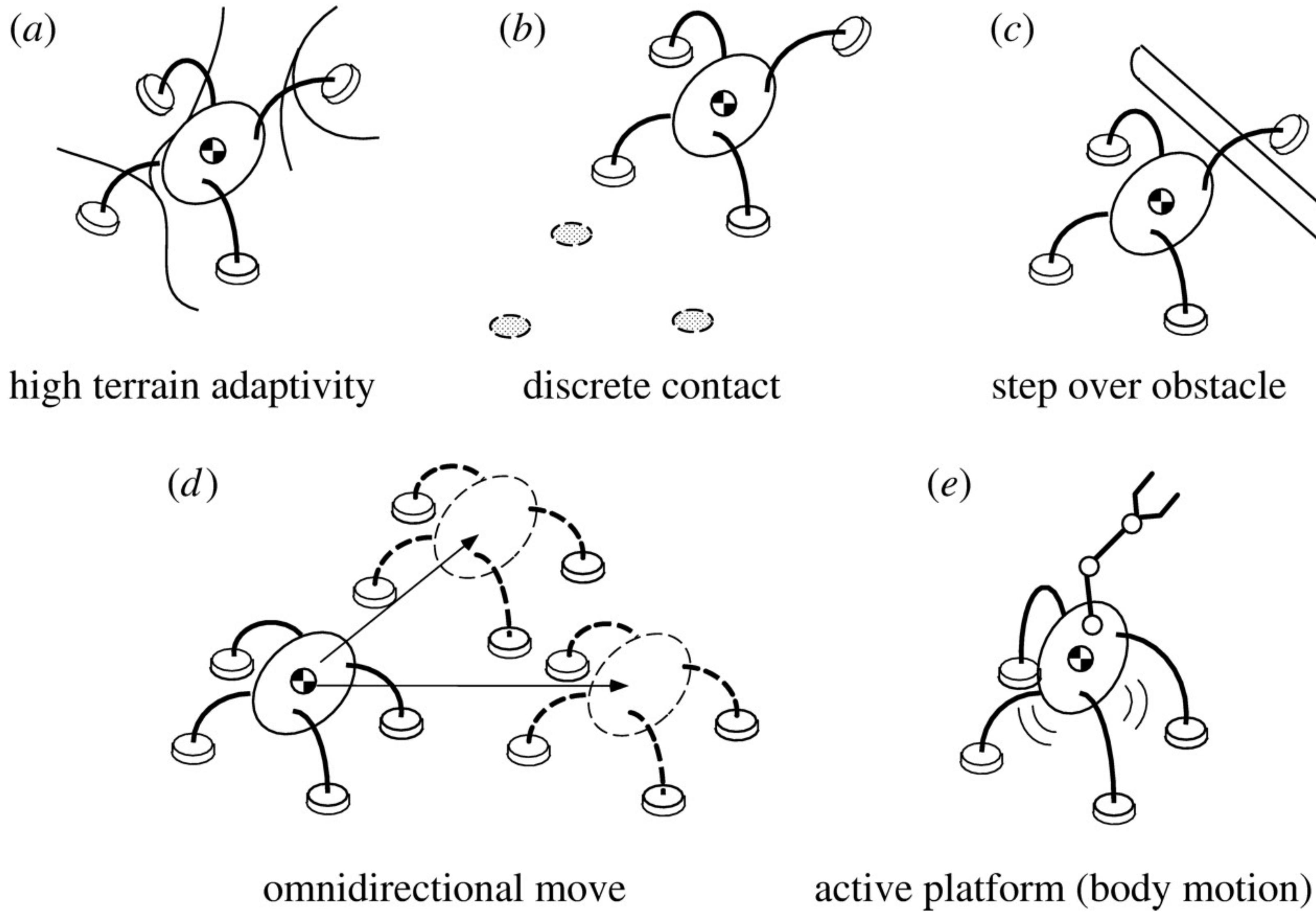
Master Course on Robotics

Legged Robots

Lecture 2

Legged Locomotion

Advantages of walking machines



Legged Robots

Legged robots have a unique ability to:

- ✓ Isolate their body from terrain irregularities
- ✓ Overcome many obstacles
- ✓ Avoid undesirable footholds
- ✓ Regulate their stability

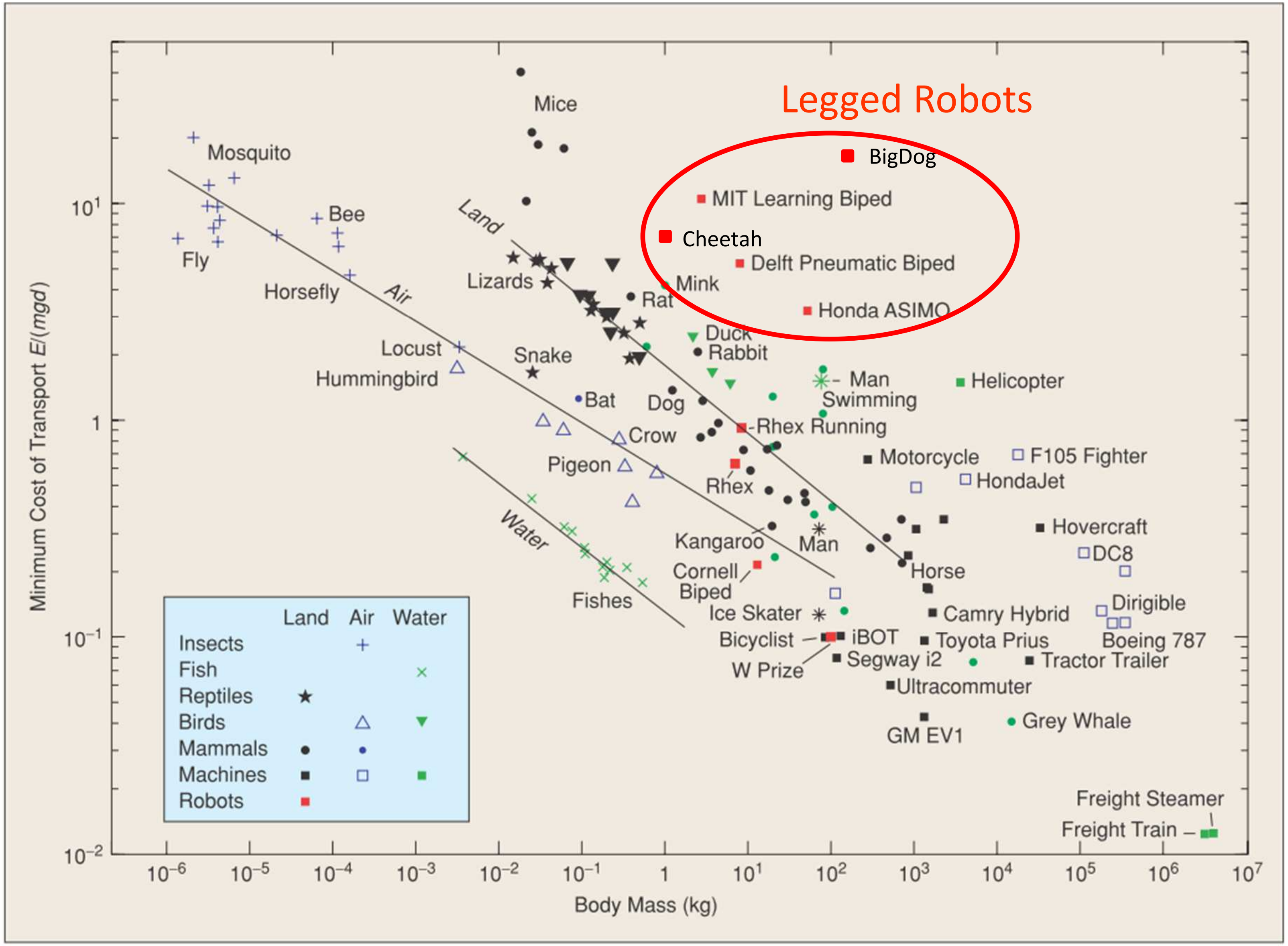
Limitations:

- — many DOFs must be **controlled** in a coordinated way (in comparison to wheels)
- — Energetically very inefficient

Legged Robots

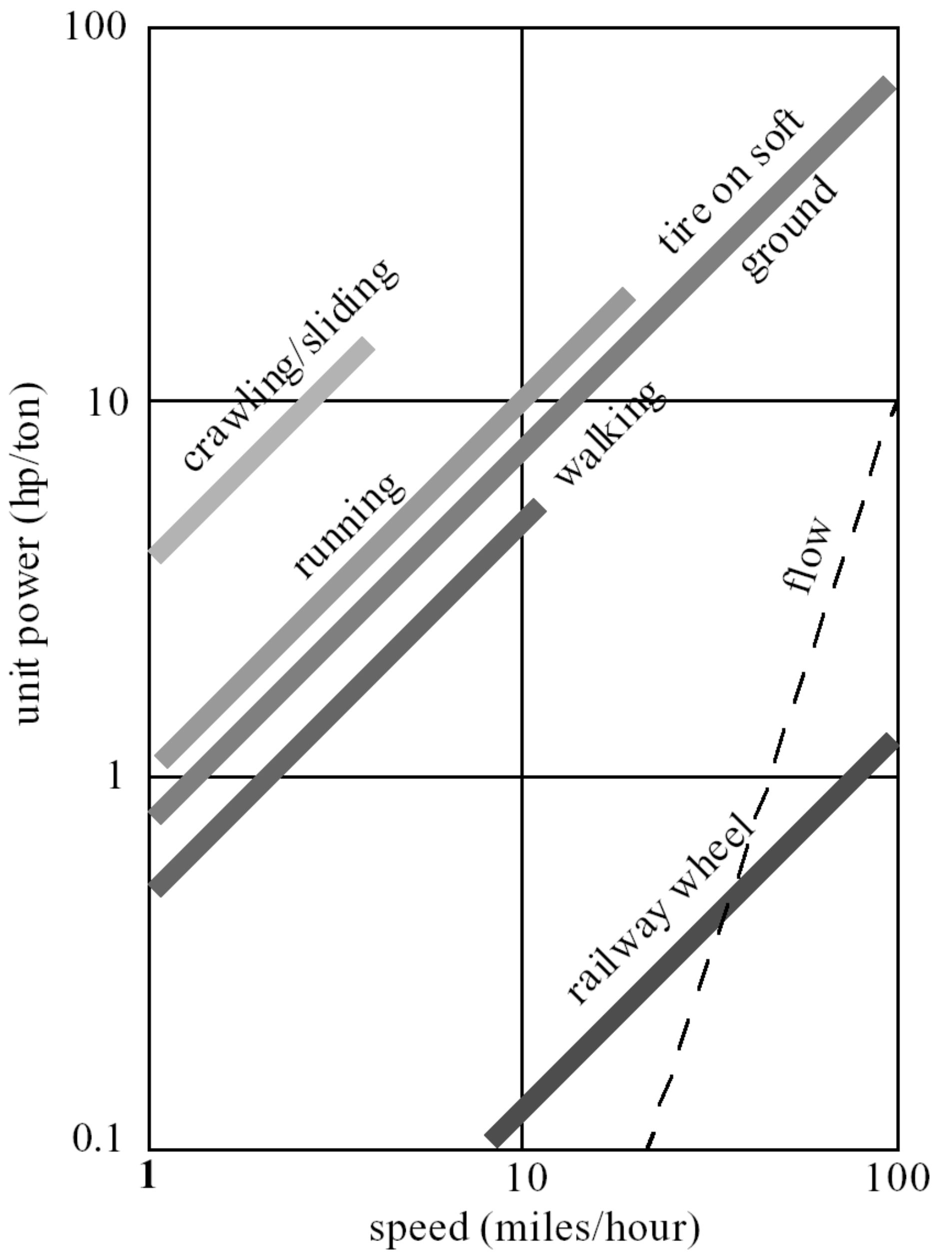
Cost of Transport (COT)

$$COT = \frac{E_{used}}{m \cdot g \cdot d} = \frac{P}{m \cdot g \cdot v}$$



Efficiency of Walking and Rolling

- number of actuators
- structural complexity
- control expense
- energy efficient
- movement of the involved masses (movement up/down of center of gravity costs)



The wheel is the most efficient locomotion mechanism

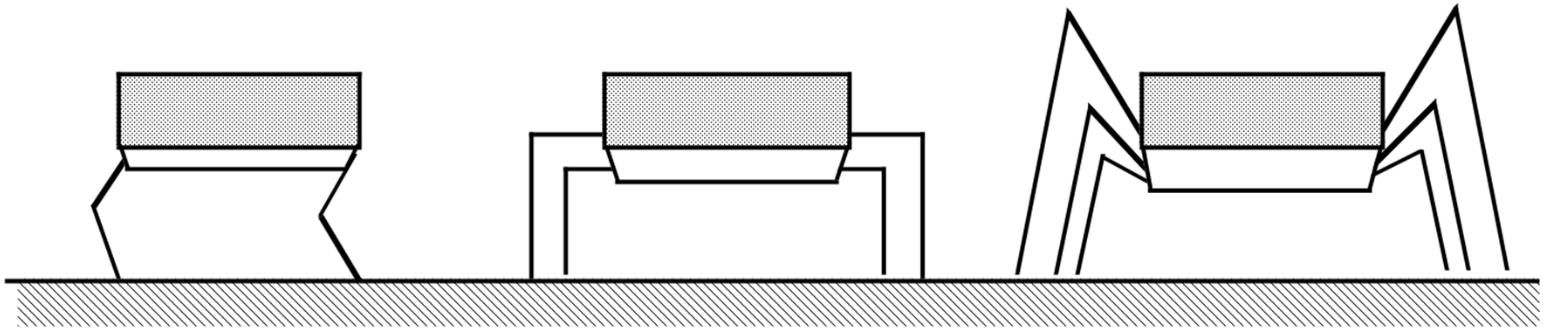
Leg Configurations and Stability

Important aspects of legged locomotion are:

- stance (the way the body is supported by the legs)
- number of legs
- functional structure of the leg and foot

- Stability requires (at least) three legs when standing still (statically stable).
- During walking some legs are lifted. Thus loosing stability?
- For static walking at least six legs are required.

Stances



- Some animals, such as humans and bears walk flat footed (palmate)
- Some, like horses and cattle walk more on their fingers (digitate)
- Smaller or stockier animals walk with wide stances (sprawling gaits) (these include insects, many reptiles, and some small mammals)
- Larger animals tend to walk with straighter legs

Stability

- **Stability** means the capability to maintain the body posture given the control patterns
- **Statically stable** walking implies that the posture can be achieved even if the legs are frozen - the motion is stopped at any time, without loss of stability
- Static stability is achieved through the mechanical design of the robot
- Statically stable systems can be controlled using kinematic models
- **Dynamic stability** implies that stability can only be achieved through active control of the leg motion (the body must actively balance or move to remain stable)
- Dynamic walking requires use of dynamical models

Statically Stable Walking

- If the robot can walk while staying balanced at all times it is **statically stable walking**

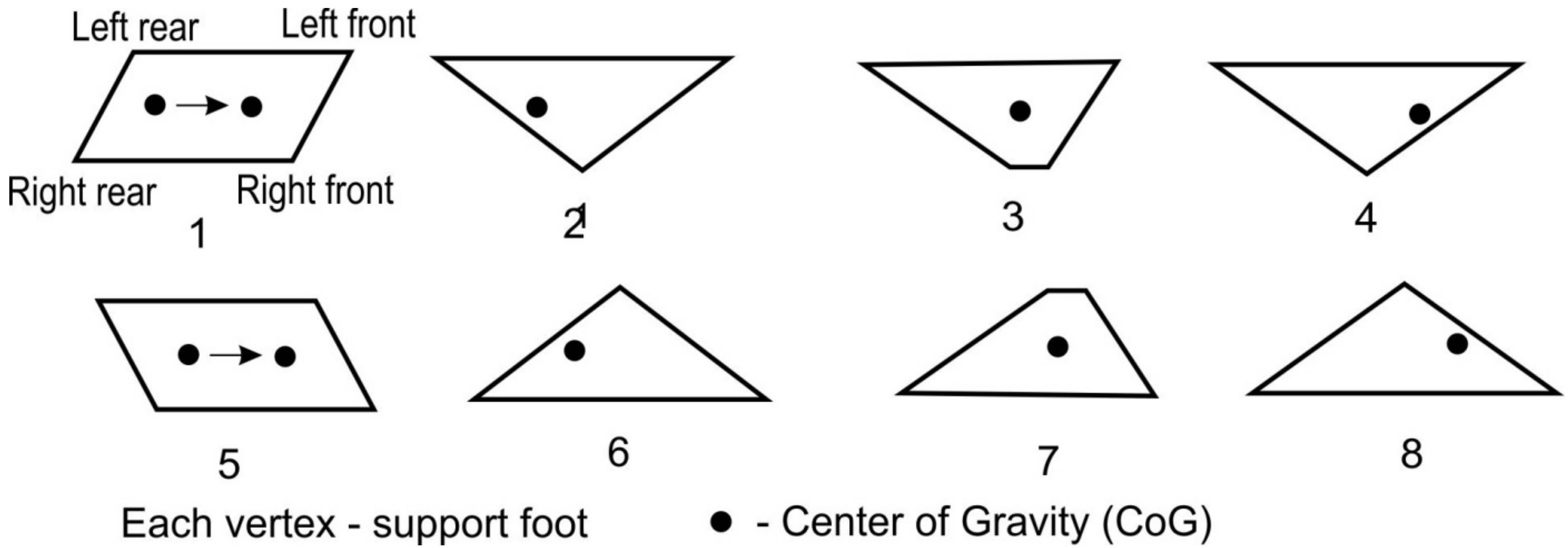
- There need to be enough legs to keep the robot stable
  - Three legged robots are not statically stable
  - Four legged robots can only lift one leg at a time (slow walking pace, energy inefficient)
  - Six legs are very popular (both in nature and in robotics) and allow for very stable walking

Stability

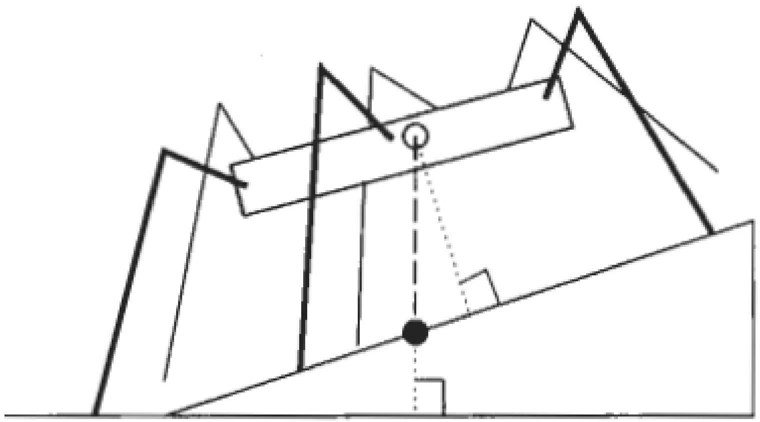
- People and humanoid robots, are not statically stable
- Standing up and walking appear effortless to us, but we are actually using **active control of our balance**
  - We use muscles and tendons
  - Robots use motors
- In order to remain stable, the robot's **Center of Gravity** (**CoG**) must fall under its polygon of support
  - The polygon is the projection between all of its support points onto the surface
  - In a biped robot, the polygon is really a line
    - The center of gravity cannot be aligned in a stable way with a point on that line to keep the robot upright

Stability

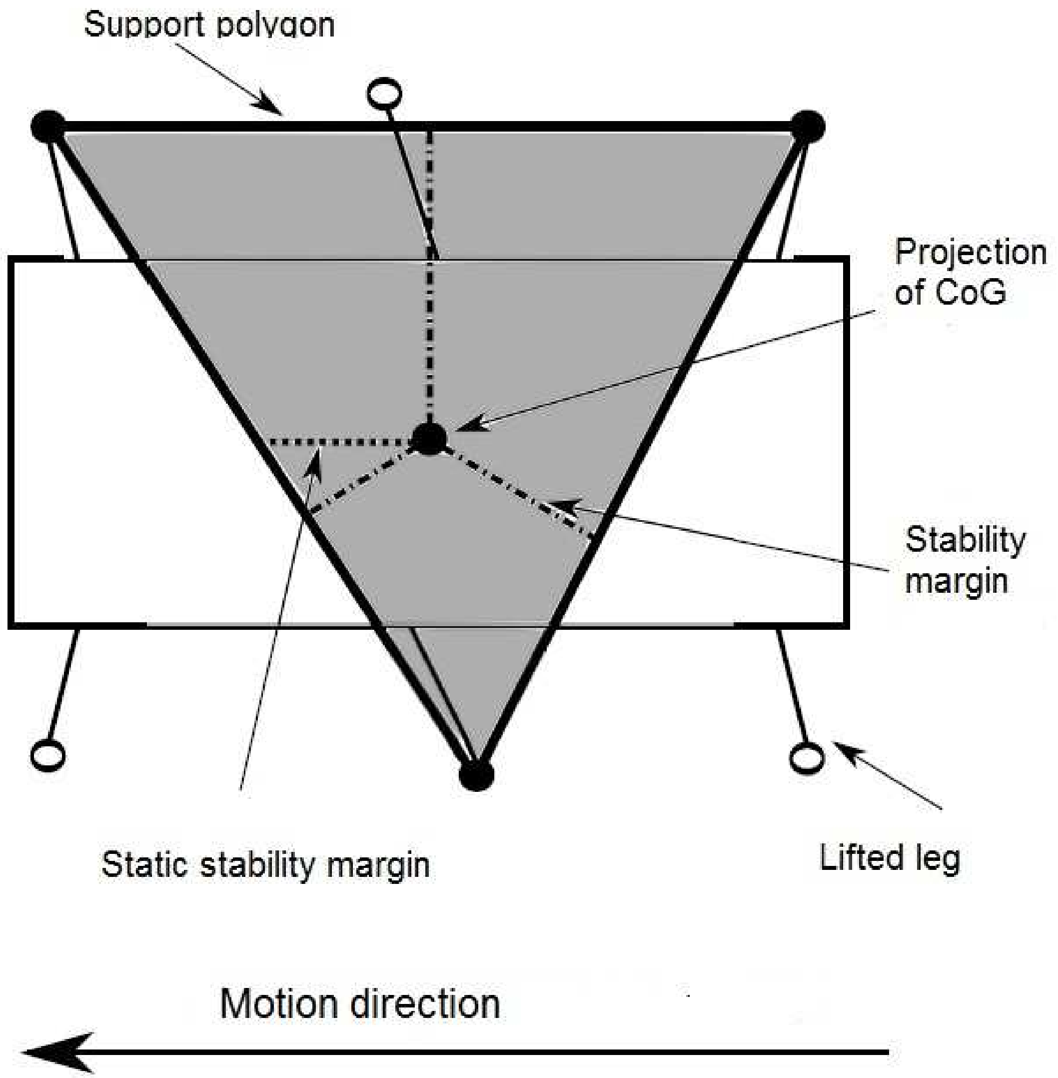
- Statically stable quadruped robot
- Projection of the **CoG** always lies inside the polygon of support



Stability



Projection of the **CoG**



Stability Margin (Tripod Gait)

Gait

The gait is characterized as the sequence of lift and release events of the individual legs.

- More legs gives more possible gaits.
- The number of possible events **N** for a walking machine with **k** legs:

$$N = (2k - 1)!$$

- For bipedal walker:

$$N = (2 \cdot 2 - 1)! = 3! = 6$$

- The six different events are:

1. lift-right-leg, 2. lift-left-leg, 3. release-right- leg, 4. release-left-leg, 5. lift-both-legs, 6. release-both-legs.

- For a robot with six legs (hexapod):

$$N = (2 \cdot 6 - 1)! = 11! = 39\,916\,800$$

Legged Locomotion Terminology

- Gait
  - Gait cycle
  - Gait period
  - Gait frequency
  - Gait phase
- Stepping
  - Step cycle
  - Step phase
  - Support stage, support duration
  - Transfer stage, transfer duration
  - Duty factor
  - Step trigger

Gaits

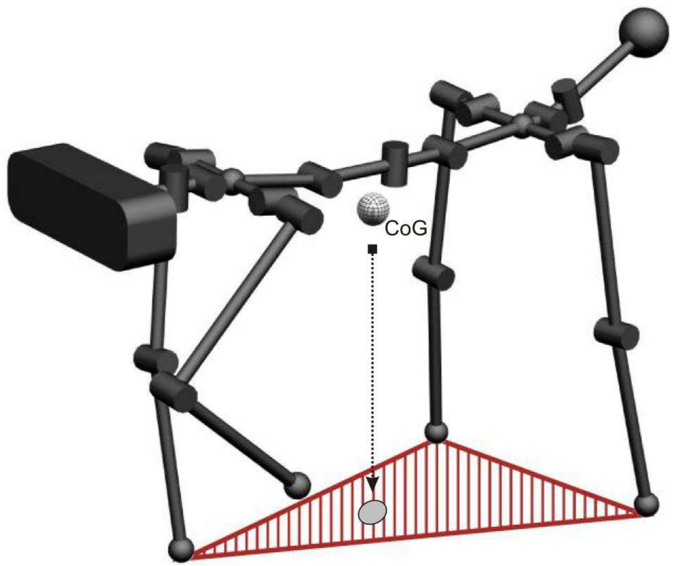
The **gait** is characterized as the sequence of **lift** and **release** events of the individual legs.

- Each repetition of the sequence is called a ***gait cycle***
- The time taken in one complete cycle is the ***gait period***
- The inverse of the period is the ***gait frequency*** (1/period)
- Normally, in one gait cycle, each leg goes through exactly one complete step cycle

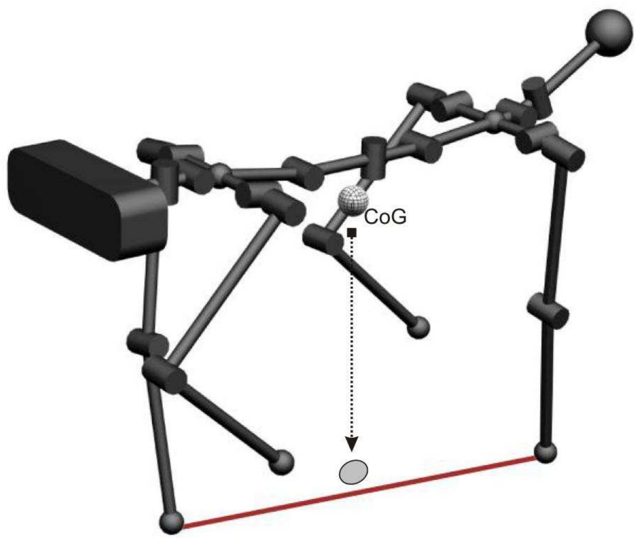
Gaits

- Gaits can be divided into two main classes:
  - **Periodic gaits -** repeat the same sequence of movements
  - **Non-periodic or free gaits** - no periodicity in the control and could be controlled by the layout of the environment
- Gaits can also be divided into:

Static Gaits



Dynamic Gaits



Gait Phase

- The *gait phase* is a value that ranges from 0 to 1 as the gait cycle proceeds
- We can choose 0 as being any arbitrary point within the cycle (such as when the front right begins its step)
- The phase is like a clock that keeps going round and round (0…1, 0…1, 0…1)
- For a particular gait, the stepping of the legs and all other motion of the character can be described relative to the gait phase

Step Cycle

- In one gait cycle, each individual leg goes through a complete ***step cycle***
- Each leg's step cycle is phase shifted relative to the main gait cycle
- The step cycle is broken into two main stages
  - ***Support stage*** (foot on ground - stance)
  - ***Transfer stage*** (foot in the air moving to the new position - fly)
- The amount of time a leg spends in the support stage is the *support duration* (and likewise for *transfer duration*)

$$\boxed{SupportDuration + TransferDuration = GaitPeriod}$$

Duty Factor

- The relative amount of time a foot spends on the ground is called the ***duty factor***

$$DutyFactor = \frac{SupportDur\ ation}{GaitPeriod}$$

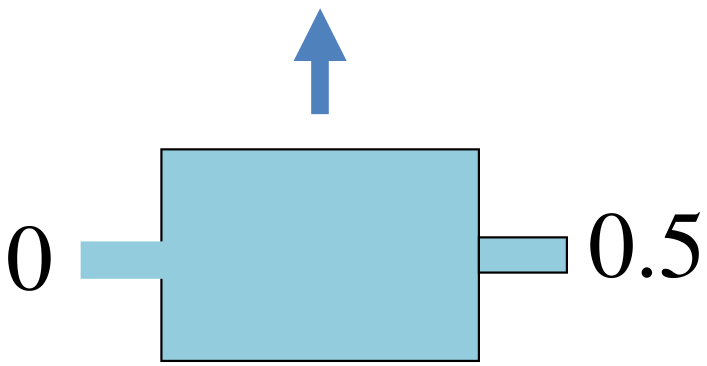
- For a human walking, the duty factor is **greater than 0.5**, indicating that there is an overlap time when both feet are on the ground
- For a run, the duty factor is **less than 0.5**, indicating that there is a time when both feet are in the air and the body is undergoing ballistic motion

Step Phase

- The ***step phase*** is a value that ranges from 0 to 1 during an individual leg's step cycle
- We can choose 0 to indicate the moment when the foot begins to lift (i.e., the beginning of the transfer phase)
- The foot contacts the ground and comes to rest when the phase equals 1 minus the duty factor

Step Trigger

- Each leg’s step cycle is phase shifted relative to the main gait cycle
- This phase shift is called the ***step trigger***
- The trigger is the phase within the main gait cycle where a particular leg begins its step cycle



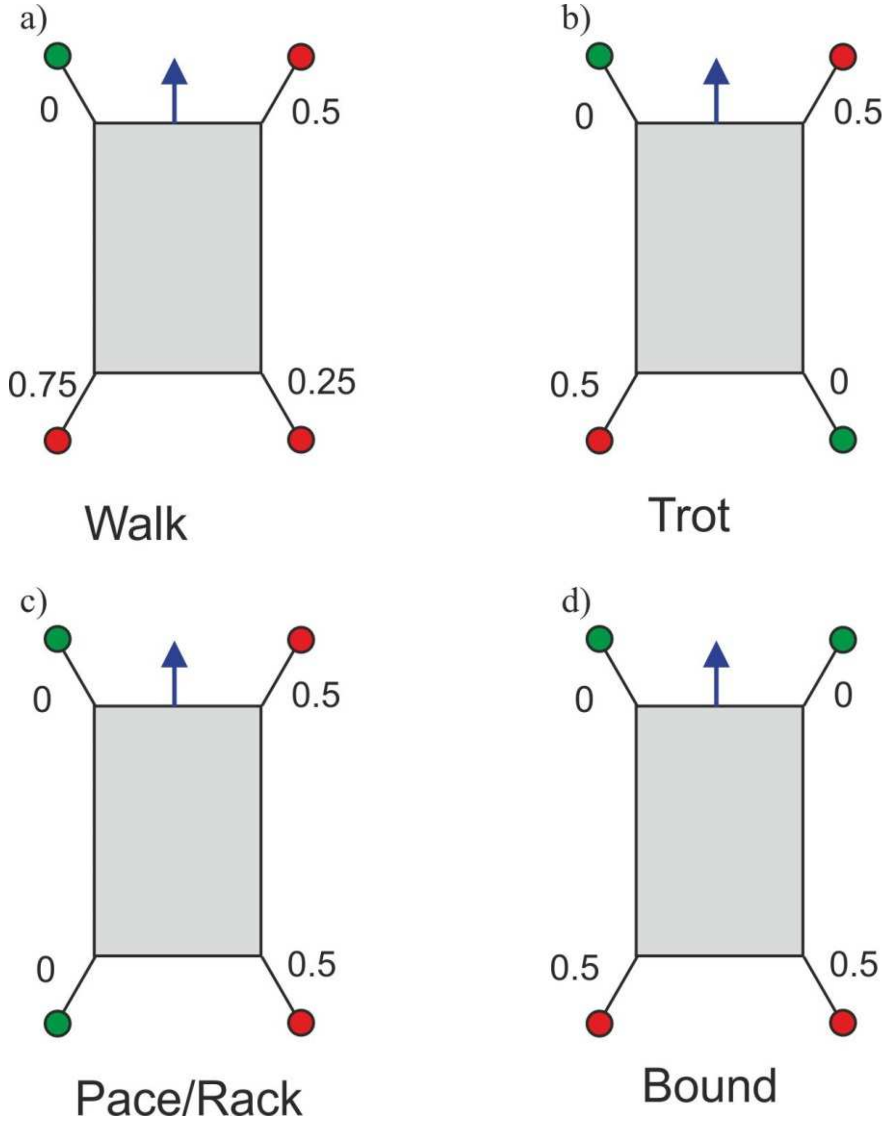
Biped Walk

Gait Description

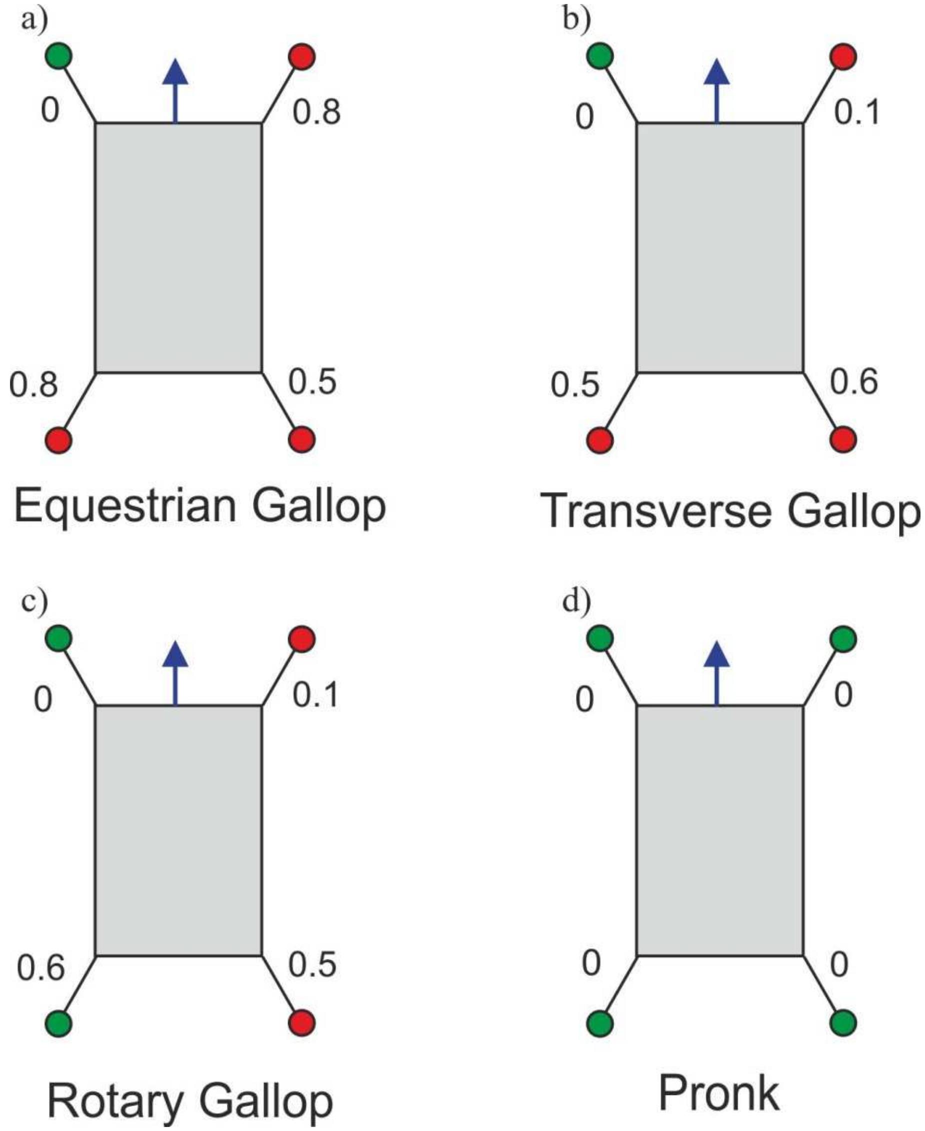
- A simple description of the timing of a particular gait requires the following information
  - Number of legs
  - Gait period
  - Duty factor and step trigger for each leg

Quadruped Gaits

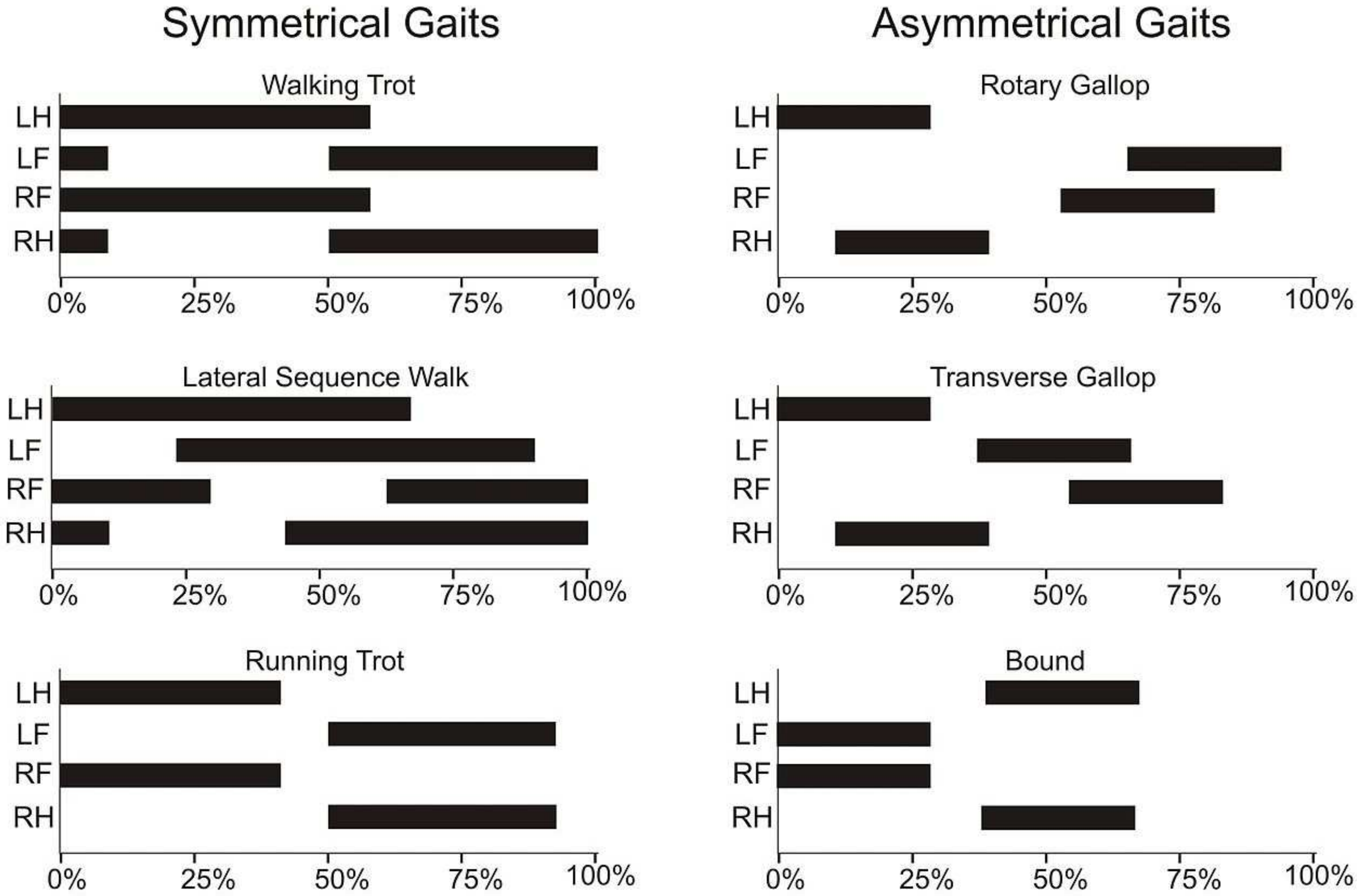
Symmetrical Gaits



Asymmetrical Gaits

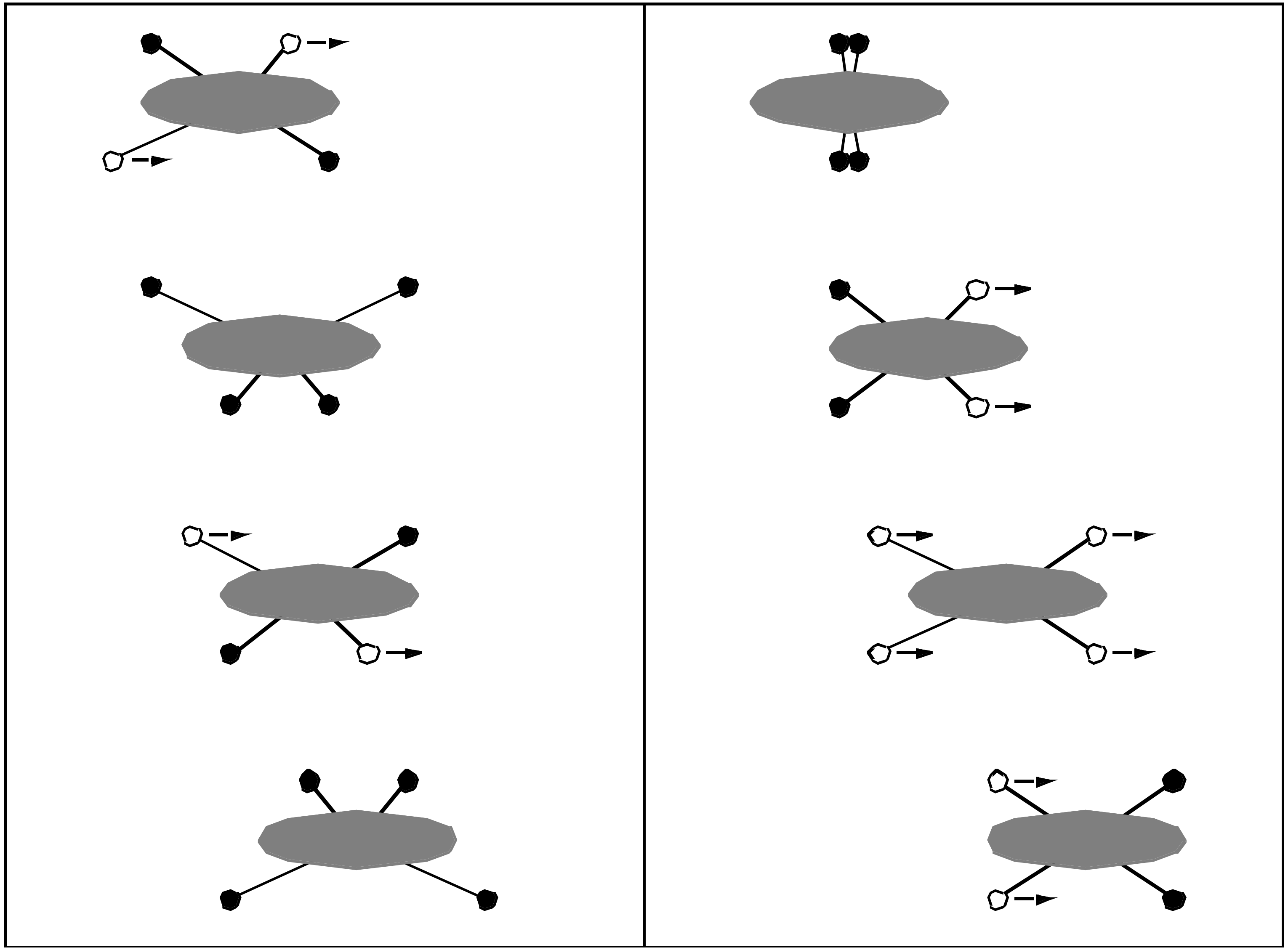


Quadruped Gaits



Dark areas indicate times of contact, bottom axis is % of cycle

Quadruped Gaits



Changeover Walking

Galloping

Quadruped Gaits

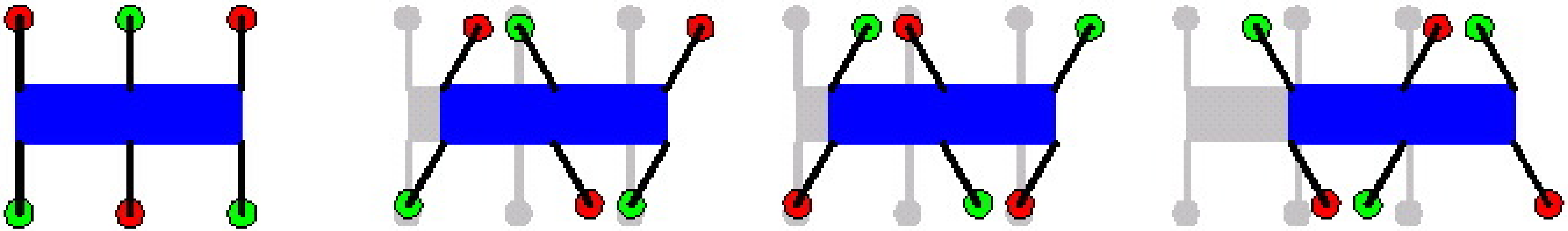
Trot:

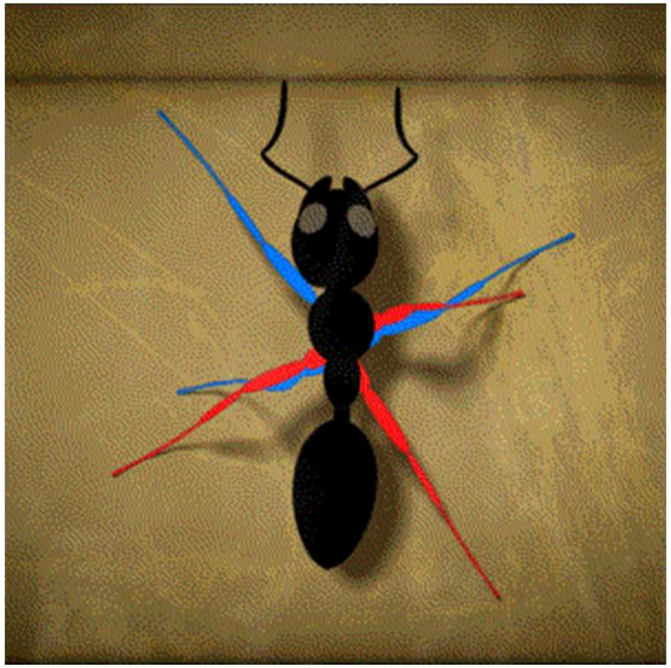
- The trot is a medium paced gait where alternate diagonal legs step nearly in sync (though often slightly led by the forefoot)
- The duty factor is usually relatively low (< 0.4) and there are moments where all 4 legs are off the ground

Horse Gaits

Hexapod Gaits

Tripod Gait

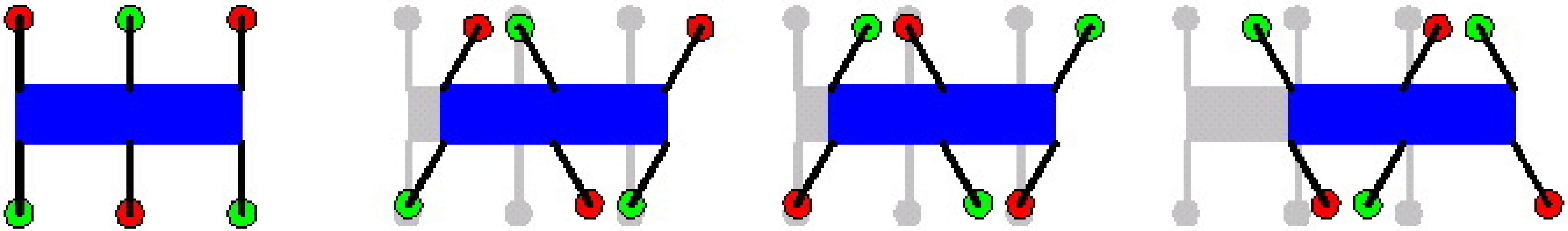




Tripod Gait - an example of a static gait with 6 legs

Hexapod Gaits

Tripod Gait



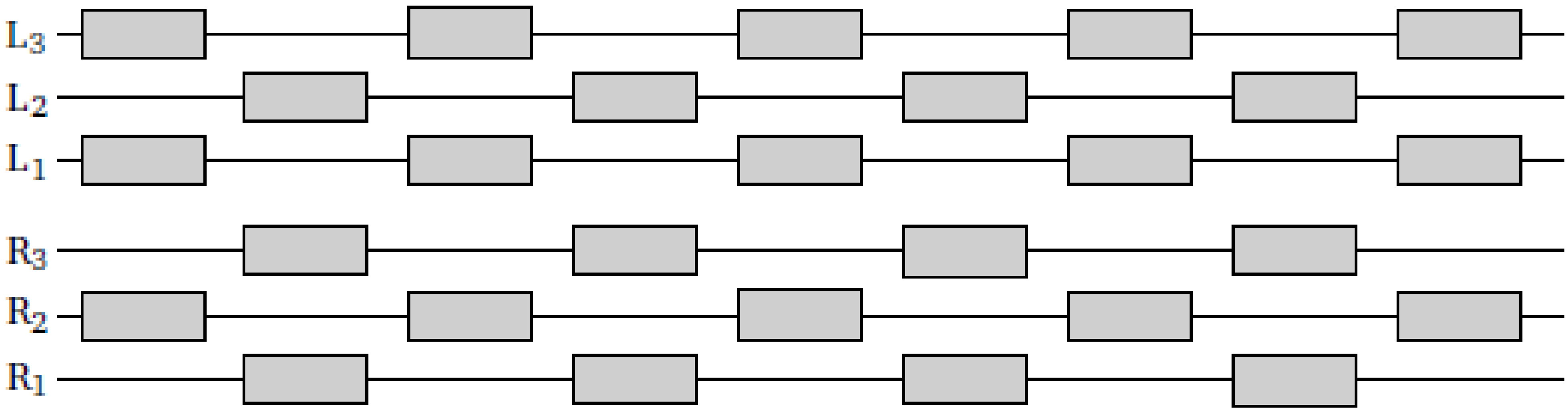
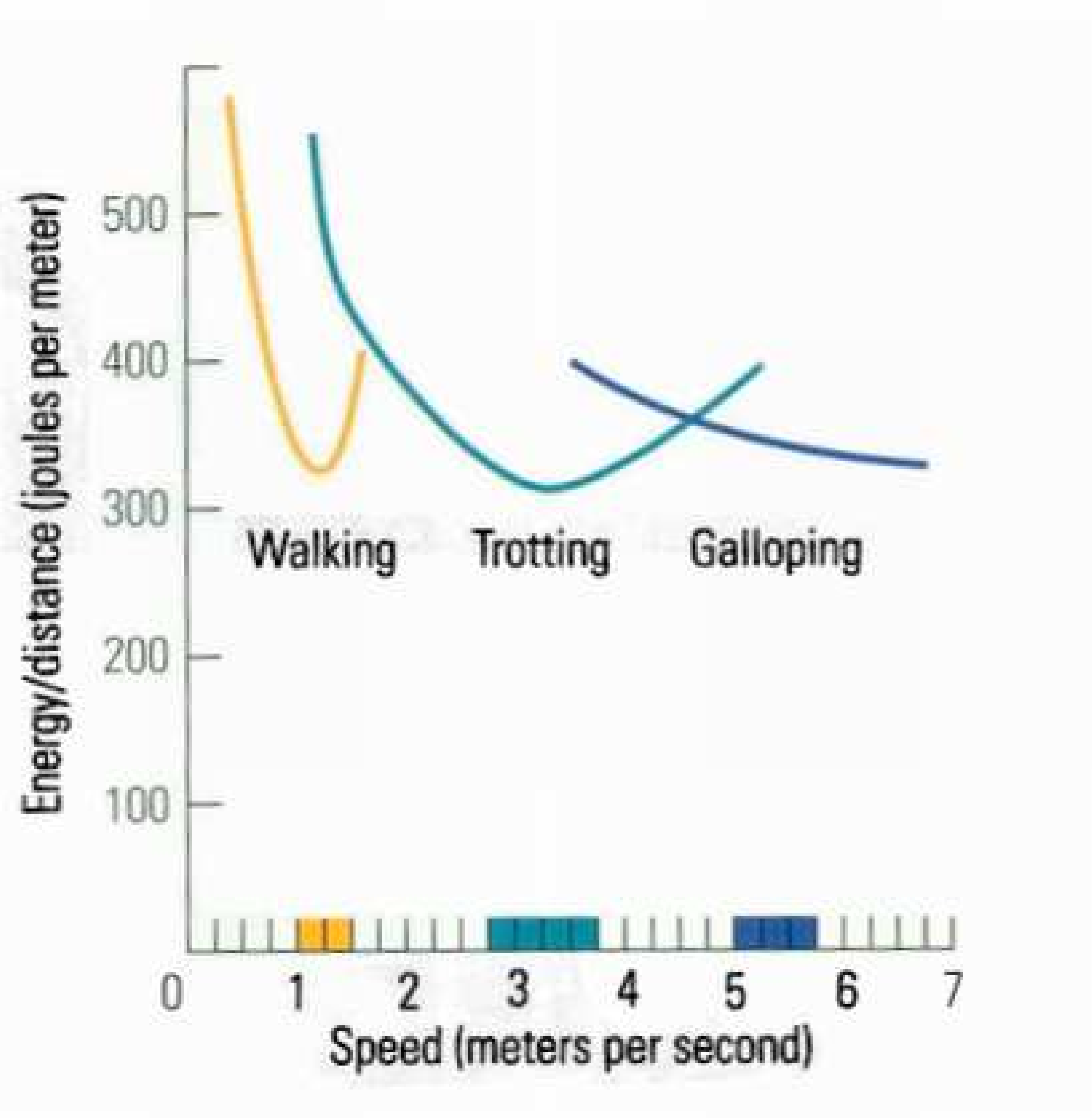


Diagram of Tripod Gait – Duty Factor = 0.5

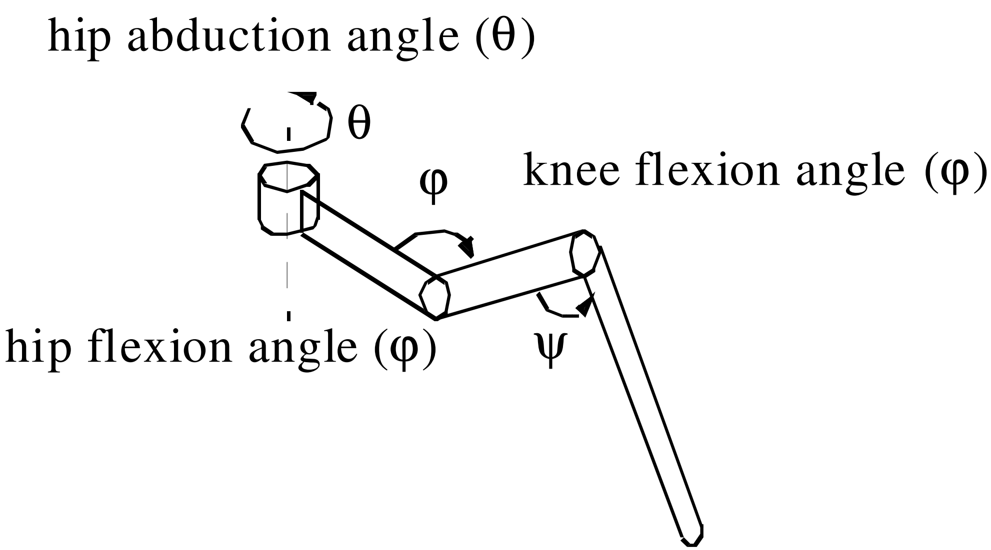
Gait Efficiency

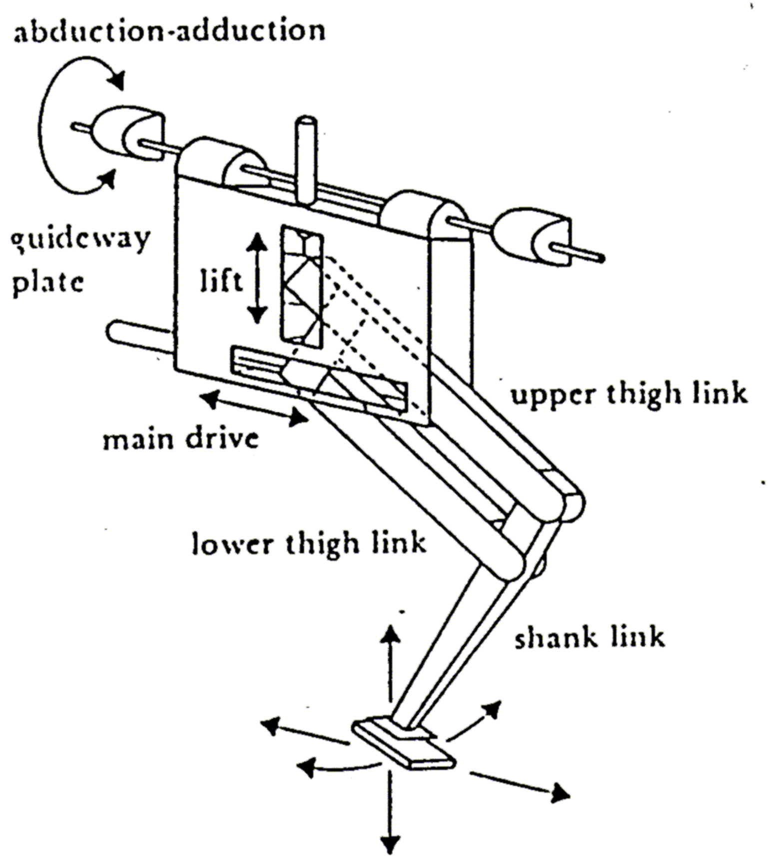


Leg Design

- The number of DOF of a leg is determined by the number of joints it has.
- At least 2 DOF is required to move a leg forward – a **lift** and a **swing** motion.
- Robot legs often have three DOF.
- A fourth ankle joint might improve walking.
- More DOF increase complexity, weight and power requirements.

Examples of Legs with 3 DOF





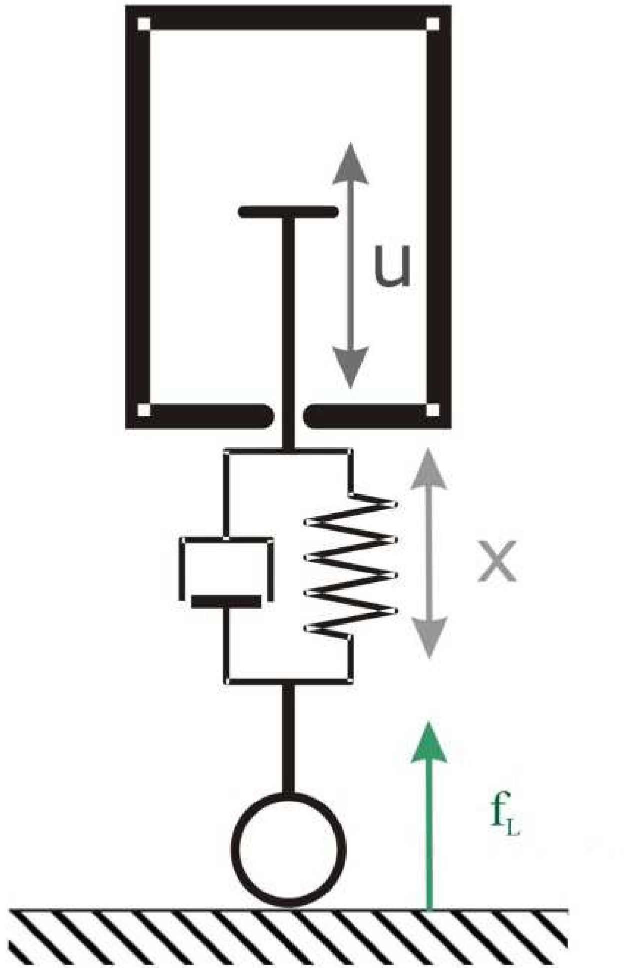
Atlas Leg Design

Efficient Dynamic Walking

The optimal actuator for dynamic walking should:

- be **backdrivable** to allow unimpeded natural dynamics
- have a low inertia and gear ratio to keep th reflected inertia small
- be able to **perform negative work**
- have an adjustable actuator compliance
- be **highly efficient**

Series Elastic Actuators can emulate some of these properties:



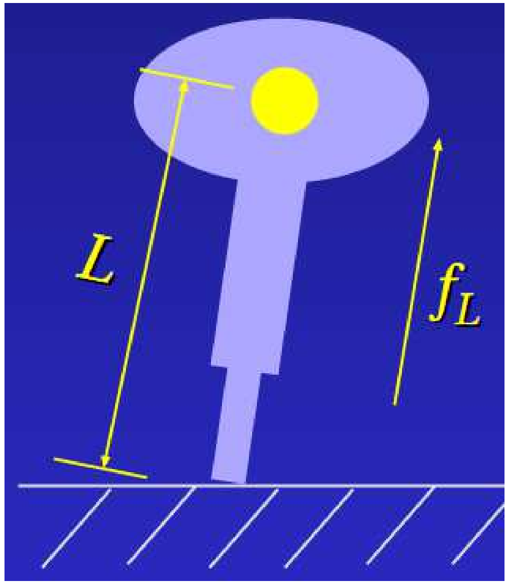
Series Elastic Actuator

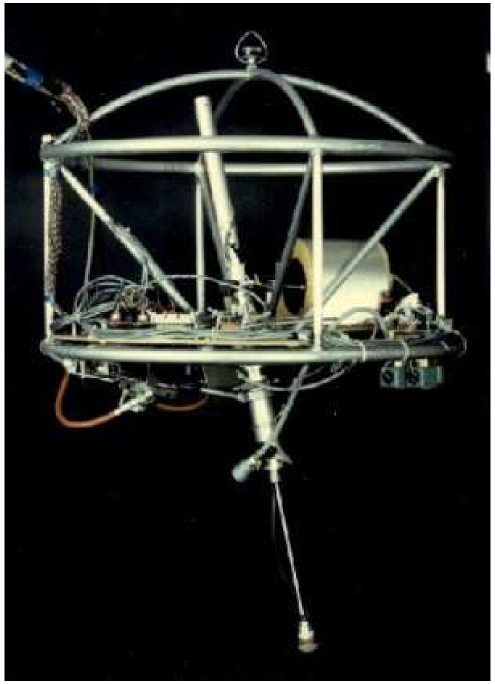
Monopeds

- The MIT 3D one-legged hopper (4 DOF) – M. Raibert [1983]
- The hip is powered by hydraulics and the leg by compressed air
- Modeled as spring and inverted pendulum with adjustable rest length L_d :

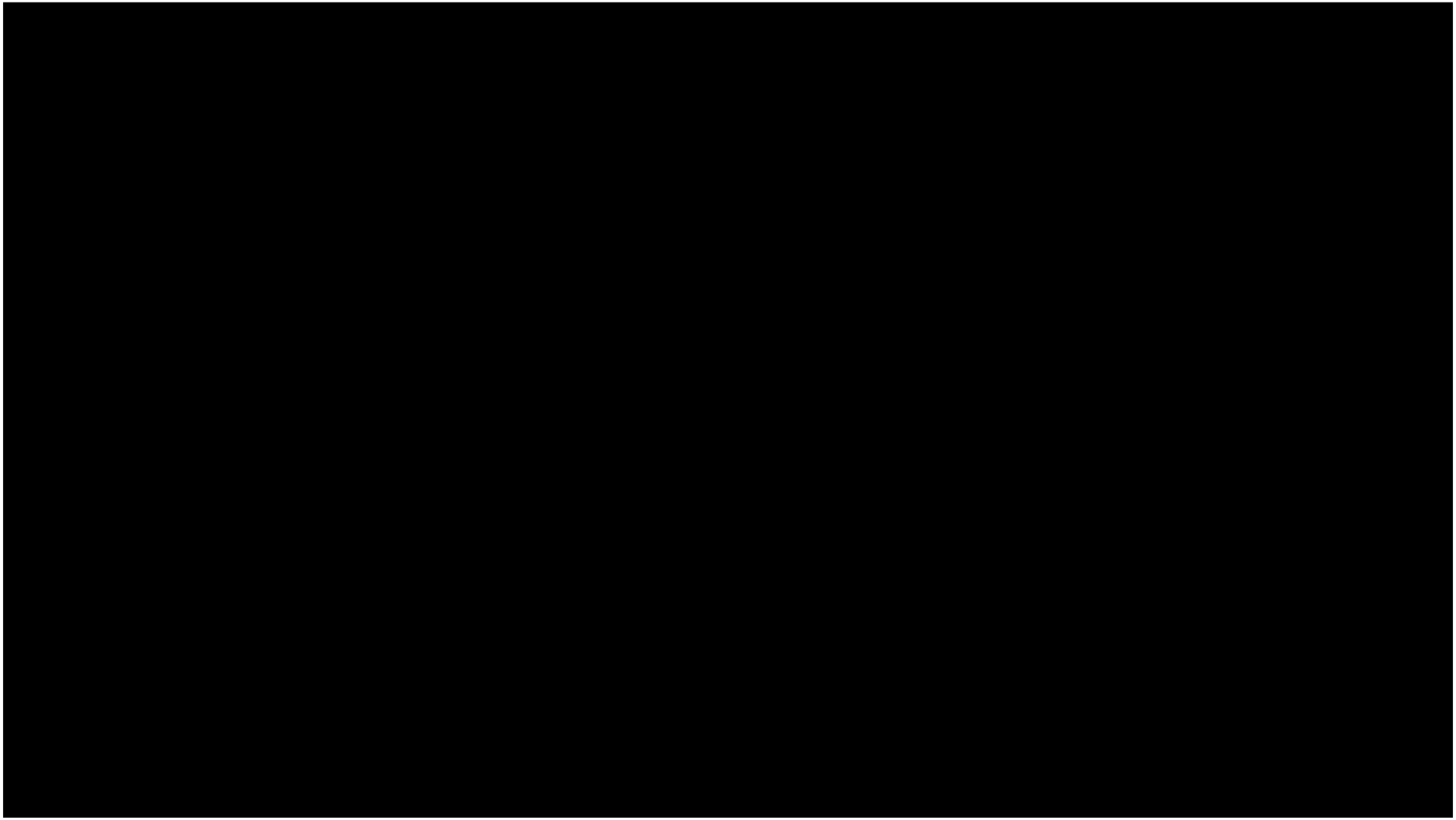
$$f_L = k_L(L - L_d) + b_L(\dot{L} - \dot{L}_d)$$

f_L - force , k_L, b_L - gains



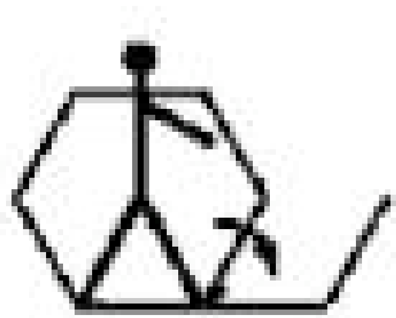


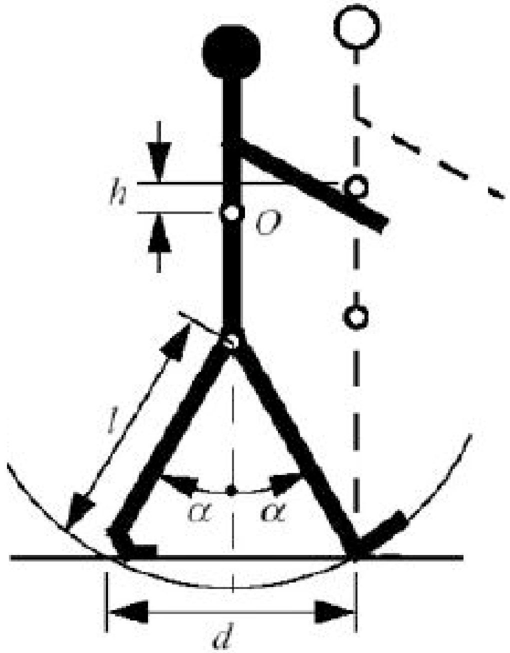
Monopeds

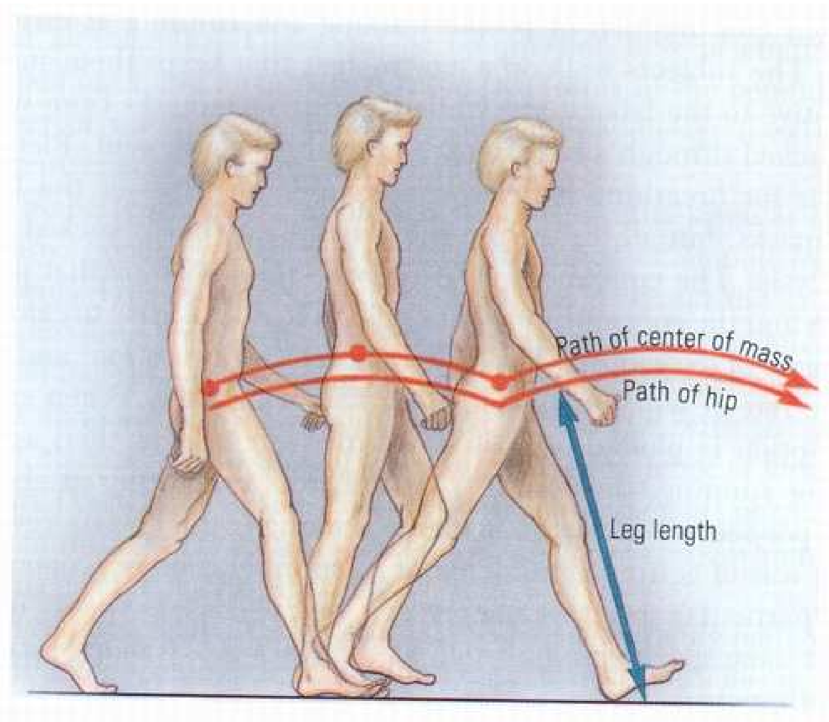


Biped Walking

- Biped walking can be approximated by a rolling polygon
  - Polygon side length = step length
  - As the step size decreases, the polygon approaches a circle



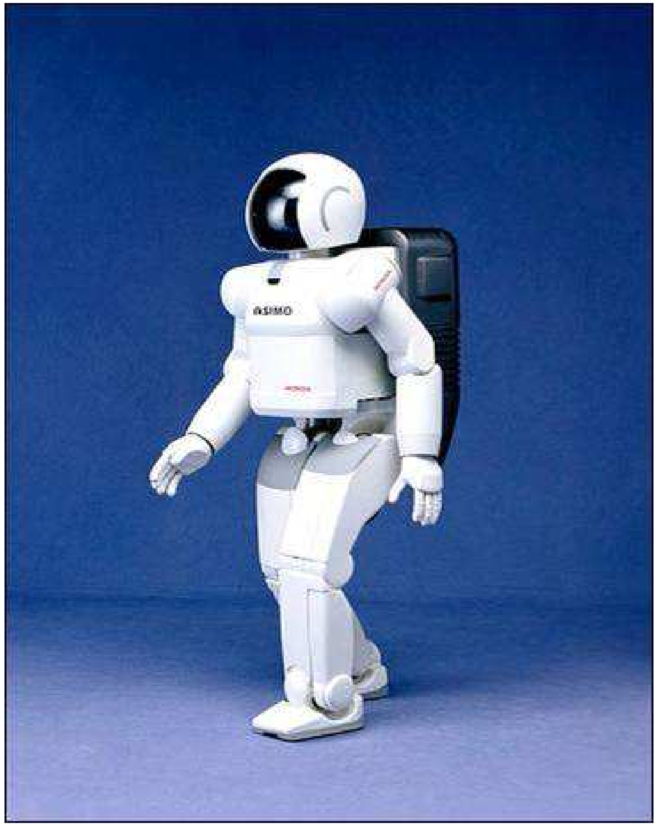




Examples of Legged Robots

Humanoid Robots

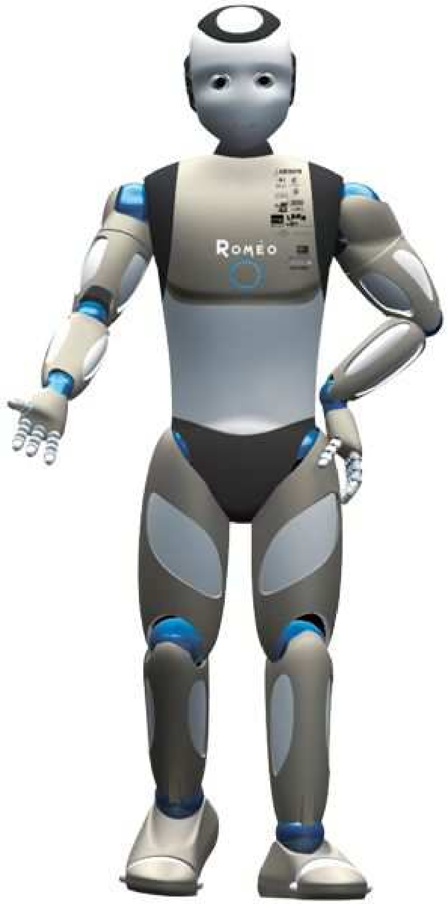
HRP Robots – Kawada Industries and AIST



Asimo – Honda

Examples of Legged Robots

Humanoid Robots



Romeo and Nao (Aldebaran Robotics)

Qrio (Sony)

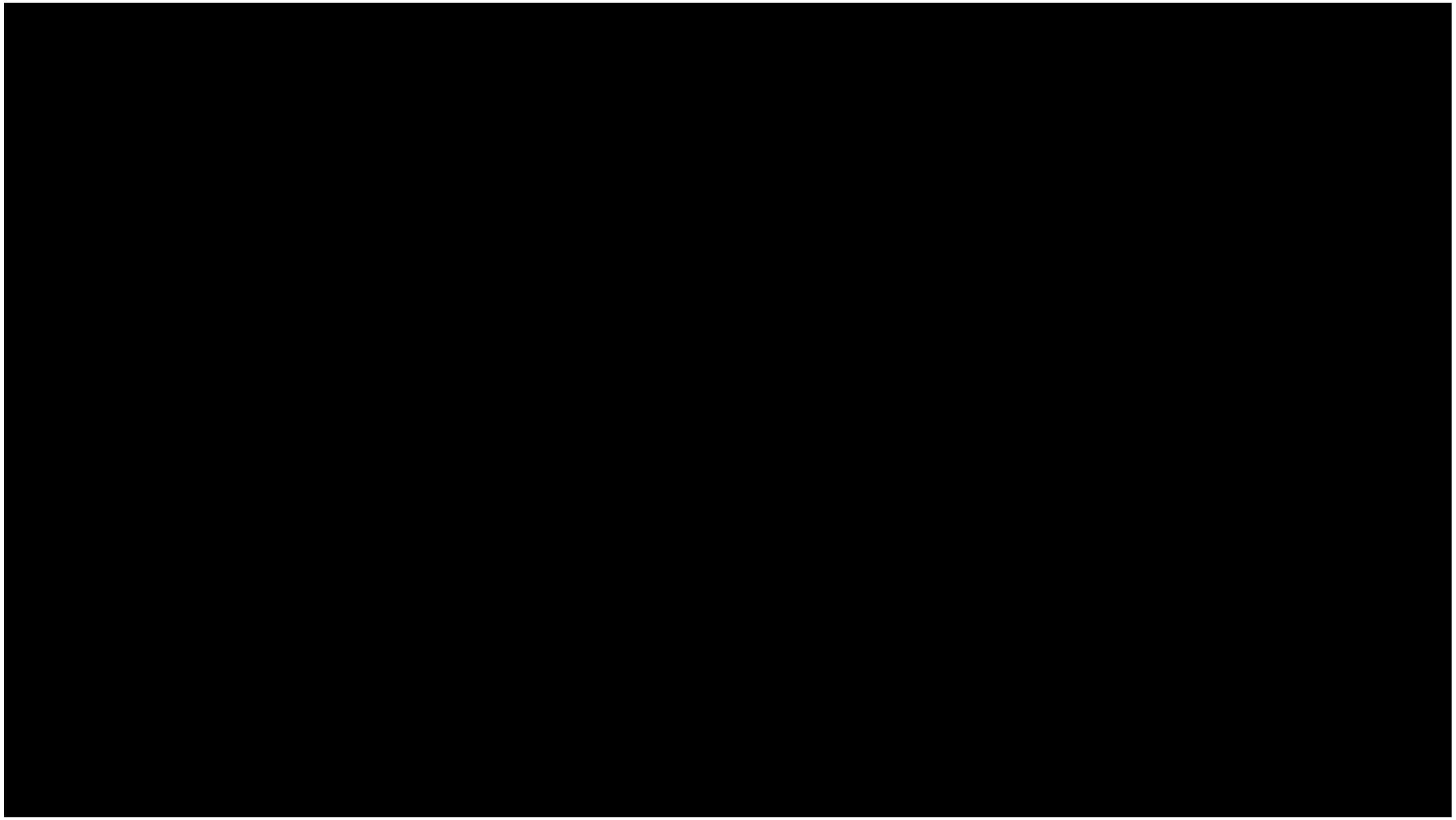
Examples of Walking Robots

Passive walking

- An approach to robot motion control based on utilizing the gravity and the momentum of swinging limbs for greater efficiency
  - Conserves momentum
  - Less number of actuators
  - Natural (anthropomorphic)
- In a purely passive dynamic walking, gravity and natural dynamics alone generate the walking cycle
  - Active input is necessary only to modify the cycle, as in turning or changing speed

Examples of Walking Robots

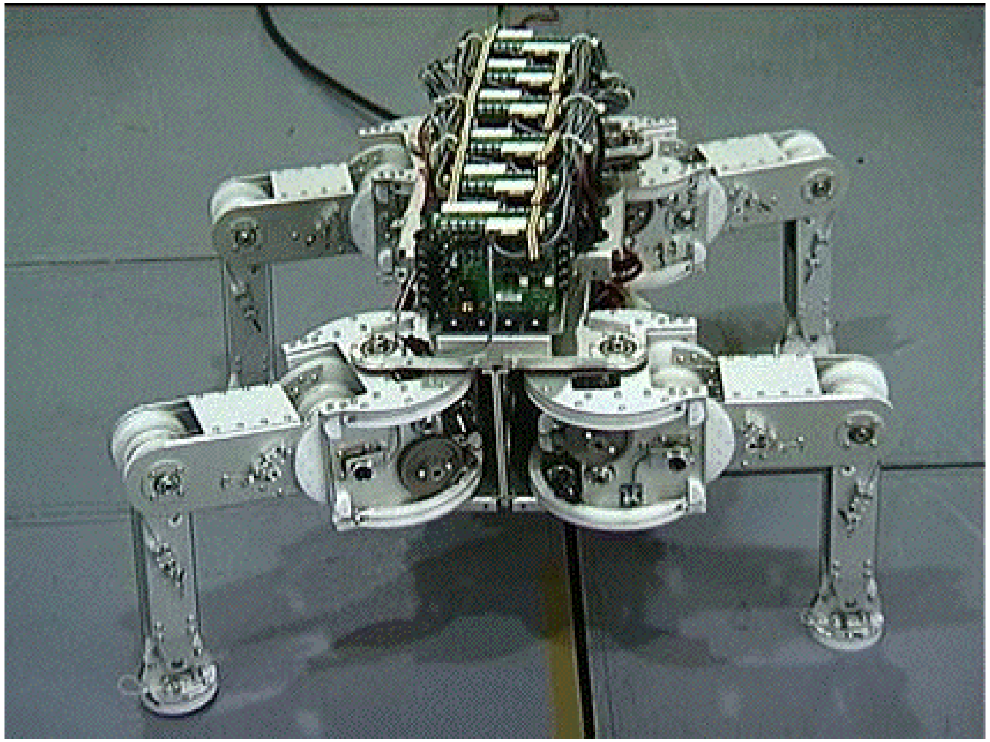
Passive walking



Quadrupeds - Robots with Four Legs

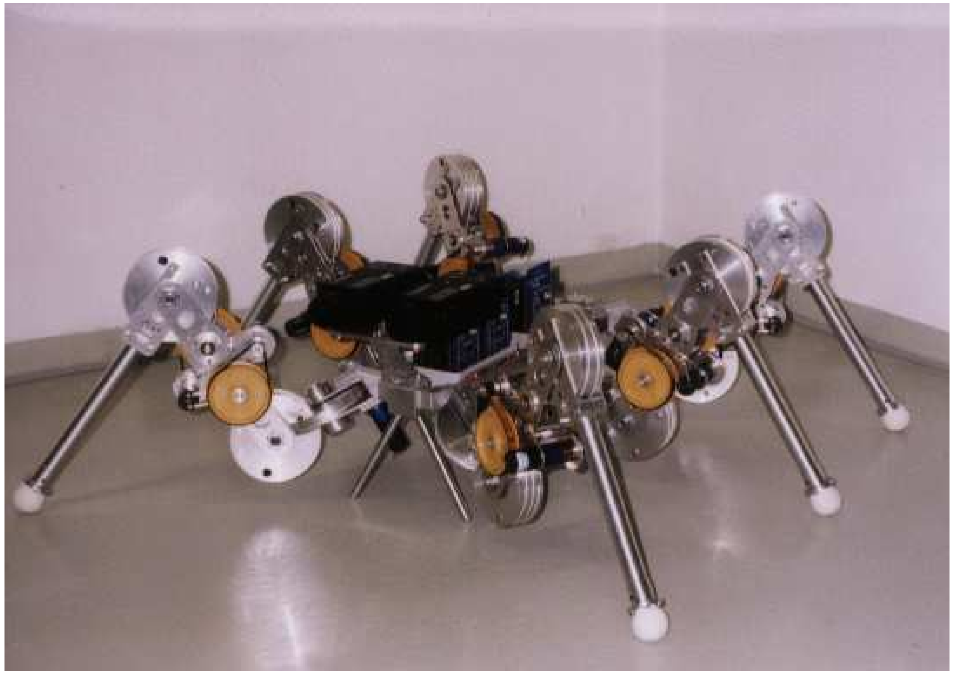
WildCat Boston Dynamics

Titan VIII, a quadruped robot, Tokyo Institute of Technology



Hexapods - Robots with Six Legs

Lauron II, University of Karlsruhe

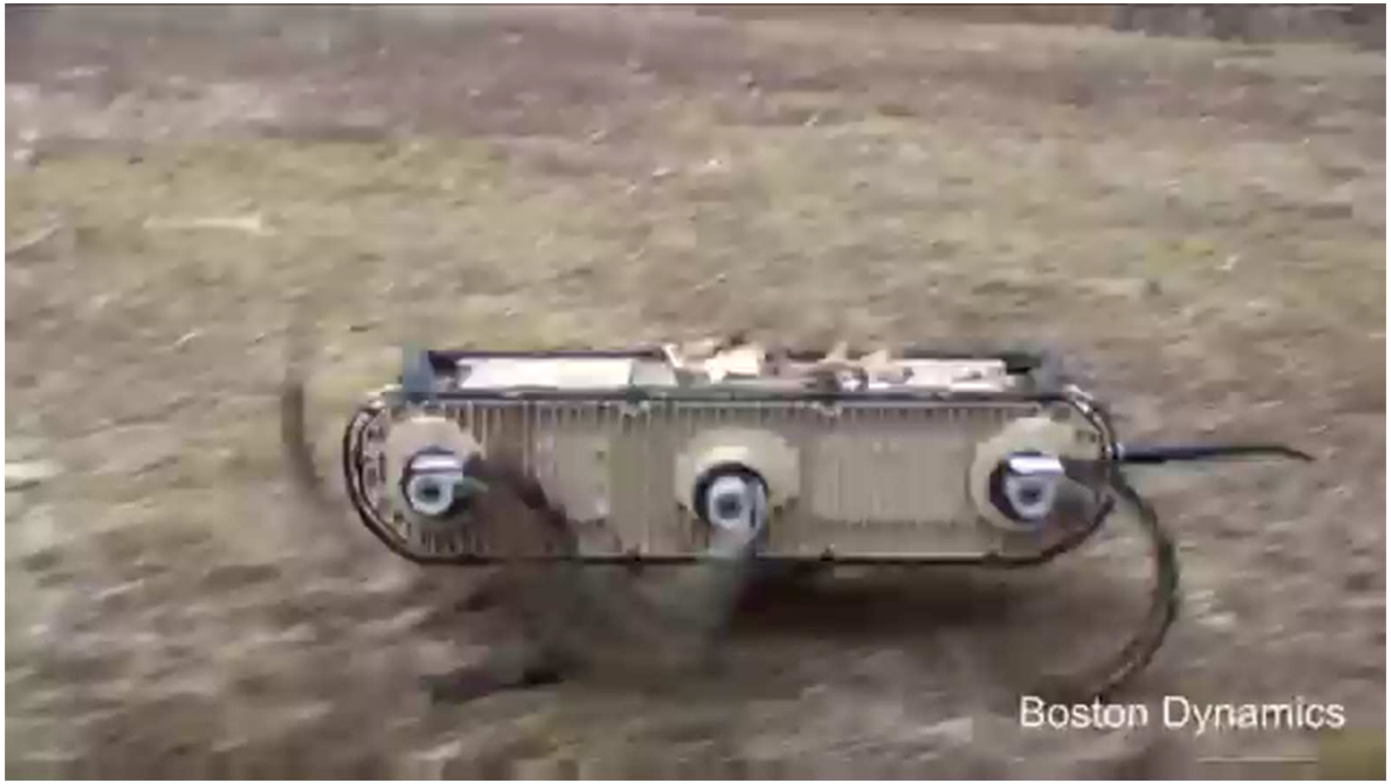


Maximum Speed: 0.5 m/s
Weight: 6 kg
Height: 0.3 m
Length: 0.7 m
No. of legs: 6
DOF in total: 6x3
Power Consumption: 10 W

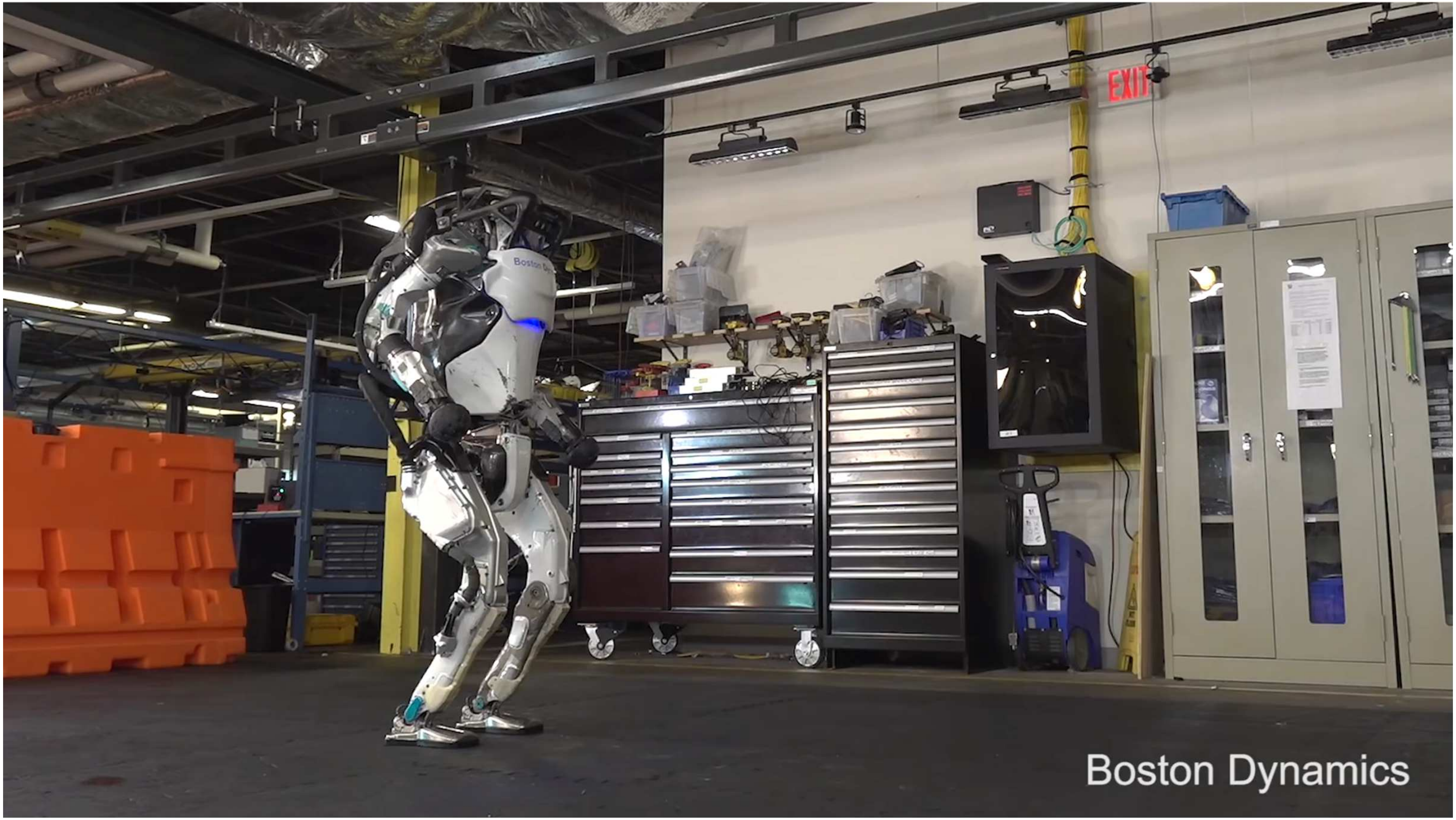
RHex, Boston Dynamics

Weight: 12 kg without batteries
Length: 0,56 m
Width: 0,4 m
Height: 0.14 m (legs not extended)

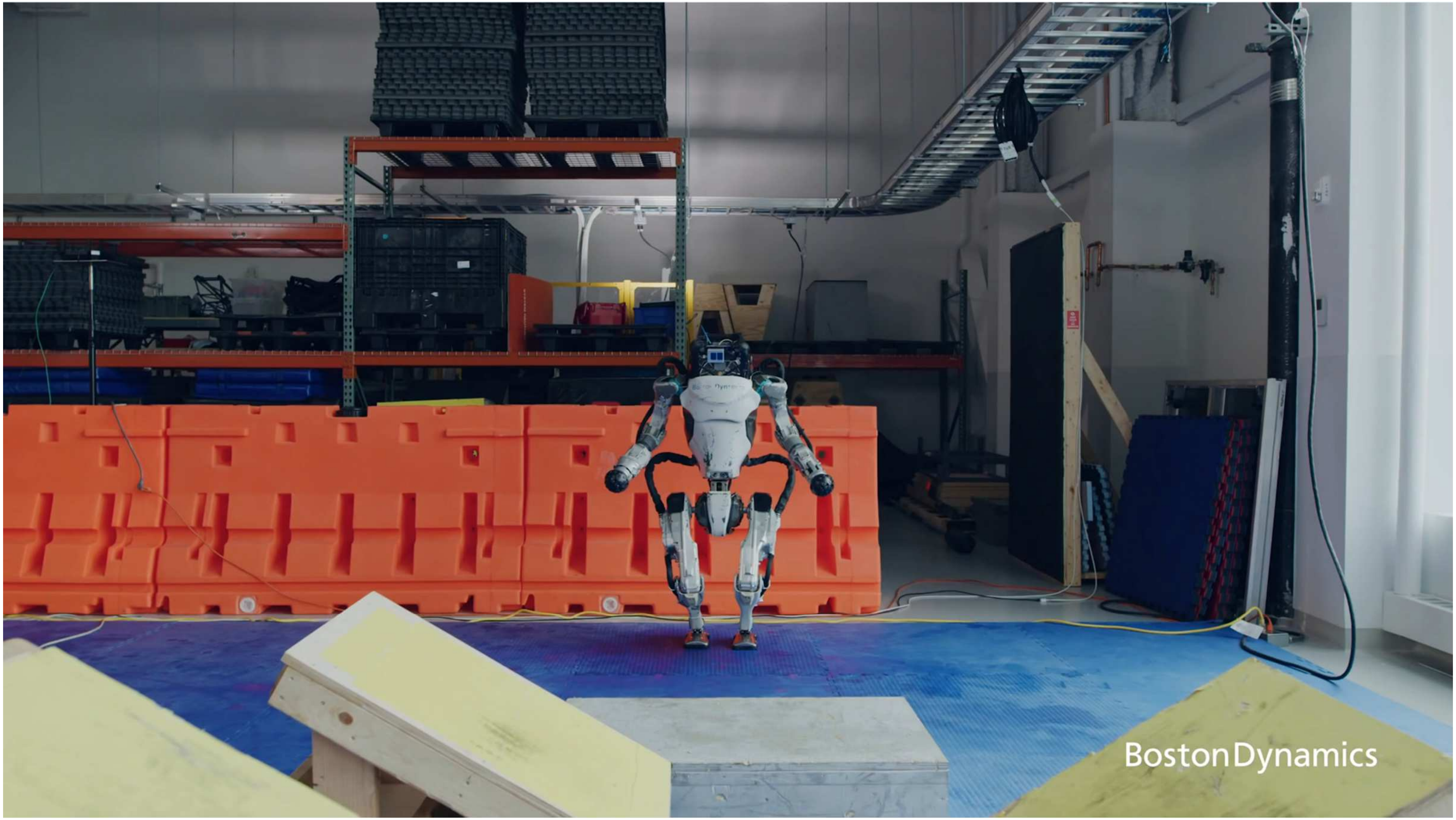
RHEX



Atlas robot



Atlas robot



Dancing robots