清華大學 深圳国际研究生院
Tsinghua Shenzhen International Graduate School

Towards Energy-Efficient and Robust Humanoid Robots

Speaker: Linqi Ye

March 31, 2021

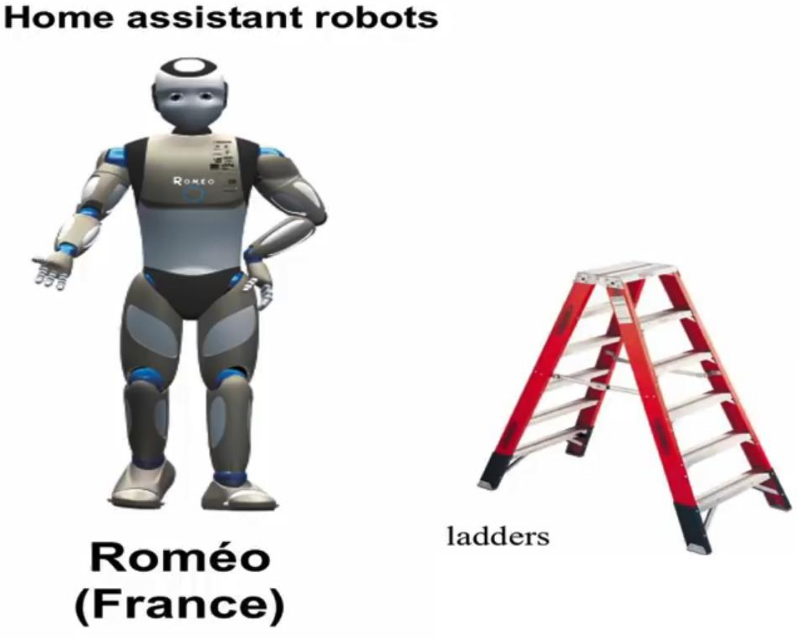
Why Humanoid Robots

Factories and homes built for human use

- Narrow passageways
- Stairs and steps
- Debris

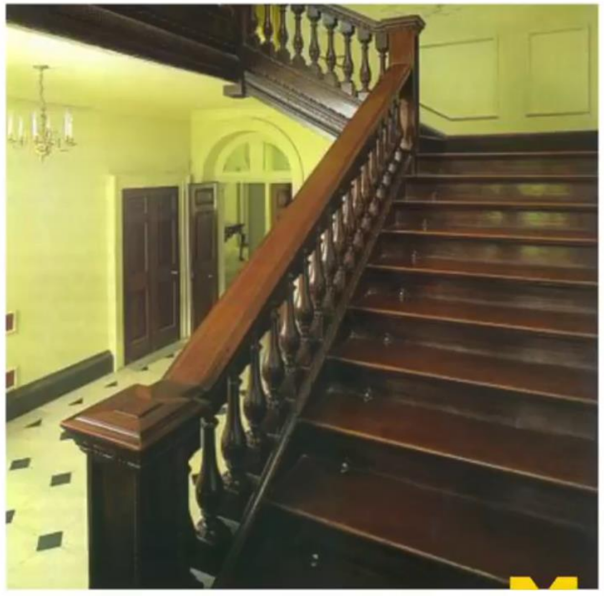
We must build humanoid robots because our world is designed for humans. We step through narrow spaces, we navigate around obstacles, we go up and down steps. Robots on wheels or tracks can't easily move around the spaces we've optimized for our own bodies.

Home assistant robots



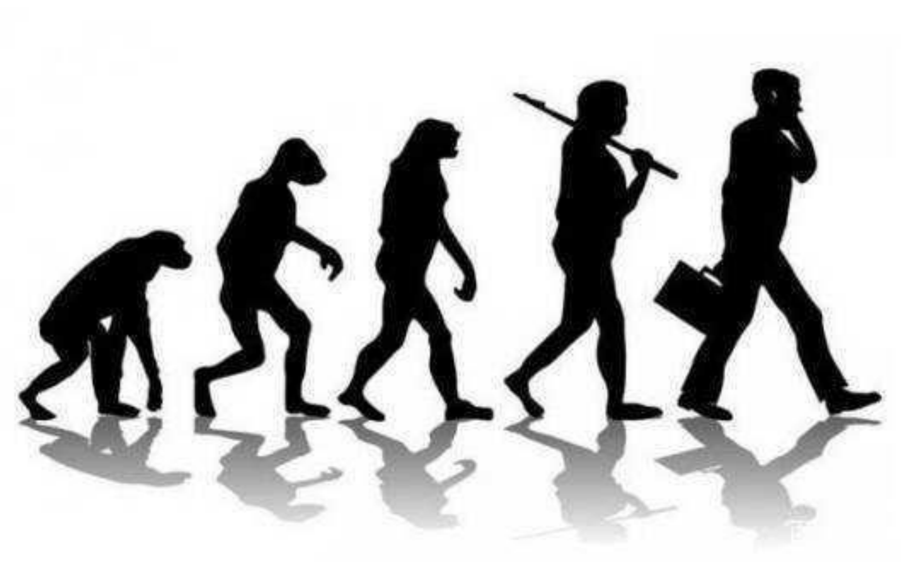
Roméo (France)

ladders

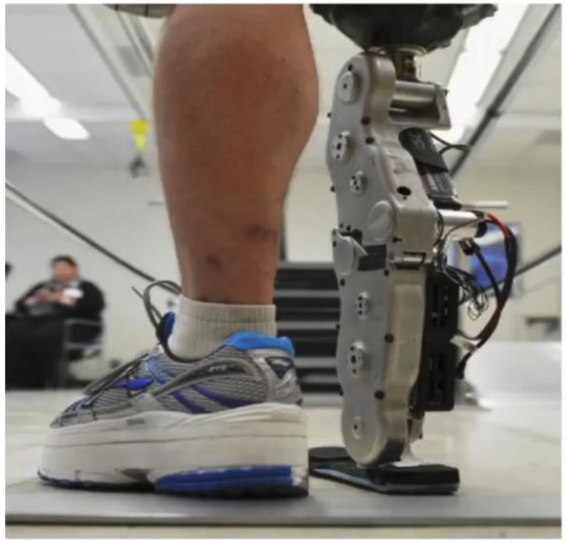


stairs

Why Humanoid Robots



It helps us to understand ourselves!



It helps the disabled to walk again!

State of the Art

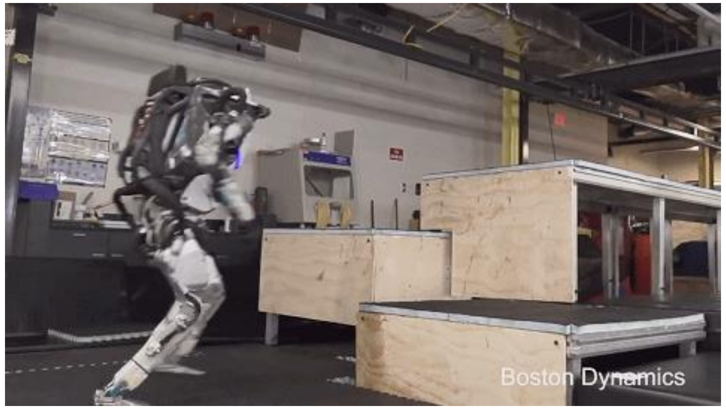
Honda and AIST, Japan

Asimo

HRP-4

Boston Dynamics, US

Petman



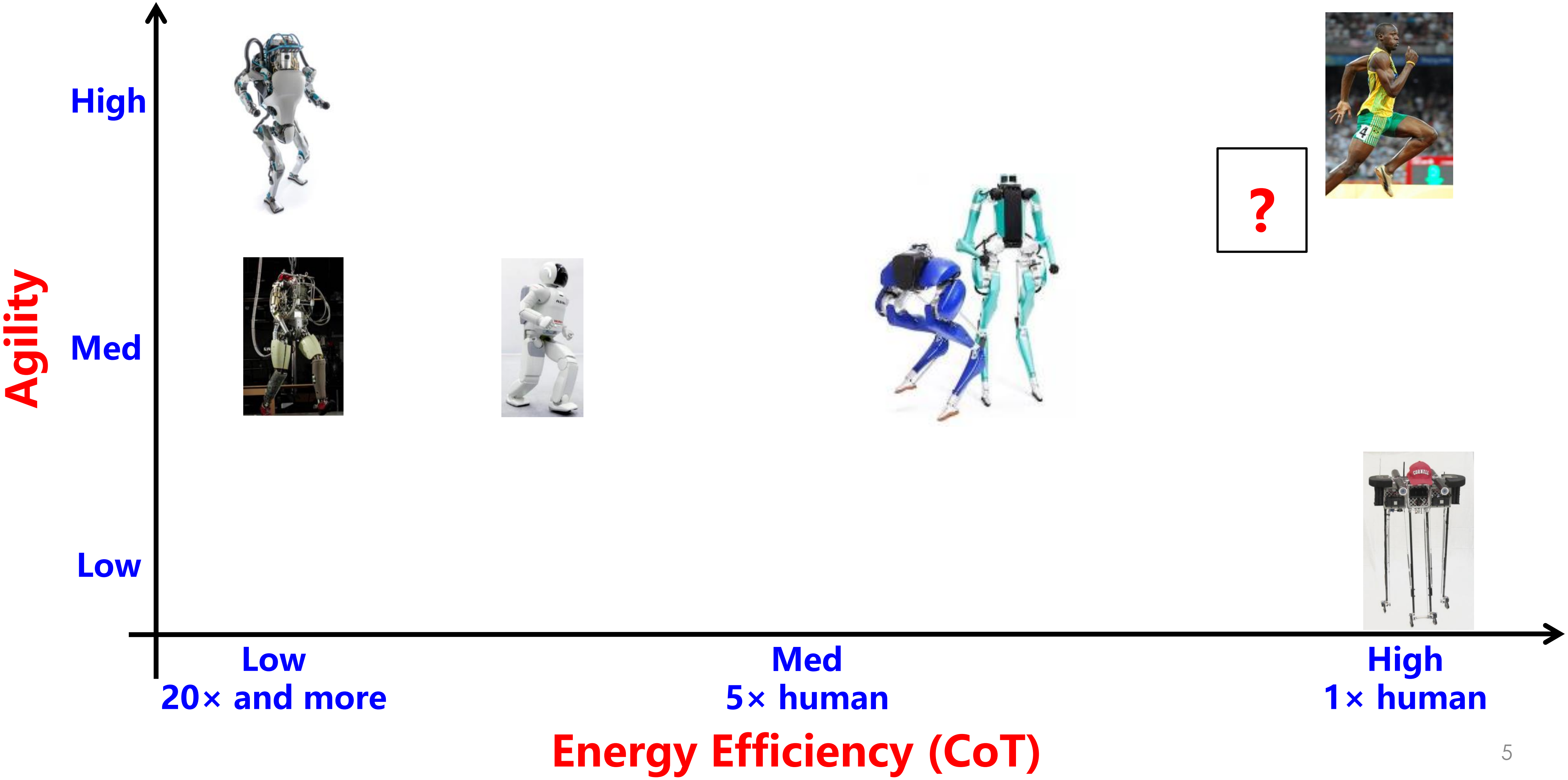
Atlas

Agility Robotics, US

Cassie

Digit

State of the Art



Agility

High

Med

Low

?

Low
20× and more

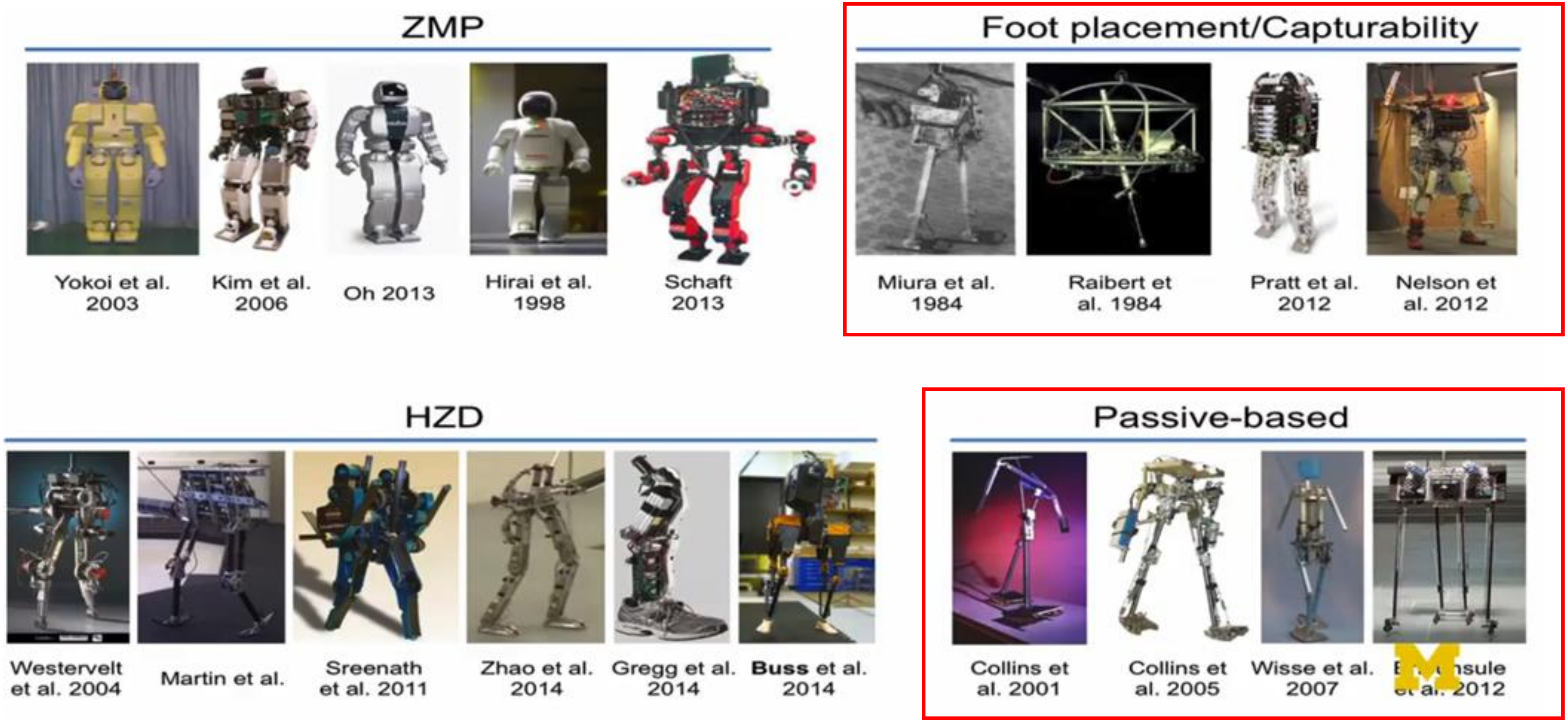
Med
5× human

High
1× human

Energy Efficiency (CoT)

State of the Art

most robust

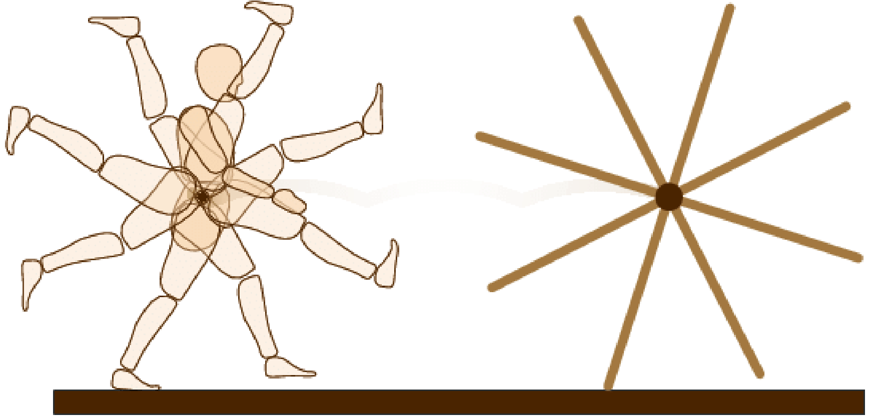


most energy-efficient

Energy Efficiency

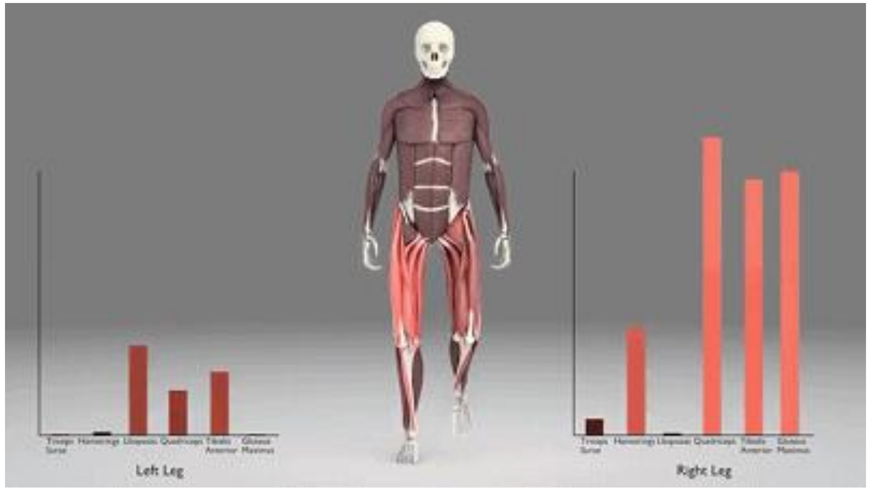
cost of transport (CoT): $\frac{\text{energy used}}{\text{weight} \times \text{distance traveled}}$

Toyota Prius COT = about 0.15
Human COT = about 0.2
Ranger COT = about 0.28
Asimo COT = about 2
Atlas COT = about 20



hydraulic valve

BLDC motors



Key Factors

- **Hardware**

  Actuators, transmissions, electronics
- **Control Algorithm**

  Use the right muscles at right time

Gears

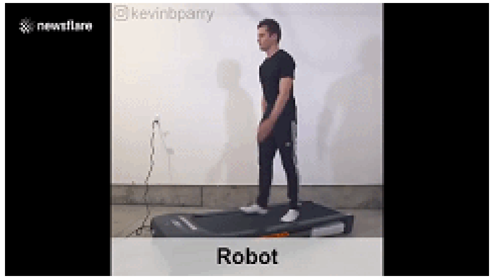
Electronics

Energy Efficiency

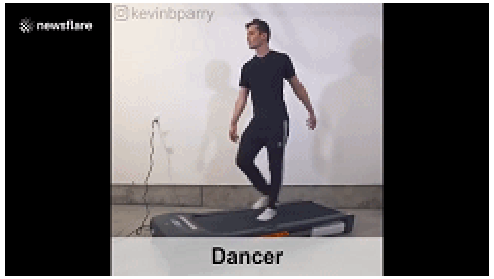

Generic

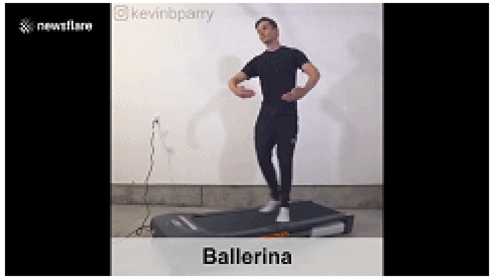

Zombie


Sneak


Robot


Skip

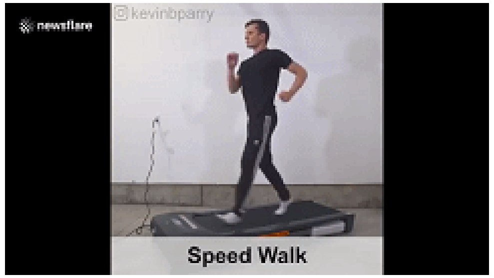

Dancer


Ballerina

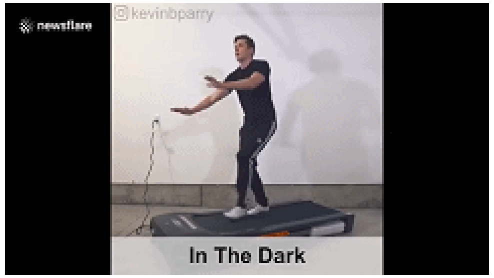

On Hot Coals


Chimpanzee

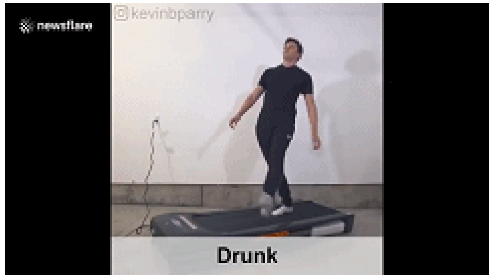

Tight Rope


Speed Walk


SCUBA Diver

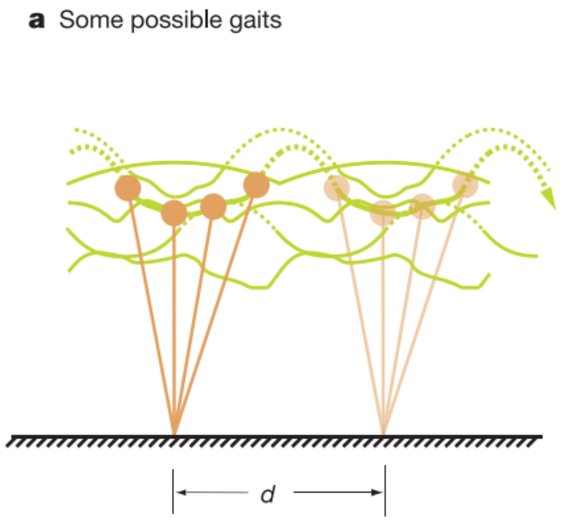

In The Dark

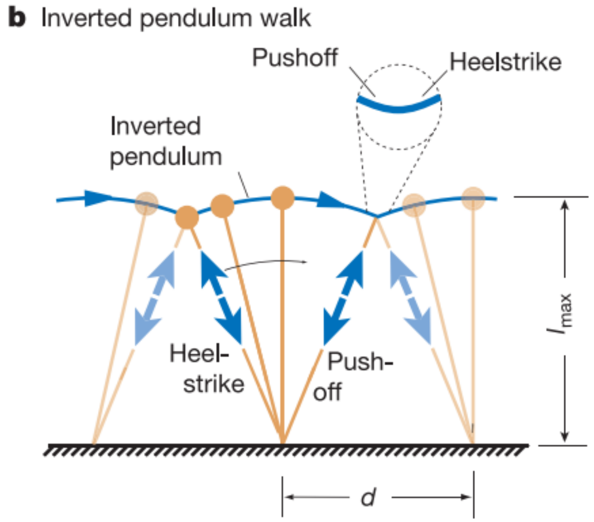

SWAT

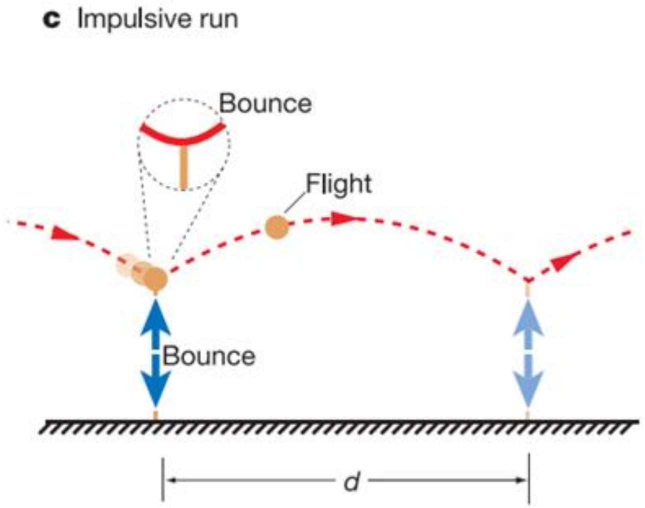

Drunk


Frankenstein's Monster

Energy Efficiency



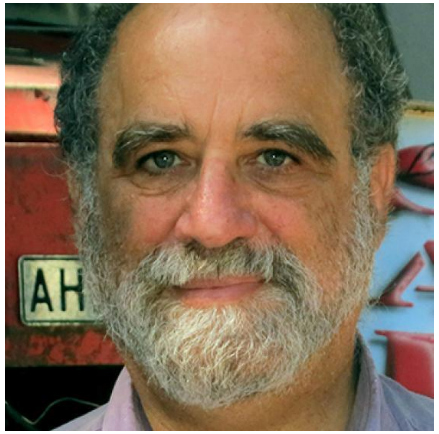




Energy Efficiency

cost of transport (CoT): $\dfrac{\text{energy used}}{\text{weight} \times \text{distance traveled}}$

$$C = \int_0^{t_{\text{step}}} [F(t)\dot{l}]^+ \, \mathrm{d}t / mgd$$



Andy Ruina
Cornell University

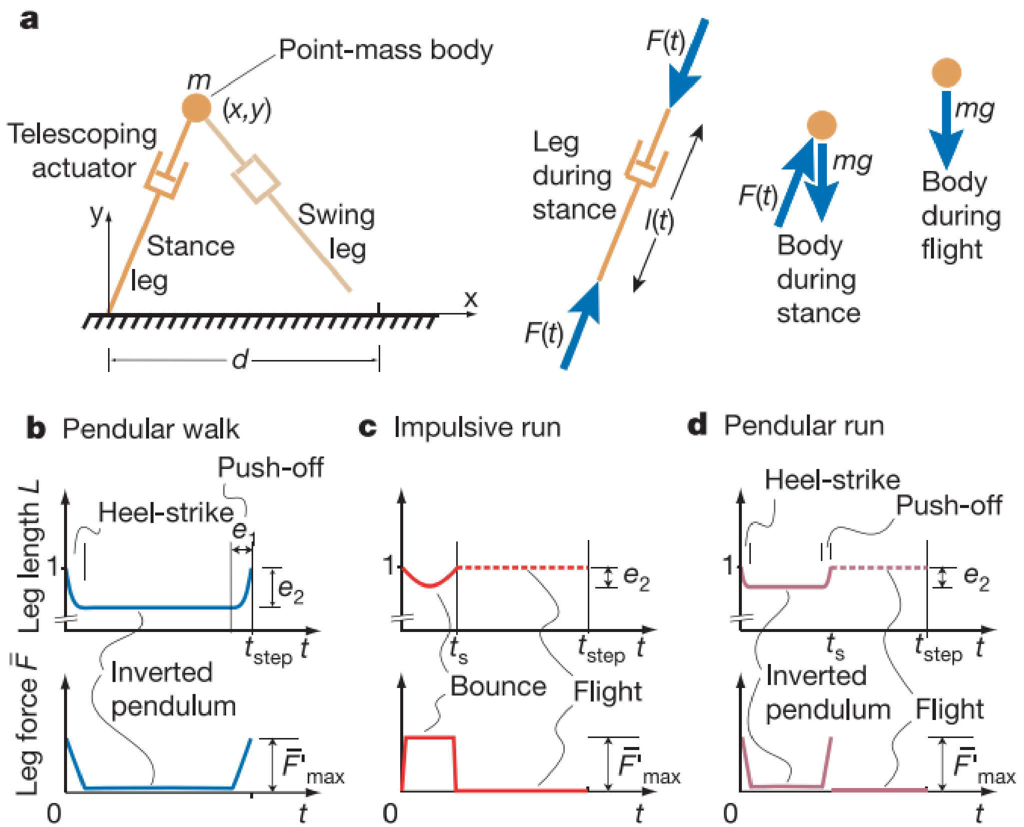


Figure 2 | Point-mass biped model and its optimal solutions.

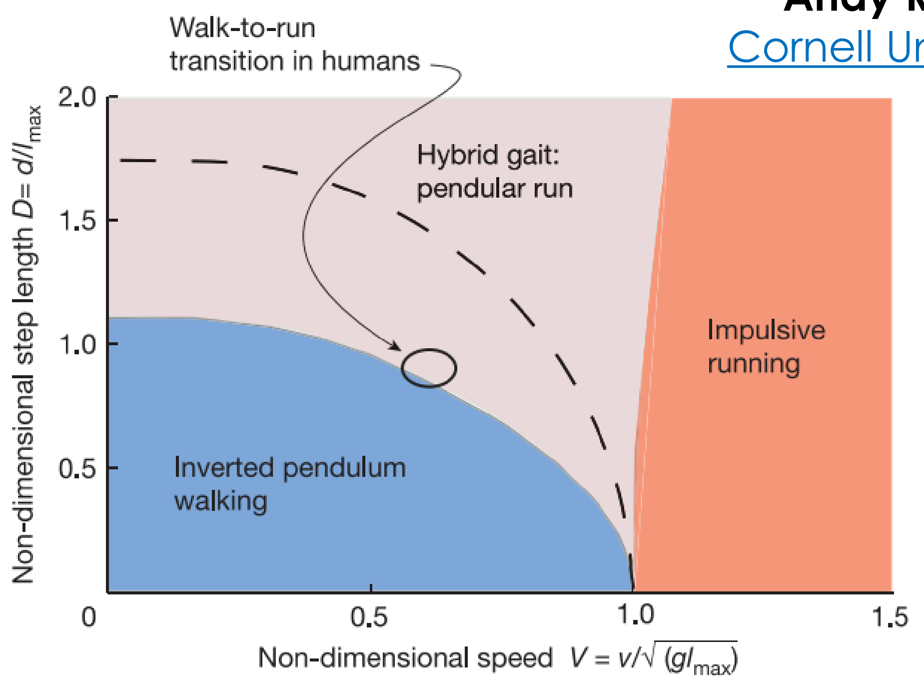


Figure 3 | The regions in which each of the three collisional gaits are optimal.

Srinivasan, Manoj, and Andy Ruina. “Computer optimization of a minimal biped model discovers walking and running.” *Nature* 439.7072 (2006): 72-75.

Humanoid Robots in Cornell University

Passive Walker
1996-2000

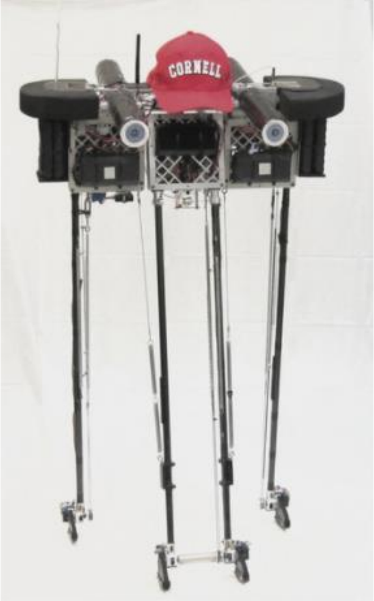
Four legged passive "biped" with knees. Walks downhill.

Passive Walker
with Knees
1999-2001

Two legs and knees. The most advanced passive-dynamic robot to date. Walks downhill.

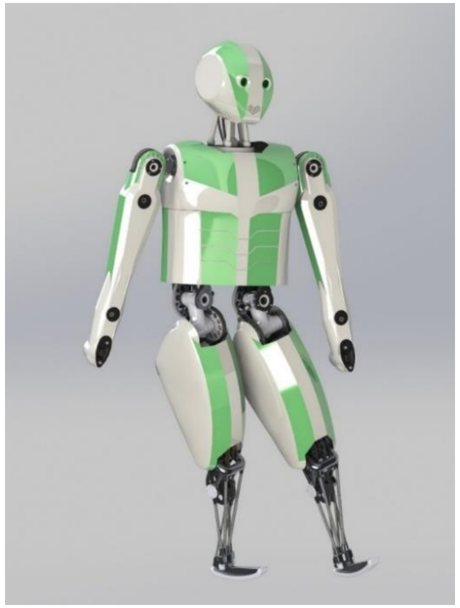
Powered Biped
with Knees
2003-2005

Ankle powered, minimally controlled. Walks on level ground.



Cornell Ranger
2001-2012

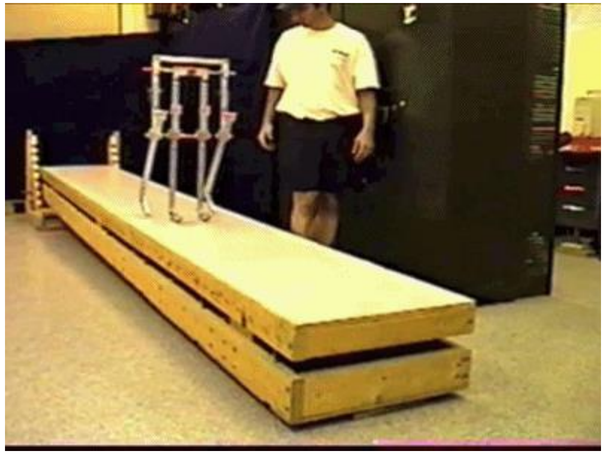
Powered, 4-leg "biped", no knees. Walks on level ground. Radio-control steering by twisting inner legs.



Cornell Tik-Tok
2012-now

Goal: Efficient, robust, and nimble legged robot. Cost of Transport in simulation ≈ 0.25. 12 actuated joints. Brushless DC motors. Chain Drives.

Passive Walking



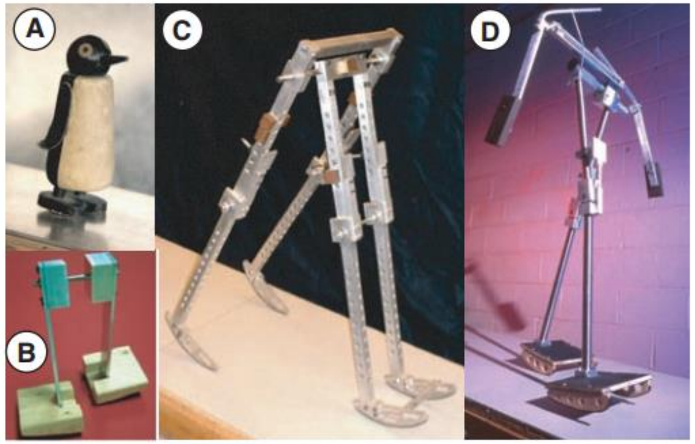


Fig. 1. "Ramp-walking," "downhill," "unpowered," or "passive-dynamic" machines. Our powered bipeds are based on these passive designs. **(A)** The Wilson "Walkie" (*27*). **(B)** MIT's improved version (*28*). Both (A) and (B) walk down a slight ramp with the "comical, awkward, waddling gait of the penguin" (*27*). **(C)** Cornell copy (*29*) of McGeer's capstone design (*7*). This four-legged "biped" has two pairs of legs, an inner and outer pair, to prevent falling sideways. **(D)** The Cornell passive biped with arms [photo: H. Morgan]. This walker has knees and arms and is perhaps the most humanlike passive-dynamic walker to date (*8*).

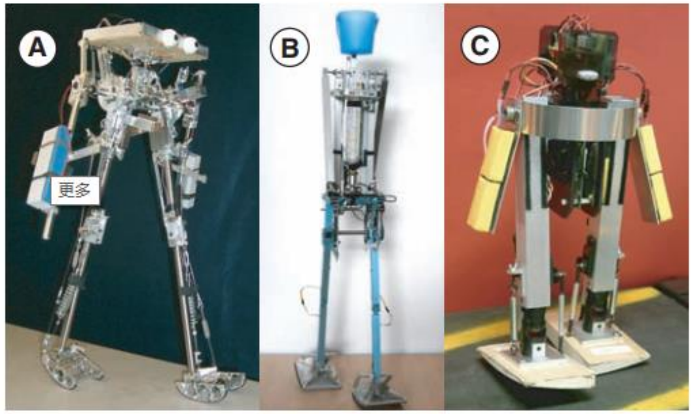


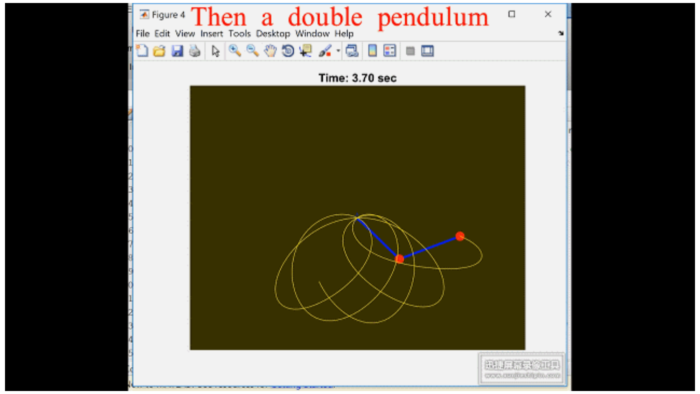
Fig. 2. Three level-ground powered walking robots based on the ramp-walking designs of Fig. 1. **(A)** The Cornell biped. **(B)** The Delft biped. **(C)** The MIT learning biped. These powered robots have motions close to those of their ramp-walking counterparts as seen in the supporting online movies (movies S1 to S3). Information on their construction is in the supporting online text (*9*).

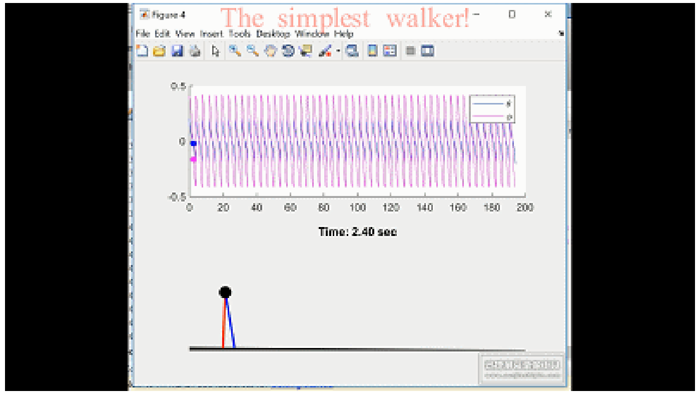
Gliders+Engines→Airplanes

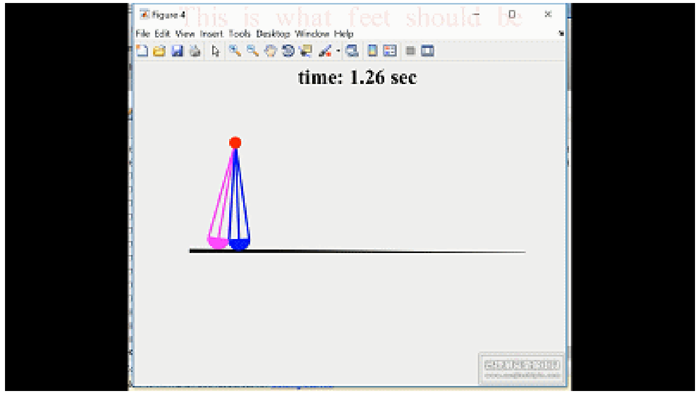
Passive walkers+Actuators→Human-level robot

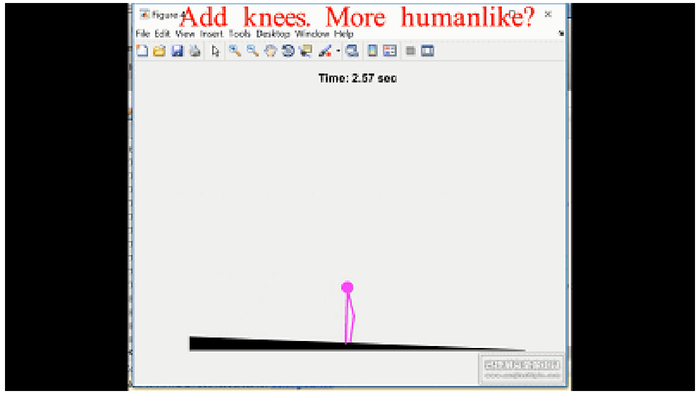
Collins, S., Ruina, A., Tedrake, R., & Wisse, M. (2005). Efficient bipedal robots based on passive-dynamic walkers. *Science*, *307*(5712), 1082-1085.

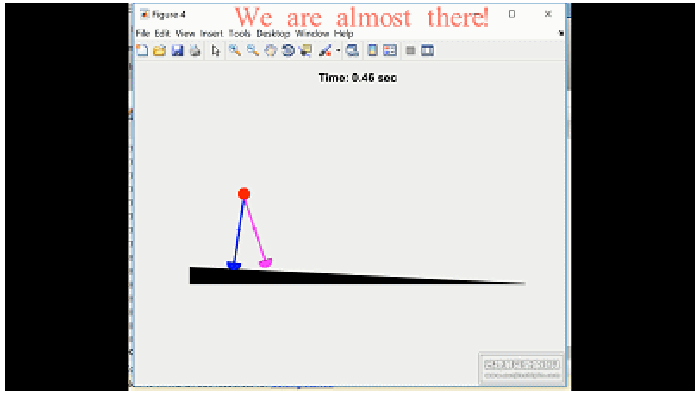
Passive Walking

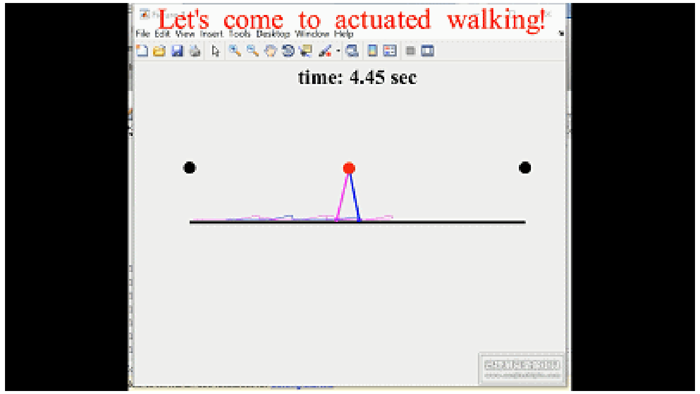

Then a double pendulum


The simplest walker!


This is what feet should be

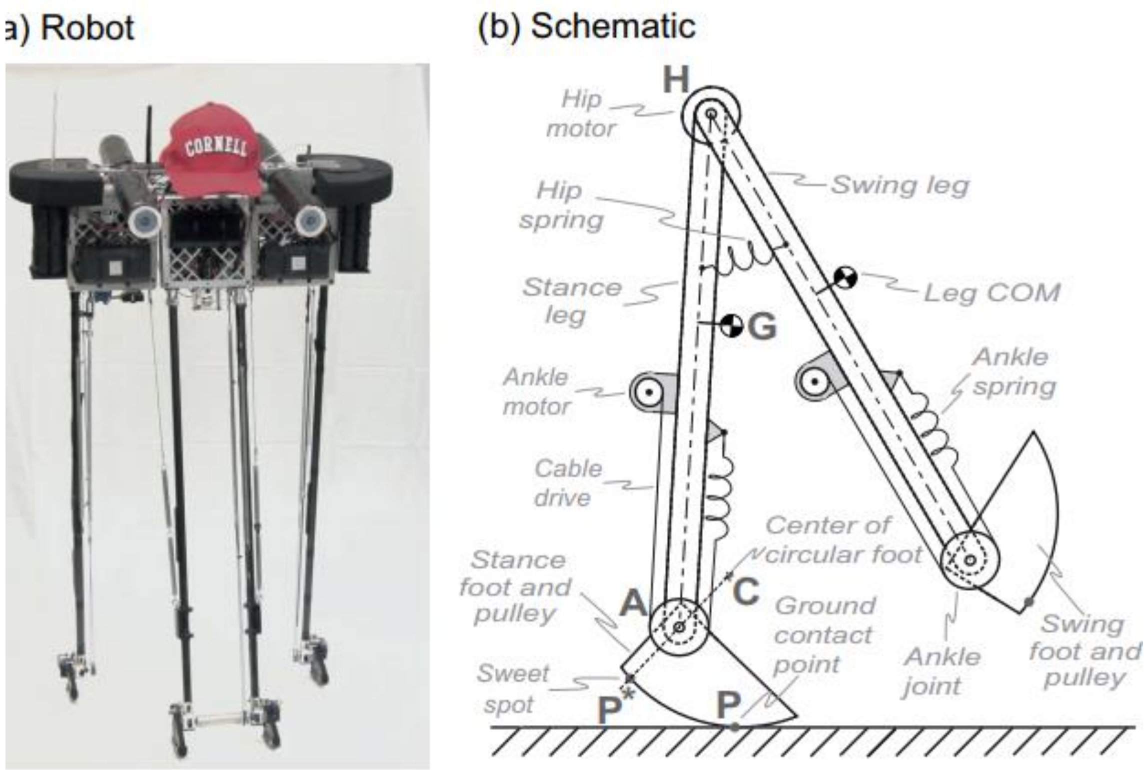

Add knees. More humanlike?


We are almost there!


Let's come to actuated walking!

The Most Energy-efficient Biped

Ranger walks non-stop 65.2 km ultra-Marathon on May 1-2, 2011



Bhounsule, P. A., Cortell, J., Grewal, A., Hendriksen, B., Karssen, J. D., Paul, C., & Ruina, A. (2014). Low-bandwidth reflex-based control for lower power walking: 65 km on a single battery charge. *The International Journal of Robotics Research*, *33*(10), 1305-1321.

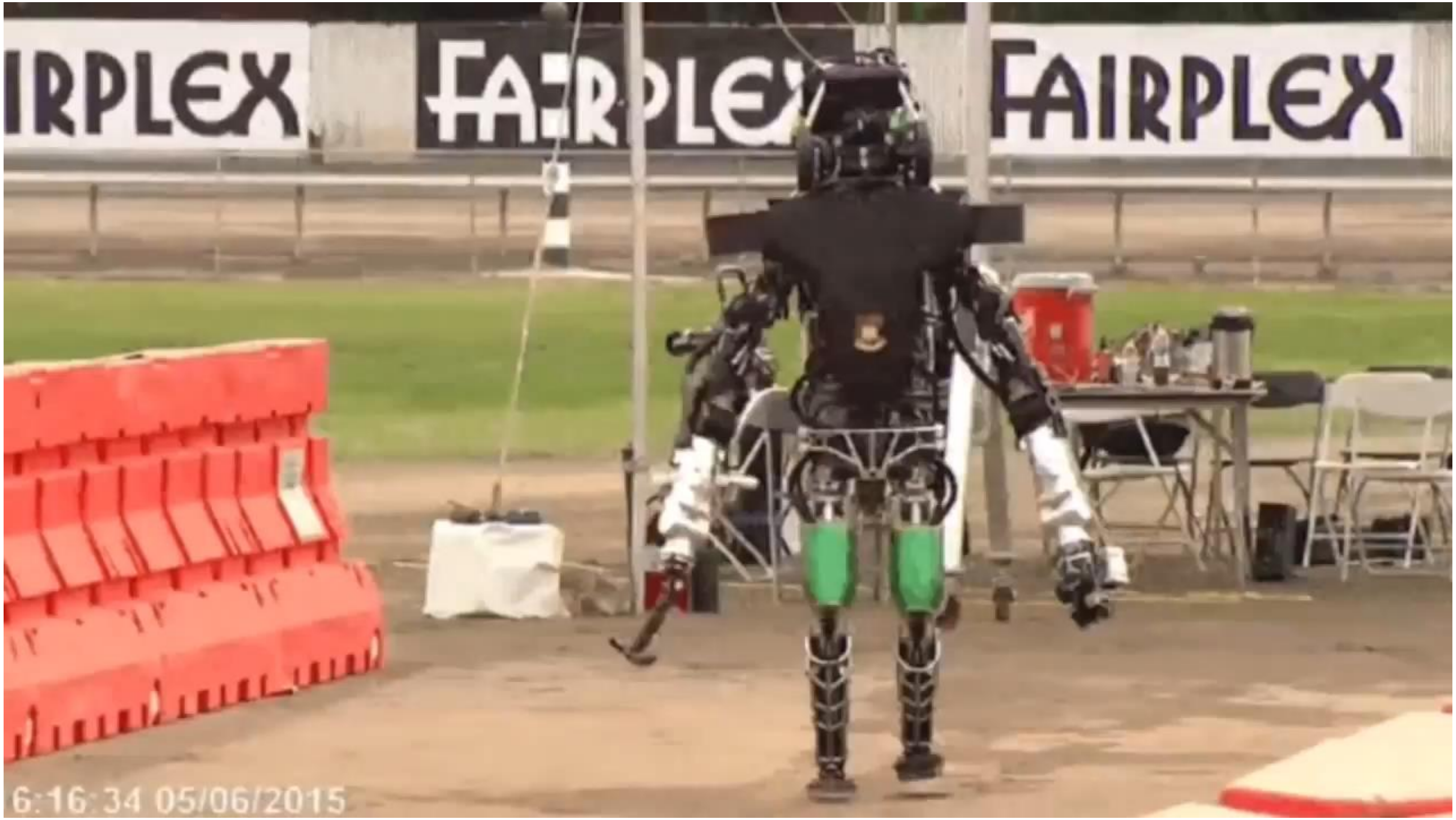
The Most Energy-efficient Biped

Total steps	186,076
Total time	30 hrs 49 min 02 seconds
Total distance	65.24 km
Average speed	0.59 m/s
Cost of transport (COT)	0.28, COT = Energy/(weight * distance). Includes energy to run the motors and all electronics
Total Robot mass	9.91 kg
Power	16.0 watts total, less than a laptop computer.
Battery	25.9V Lithium-ion, 2.8 kg, 493 watt-hours
Comparisons	Toyota Prius COT = about 0.15 Human COT = about 0.2 (a bit better than Ranger) Asimo COT = about 2 (54 kg@ 1.5 m/s, 1.8 kW) Atlas COT = about 20 (12.8 miles, 4 gal gas, 110 kg)

Cornell Ranger, 2011

4-legged bipedal robot

Robust Balance



Robust Balance

Balance strategies for a biped:

1. Apply ankle torques. Base of support diameter up to 0.2 m
2. Bend the upper body/spin arms.
   Effective base of support up to 0.2 m
3. Foot placement. Effective base of support up to 1 m

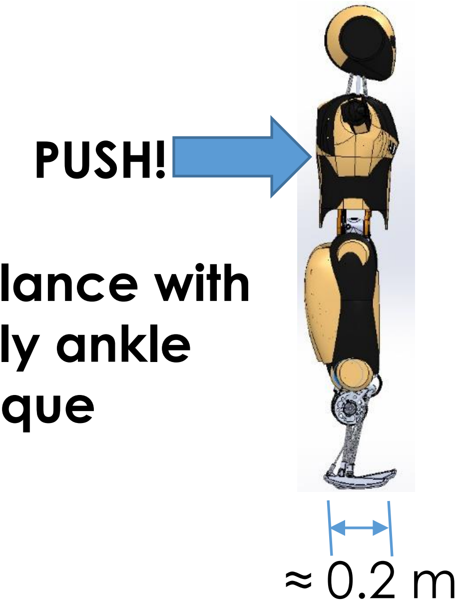
Therefore robust balance mainly depends on fast leg swing.

How quickly should the legs be able to swing?

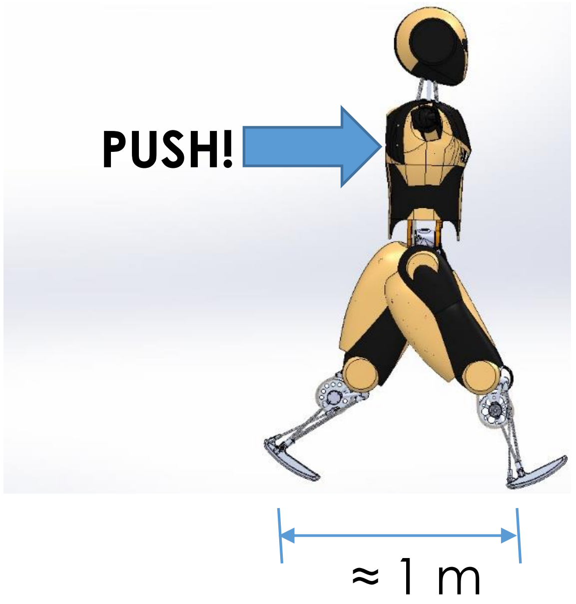
- Fastest human leg swing time is about 0.2 seconds for 1 radian
- Boston Dynamic BigDog and Atlas swing times are about 0.3 seconds.

How to make legs swing fast?

- High joint actuator torque and speed (high power)
- Small leg angular inertia



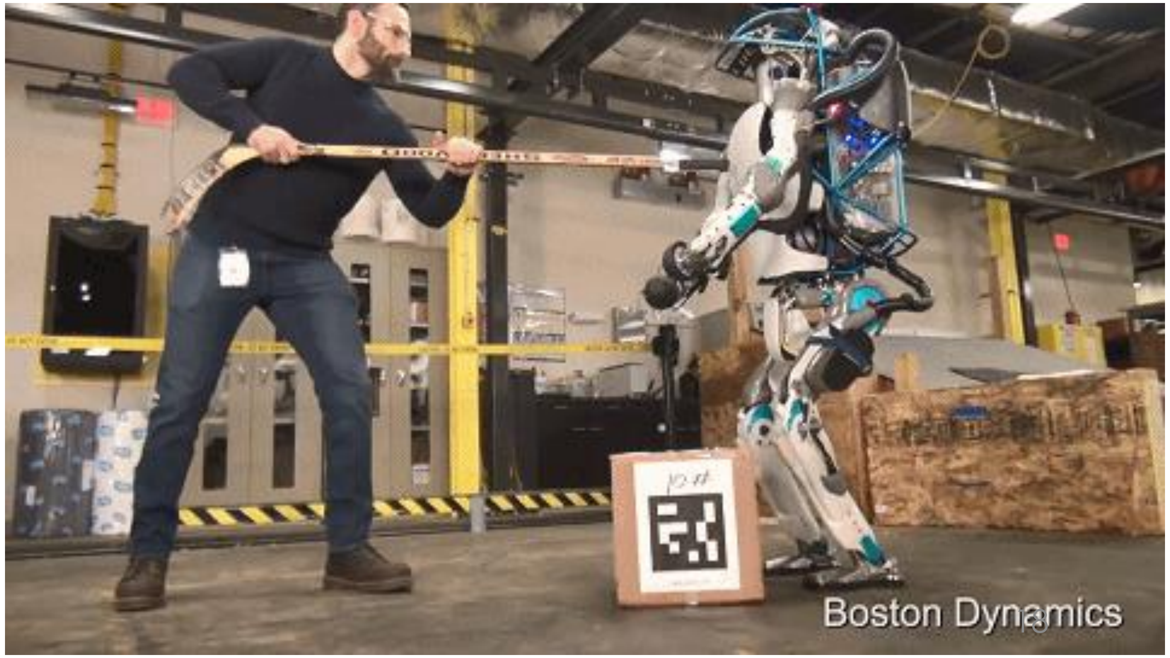
Balance with only ankle torque



It's better to take a step!

The Most Robust Biped

Marc Raibert
Boston Dynamics



Foot Placement Control

The neutral point

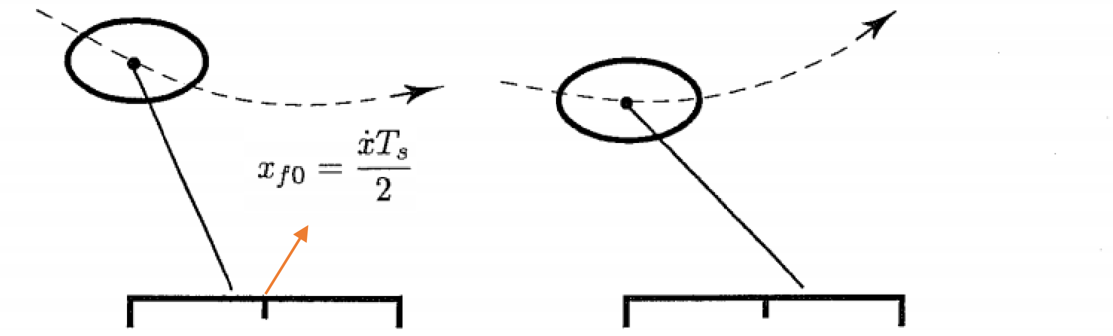


Figure 2.11. Asymmetric trajectories. Displacement of the foot from the neutral position accelerates the body by skewing its trajectory. When the foot is placed behind the neutral point, the body accelerates forward during stance (left). When the foot is place forward of the neutral point, the body accelerates backward during stance (right). Dashed lines indicate the path of the body, and solid horizontal lines under each figure indicate the CG-print.

Three-part control

Hopping:

Thrust for specified duration during stance.

Exhaust to specified pressure during flight.

Forward Speed:

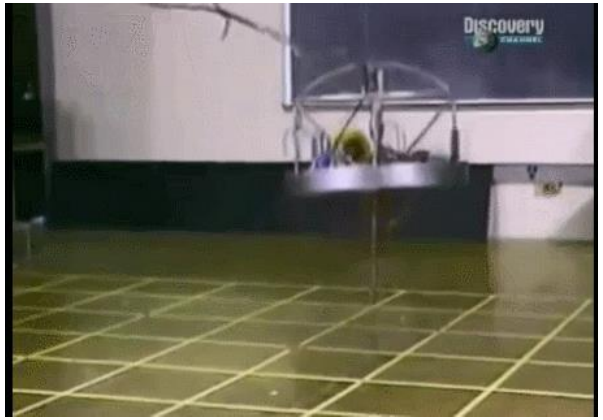
Choose foot position $x_f = \frac{\dot{x} T_s}{2} + k_{\dot{x}}(\dot{x} - \dot{x}_d).$

Convert to hip angle $\gamma_d = \phi - \arcsin\left(\frac{x_f}{r}\right).$

Servo hip angle $\tau = -k_p(\gamma - \gamma_d) - k_v(\dot{\gamma}).$

Body Attitude:

Servo body angle $\tau = -k_p(\phi - \phi_d) - k_v(\dot{\phi}).$



Foot Placement Control

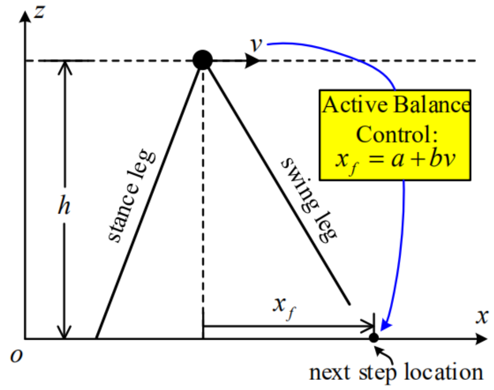


Figure 2. Diagram of active balance control. The next step location is determined by a linear function of the body velocity.

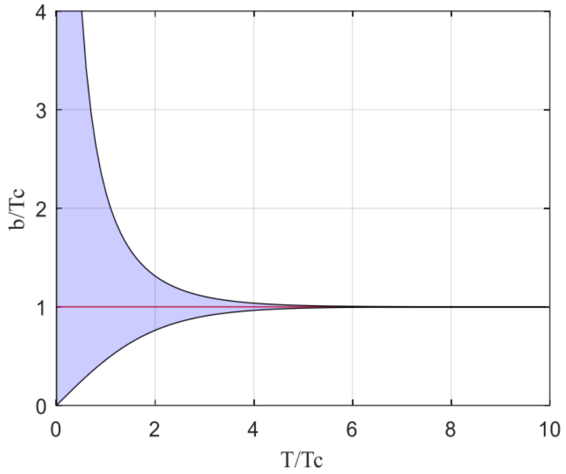


Figure 4. Stability condition of ABC. The blue area represents the parameter space that leads to stable walking, where the capture-point parameter $b = T_c$ (the red line) is a special case in this area.

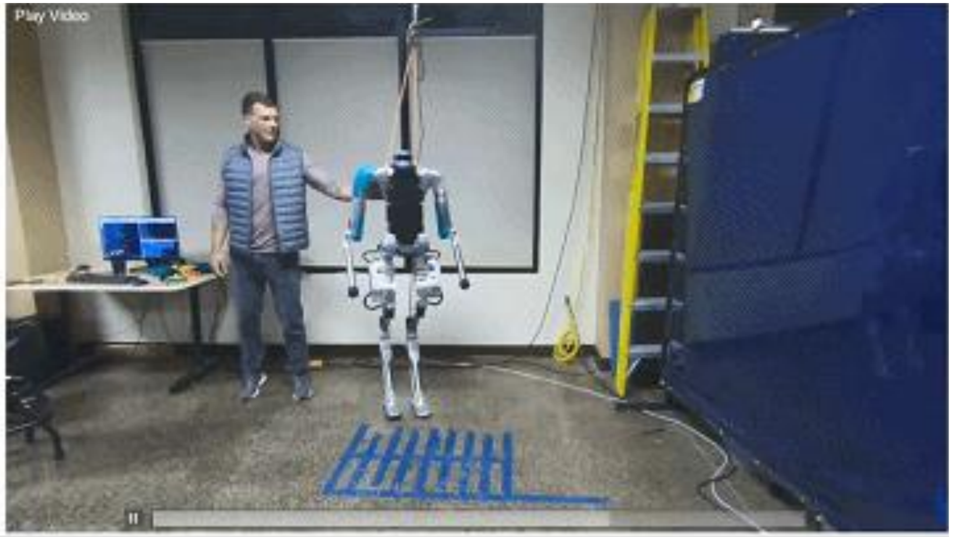
Push Recovery

external force, ball collision

Active balance control for biped walking, submitted to IROS 2021

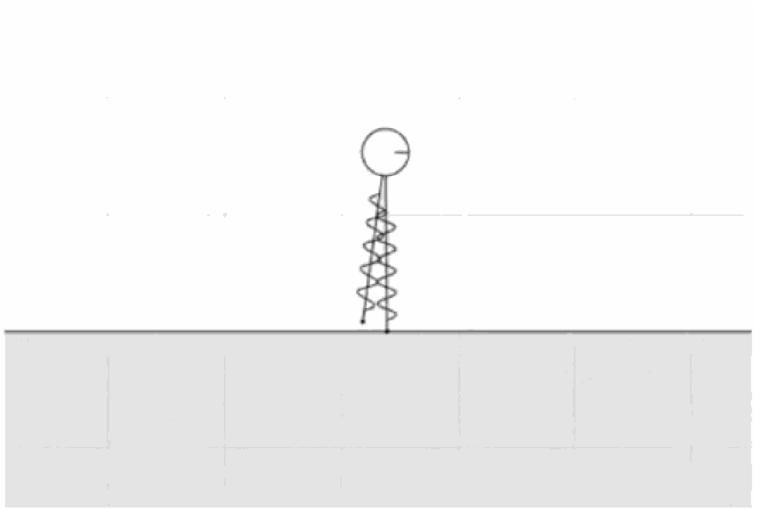
The Most Robust Biped

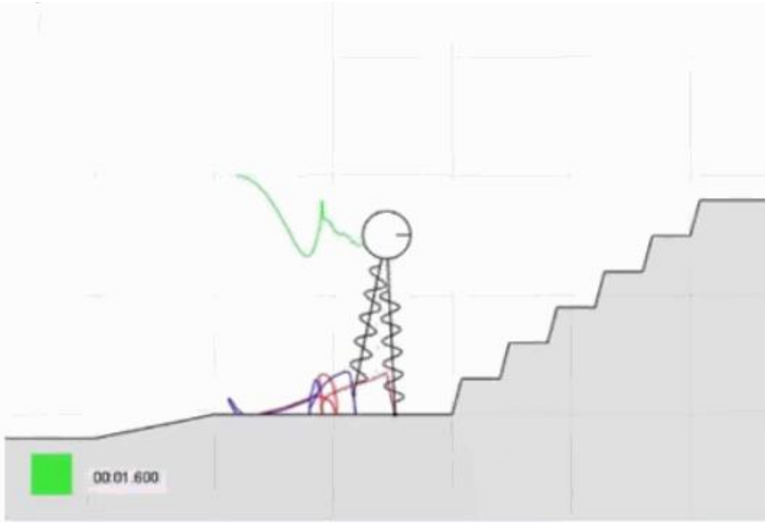
Jonathan Hurst
Agility Robotics



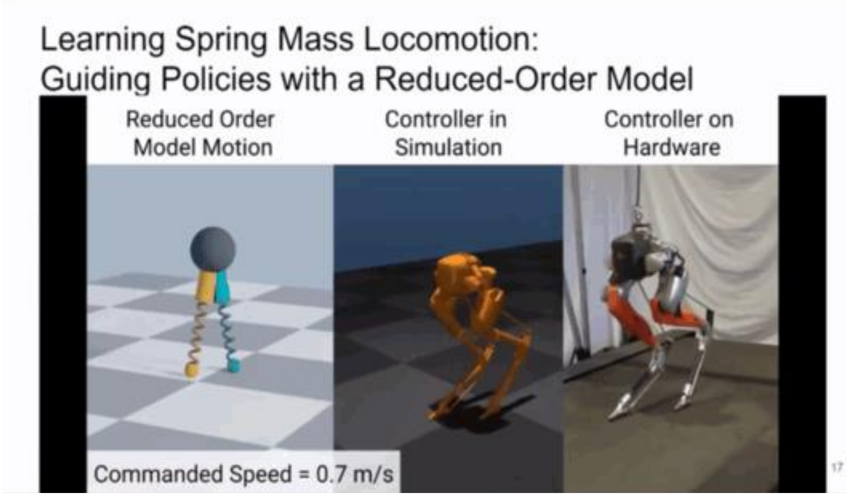
Robust Walking Controller

Simple Controller: 2-step lookahead





Reinforcement Learning



Learning Spring Mass Locomotion:
Guiding Policies with a Reduced-Order Model

Reduced Order Model Motion

Controller in Simulation

Controller on Hardware

Commanded Speed = 0.7 m/s

17

There's a lot of testing.

The Way to Achieve Human-level

The goals

Walking performance equivalent to a typical human. The robot should be capable of moving in homes, offices, and out on the streets, including curbs and stairs, without falling.

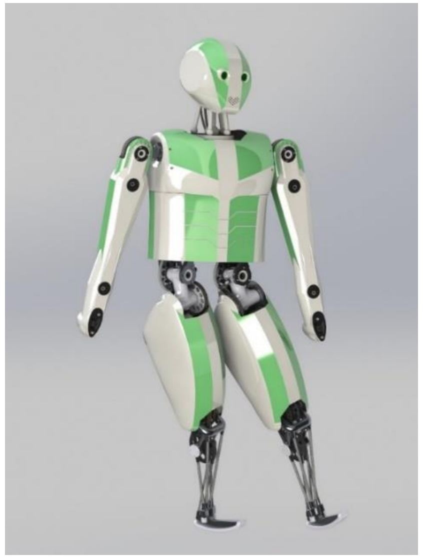
Think of it as a Segway with legs!

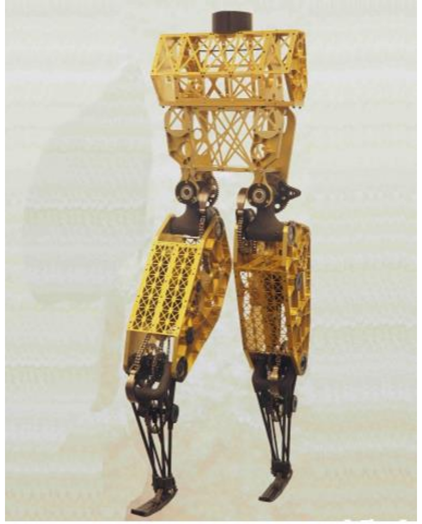
A) Robust balance. Almost never falls.
B) Can sit and stand.
C) Can climb (some) stairs.
D) Energy-efficient, like a human. All day on one charge!
E) Resistant to fall damage, if it does fall.
F) Safe enough to work around humans.
G) Also helpful: not too expensive.

How to get there?

- The refinement of hardware that is powerful enough to reliably recover from large disturbances, yet energy-effective and inexpensive;
- The development of theories of balance and optimization methods for low energy use.

Tik-Tok: A Human-level Robot





Design goals

- Suitable for reliable locomotion in environments designed for humans.
- Low energy with CoT ≈ 0.25 (better than all other robot bipeds).
- Robust balance, based on high-speed, high-accuracy foot placement for balance correction. Should match the robustness of other successful walking robots (Petman, New ATLAS, Cassie).
- Leg swing time for foot placement, 1 radian in < 0.25s (≈ human).
- Squat, sit down, stand up, climb steps and curbs.
- Jog, dance, skip, hop, etc. (optional, but the physical capability will likely follow from the other requirements).

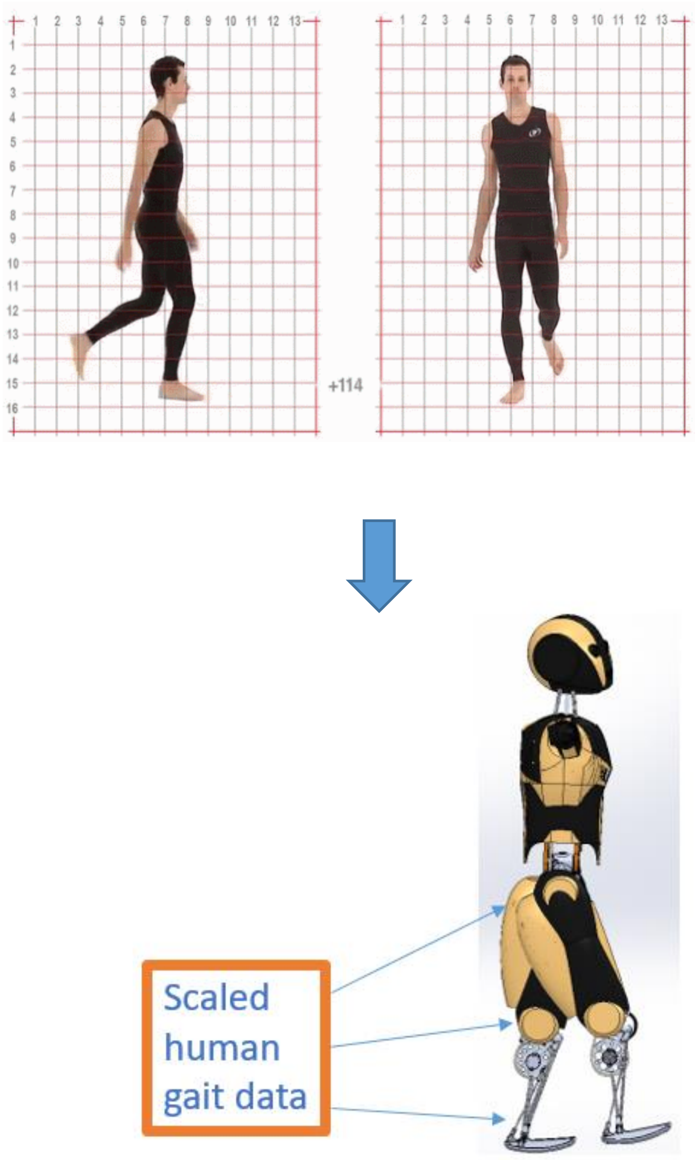
General Details

- 1.5 m tall (full robot, as at left)
- 30 kg mass.
- 0.8 m leg length (below, left).
- 12 actuated joints: 4 arm, 4 hip , 2 knee, 2 ankle.

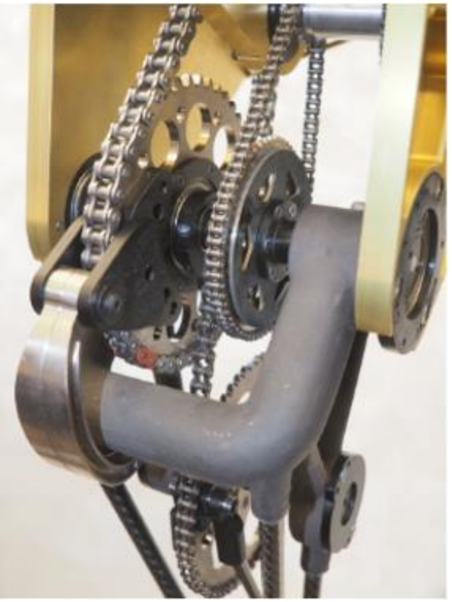
Hardware Optimization

We would like to optimize the hardware for efficient walking, but how – with no finished design, no optimized trajectories? Solution: we put the robot's actuators through a human gait trajectory, using Winter's joint kinematics and moments measured from a walking human ("Biomechanics and Motor Control of Human Movement, 2009), but with the moments scaled to the weight of the robot. This helped us select suitable motors, gear ratios, and spring constants.

Parameter	Optimized for efficient walking	Overall design choice
Leg swing gear ratio	51:1	51:1
Knee gear ratio	31:1	51:1
Ankle gear ratio	60:1	62:1
Ankle/knee "biarticulation" ratio	8.7:1	4.3:1
COT (motor electrical)	0.20	0.21



Scaled human gait data



Notable design features:

Chain drive transmission (with a few planetary gearboxes too). The chain drives give us:

- \+ High power to weight ratio
- \+ Efficient even at low loads
- \+ Resistance to dirt and misalignment
- \+ Flexible configuration
- \+ Low-cost custom components

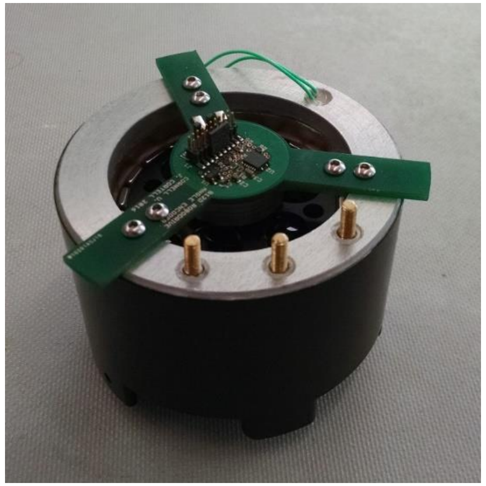
… and on the negative side

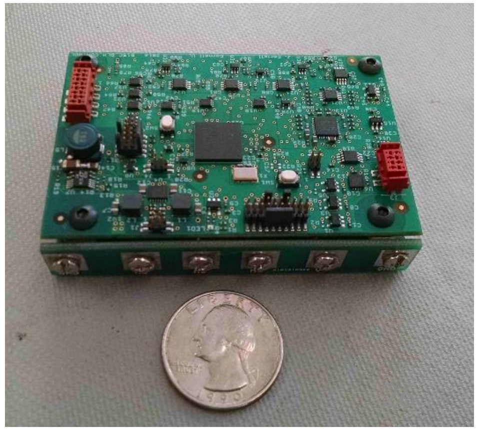
- \- Not very modular
- \- Backlash is a challenge
- \- Bulky – up to 36 chains and 72 sprockets in all!

High-power brushless motors with water cooling capability.

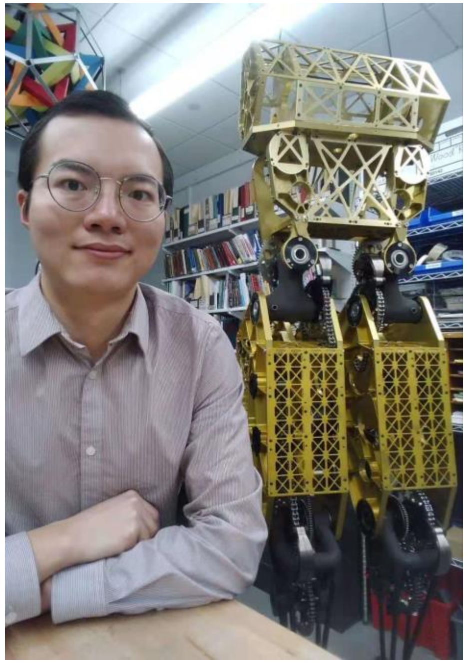
Motor selection is key to the performance of the robot. We want motors that are:

1) Light weight
2) Small in size
3) Highly efficient at low power levels (for normal locomotion)
4) Minimal rotor inertia, to allow quick reactions to external torque.
5) Huge power outputs for their size and weight (for emergency balance maneuvers, climbing steps, etc.)





Conclusions



- **Human-level robots require good hardware design as well as robust control and careful optimization.**
- **Tik-Tok might be the first humanoid robot to achieve human-level in both agility and energy efficiency**

Tik-Tok is expected to meet the following design goals:

- Under 30 kg
- COT of under 0.3; this is over 10 km on one charge of the 2 kg battery pack.
- 200 N m peak joint torque for the knee and hip swing actuators – the robot should not only have excellent foot placement speed for balance, but should be able to jump quite high!
- With water cooling implemented, Tik-Tok could run or climb stairs continuously. Without, it could do this intermittently – a short burst of speed or single flight of stairs.
- Could be the first robot to finish a marathon alongside human runners. (Tik-Tok would be walking or jogging – it is not optimized for winning such a race!)

The End

Thank you!