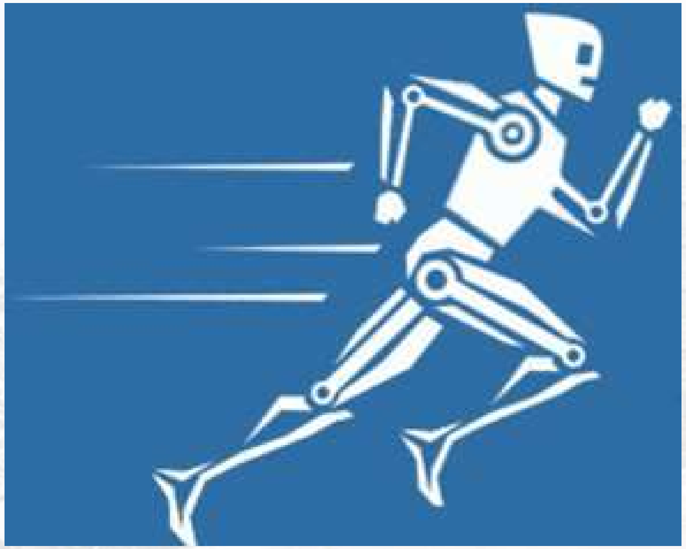
# 打造具有人类水平的人形机器人

叶林奇 （上海大学，副研究员）



# 为什么研究人形机器人

**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.

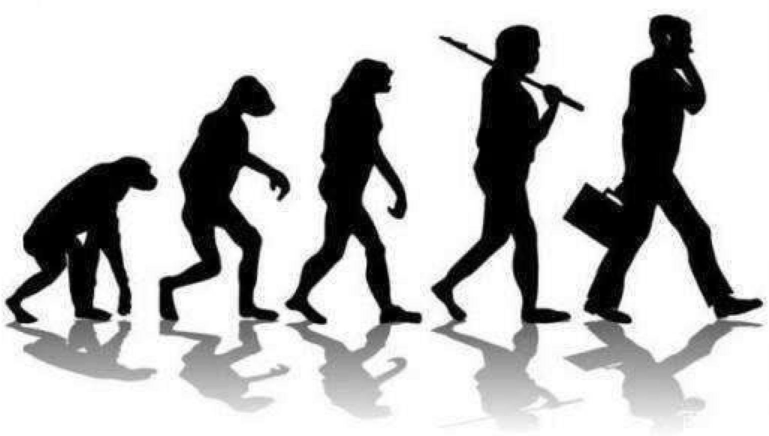
**Home assistant robots**

**Roméo (France)**

ladders

stairs

# 为什么研究人形机器人



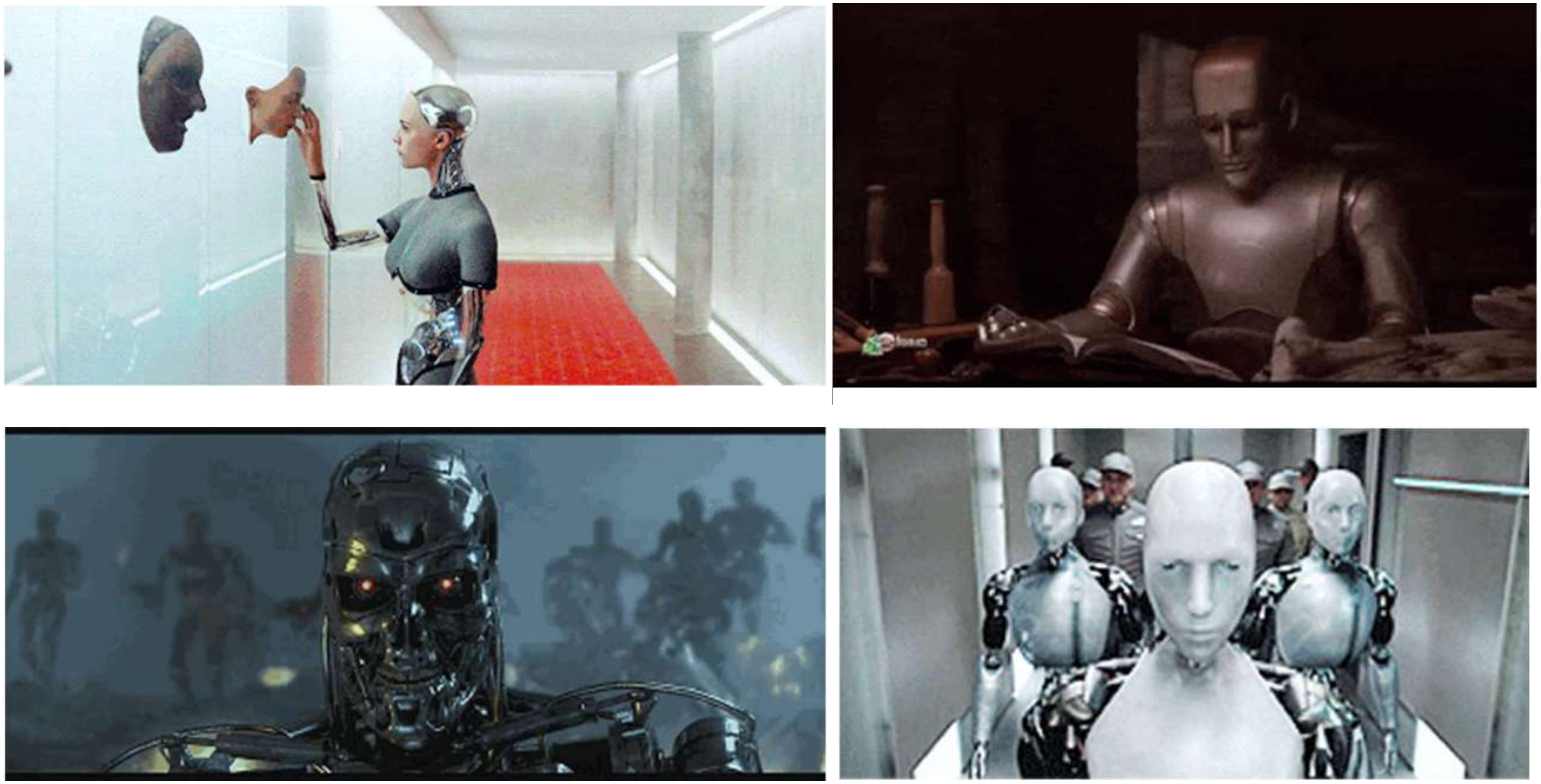
**It helps us to understand ourselves!**

**It helps the disabled to walk again!**

# 为什么研究人形机器人

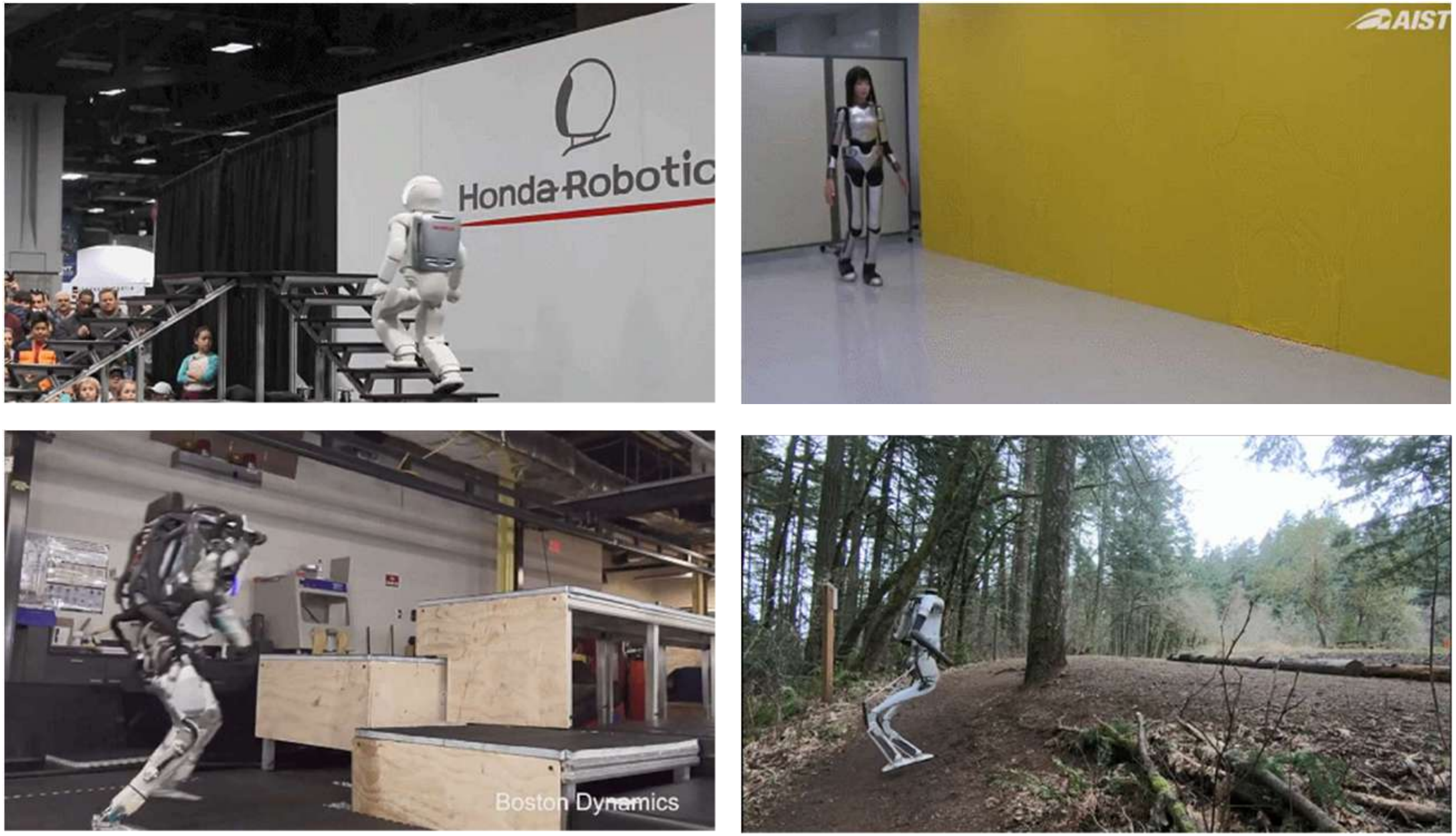
**人形机器人是科幻电影中的重要元素，承载了极其重要的文化内涵和人类想象。**

《机械姬》
《机器管家》
《我，机器人》
《铁甲钢拳》
《环太平洋》
《星球大战》
《变形金刚》
《终结者》
《机器人总动员》
《超能陆战队》



# 人形机器人研究现状

- □Boston Dynamics
- □Honda
- □Agility Robotics
- □Tesla
- □Cornell
- □MIT
- □NASA
- □DLR
- □Delft
- □KAIST
- □北理工
- □浙大
- □优必选
- □小米



# 人形机器人研究现状

## 特斯拉Optimus推出时间节点

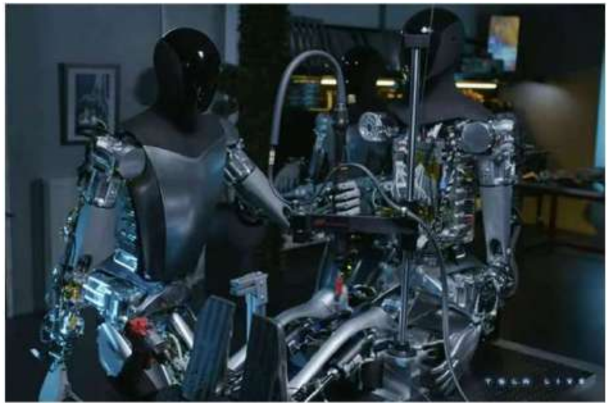
- **首次发布：**2021年8月20日，马斯克在首届特斯拉人工智能日（AI DAY）上首次发布特斯拉人形机器人（Tesla Bot）计划，代号“擎天柱”（Optimus）。
- **项目开发计划：**2022年4月，马斯克在财报会议上指出，Optimus的重要性将在未来几年逐渐显现，最终将比汽车业务、比FSD更具价值。
- **原型机发布时间：**2022年6月，马斯克在推特上发文，将特斯拉第二个人工智能日（AI Day）由原定的8月19日推迟到9月30日，并表示到时候可能推出能够运转的人形机器人原型机Optimus。

图表：特斯拉人形机器人时间轴

首次发布
2021年8月20日
首届AI日

开发计划
2022年4月
财报会议

原型机发布时间
2022年6月
推特



# 人形机器人研究现状

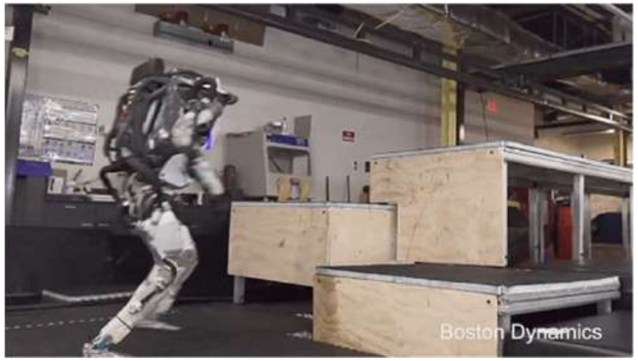
## Honda and AIST, Japan

**Asimo**

**HRP-4**

## Boston Dynamics, US

**Petman**



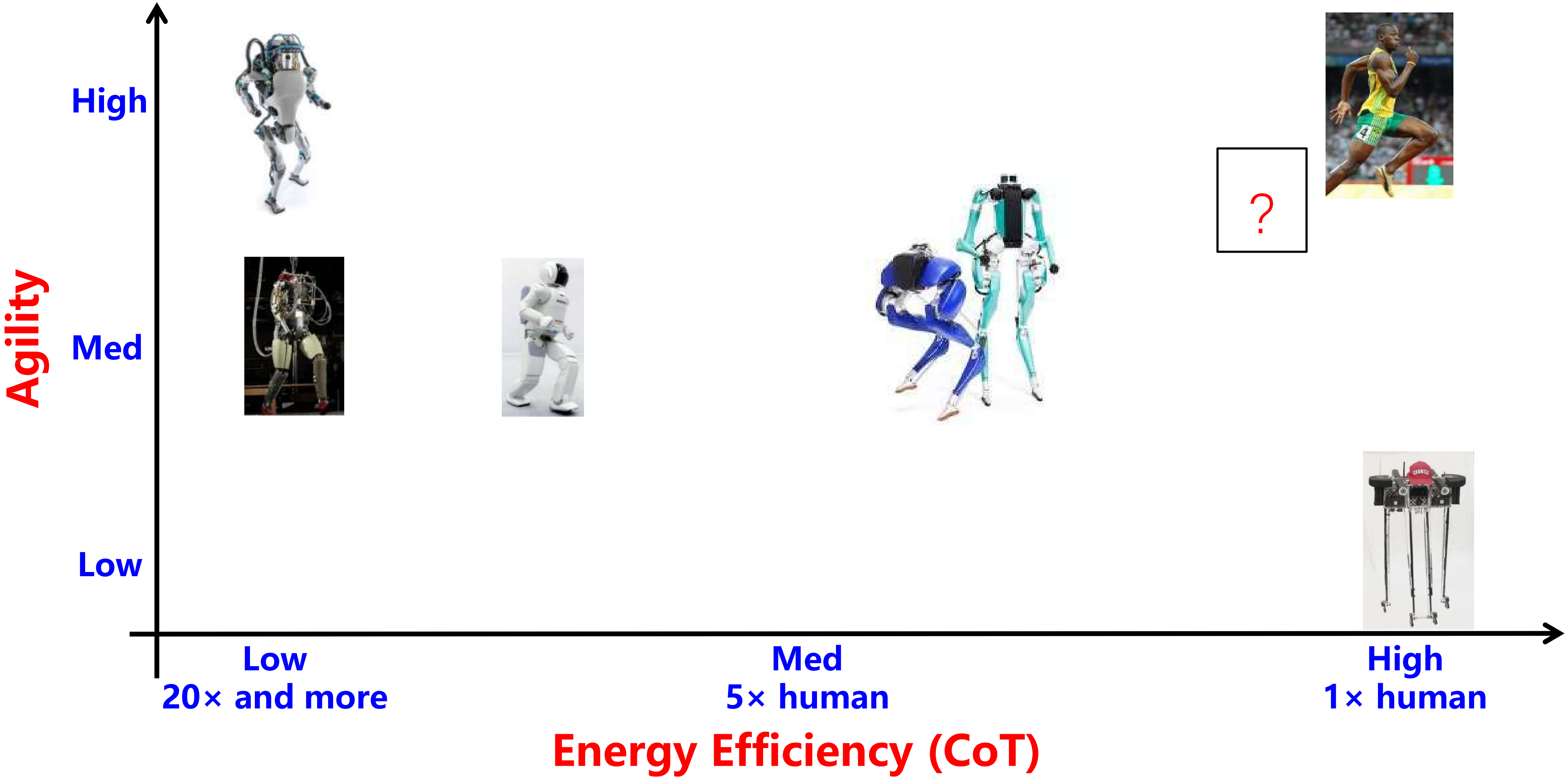
**Atlas**

## Agility Robotics, US

**Cassie**

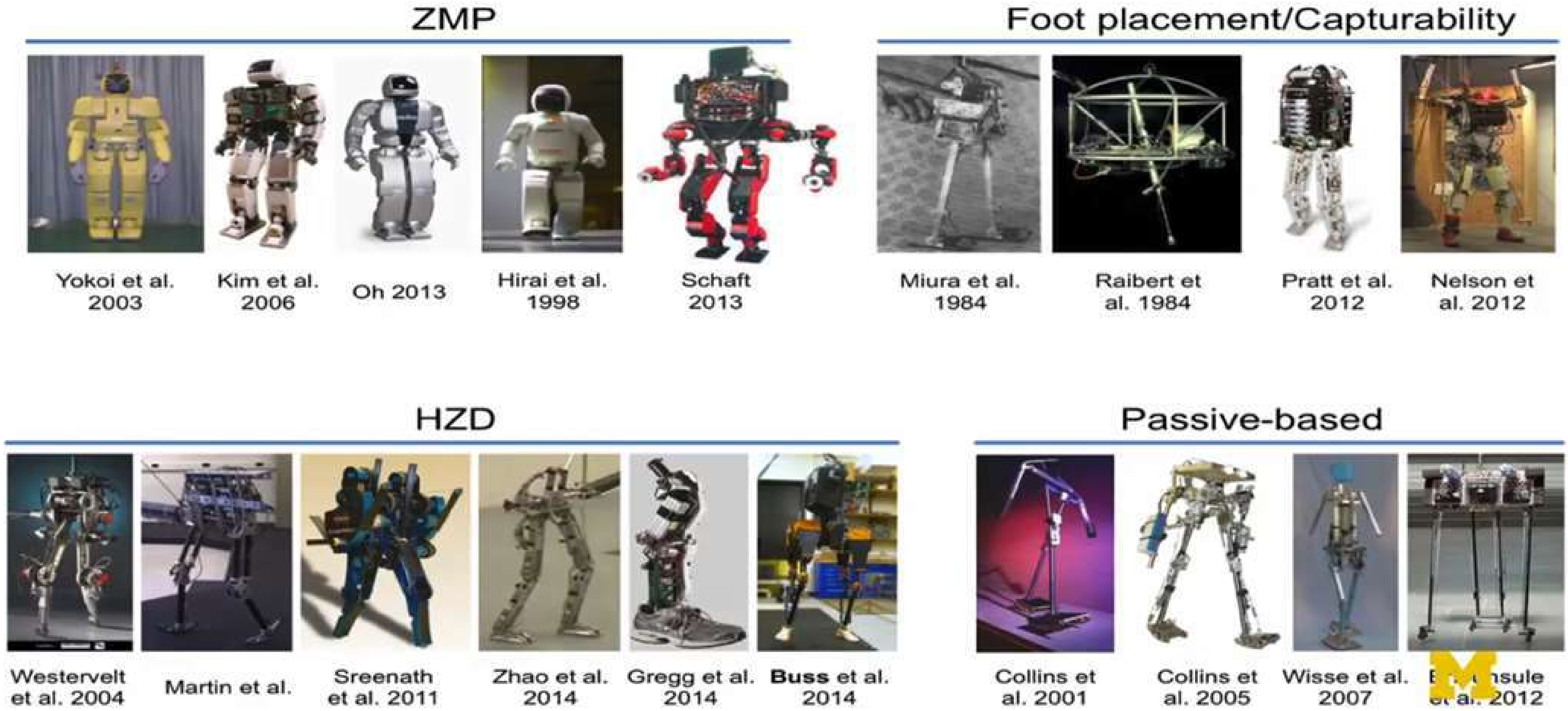
**Digit**

# 人形机器人研究现状


Agility
High
Med
Low
?
Low
20× and more
Med
5× human
High
1× human
Energy Efficiency (CoT)

# 人形机器人研究现状

most robust

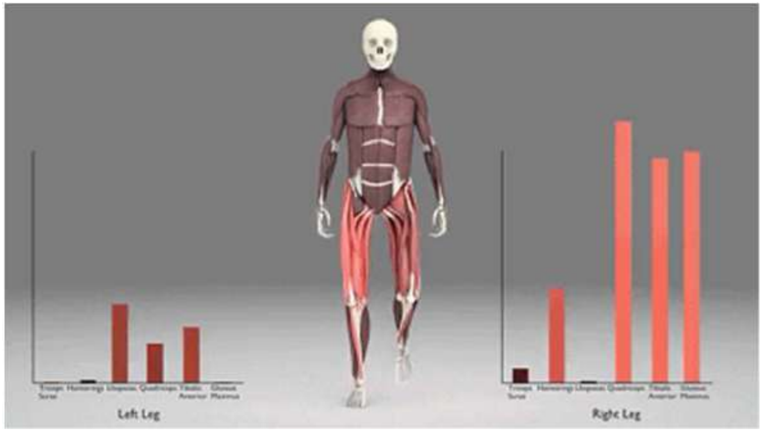


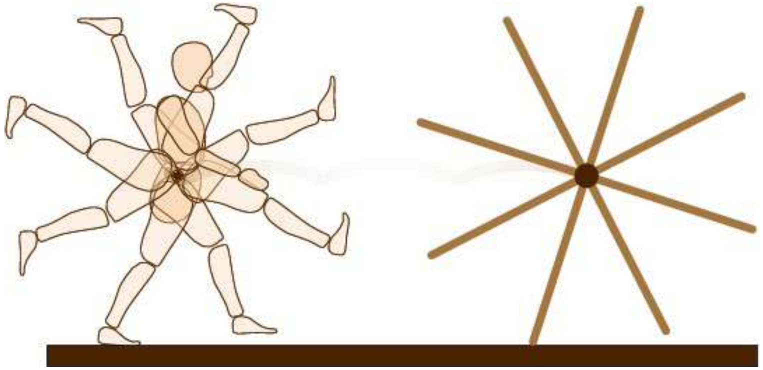
most energy-efficient

# 能量效率

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

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


Gears


Electronics

## Key Factors

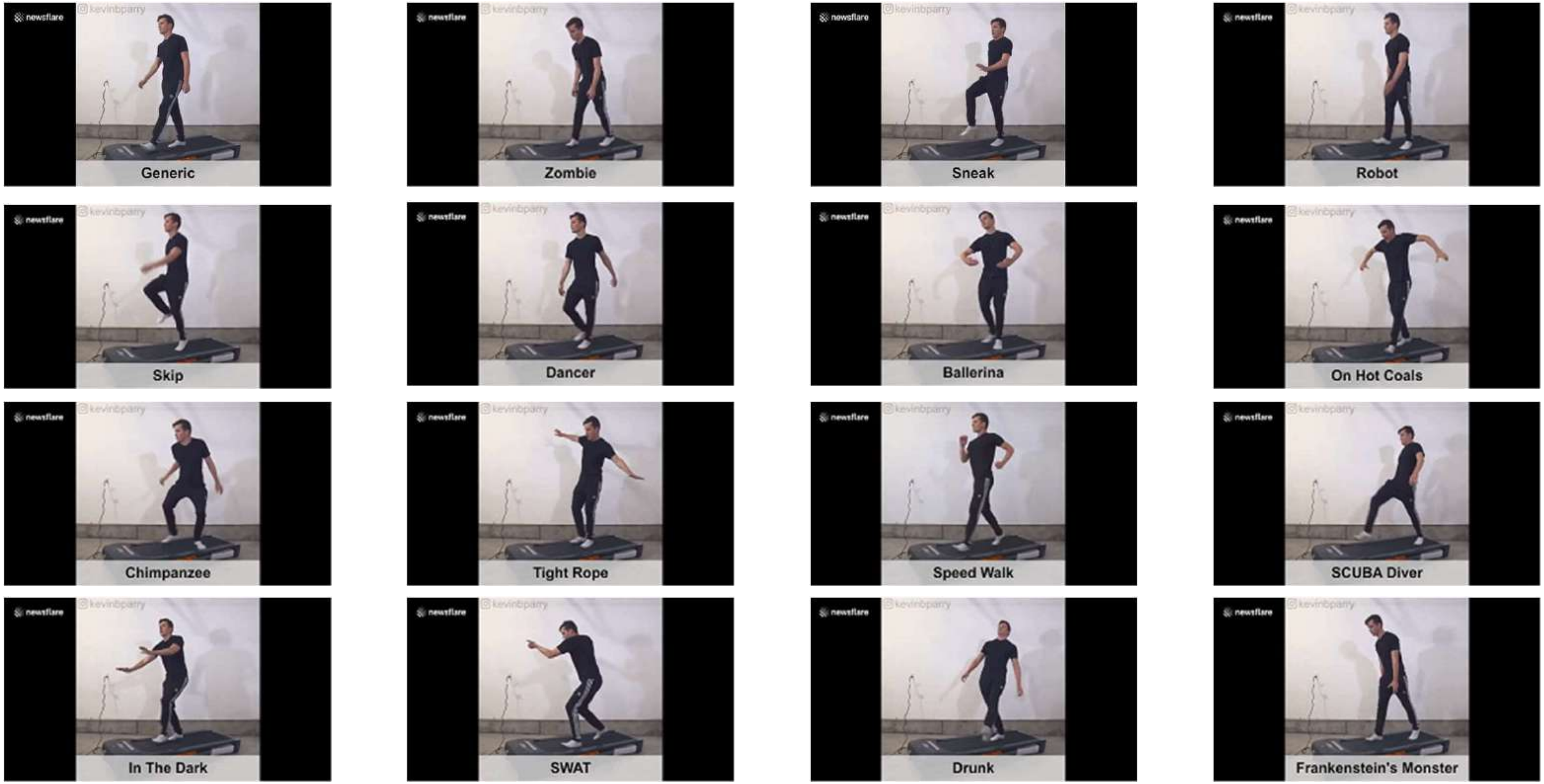
- **Hardware**

  Actuators， transmissions， electronics

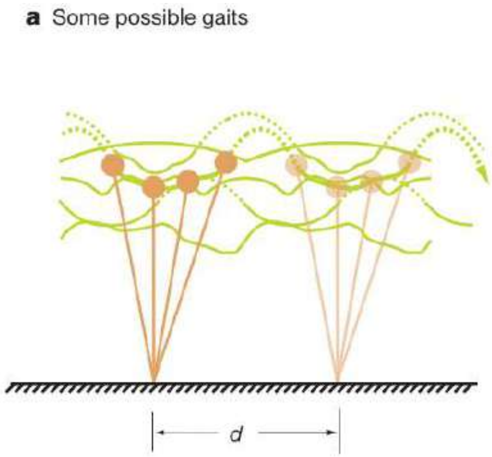
- **Control Algorithm**

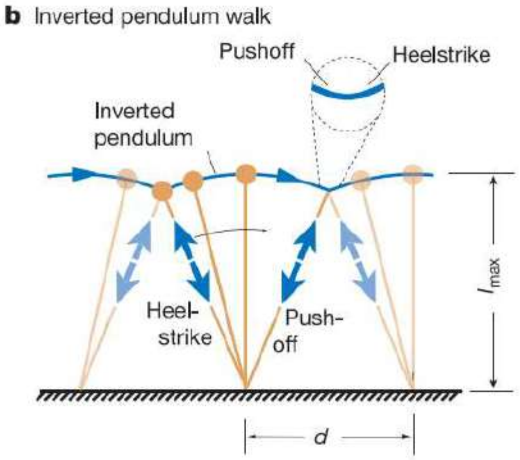
  Use the right muscles at right time

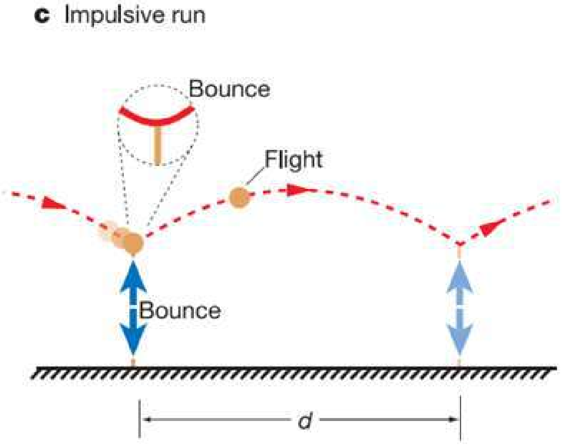
# 能量效率

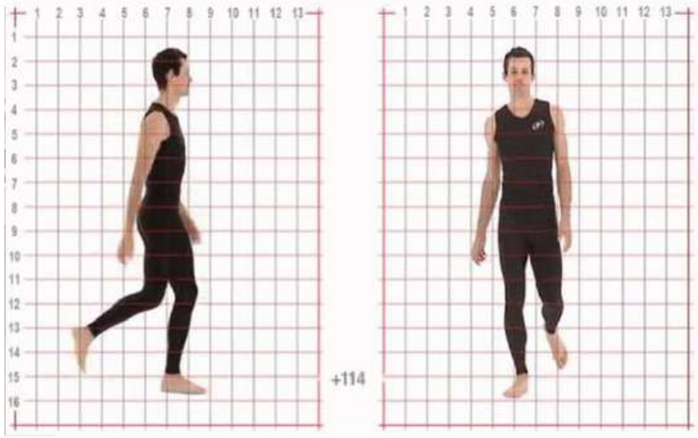

newsflare
@kevinbparry
Generic
Zombie
Sneak
Robot
Skip
Dancer
Ballerina
On Hot Coals
Chimpanzee
Tight Rope
Speed Walk
SCUBA Diver
In The Dark
SWAT
Drunk
Frankenstein's Monster

# 能量效率


a Some possible gaits
d


b Inverted pendulum walk
Pushoff
Heelstrike
Inverted pendulum
Heel-strike
Push-off
$l_{max}$
d


c Impulsive run
Bounce
Flight
Bounce
d

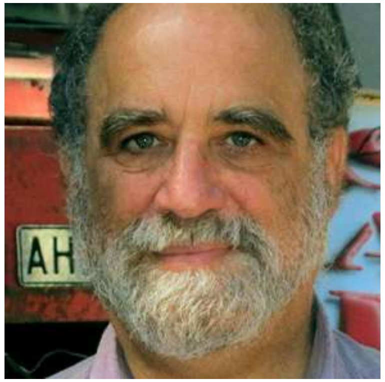

+114


200
800
3000

# 能量效率

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

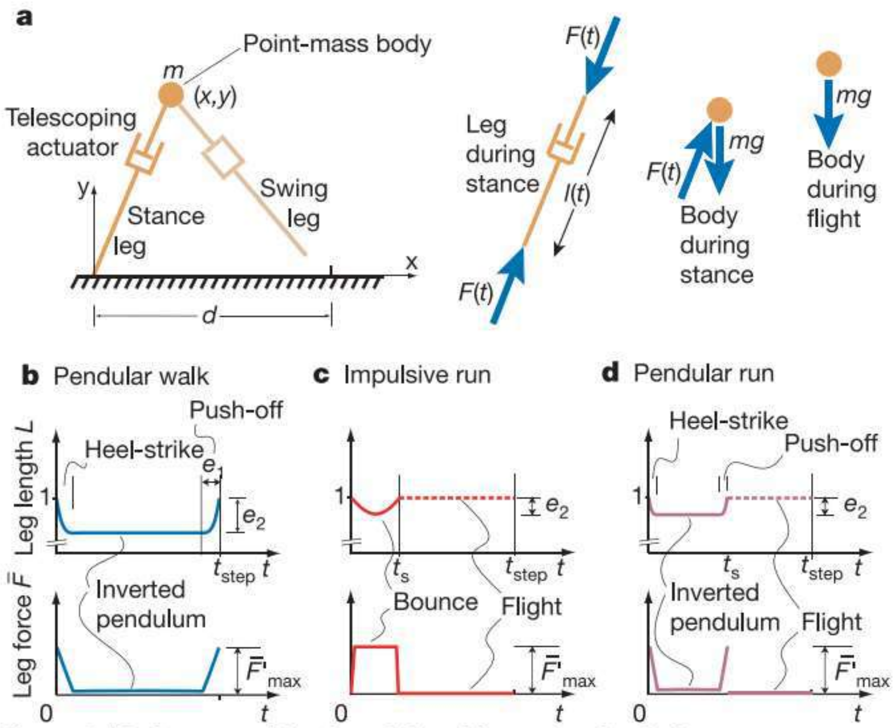


**Figure 2** | **Point-mass biped model and its optimal solutions.**

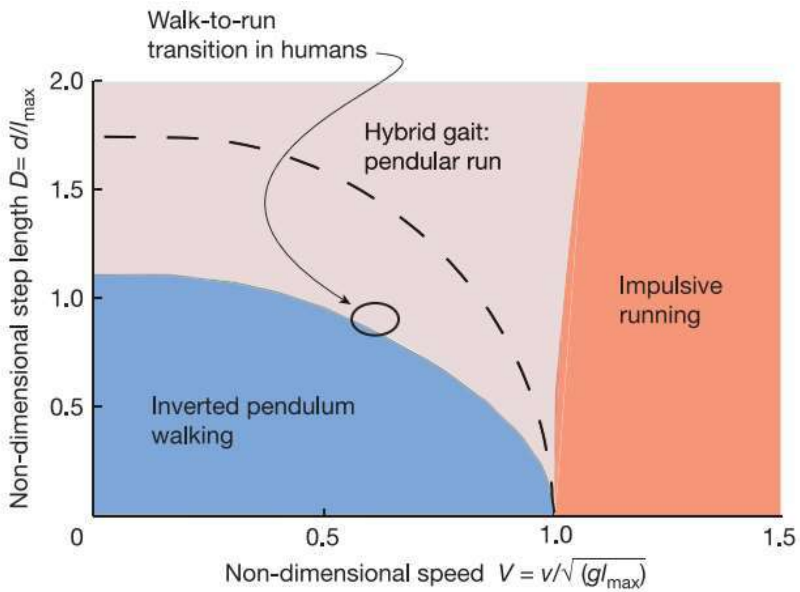
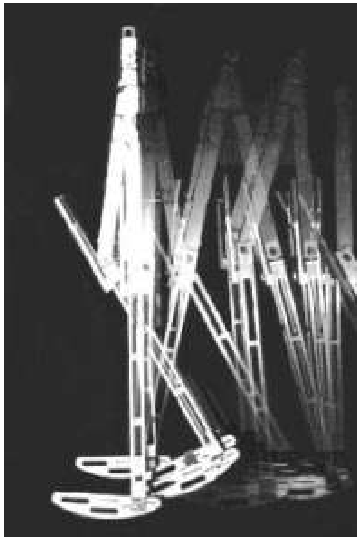


**Figure 3** | **The regions in which each of the three collisional gaits are optimal.**

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

# 康奈尔大学人形机器人



Passive Walker
1996-2000

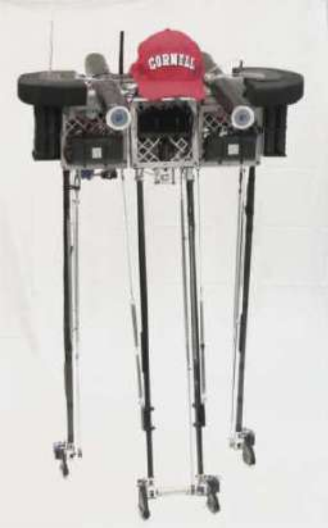
Four legged passive "biped" with knees. Walks downhill.

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.



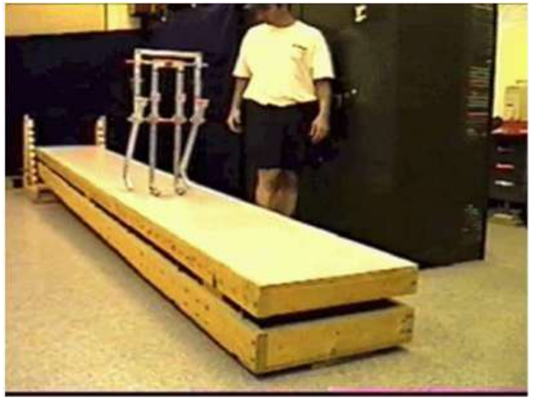
Cornell Ranger
2001-2012

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

Ranger Max
2012-now

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

# 被动行走



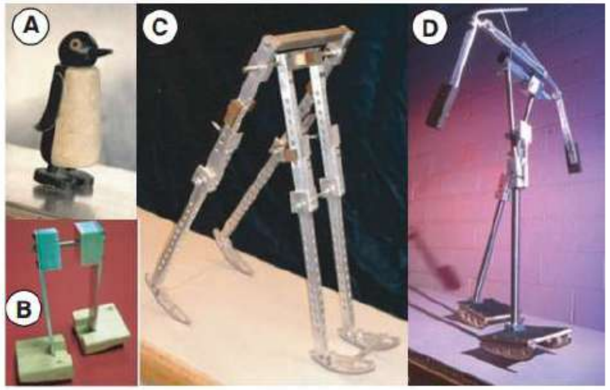


**Fig.** 1. "Ramp-walking," "downhill," "unpowered," or "passive-dynamic" machines. Our powered bipeds are based on these passive designs. (**A**) The Wilson "Walkie" (27). (**B**) MIT's improved version (28). Both (A) and (B) walk down a slight ramp with the "comical, awkward, waddling gait of the penguin" (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).

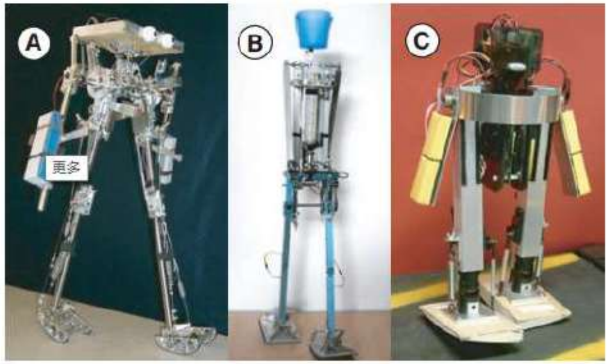


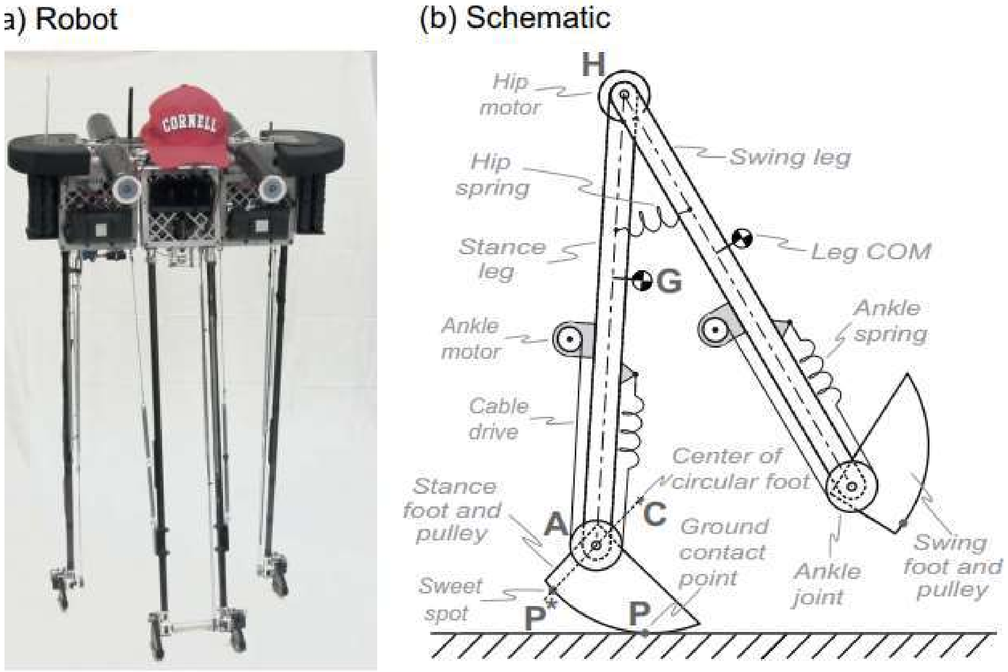
**Fig. 2.** Three level-ground powered walking robots based on the ramp-walking designs of Fig. 1. (**A**) The Cornell biped. (**B**) The Delft biped. (**C**) The MIT learning biped. These powered robots have motions close to those of their ramp-walking counterparts as seen in the supporting online movies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

# 最高效节能的足式机器人

**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.

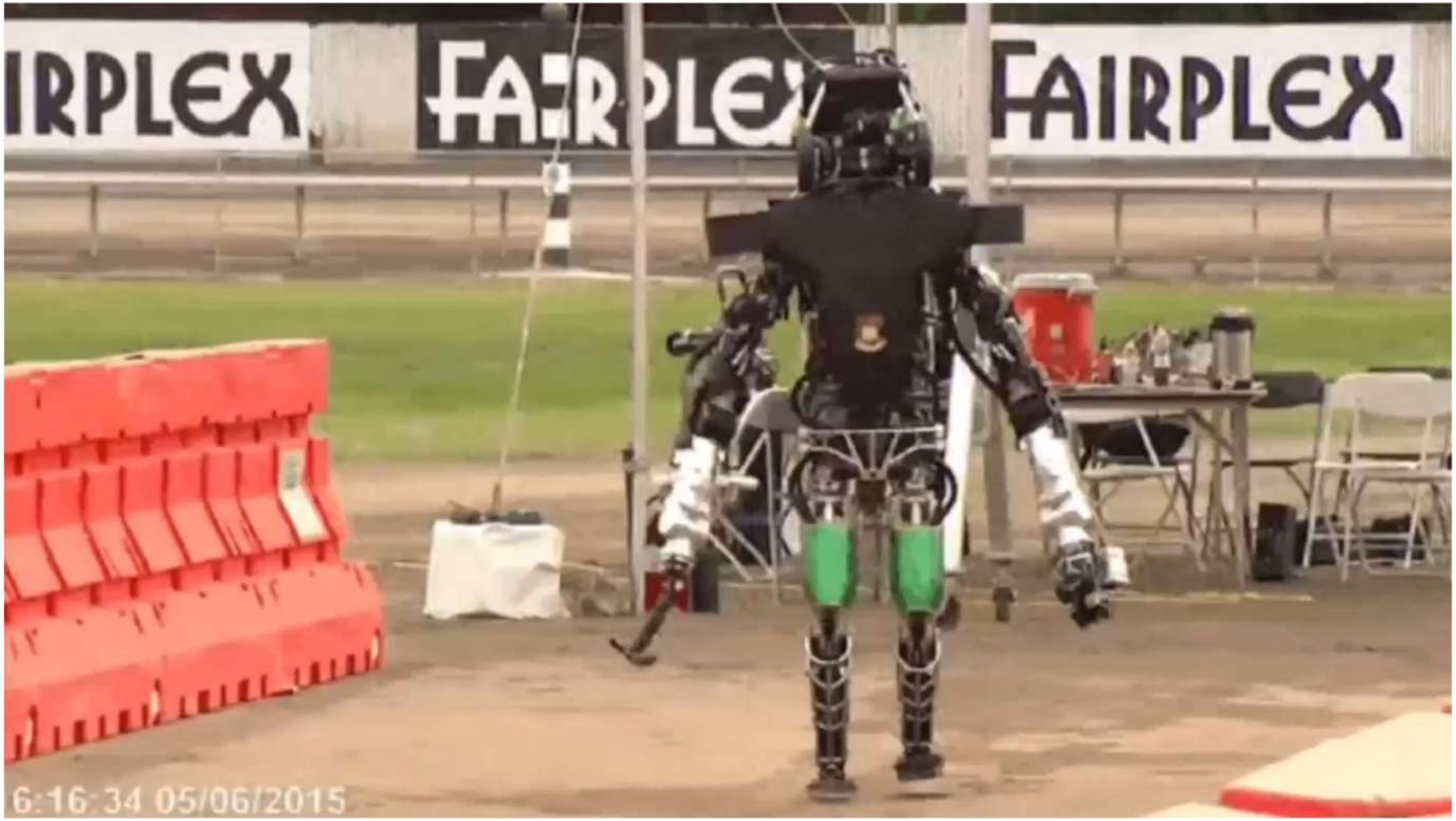
# 最高效节能的足式机器人

| | |
|---|---|
| **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<br>Human COT = about 0.2 (a bit better than Ranger)<br>Asimo COT = about 2 (54 kg@ 1.5 m/s, 1.8 kW)<br>Atlas COT = about 20 (12.8 miles, 4 gal gas, 110 kg) |

**Cornell Ranger, 2011**

**4-legged bipedal robot**

# 行走的鲁棒性



# 最高效节能的足式机器人

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

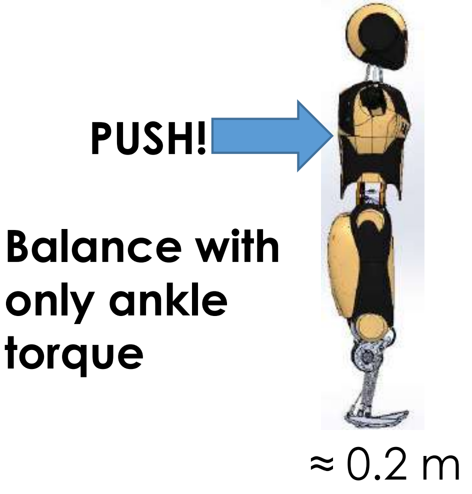
Therefore robust balance mainly depends on fast leg swing.

How quickly should the legs be able to swing?

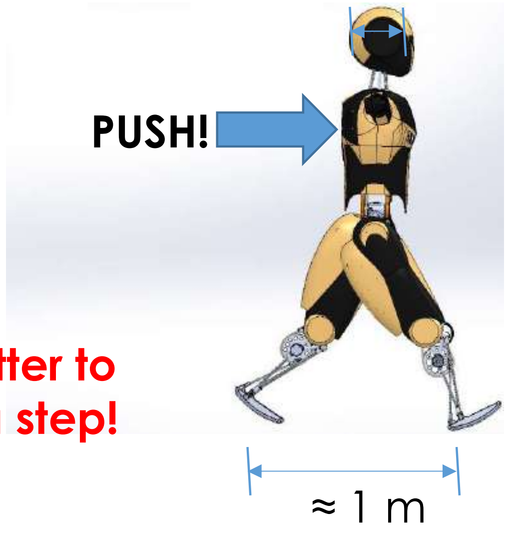
- Fastest human leg swing time is about 0.2 seconds for 1 radian
- Boston Dynamic BigDog and Atlas swing times are about 0.3 seconds.

How to make legs swing fast?

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



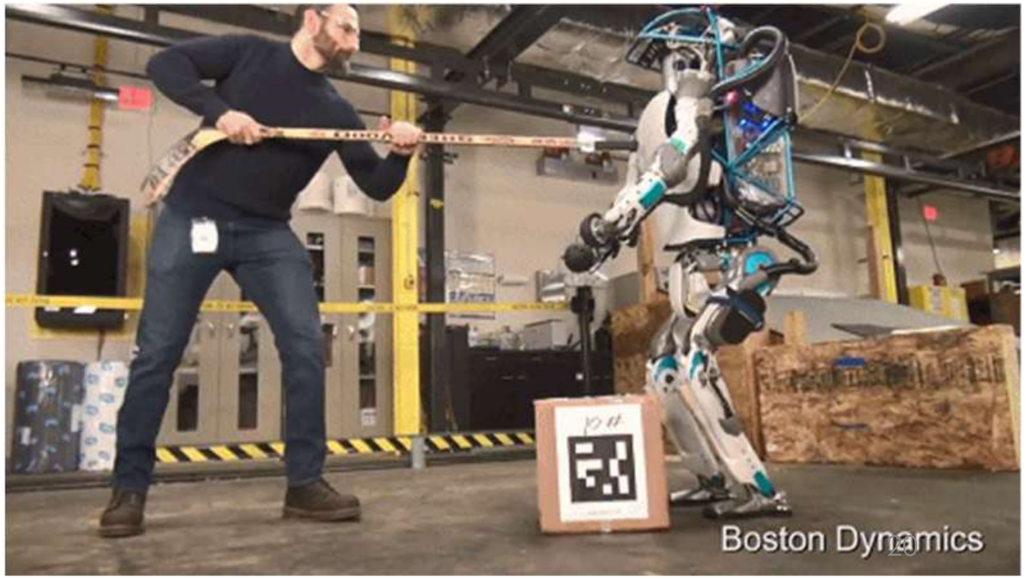
**Balance with only ankle torque**



**It's better to take a step!**

# 鲁棒性最强的双足机器人

**Marc Raibert**
Boston Dynamics



# 鲁棒行走的关键—落脚点控制

## The neutral point

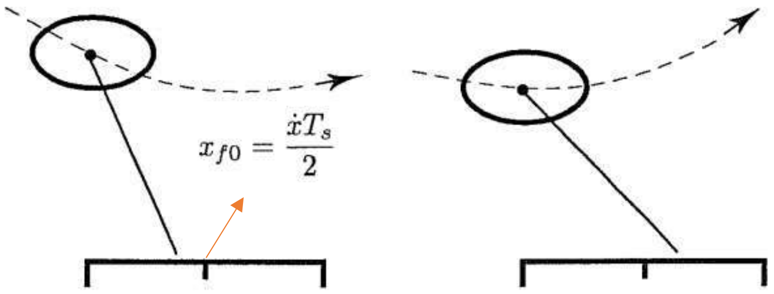
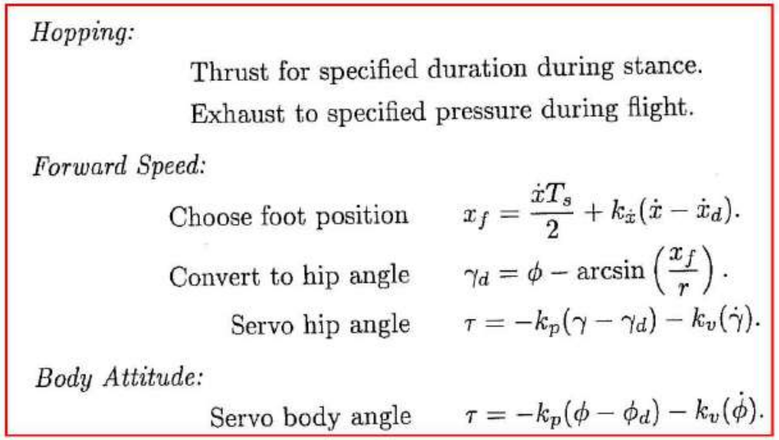


**Figure 2.11.** Asymmetric trajectories. Displacement of the foot from the neutral position accelerates the body by skewing its trajectory. When the foot is placed behind the neutral point, the body accelerates forward during stance (left). When the foot is place forward of the neutral point, the body 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 $\gamma_d = \phi - \arcsin\left(\frac{x_f}{r}\right).$

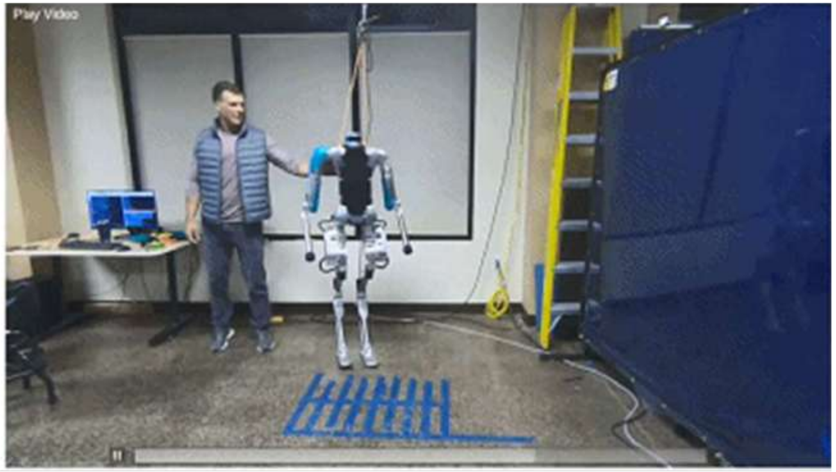
Servo hip angle $\tau = -k_p(\gamma - \gamma_d) - k_v(\dot{\gamma}).$

*Body Attitude:*

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

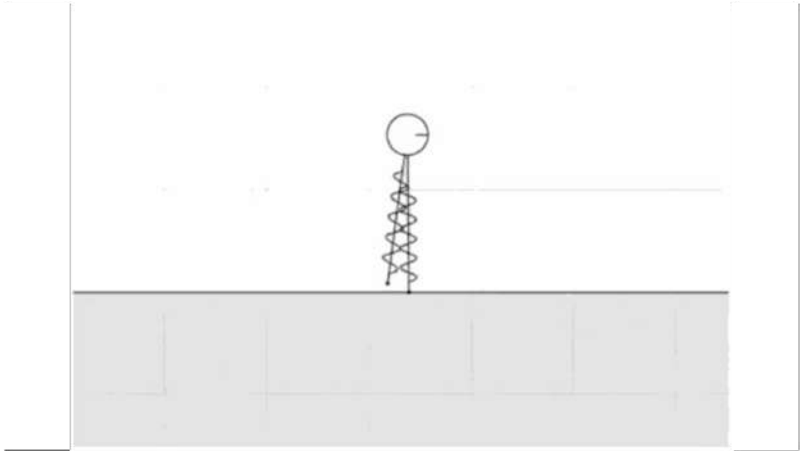
# 鲁棒性最强的双足机器人

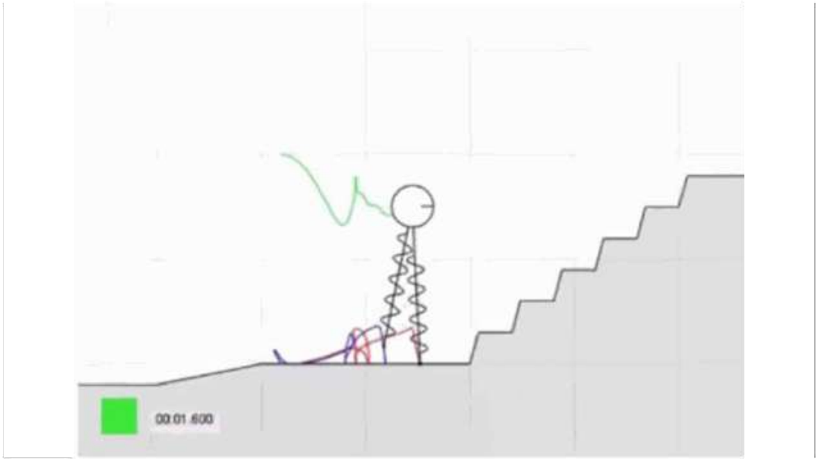
**Jonathan Hurst**
Agility Robotics



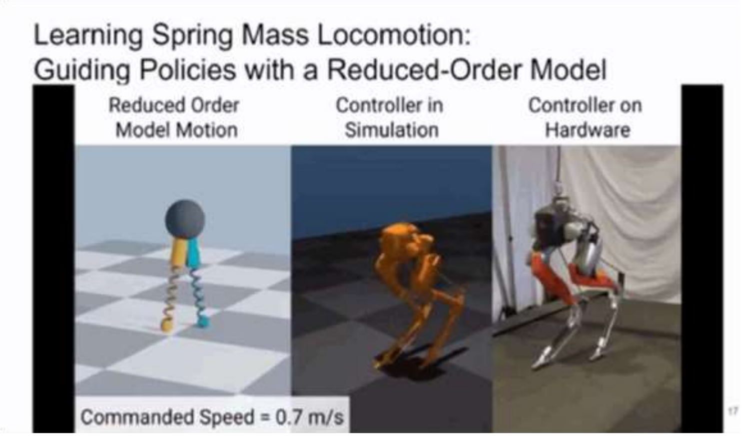
# 鲁棒性最强的双足机器人

Simple Controller: 2-step lookahead





Reinforcement Learning



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

There's a lot of testing.

## 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.

# Ranger Max机器人

**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).

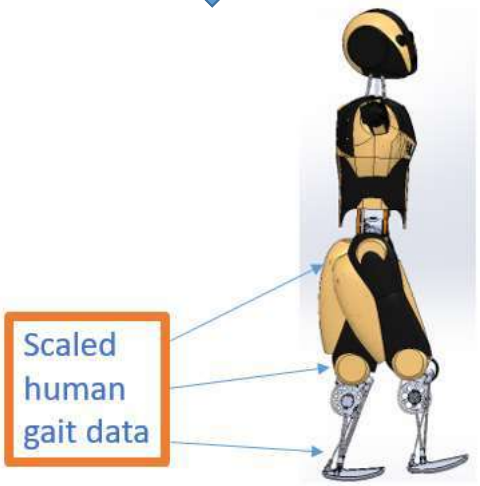
**General Details**

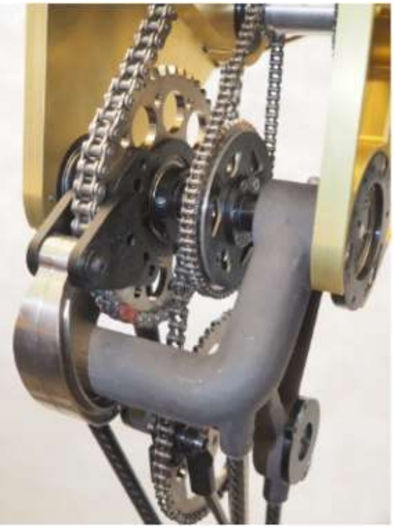
- 1.5 m tall (full robot, as at left)
- 30 kg mass.
- 0.8 m leg length (below, left).
- 12 actuated joints: 4 arm, 4 hip , 2 knee, 2 ankle.

# Ranger Max 硬件优化

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

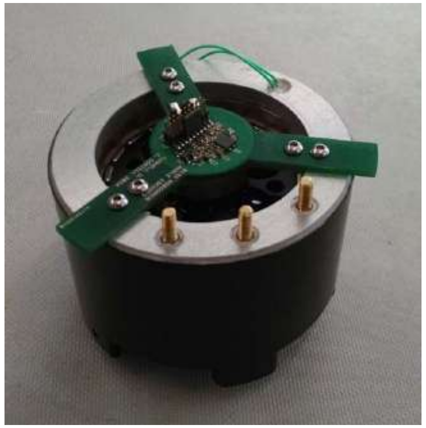
… and on the negative side

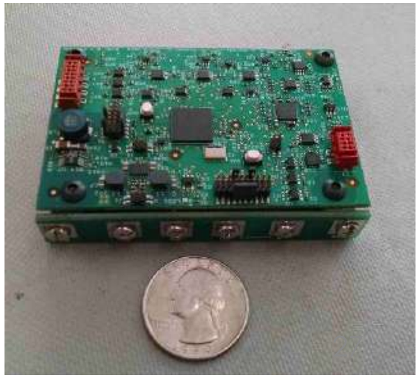
- Not very modular
- Backlash is a challenge
- Bulky – up to 36 chains and 72 sprockets in all!

**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.)





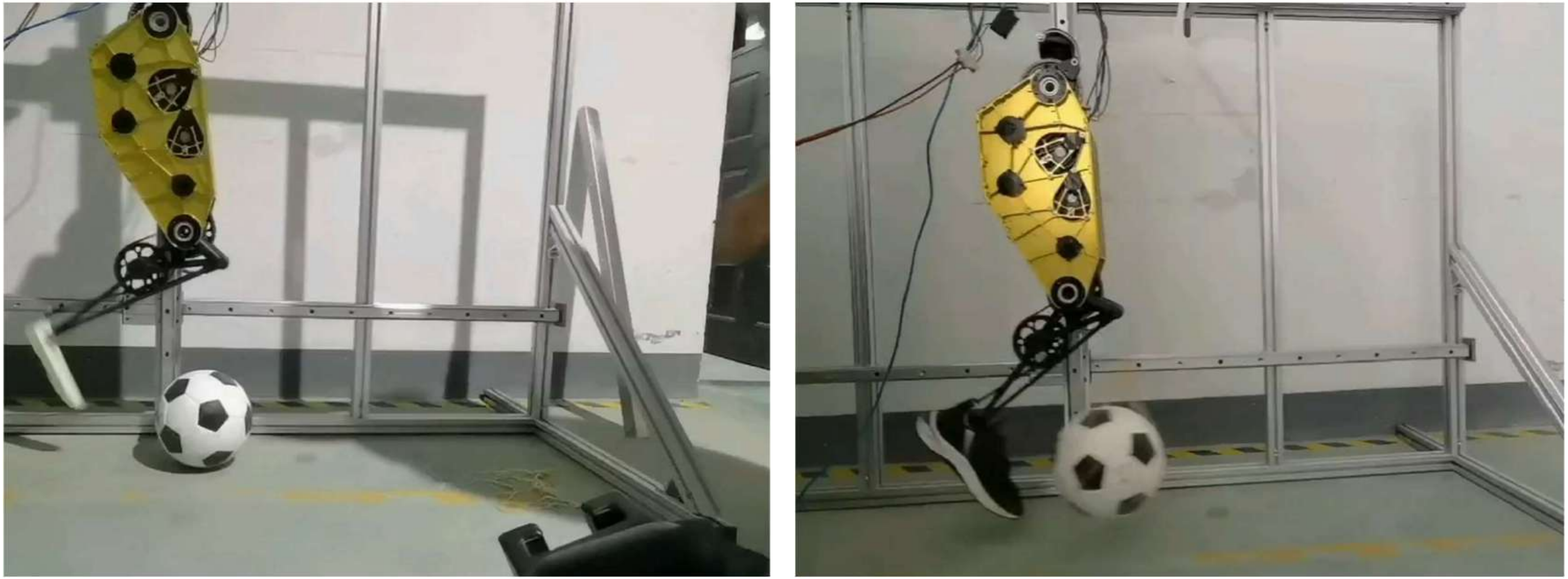
# Ranger Max 硬件优化

**与人类及世界上最先进的双足机器人对比**

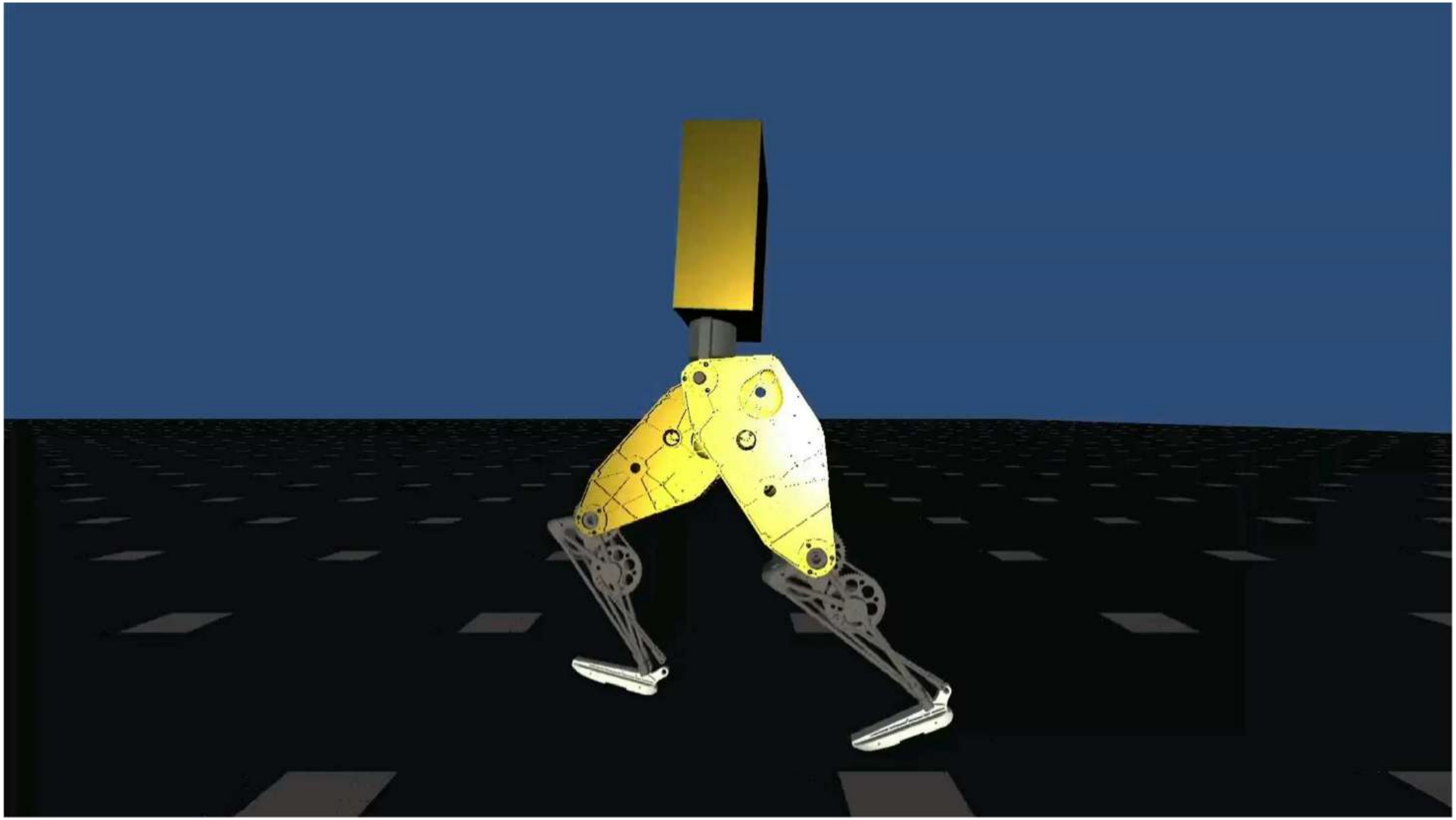
| | 人类 | Atlas | Asimo | Digit | Ranger Max |
|---|---|---|---|---|---|
| 驱动方式 | 肌肉 | 液压 | 电机+谐波 | 电机+连杆 | 电机+链条 |
| 重量 | 65kg | 80 kg | 50kg | 42kg | 30kg |
| 高度 | 1.75m | 1.5m | 1.3m | 1.55m | 1.5m |
| 能耗指标<br>能耗/(重量×距离) | 0.2 | 5 | 2 | 0.7 | 0.25 |
| 摆腿速度<br>(腿摆动1弧度用时) | 0.2s | 0.3s | 0.32s | 0.4s | 0.25s |

Ranger Max可实现与人类相当的运动性能与能耗水平，超越当前其他双足机器人，有望成为世界上最高效节能的双足机器人。

# Ranger Max 硬件优化



# Ranger Max 强化学习控制



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