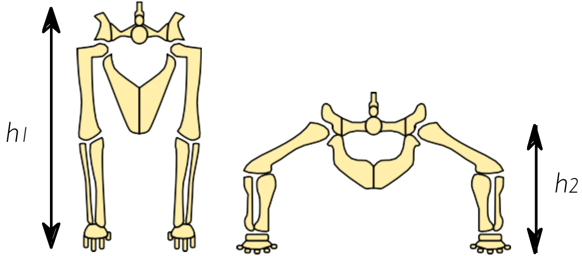
Why do sprawled animals have more legs?

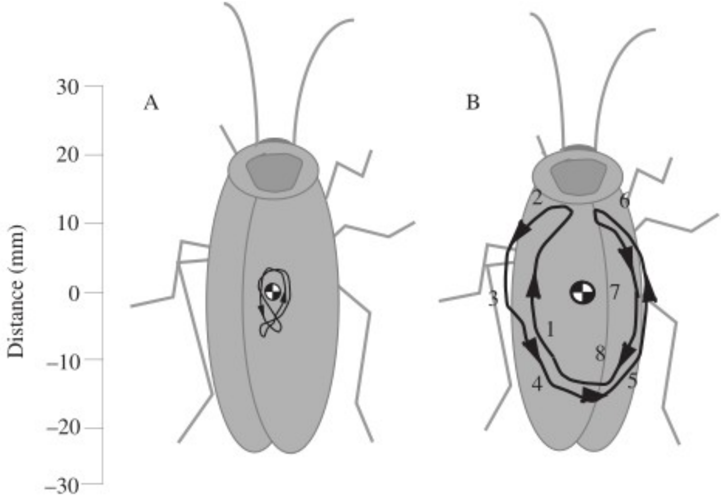


Derived from "Sprawling and erect hip joints - horizontal" by Fred the Oyster. Licensed under CC BY-SA 4.0 via Commons

- From Alexander [1982]
    - Assume: CoM height h, stride period
    - Time to fall $(2h/g)^{1/2}$
    - Reaction time $\boldsymbol{\sigma} := f\,(2h/g)^{1/2}$ stride periods
- Example (dog vs. cockroach)

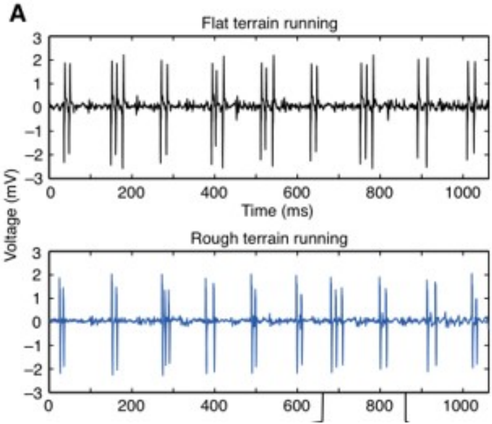
So do cockroaches move quasi-statically?

- *P. americana*: 1.5 m/s (50 body lengths/s) Full and Tu [1991]
- Cheetah: 16 body lengths/s
- Ting et al. [1994]

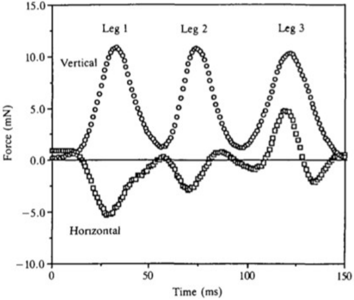


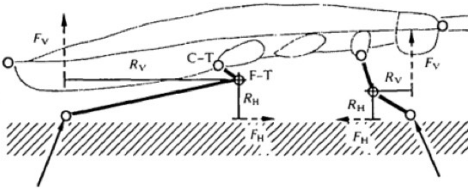
Do cockroaches actively stabilize dynamic gaits?

From Sponberg and Full [2008], in *B. discoidalis*



Why are cockroach legs splayed?

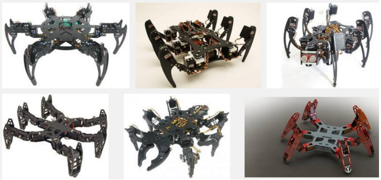




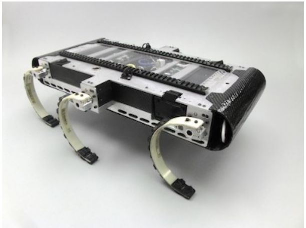
- Legs seem to push against each other
- GRF patterns have large horizontal forces
- Horizontal forces direct GRF towards joints

Sprawled posture robots

- 18 active DOF



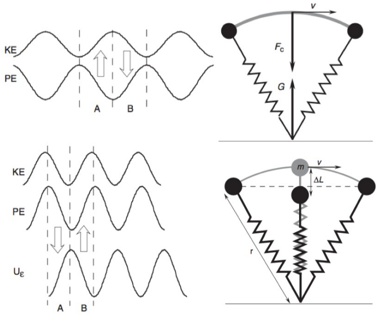
- 6DOF



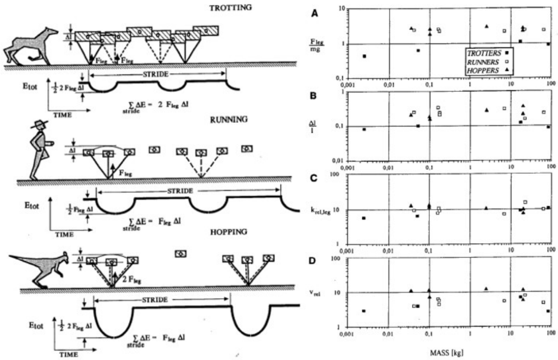
- Which one is more like the cockroach/spider/crab?

Design implications for running

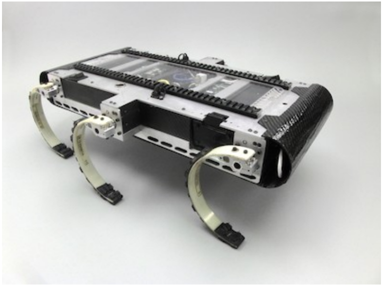
From Cavagna et al. [1977];
figure from Biewener [2003]

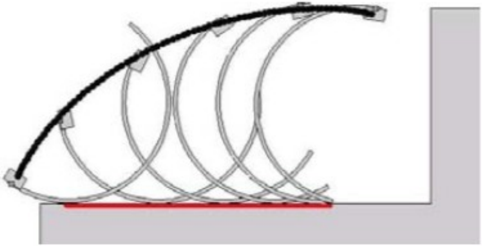


Universality of "bouncing:"
Blickhan and Full [1993]



RHex design





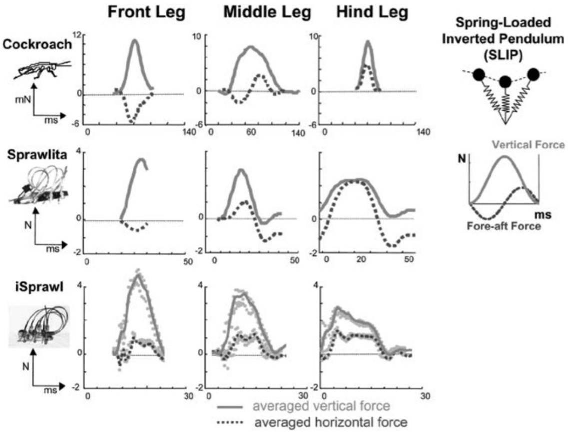
- 6 legs
- 1 actuator/leg
- Compliance
- "C" shape Moore [2002]

Much more on the conceptual development of RHex in 4.1!

Leg differentiation

iSprawl (0.3 Kg, 15 bl/s), from Kim et al. [2006]

https://www.youtube.com/watch?v=Jol_onXm5rE



Lessons from sprawled animals and robots

Biomechanists tell us

- Sprawled animals need more legs—Alexander [1982]
- But they run dynamically—Ting et al. [1994]
- They don't use their brains—Sponberg and Full [2008], Jindrich and Full [2002]

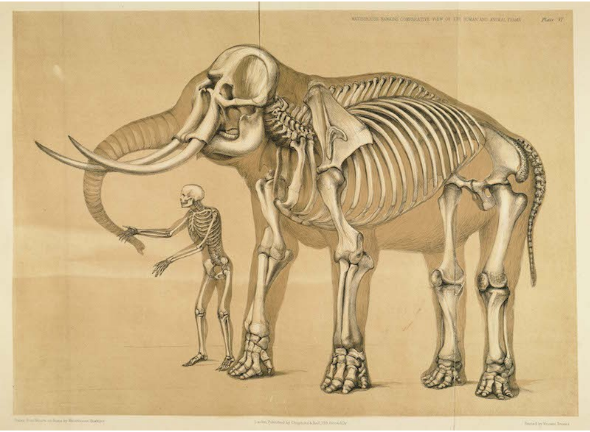
Roboticists learn

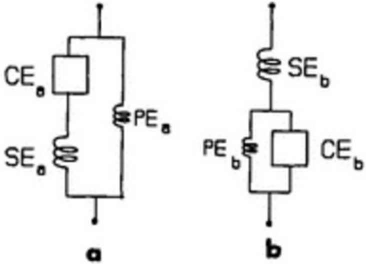
- Dynamic locomotion offers advantages—Raibert and Hodgins [1993]
- Important to think of energy exchange to "run"—Saranlı et al. [2001]
- Bodies are designed accordingly—Saranlı et al. [2001], Kim et al. [2006]

Revisit: do robots need 6 legs?

What's (different) in a quadruped?

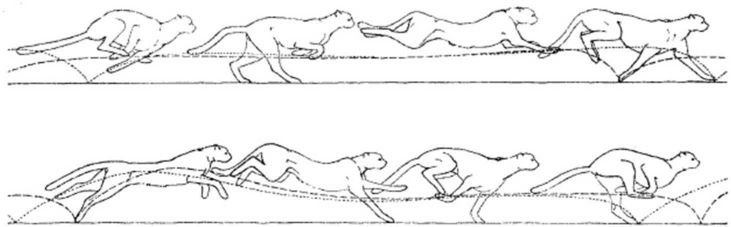
- Leg/foot structure
- Unguligrade, digitigrade, plantigrade
- Tendons, muscles form viscoelastic systems—Winters [1990]



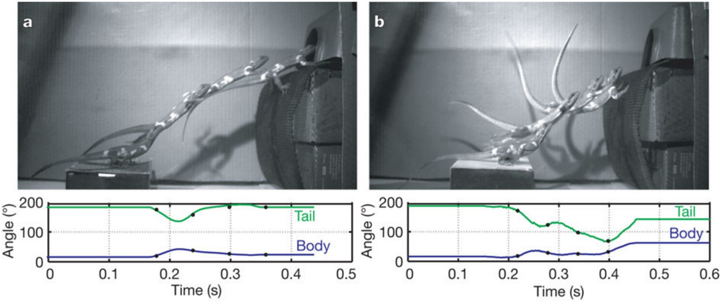


Quadrupeds use their core

From Hildebrand [1961]

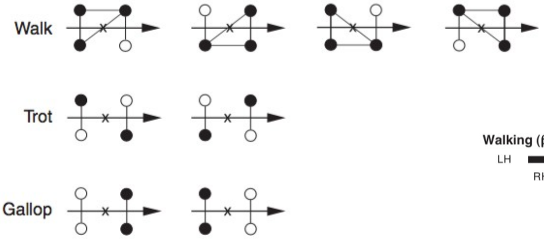


From Libby et al. [2012]

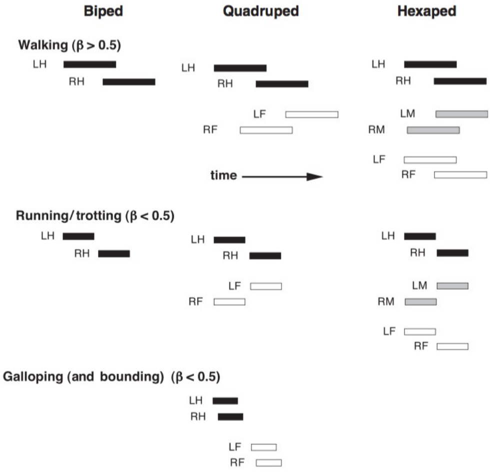


Gaits in nature's quadrupeds

- "Limb support pattern"—Biewener [2003]

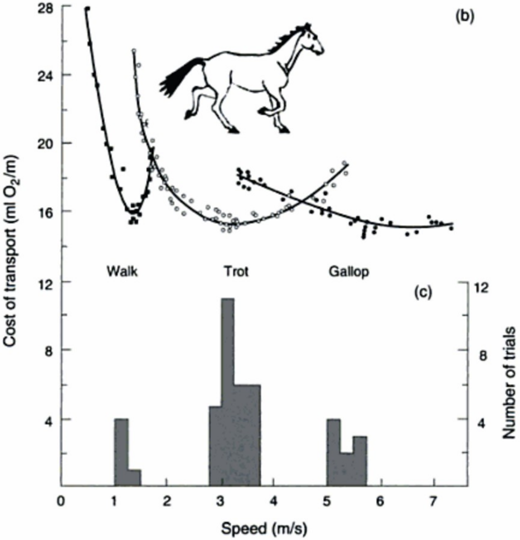


- "Gait diagram"



Gait energetics

Energetics—Biewener [2003]

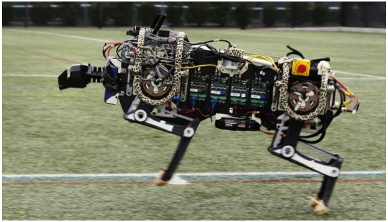


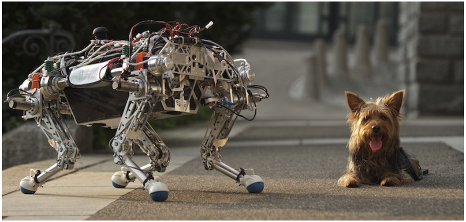
$$\mathrm{CoT} := \frac{\text{metabolic power}}{mgv}$$

A very short list of other robotic quadrupeds

- Boston Dynamics': LittleDog, Spot, BigDog, WildCat, LS3

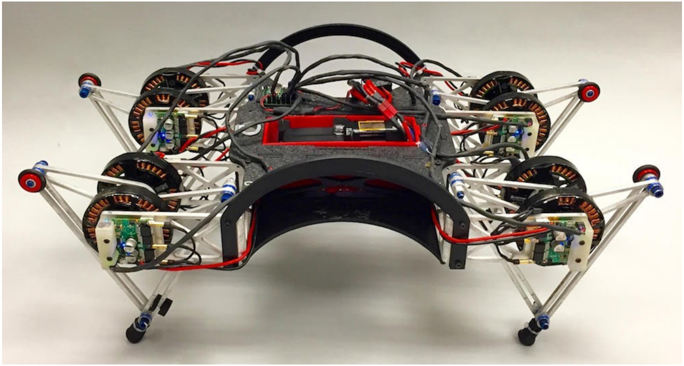
- MIT Cheetah—Seok et al. [2015]
- StarlETH—Hutter et al. [2012]





- And many more…

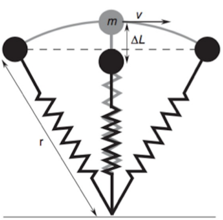
Minitaur

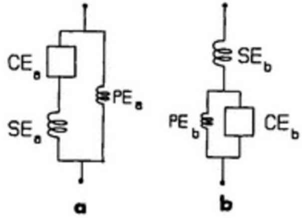


- Task-optimal leg design—Kenneally and Koditschek [2015]
- Direct drive—Kenneally et al. [2015]

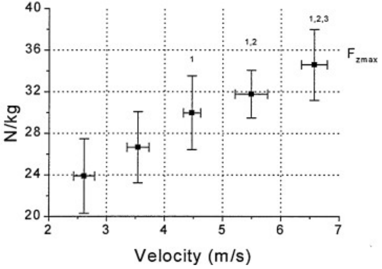
Robot design from the bottom up

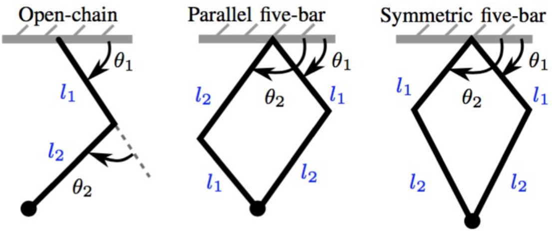
- Recall animal legs





- Tunable stiffness (e.g. human running—Arampatzis et al. [1999])





- Minitaur legs: 2DOF, force transmission, proprioception—Kenneally et al. [2015]

Lessons from quadrupedal animals and robots

Biomechanists tell us

- Legs need to swing, retract—Biewener [2003]
- Gaits emerge from energetics, control needs

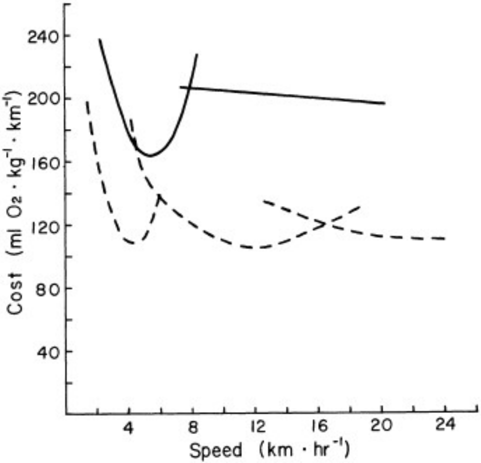
Roboticists learn

- Build legs with enough DOFs
- Control ideas varied (more in the last week)
- Spines / tails not popular yet

Structural changes for bipedalism

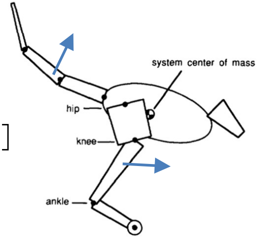
- Orthograde (upright posture)
- Muscles for core support
- Mechanisms for endurance
  - Carrier et al. [1984]: "Carrier's constraint"

The reptilian idea of fun
Is to bask all day in the sun.
A physiological barrier,
Discovered by Carrier,
Says they can't breathe, if they run.
—Richard Cowen



  - Flat running CoT
  - Bigger stores; better dissipation

Tails in nature's bipeds



From Raibert and Hodgins [1993]

Counterbalance legs

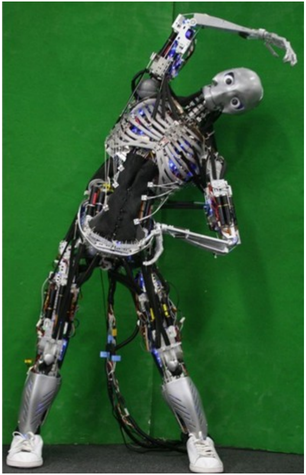
Power walking at slow speeds

https://www.youtube.com/watch?v=yZ4_7051rEE

https://www.youtube.com/watch?v=bgWJ9DN1Qak

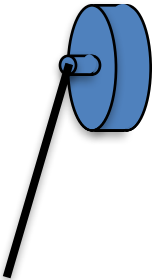
Some robotic bipeds

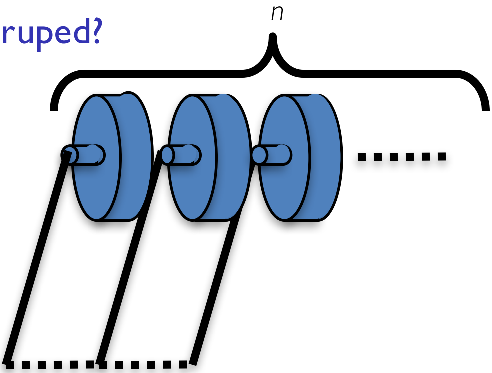
Kenshiro—Nakanishi et al. [2012]
(~100 actuated DOF)



ATRIAS (6 actuated DOF)

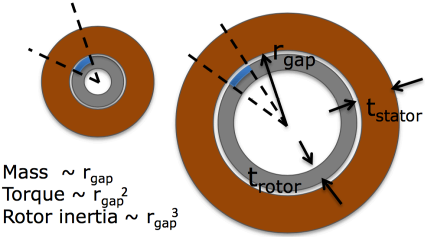
Why a biped vs. a quadruped?





- Framing costs—Kenneally et al. [2015]
- "Parallel motors" as in multiple legs, not multiple DOFs/leg

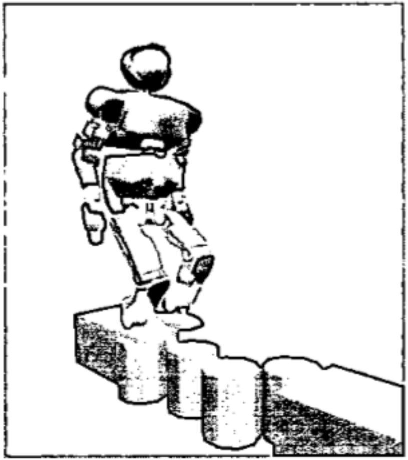
- Torque/motor: $\boldsymbol{\tau}/n \sim r^2$
  Mass/motor: $m/n \sim r$ (Seok et al [2012])
- $\boldsymbol{\tau}/n \sim (m/n)^2$, so $\boldsymbol{\tau} \sim n^{-1}$ (fix total mass budget m)

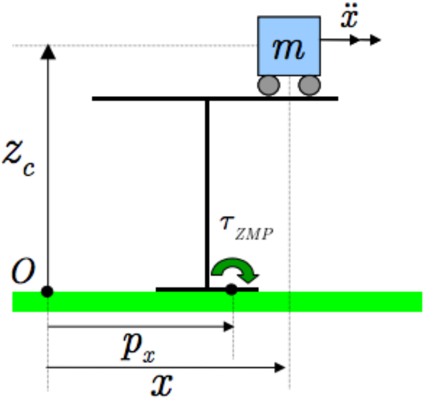


Torque density ~ r_{gap}
Torque/inertia ~ $1/ r_{gap}$

Balance with feet

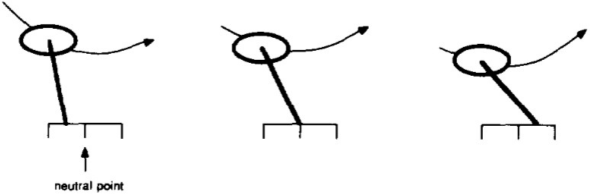
ZMP—e.g. in Kajita et al. [2003]



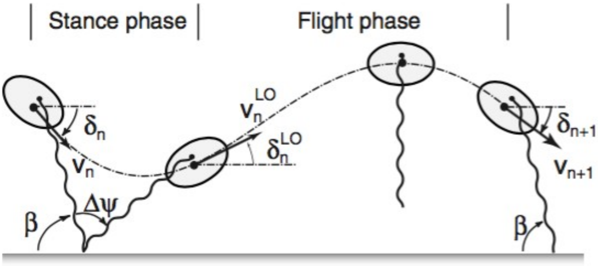


Dynamic balance

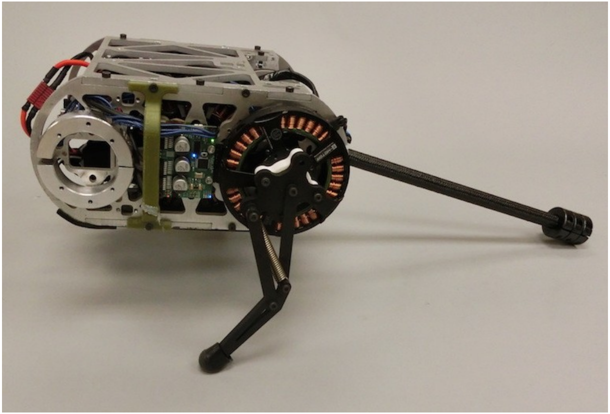
- Leg modelled as sprung mass
- Neutral point Raibert [1986] (recall from 2.1)



- "Simply stabilized" Ghigliazza et al. [2005]

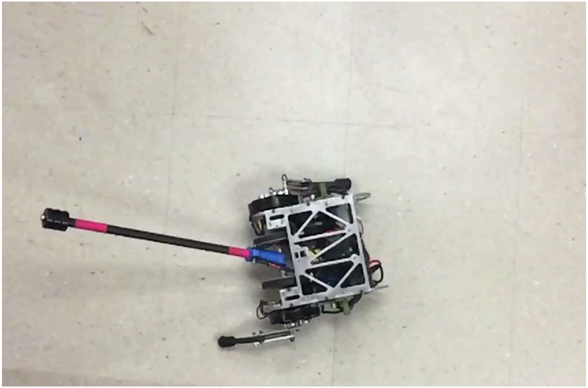


Jerboa design



- Direct drive—Kenneally et al. [2015]
- Springy legs; passive extension—De and Koditschek [2015c]
- 2DOF actuated tail
- Leg+tail vs. 2DOF leg

Some uses of a robotic tail



- Turning
- Reorientation
- More in next segment

Lessons from bipedal animals and robots

Biomechanists tell us

- Animals went bipedal for physiological reasons—Carrier et al. [1984]

Roboticists learn

- Build robots with as few actuated DOFs as possible
- Tails can be used to inertially to control body orientation (and more!)