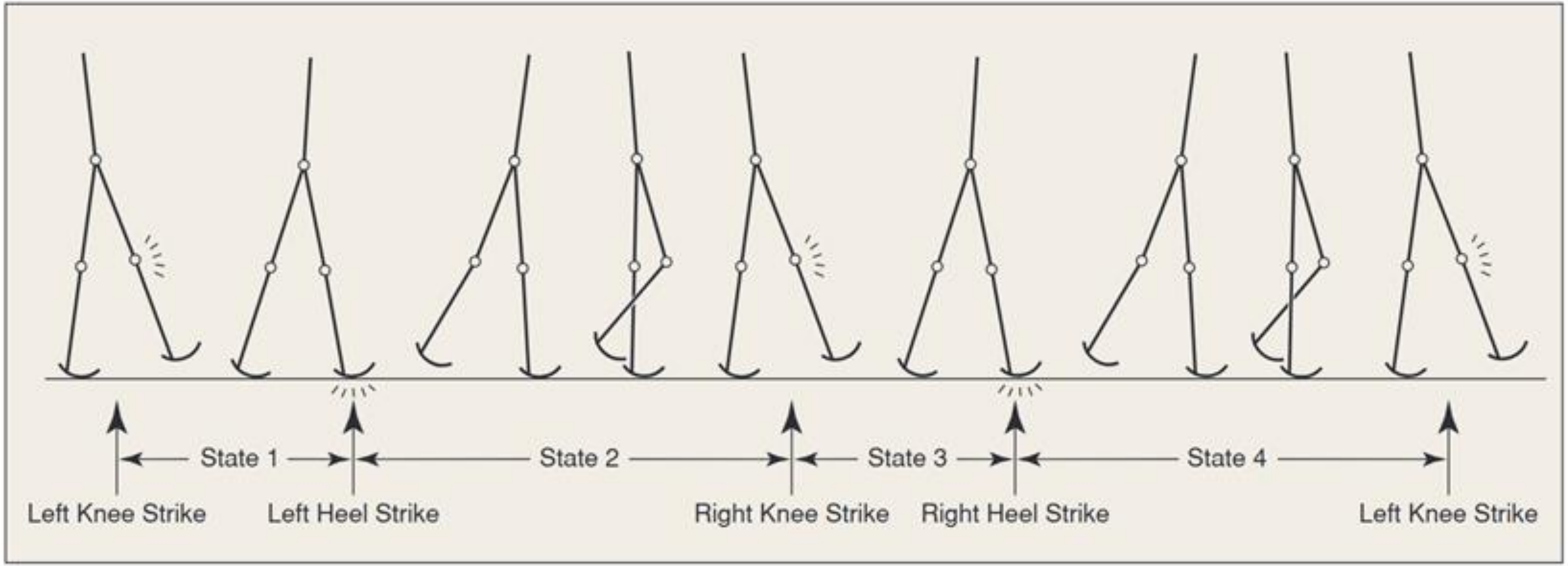
[1]



Robot’s DOF [4]

Delft Biped Robot - Control

- Ground contact sensor on each foot, generates heel strike event
- Opposite knee unlatched
- Opposite muscle pulls leg forward

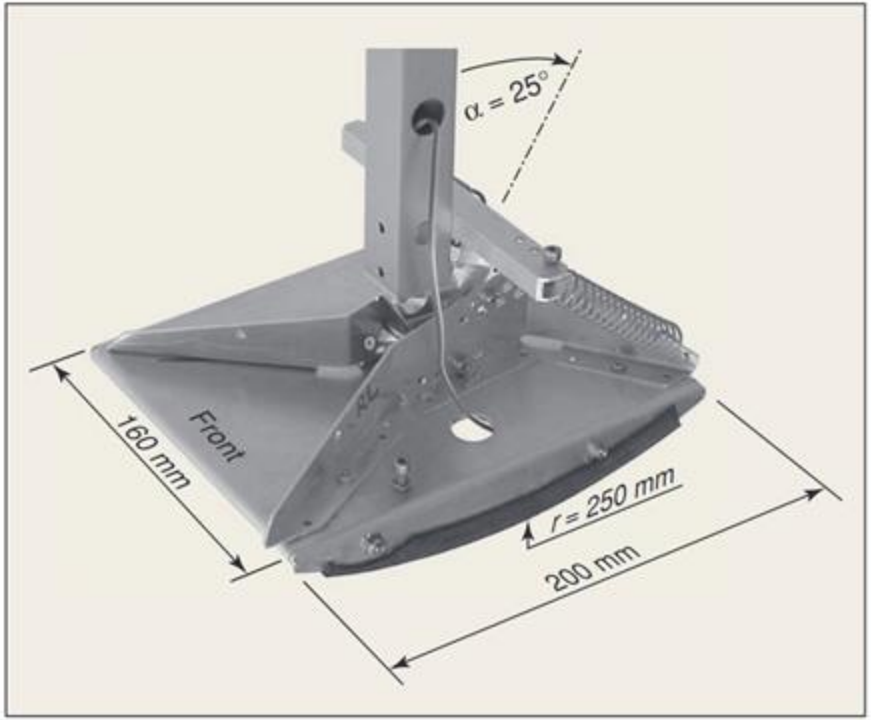


- Controller: State machine with 4 states [4]

Delft Biped Robot - Stability

- Sufficient fore-aft swing leg actuation
    - sagittal + lateral balance

- Kinematic coupling in the ankle between leaning and steering motions:
    - Provides restoring moments, which helps lateral balance



Foot design: lateral ankle joint [4]

Delft Biped Robot - Results

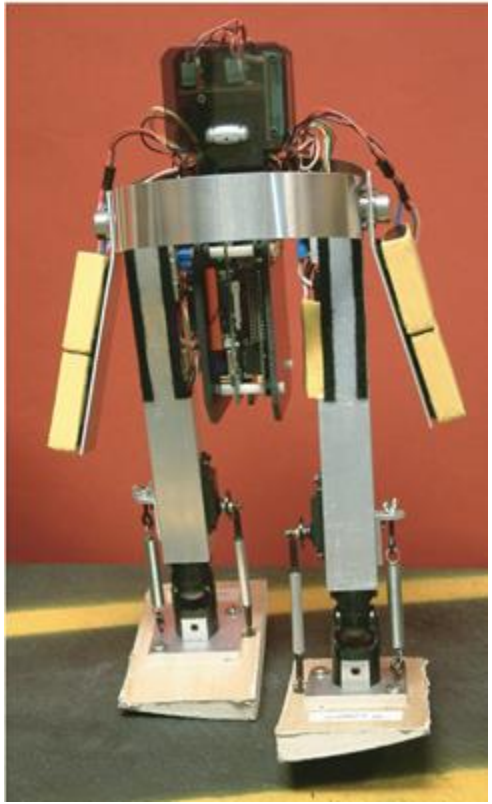
- Natural human like gait
- Energy efficient: Specific Mechanical Cost Of Transport = 0.08
- Can handle floor disturbances up to 6 mm (leg length=0.7 m)
  - On a normal carpeted office floor, takes on average 20 steps before falling.

MIT bipedal walker - Introduction video

EPFL

MIT bipedal walker - Technical design

- Inspired by simple ramp walkers
- 6 internal degrees of freedom :
  - 1 at the hip and two at the ankle for each leg
- 2.75kg, 43cm tall
- Actuators : two servo motors in each ankle
- Sensors : potentiometers at each joint + tilt sensors + rate gyros
- Uses reinforcement learning to adopt a control policy (tuning of 35 parameters)
  - Inputs : body angle & angular velocity
  - Outputs : target angles for the ankle servo motors
  - Cost function : penalizes deviations from reference controller



MIT bipedal robot [3]

EPFL

Improvements made through training

- Before learning (△) :
  - energy loss at each step
  - poor performance
  - angular velocity converges to 0

- After learning (x) :
  - efficiency increase
  - approaching ideal performance
  - satisfying performance obtained in reasonable timeframe (~10 min or 600 steps)

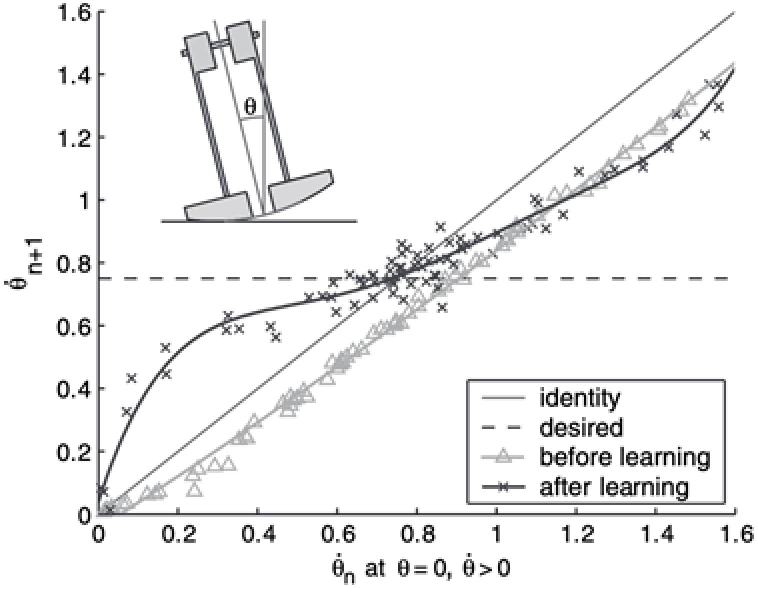


Fig. 3. Step-to-step dynamics of the MIT biped walking in place on a level surface, before (△) and after (x) learning. Shown is the roll angular velocity when the right foot collides with the ground ($\theta = 0$, $\dot{\theta} > 0$) at step $n + 1$ versus step n. Intersections of the plots with the solid identity line are fixed points. The horizontal dashed line is the theoretical ideal; the robot would reach $\dot{\theta} = 0.75\ s^{-1}$ in one step. This ideal cannot be achieved due to limitations in the controllability of the actuation system. On a level surface, before learning, the robot loses energy on every step ($\dot{\theta}_{n+1} < \dot{\theta}_n$), eventually coming to rest at $\dot{\theta} = 0$. After learning, the robot quickly converges near $\dot{\theta} = 0.75\ s^{-1}$ for $0 \le \dot{\theta}_0 \le 1.7\ s^{-1}$.

Results of the learning, shown in [1]

External Citations

- Cited 2629 times
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  - Describes how walking has specific forms derived from passive dynamics
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  - Applies the analysis of passive walkers towards design of exosuits
- J. Reher and A. D. Ames, "Dynamic Walking: Toward Agile and Efficient Bipedal Robots," Annual Review of Control, Robotics, and Autonomous Systems, vol. 4, pp. 535–572, 2021, doi: 10.1146/annurev-control-071020-045021.
  - Uses the examples from the paper to illustrate the benefits of passive walkers compared to ZMP

Pros and Cons

Pros:

- Cornell and Delft robots have very high efficiency and low control complexity
- MIT robot is able to quickly learn simple control policy
- Natural human-like walking

Cons:

- Only traverses level ground
- Cornell and Delft robots lack heading stability and versatility in task performance
- The learning process is power-demanding

Exam Questions

1. How do powered dynamic walkers differ from trajectory controlled robots, and what are their benefits and drawbacks? Slides 3-4
2. What method does the MIT robot use to learn its control policy ? What are the inputs needed and the outputs of such method ? Slide 16

Bibliography

[1] S. Collins, A. Ruina, R. Tedrake, and M. Wisse, "Efficient Bipedal Robots Based on Passive-Dynamic Walkers," *Science*, vol. 307, no. 5712, pp. 1082–1085, 2005, doi: 10.1126/science.1107799.

[2] S. H. Collins and A. Ruina, "A Bipedal Walking Robot with Efficient and Human-Like Gait," *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, 2005, pp. 1983-1988, doi: 10.1109/ROBOT.2005.1570404.

[3] Collins, Steven H., Andy Ruina, Russ Tedrake, and Martijn Wisse. "SUPPORTING ONLINE MATERIAL for Efficient bipedal robots based on passive-dynamic walkers." *Mechanical Engineering, University of Michigan* (2005): 1-8.

[4] Marjin Wisse, Guillaume Feliksdal, Jan Van Frankenhuyzen, "Passive-Based Walking Robot", 2007