Robot Modeling & Control ME331

Section 19： Control III

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Dept. of MEE， SUSTech

Final Project Presentation

Date: May 28, 2025

1. **8 minutes for Group Presentation + 3 minutes for Q&A;**
2. **The presentation needs to clarify the specific contribution of each group member to the project;**
3. **Use podium desktop PC (make sure video can be played), or your own laptop (HDMI interface);**
4. **PPT, WORD report and other attachments (programs, data, videos, etc.). Please submit them in BB system before June 11, 2025 (submission as a group ZIP file).**

小课题研究题目(二号黑体)

唐三藏 孙悟空 朱悟能 沙悟净(四号仿宋)

摘要(小五，黑体)：提出具有负刚度特性的欧拉屈曲梁结构并分析其静态特性，将负刚度机构和线性隔振器并联使用，设计
准零刚度隔振器。如果隔振器的载荷选用得当，系统将在零刚度点平衡，若载荷发生改变，系统平衡点将偏离零刚度点。
虑载荷的影响，对零刚度隔振器进行动态建模，并采用谐波平衡法求解准零刚度隔振器的响应。定义准零刚度隔振器平衡
不在刚度零点时系统的力传递率，分析激励幅值和载荷对隔振器性能的影响并和线性隔振器的性能进行比较。结果表明，
设计的零刚度隔振器具有低频隔振效果，其响应和隔振性能受到激励幅值和载荷的影响，可以使系统的特性从单纯的渐硬
度向渐软刚度以及渐软-渐硬刚度混合的特性改变，并显著改变系统的传递性能。(小五，宋体)

关键词(小五，黑体)：负刚度；隔振；非线性系统；谐波平衡法；载荷(小五，宋体)

中图分类号(小五，黑体)：TG156(小五，Times New Roman)

Influence of Excitation Amplitude and Load on the Characteristics of a Quasi-zero Stiffness Isolator(小三，加粗)

TANG Sanzang SUN Wukong ZHU Wuneng SHA Wujing (小四，姓大写)

Abstract(小五，加粗)：An Euler buckled beam formed negative stiffness mechanism is proposed and the static characteristic
which is analyzed. A quasi-zero stiffness isolator is designed by parallel connected the negative stiffness mechanism and a line
isolator. The Euler buckled beam structure functions as a stiffness corrector to lower the stiffness of the linear isolator. If the load
chosen properly, the equilibrium point will be set at the zero stiffness point, any changes of the load will lead the equilibrium poi
deviating from the zero stiffness point. The dynamic model is built considering the load effect and the Harmonic balance method
employed to solve for the dynamic response of the system. Force transmissibility of the zero stiffness isolator is defined ar
compared with that of an equivalent linear one. The effect of excitation amplitude and load on the performance is analyzed. Tl
results show that the force excitation amplitude and load can change the characteristic of the nonlinear isolator from a hardenir
stiffness system to a softening stiffness system and even a mixed softening-hardening stiffness system. The excitation amplitude ar
load also have great affection on the transmissibility performance. (小五)

Key words(小五，加粗)：Negative stiffness；Vibration isolation；Nonlinear systems；Harmonic balance method；load

0 研究动机(一级标题：四号，宋体)

(正文：五号，宋体)随着精密工程、纳米工程等的发展，对隔离外界环境的振动提出了越来越高的要求，例如在引力波探测以及高精密光学成像等领域，对低频隔振的需求更加迫切。然而，普通的隔振器很难在低频范围有效隔振，研发在低频区域隔振性能好、承载能力强的隔振器一直是各国学者的研究热点。线性理论表明，在一定载荷下，降低隔振器的刚度可以显著降低隔振器起始隔振频率，从而获取低频隔振性能。但是降低隔振器的刚度又

使得隔振器的静态变形增加而丧失承载能力，同时
会带来稳定性以及占用空间过大等问题。近年来，
国内外诸多学者通过在线性隔振器的基础上引入1
刚度机构来获取低频隔振性能，同时保持隔振器
静态承载能力，取得了很好的效果。PLATUS 等[1-
利用两端受压杆的结构提供负刚度设计了超低频
振器，其固有频率可以达到 1 Hz 以下，但其对负
度的原理及系统的非线性特性涉及较少。
CARRELLA 等[3-4]采用了斜置弹簧提供负刚度，
将准零刚度隔振器模型简化为杜芬方程进行了系
响应的求解。其中，前者还对零刚度区间进行了
化[5]，以在系统平衡位置附近获取尽量大的小刚
区间，但提供负刚度的两根斜置弹簧在变形时可
存在横向失稳。LE 等[6-8]也对这种负刚度结构进行

Template for Preparation of Papers for IEEE Sponsored Conferences & Symposia

First A. Author, Second B. Author, Jr., and Third C. Author, *Member, IEEE*

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- Do not mix complete spellings and abbreviations of units: “Wb/m2” or “webers per square meter”, not “webers/m2”. Spell out units when they appear in text: “. . . a few henries”, not “. . . a few H”.
- Use a zero before decimal points: “0.25”, not “.25”. Use “cm3”, not “cc”. (*bullet list*)

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Outline

- Review
  - IndepComputed Torque Control
  - Cartesian-based Control
- Force Control
  - Direct Force Control
  - Impedence Control
  - Hybrid Force/Motion Control
- Introduction of Locomotion
  - Walking Principles
  - History of Legged Robots

Multivariable Control

- **Computed Torque Control**
  - Robot system:

$$\boldsymbol{D}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau}$$

  - Controller:

$$\boldsymbol{\tau} = \boldsymbol{D}(\boldsymbol{q})\left[\ddot{\boldsymbol{q}}^{\mathrm{d}} + \boldsymbol{k}_{\mathrm{v}}\left(\dot{\boldsymbol{q}}^{\mathrm{d}} - \dot{\boldsymbol{q}}\right) + \boldsymbol{k}_{\mathrm{p}}\left(\boldsymbol{q}^{\mathrm{d}} - \boldsymbol{q}\right)\right] + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q})$$

$$(\ddot{q}^{d} - \ddot{q}) + k_v(\dot{q}^{d} - \dot{q}) + k_p(q^{d} - q) = 0$$

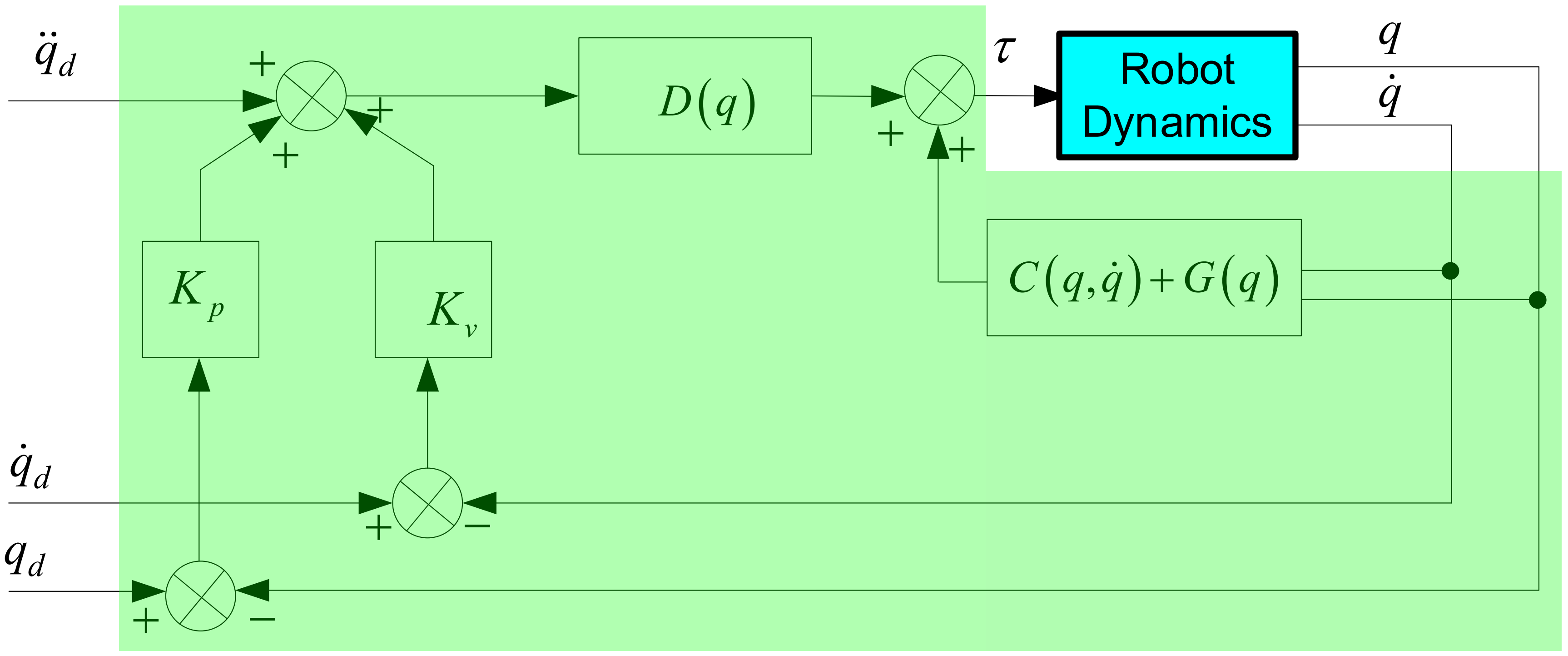
Error dynamics $\quad \ddot{e} + k_v\dot{e} + k_p e = 0$

Advantage: the joint coupling effect was compensated

Condition: the precise model of robot dynamics

Computed Torque Control

$$\boldsymbol{\tau} = \boldsymbol{D}(\boldsymbol{q})\left[\ddot{\boldsymbol{q}}^{\mathrm{d}} + \boldsymbol{k}_{\mathrm{v}}\left(\dot{\boldsymbol{q}}^{\mathrm{d}} - \dot{\boldsymbol{q}}\right) + \boldsymbol{k}_{\mathrm{p}}\left(\boldsymbol{q}^{\mathrm{d}} - \boldsymbol{q}\right)\right] + \boldsymbol{C}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q})$$

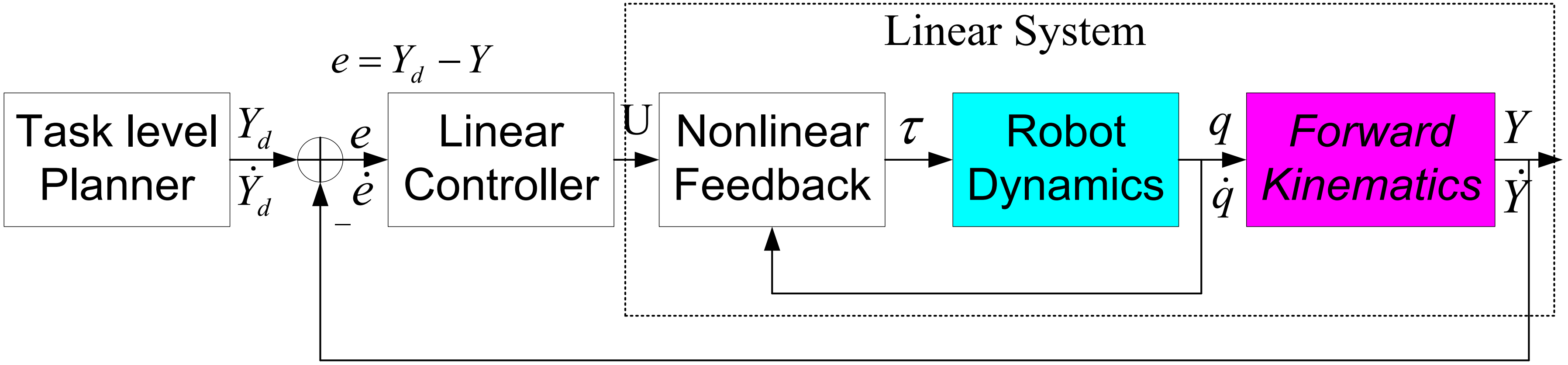


Error dynamics $\ddot{e} + k_v\dot{e} + k_p e = 0$

Choose *Kp*, *Kv* to make the system stable.

Cartesian-based Control

- **Non-linear Feedback Control**



Robot System:

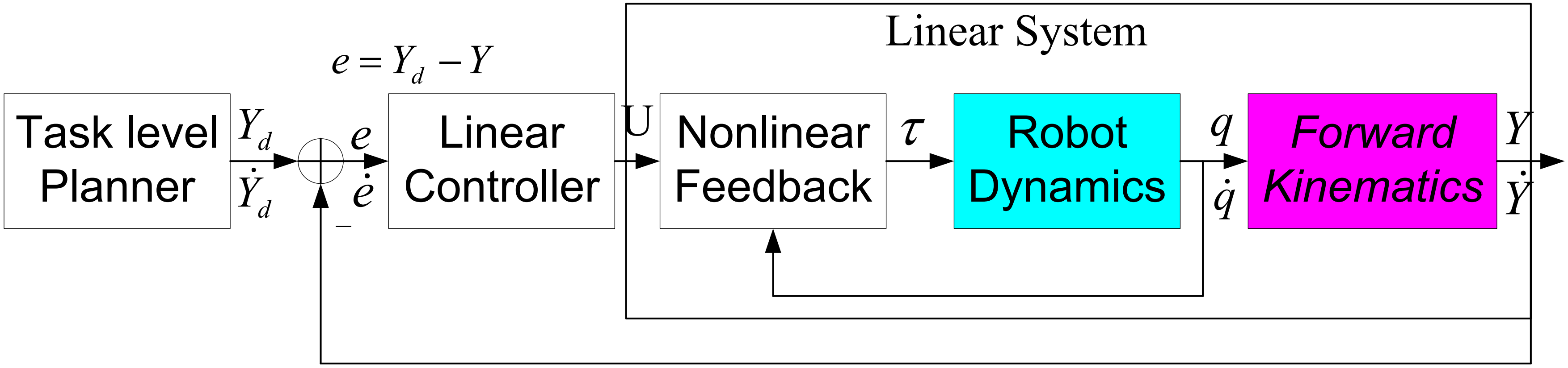
$$\begin{cases} D(q)\ddot{q} + C(q,\dot{q}) + G(q) = \tau \\ Y = h(q) \end{cases}$$

Jacobian: $\dot{Y} = \dfrac{d}{dq}[h(q)] \cdot \dot{q} = J\dot{q} \Longrightarrow \ddot{Y} = \dot{J}\dot{q} + J\ddot{q} \Longrightarrow \ddot{q} = J^{-1}(\ddot{Y} - \dot{J}\dot{q})$

$$D(q)J^{-1}\left(\ddot{Y} - \dot{J}\dot{q}\right) + C(q,\dot{q}) + G(q) = \tau$$

Cartesian-based Control

Non-linear Feedback Control



Design the nonlinear feedback controller as:

$$\tau = D(q)J^{-1}\left(U - \dot{J}\dot{q}\right) + C(q,\dot{q}) + G(q)$$

Then the linearized dynamic model:

$$D(q)J^{-1}\ddot{Y} = D(q)J^{-1}U \quad \Rightarrow \quad \ddot{Y} = U$$

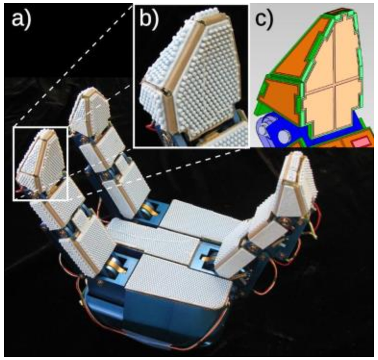
Design the linear controller: $U = \ddot{Y}_d + k_v(\dot{Y}_d - \dot{Y}) + k_p(Y_d - Y)$

Error dynamic equation: $\ddot{e} + k_v\dot{e} + k_p e = 0$

Force Control

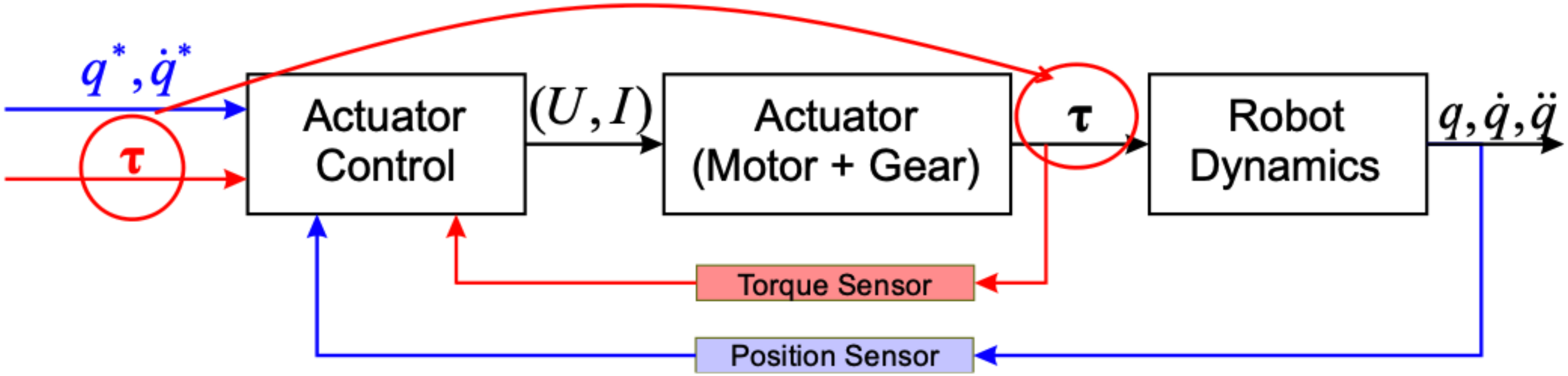
Force and Torque Sensing:

1. Wrist force sensors
2. Joint torque sensors
3. Tactile or hand sensors



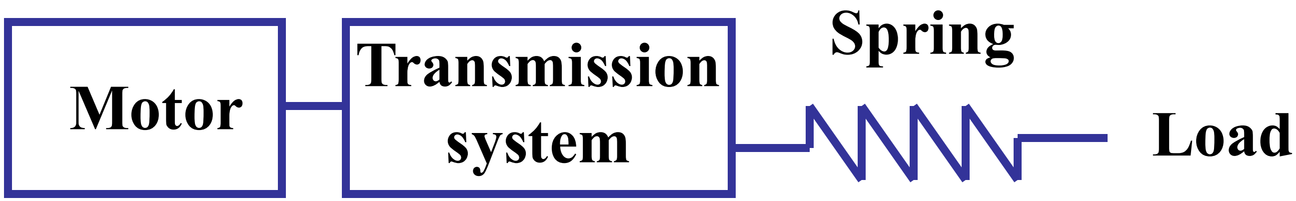
Types of Force Control:

1. Direct force control

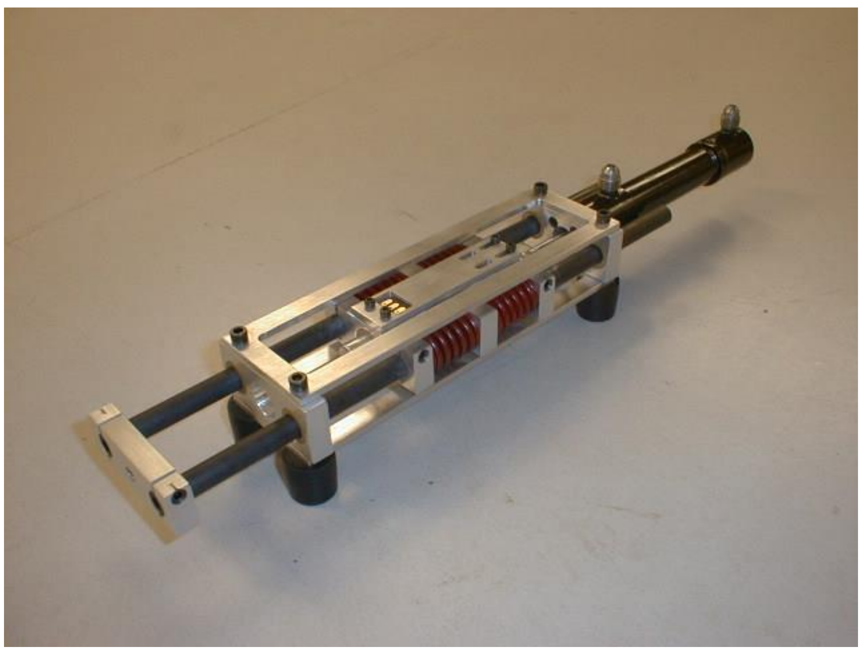


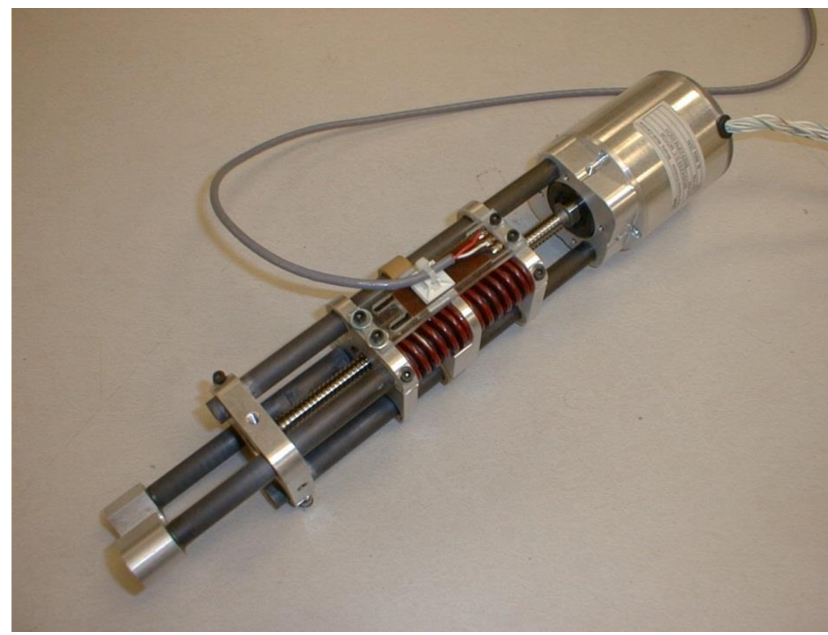
Joint Torque Control of a Robot Arm

Force Control



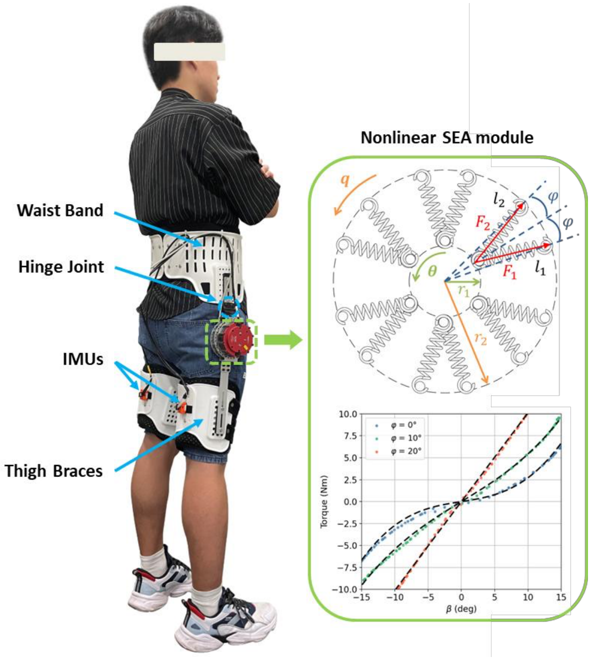
SEA （Series Elastic Actuator）

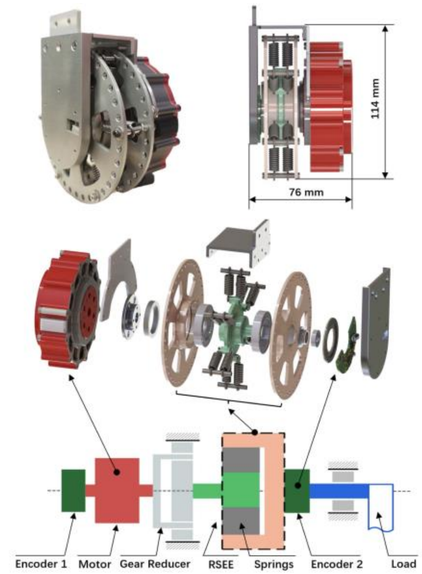


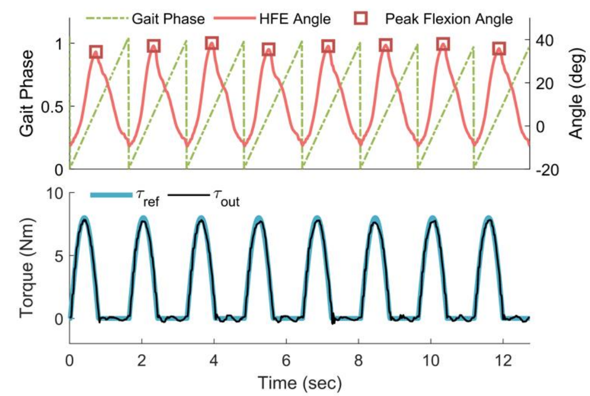


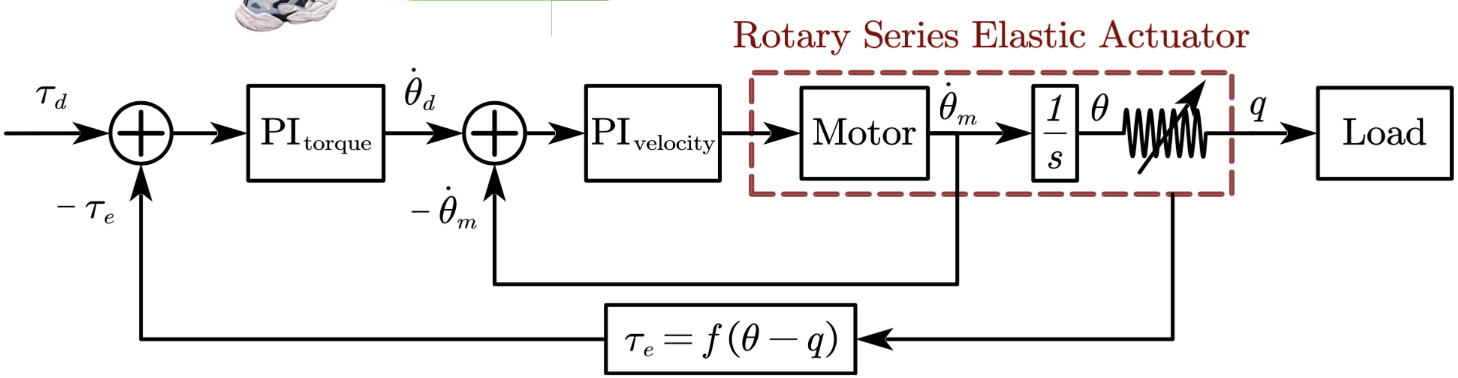
Force Control

1. Direct force control







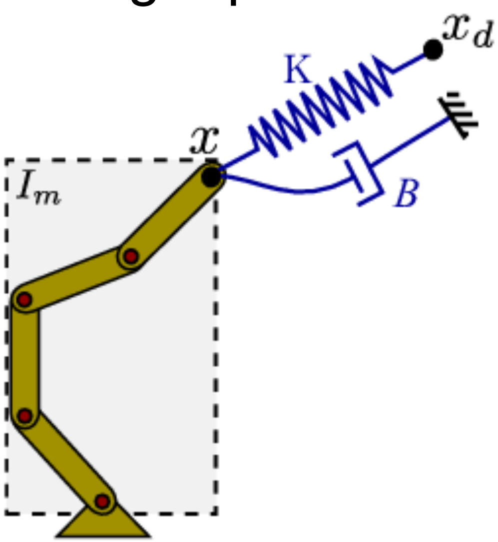


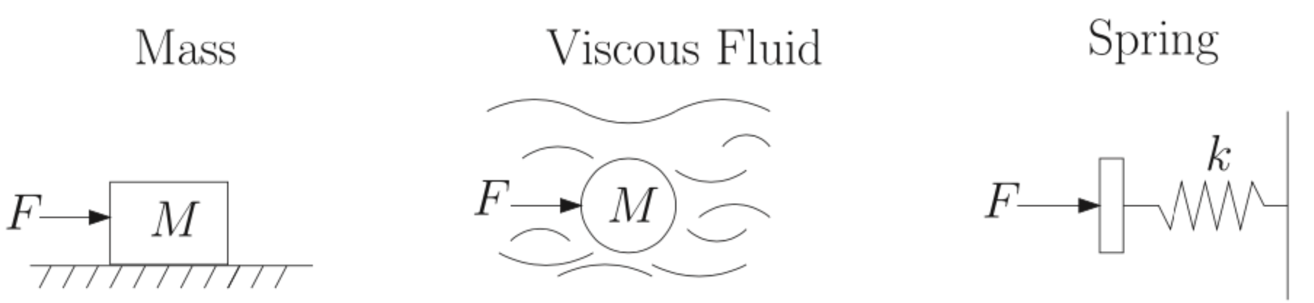
Y. Qian, S, Han, Y. Wang, H. Yu, C. Fu. Toward Improving Actuation Transparency and Safety of a Hip Exoskeleton with a Novel Nonlinear Series Elastic Actuator. **IEEE/ASME Transactions on Mechatronics**, 28(1): 417-428, 2023.

Force Control

2. Impedance control

Impedance control applies a virtual mass-spring-damper between the target position and the actual position of the robot.



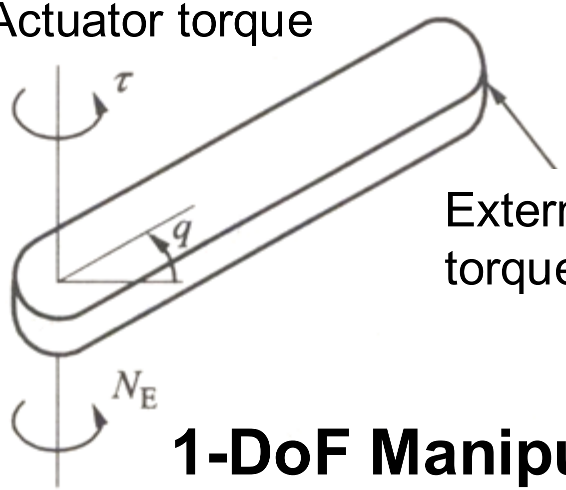


(a) Inertial (b) Resistive (c) Capacitive

Force Control

2. Impedance control

Actuator torque



External torque N_E

1-DoF Manipulator

Plant model： $m\ddot{q} + d\dot{q} = \tau + N_E$

Impedance model：

$$m_d\ddot{q} - d_d\dot{q} + k_d(q - q_d) = N_E$$

（1）External torque N_E is detectable

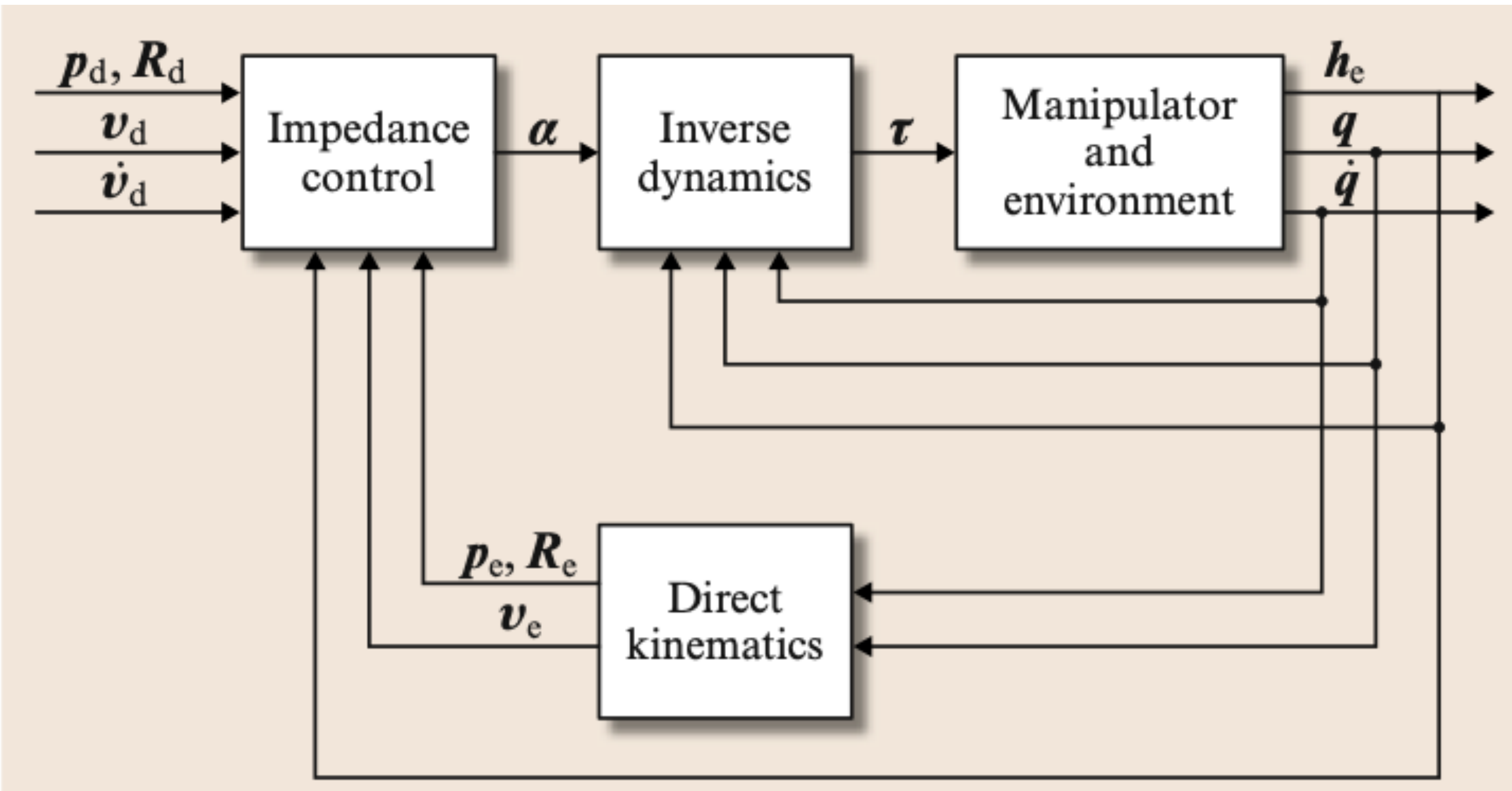
$$\tau = \left(d - \frac{m}{m_d}d_d\right)\dot{q} + \frac{m}{m_d}k_d(q_d - q) + \frac{m}{m_d}d_d\dot{q} - (1 - \frac{m}{m_d})N_E$$

（2）Joint acceleration is detectable

$$\tau = (m - m_d)\ddot{q} + (d - d_d)\dot{q} + k_d(q_d - q) + d_d\dot{q}$$

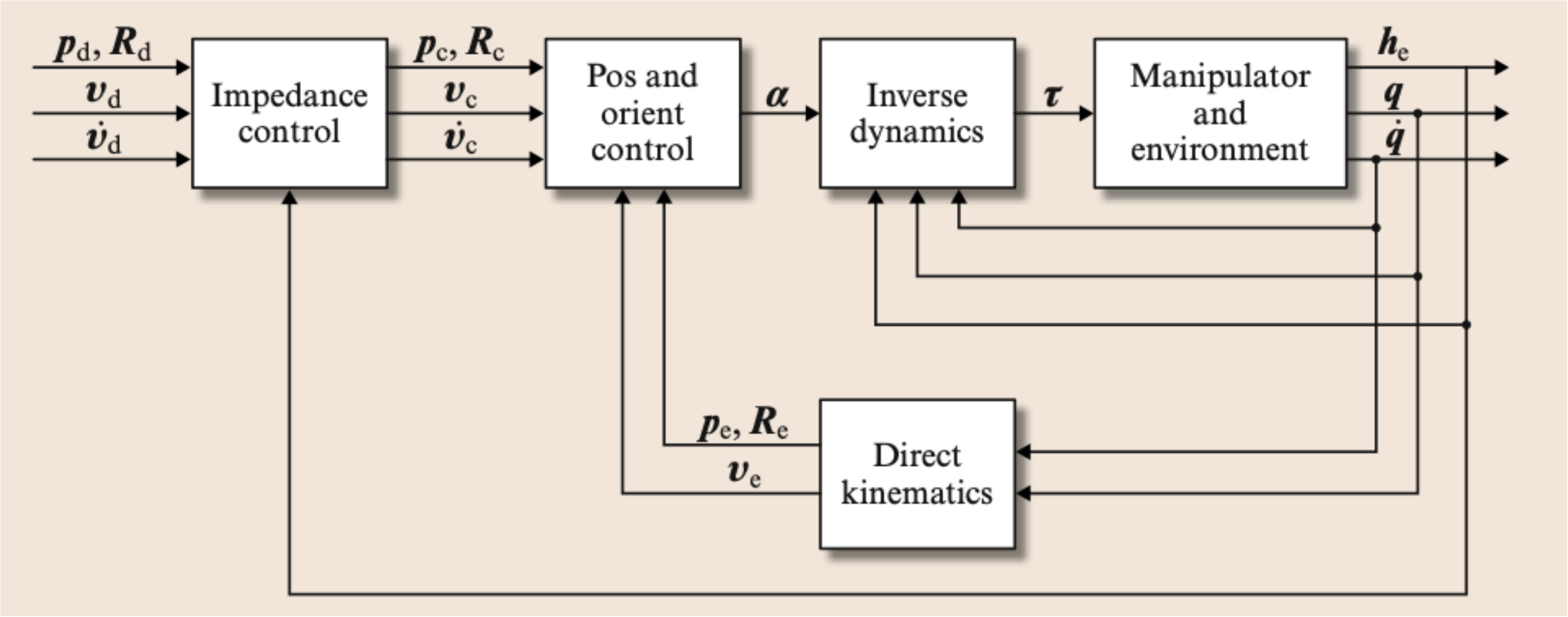
Force Control

2. Impedance control



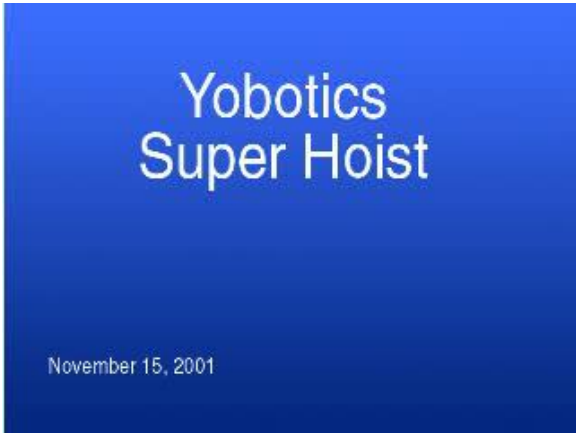
Force Control

2. Impedance control with inner motion control loop (admittance control)



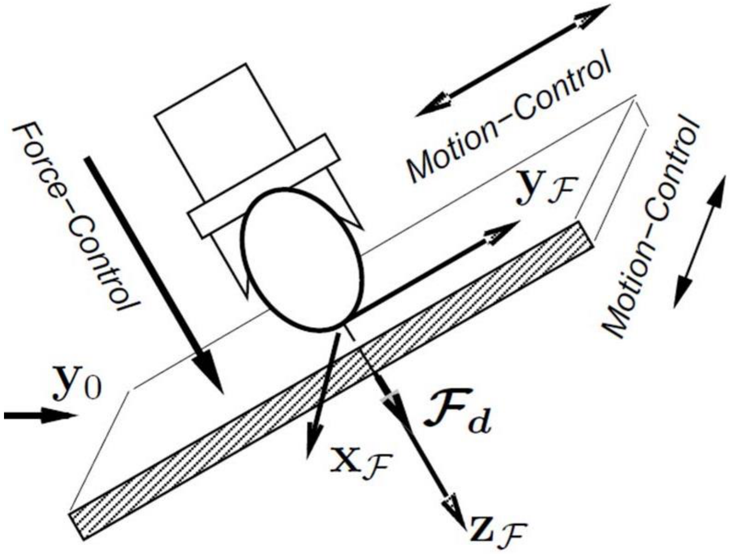
Force Control

SEA （Series Elastic Actuator）



Force Control

2. Hybrid force/position control



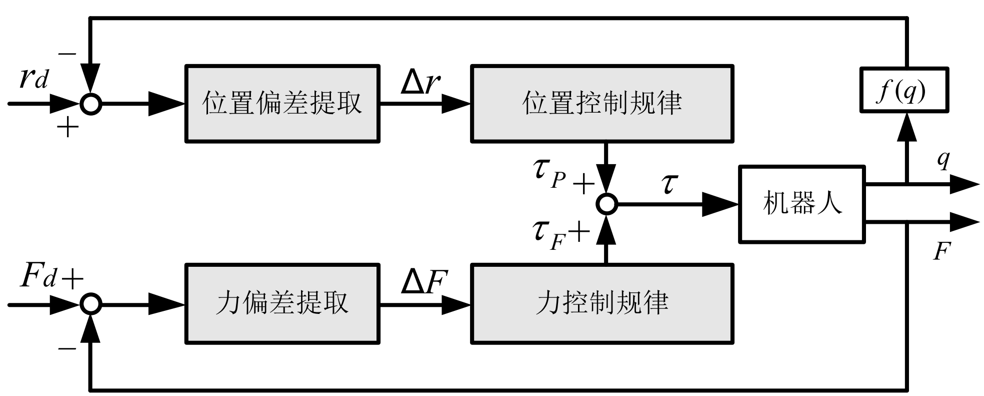
Constrained 2-DoF manipulator

[Basic idea]

It separates all 6 axes of the task (3 force and 3 torque) and applies either a motion based control or a force based control onto each of the axes.

[Position error] $\Delta r = \{e_P^T(r_d - r)\}e_P, r = f(q)$

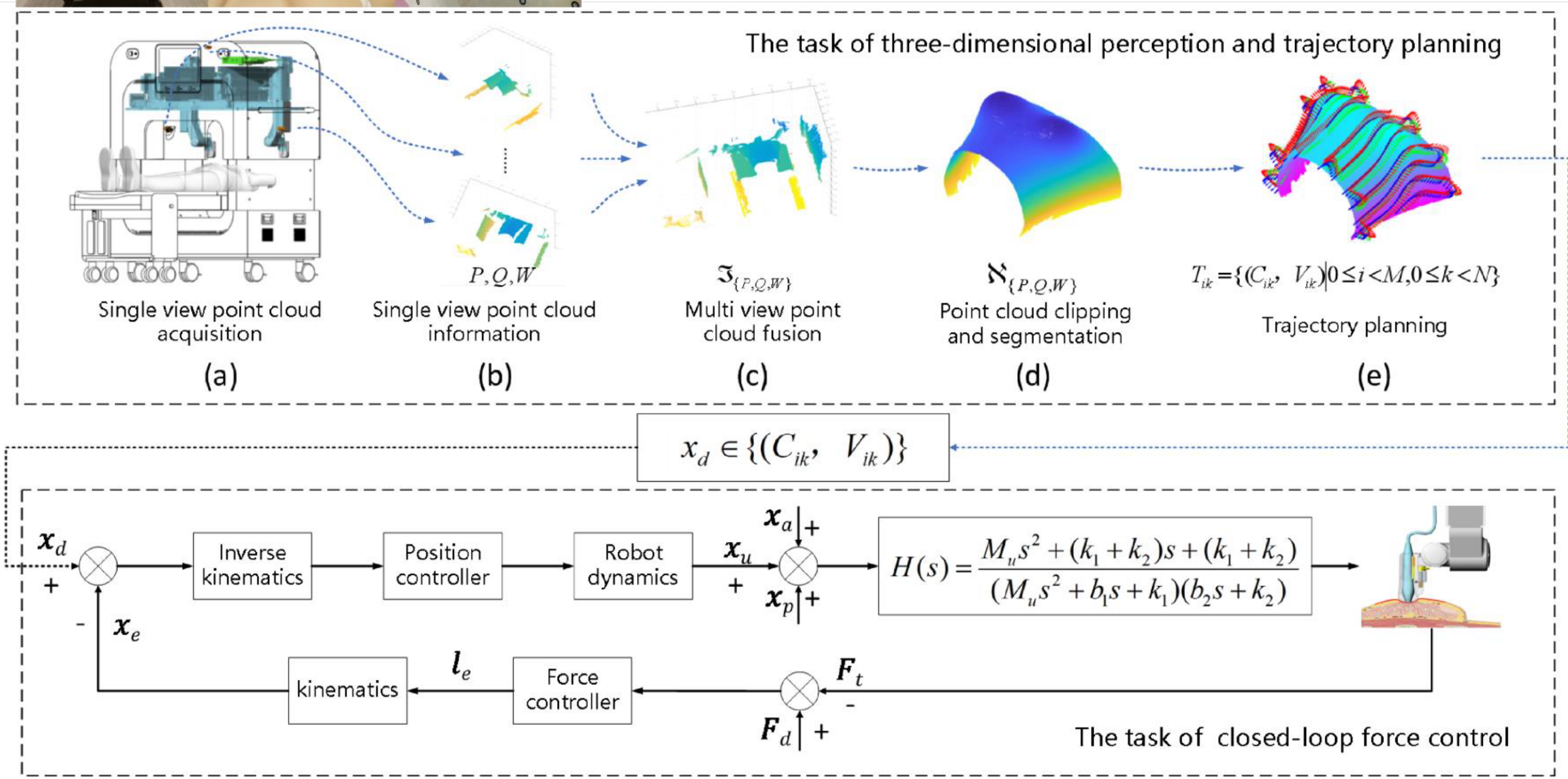
[Force error] $\Delta F = \{e_F^T(F_d - F)\}e_F$



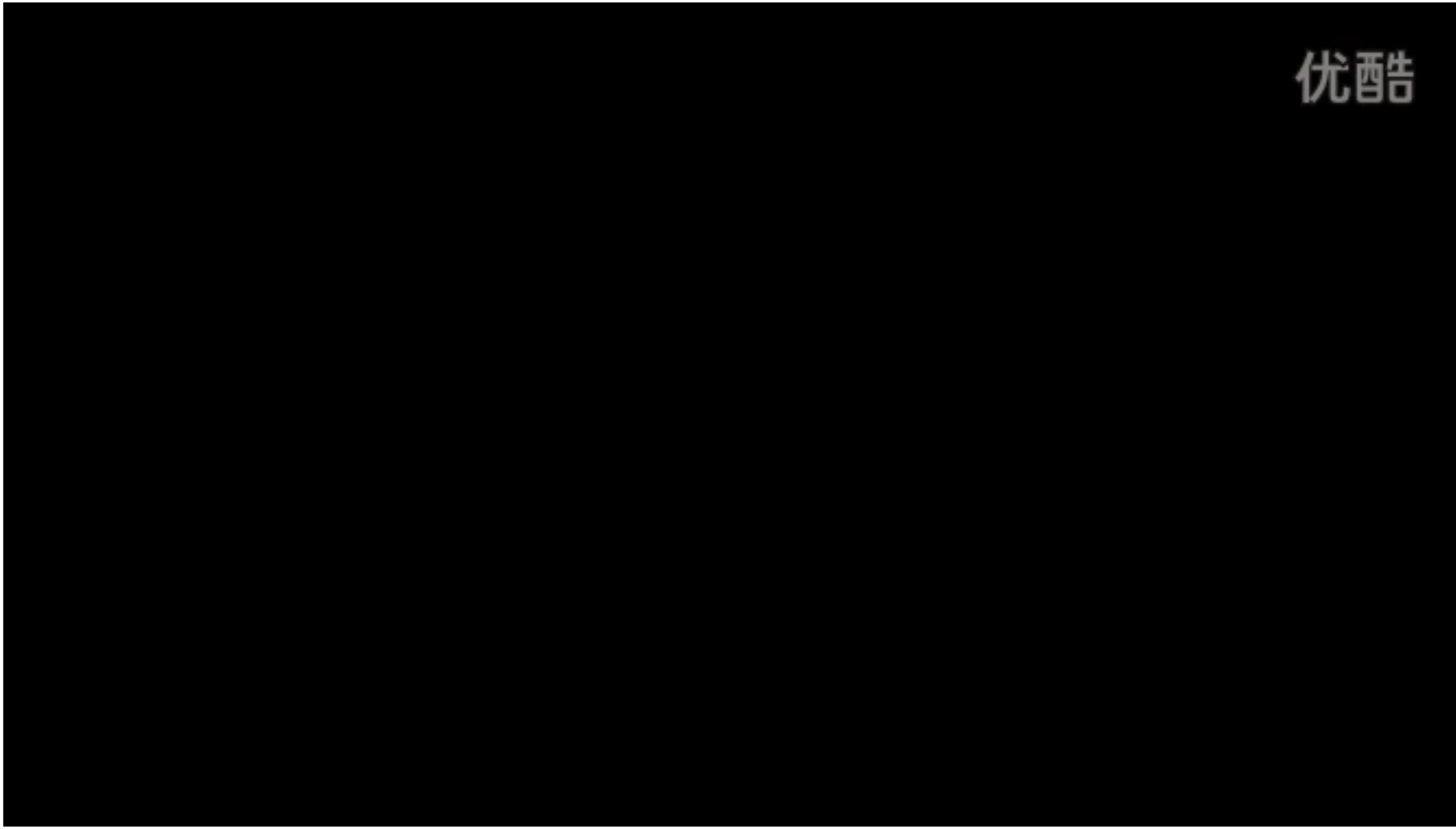
Force Control

2. Hybrid force/position control

J. Tan, B. Li, Y. Li, B. Li, X. Chen, J. Wu, B. Luo, Y. Leng, Y. Rong, C. Fu. A Flexible and Fully Autonomous Breast Ultrasound Scanning System. **IEEE Transactions on Automation Science and Engineering**, 20(3): 1920-1933, 2023.



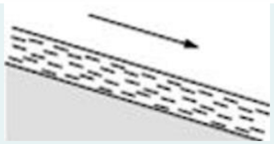
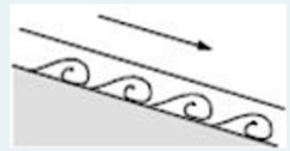
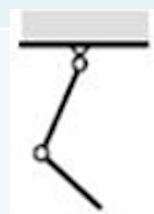
Animal Locomotion



Animal locomotion is beautiful!

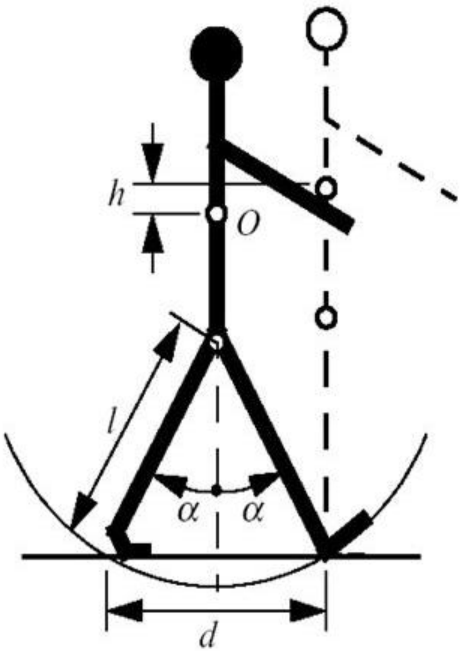
Locomotion: moving from place to place

Locomotion: mechanisms found in nature

Type of motion	Resistance	Basic kinematics
Flow in a channel 	Hydrodynamic forces	Eddies 
Crawl 	Friction forces	 Longitudinal vibration
Sliding 	Friction forces	 Transverse vibration
Running 	Loss of kinetic energy	Oscillatory Movement of a multi-link pendulum 
Walking 	Gravitational forces	Rolling of a polygon 

- **Concepts found in nature is difficult to imitate technically.**
- **Most technical systems use wheels or caterpillars.**
- **Rolling is most efficient, but not found in nature. Nature never invented the wheel !**
- **The movement of a walking biped is *close to rolling.***

Locomotion: biped walking

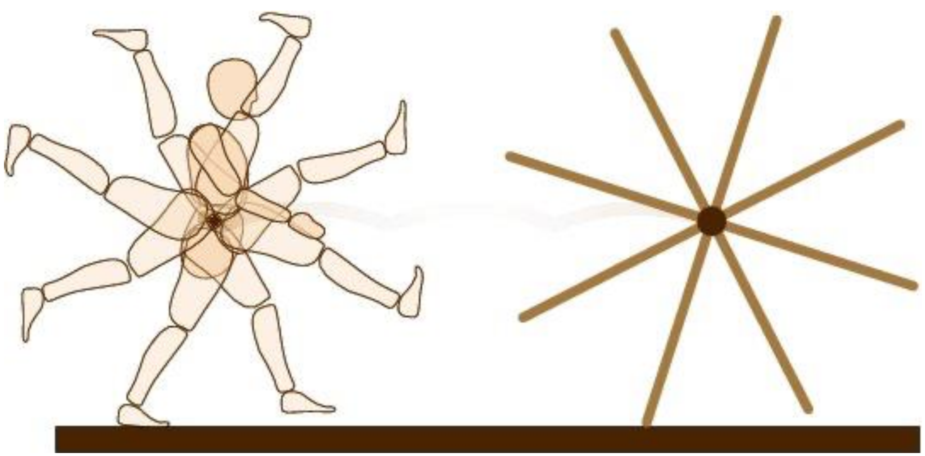


- Biped walking mechanism

✓ similar to rimless wheel.

✓ rolling of a polygon with side length equal to the length of the step.

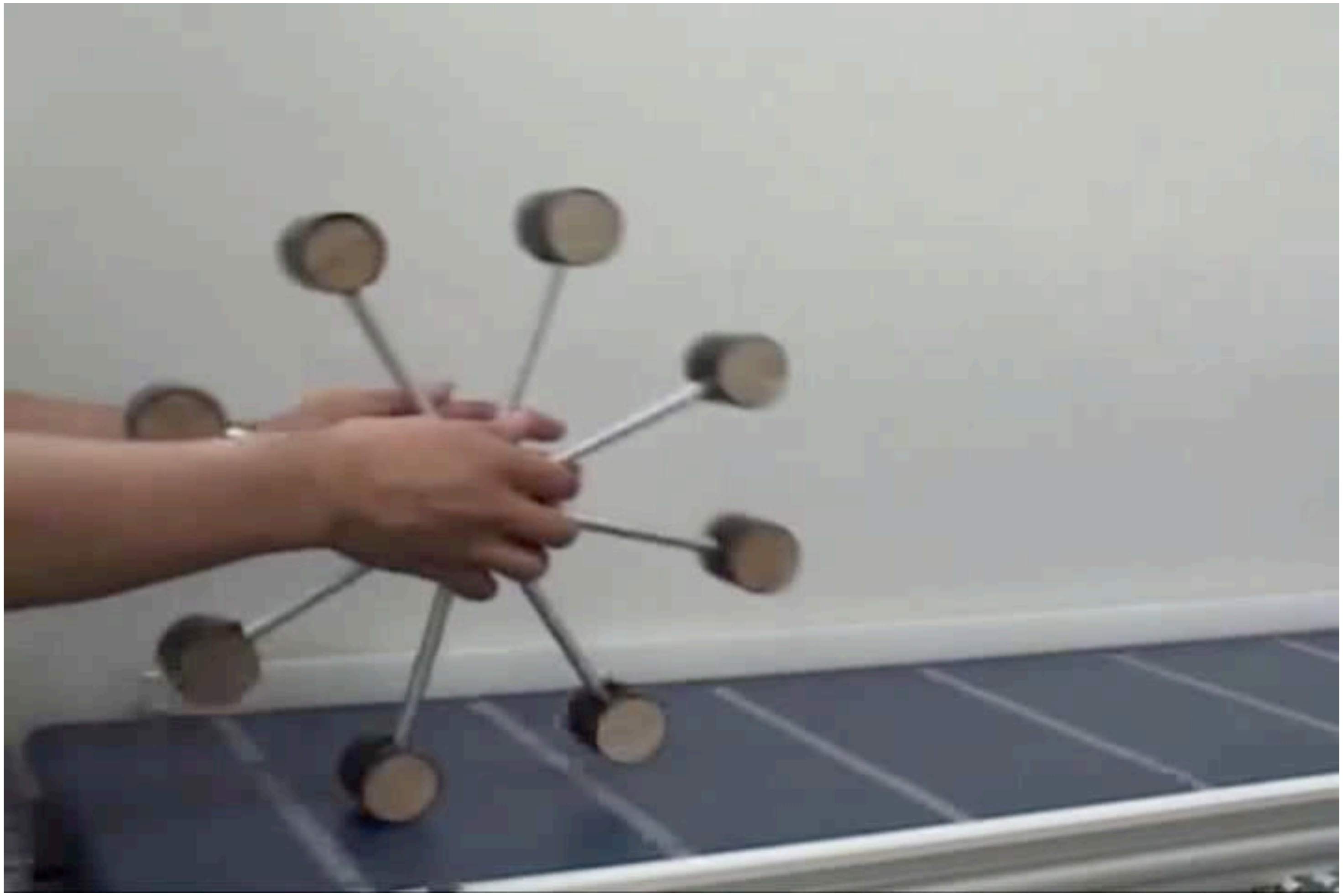
✓ the smaller the step gets, the more the polygon tends to a wheel.



- However, fully rotating joint was not developed in nature.

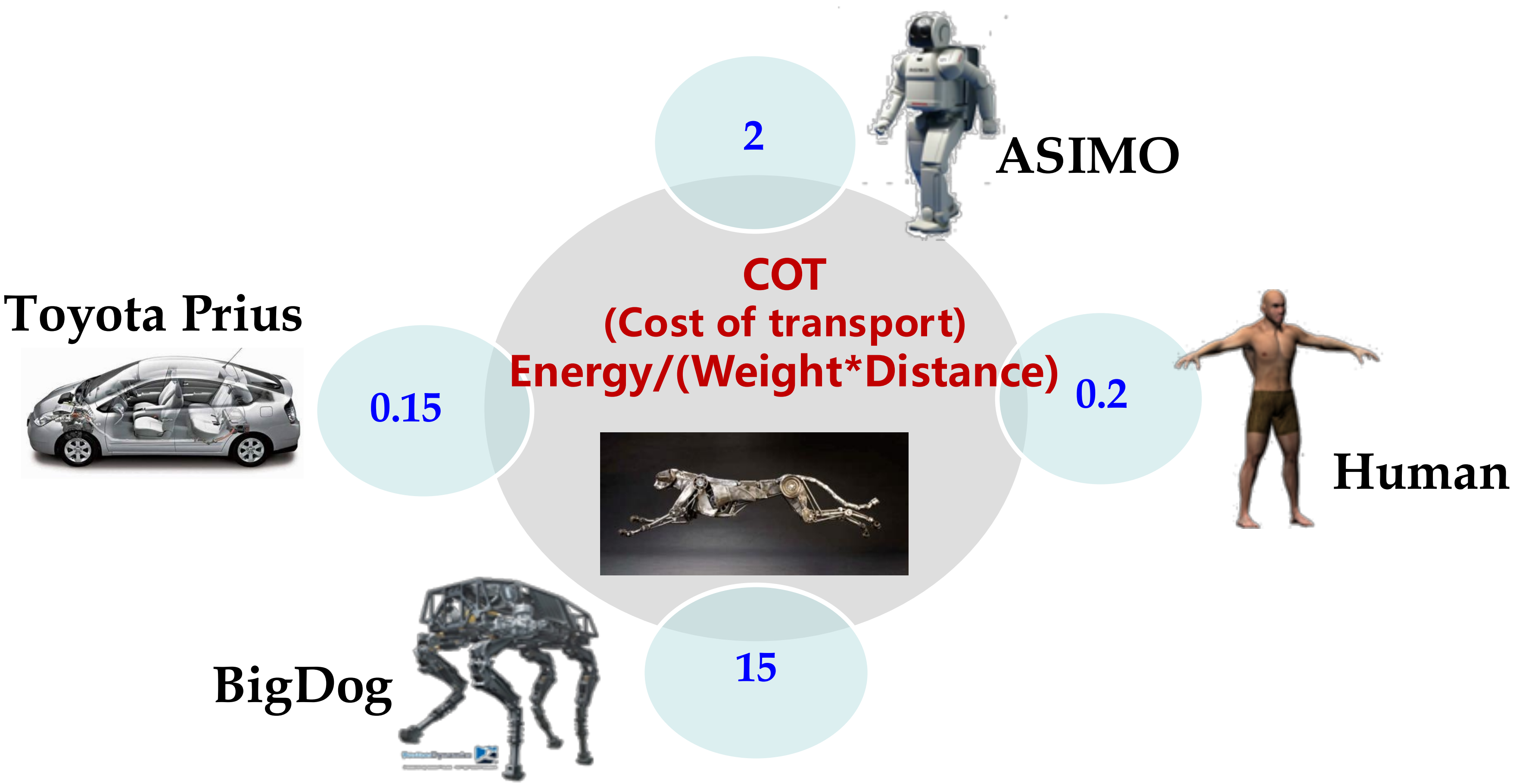
Locomotion: biped walking

Walking toys – rimless wheel



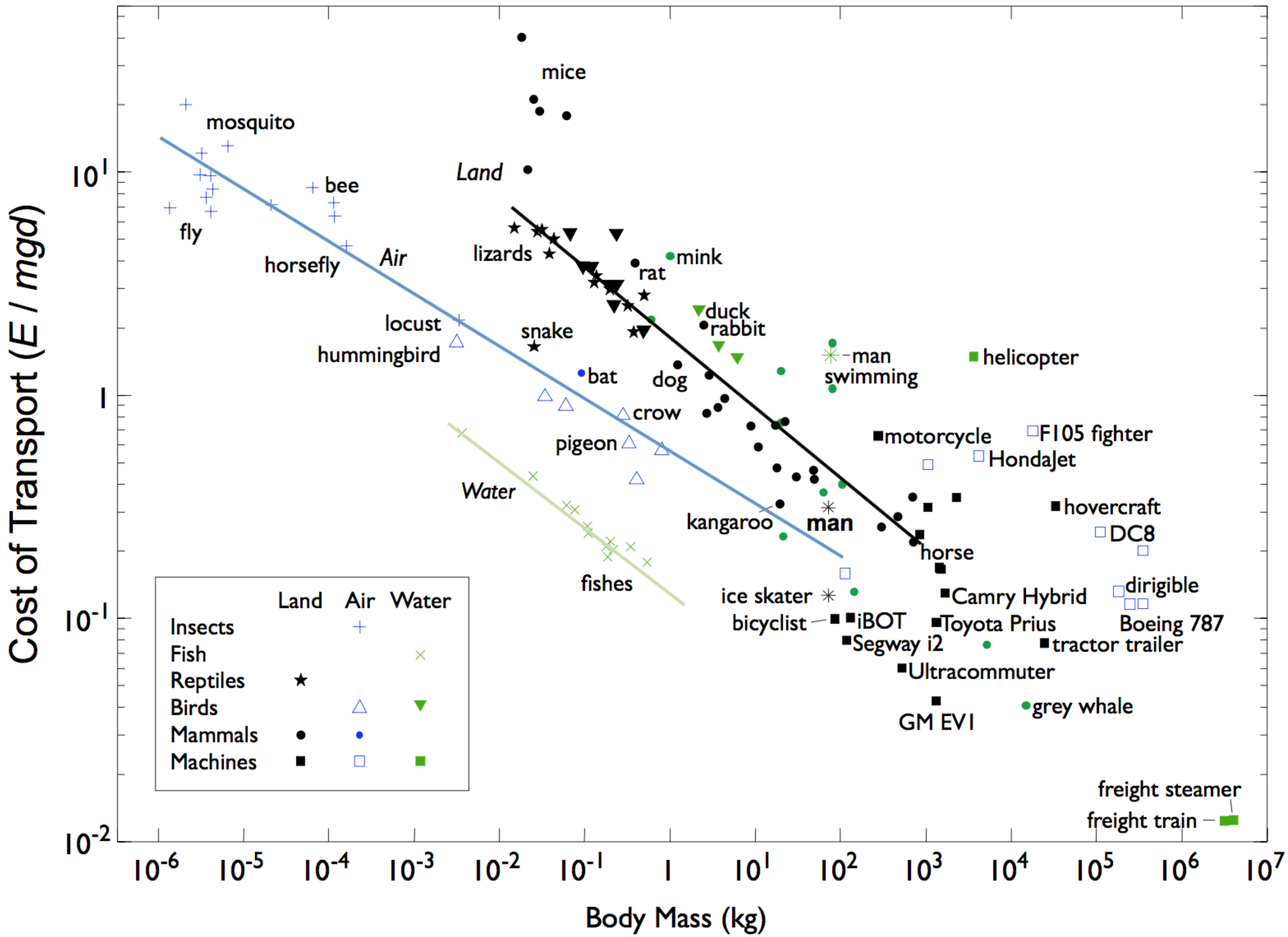
Challenge problem of legged locomotion

Simultaneously achieving robustness and efficiency

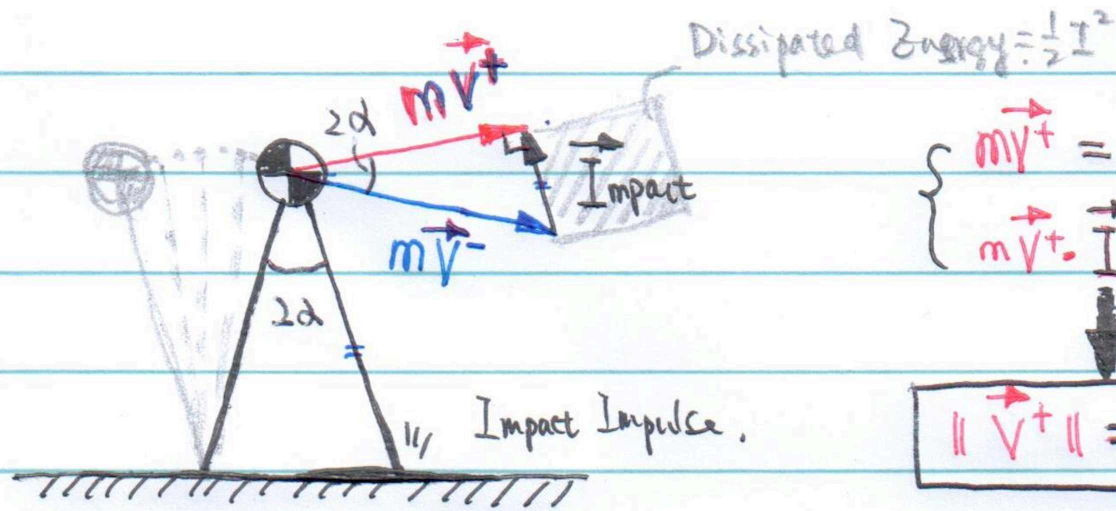


Robust control of a horse-sized robot should not use 10-20 horsepower!

Locomotion: energetics



Walking Principles



$$\begin{cases} m\vec{v}^+ = m\vec{v}^- + \vec{I} \\ m\vec{v}^+ \cdot \vec{I} = 0 \end{cases}$$

$$\Downarrow$$

$$\boxed{\|\vec{v}^+\| = \|\vec{v}^-\| \cdot \cos 2\alpha}$$

① Walking = Single Support Phase + Double Support Phase

$\downarrow$ inverted pedulum model

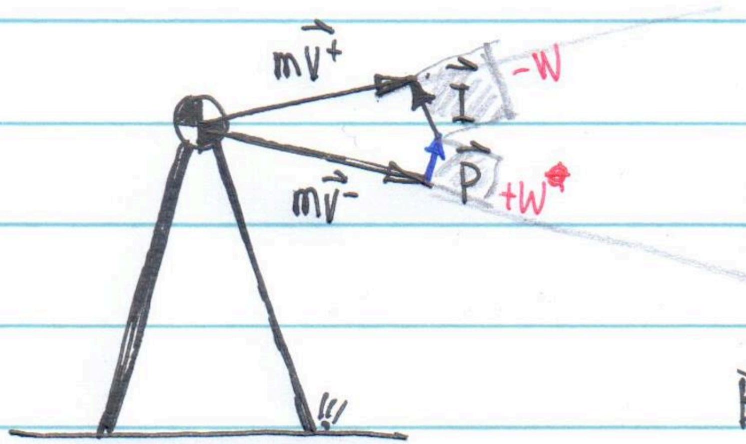
$\downarrow$ step-to-step transition

② Step-to-step transition dissipates energy.

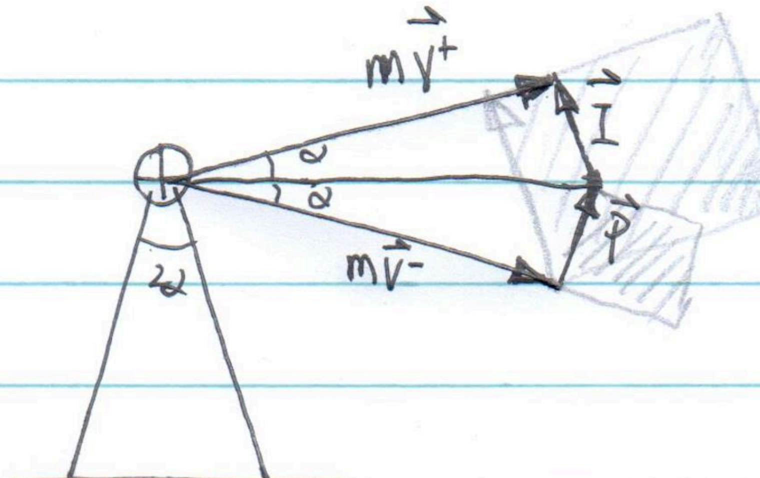
$$\text{Dissipated energy} = \frac{1}{2}m\|\vec{v}^+\|^2 - \frac{1}{2}m\|\vec{v}^-\|^2$$

$$= \frac{1}{2}m\left(\|\vec{v}^+\|^2 - \|\vec{v}^-\|^2\right) = \frac{1}{2}I^2 = \frac{1}{2}m^2\|\vec{v}\|^2\sin^2 2\alpha \approx \frac{1}{2}m^2\|\vec{v}\|^2 4\alpha^2$$

Walking Principles



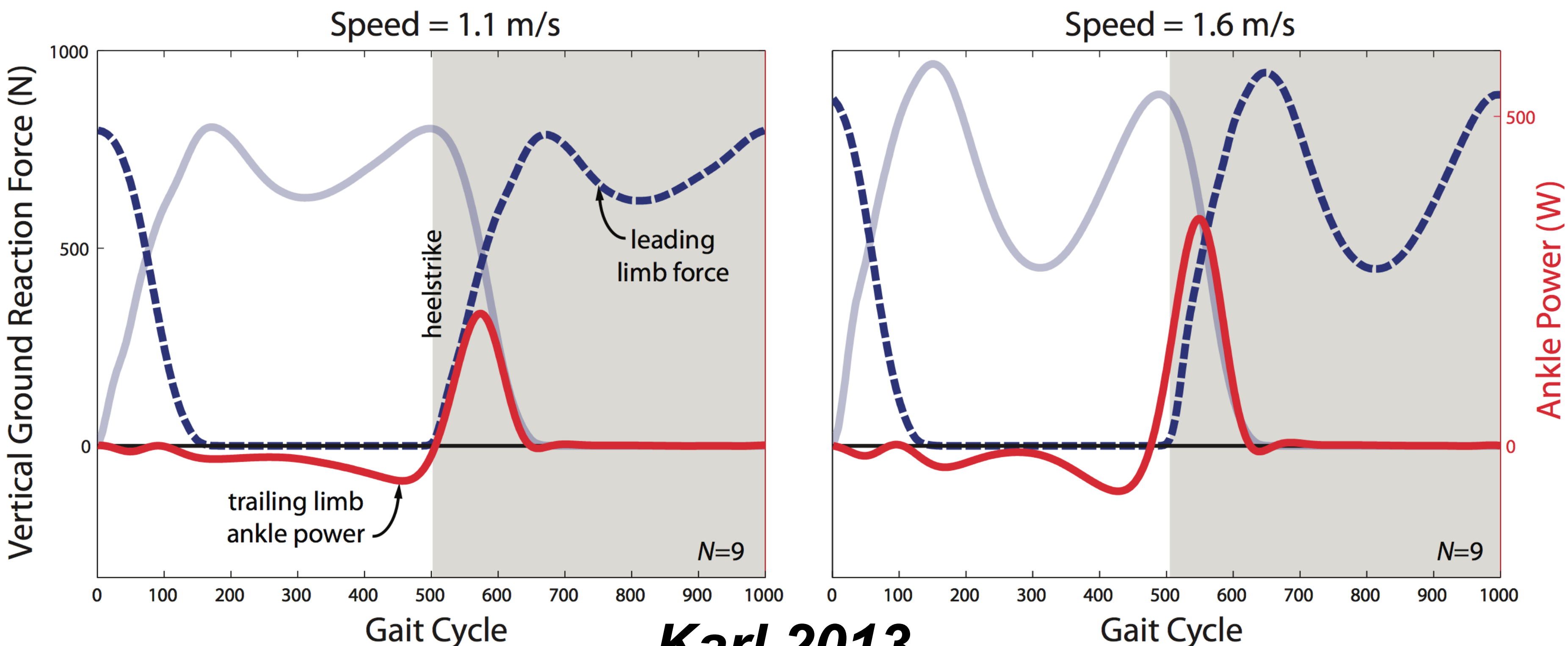
$$\left.\begin{array}{l} \begin{cases} m\vec{v}^+ = m\vec{v}^- + \vec{p} + \vec{I} \\ \vec{v}^- \cdot \vec{p} = 0 \\ \vec{I} \cdot \vec{v}^+ = 0 \end{cases} \\ \text{Boundary Condition } \|\vec{v}^+\| = \|\vec{v}^-\| \end{array}\right\} \Rightarrow \|\vec{p}\| = \|\vec{I}\|$$



$$\text{Dissipated energy} = \frac{1}{2}\|\vec{I}\|^2 = \frac{1}{2}\|\vec{p}\|^2$$
$$= \frac{1}{2} m^2\|v\|^2 \cdot \tan^2\alpha \approx \frac{1}{2} m^2\|v\|^2 \alpha^2$$

Push-off impulse is four times less costly than hip actuation!

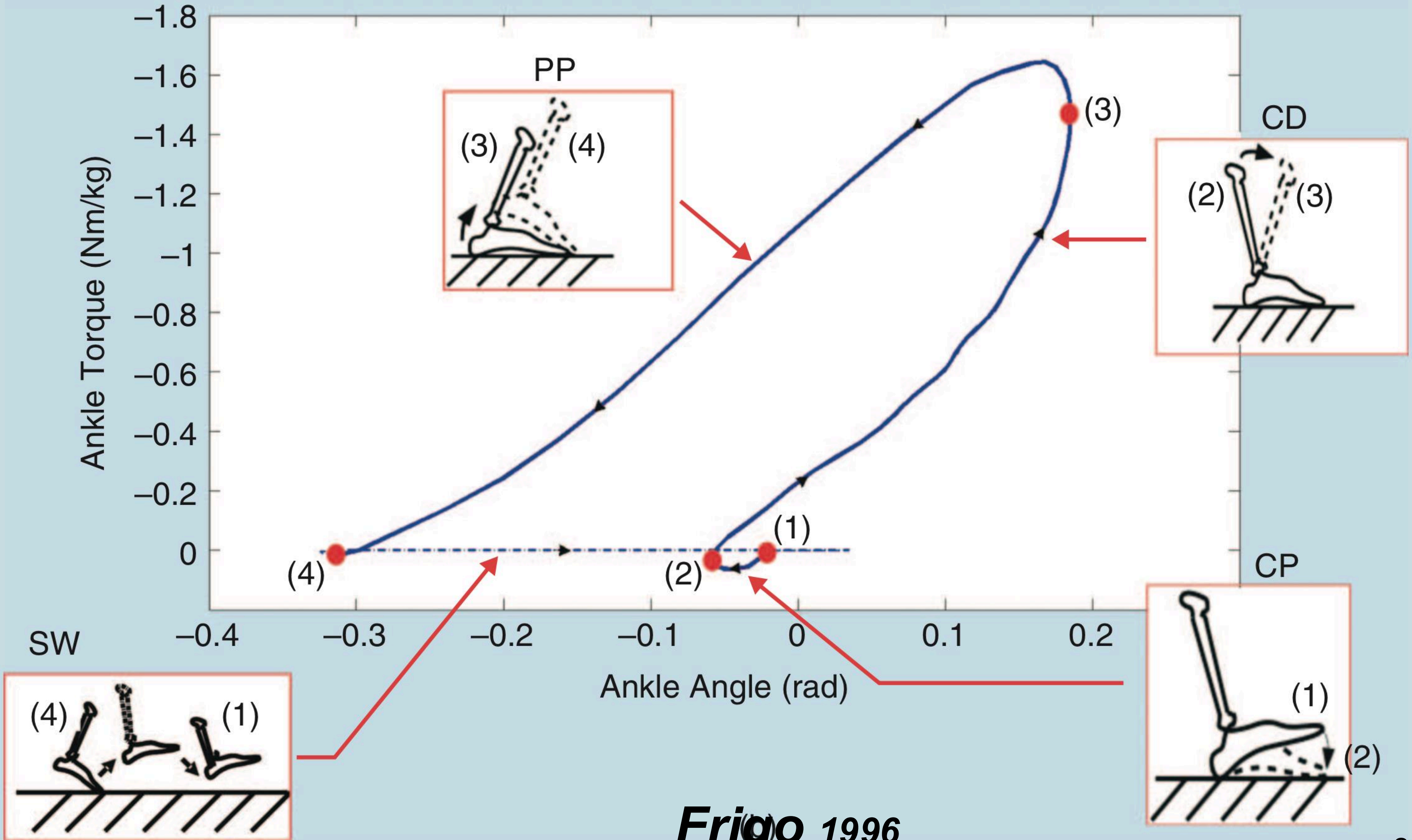
Biological evidence



Karl 2013

Figure 2.15: Timing of positive ankle power relative to heelstrike in human walking. Vertical ground reaction forces for both limbs, and trailing limb ankle power are shown. The white to gray background transition delineates leading limb heelstrike. At slower speeds (e.g., 1.1 m/s) positive ankle power coincides with contralateral heelstrike, suggesting the transition of weight from trailing to leading limb may facilitate the release of elastic ankle energy. At faster speeds (e.g., 1.6 m/s) the positive ankle power precedes contralateral heelstrike, suggesting that a different mechanism allows the ankle to return elastic energy before the limb begins unloading. Human ankle torque vs. angle data (Figure 2.8) suggests that stiffening of the joint, likely from muscle contraction, allows this preemptive push-off. Force and ankle power data is from normal human walking (*N*=10) [35].

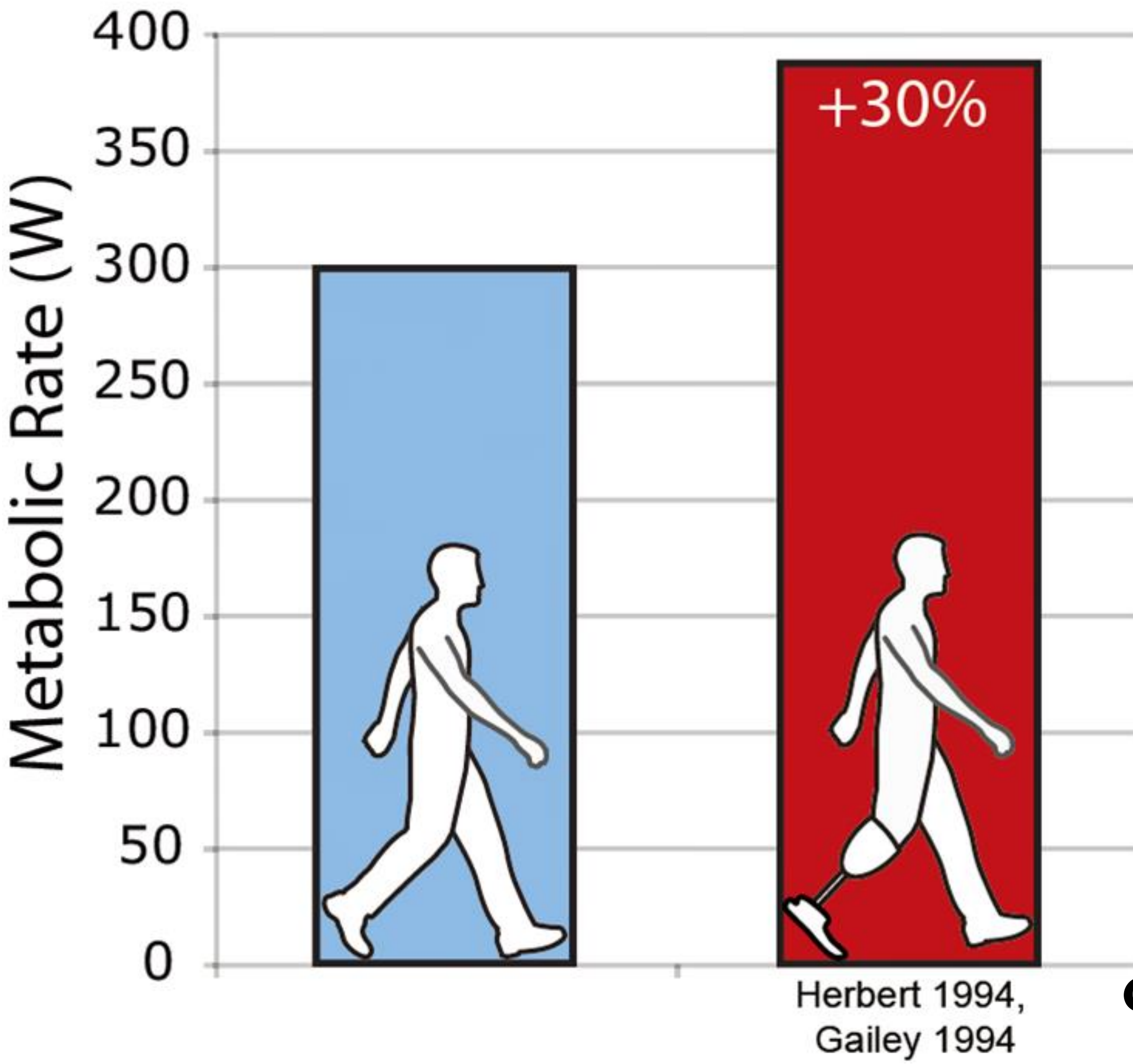
Biological evidence

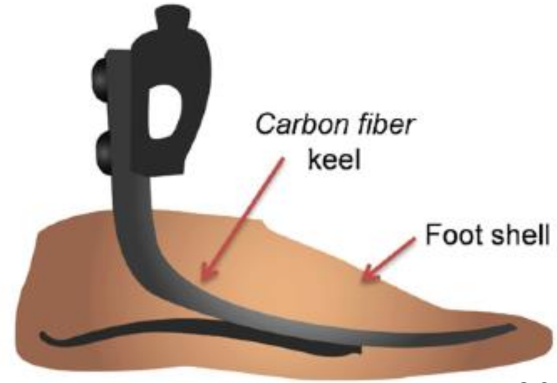


***Frigo** 1996*

Prosthetic Limbs

Amputees expend more energy to walk



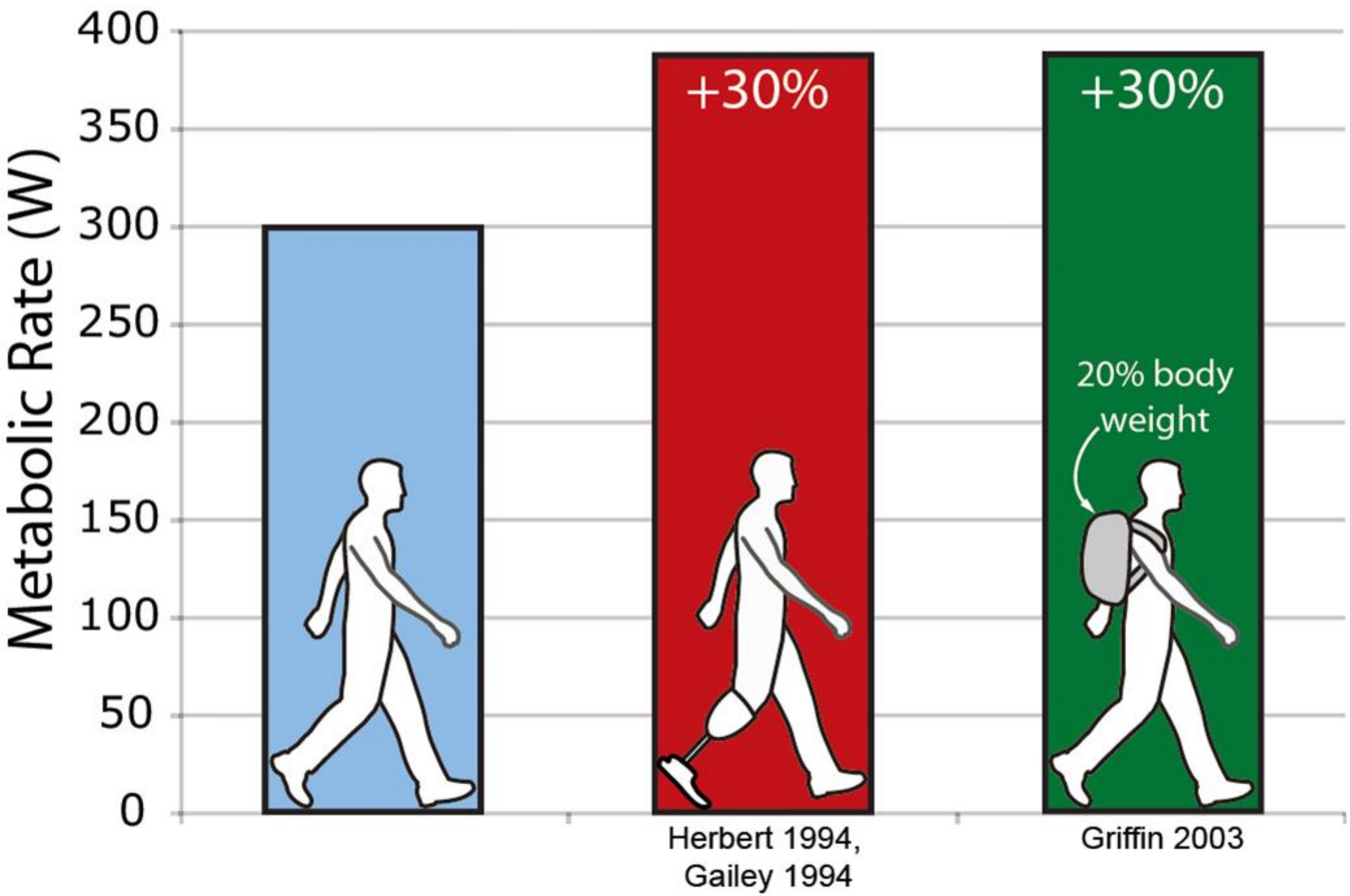


Morgenroth et al. 2011

Conventional Prosthesis

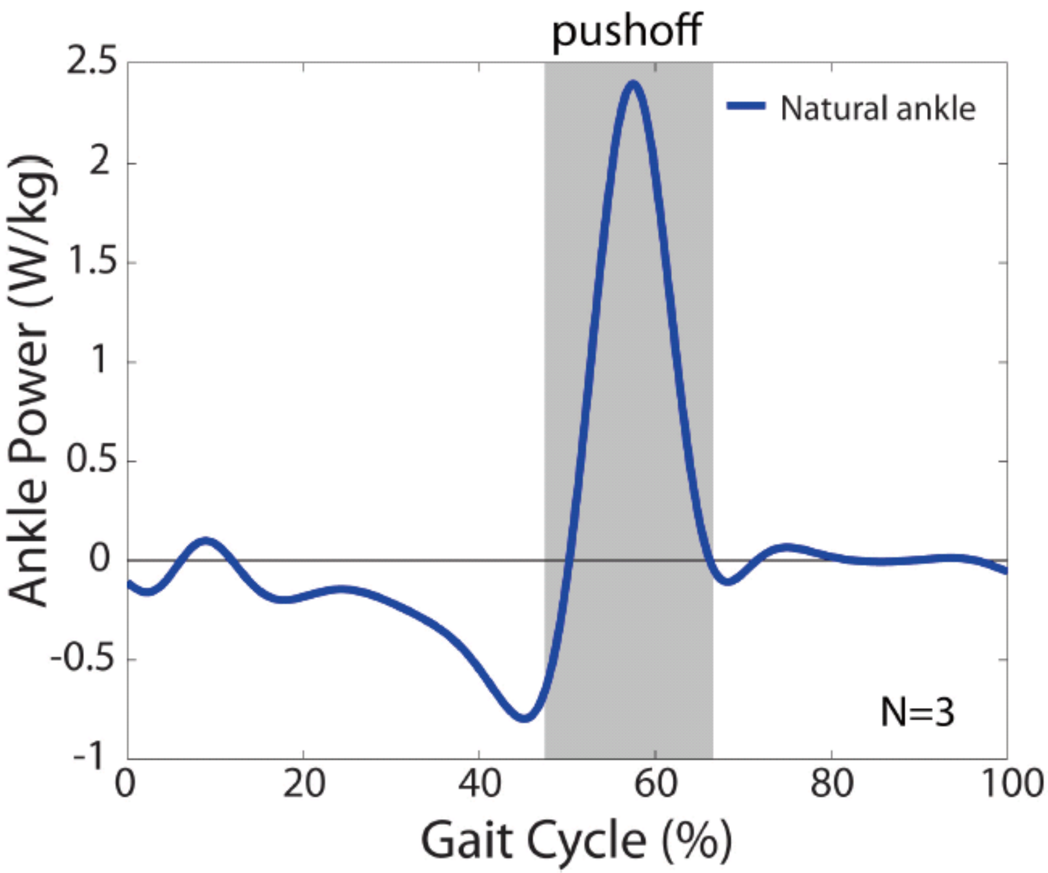
Prosthetic Limbs

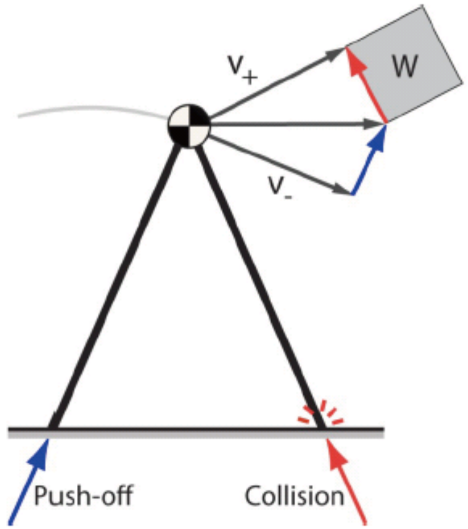
Amputees expend more energy to walk



Prosthetic Limbs

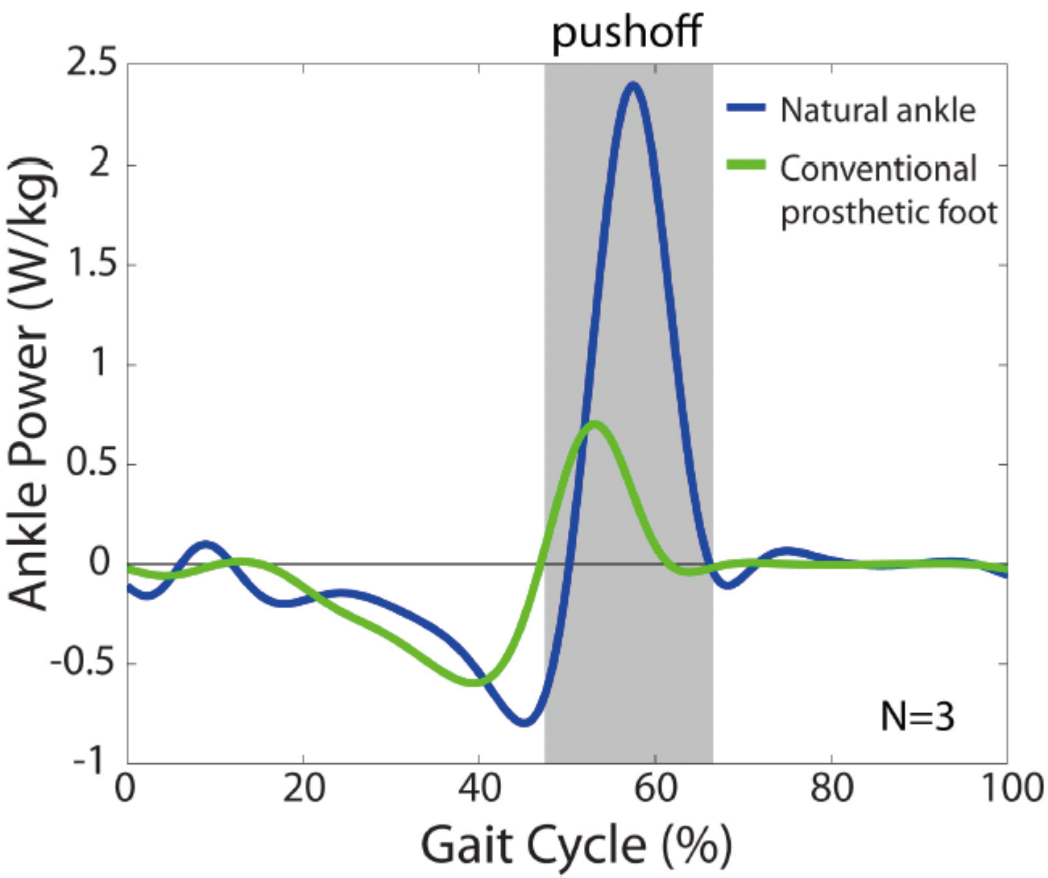
Non-amputees: burst of ankle push-off work

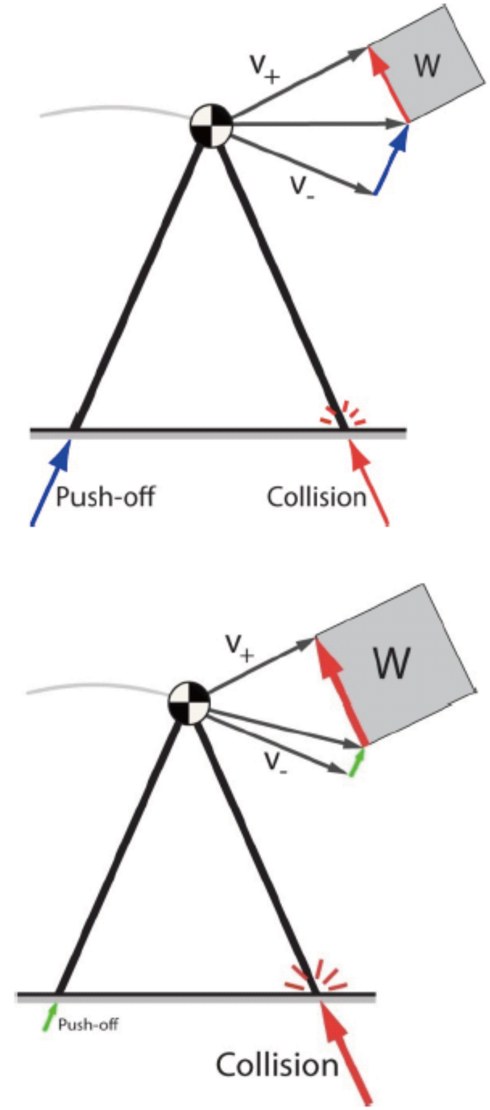


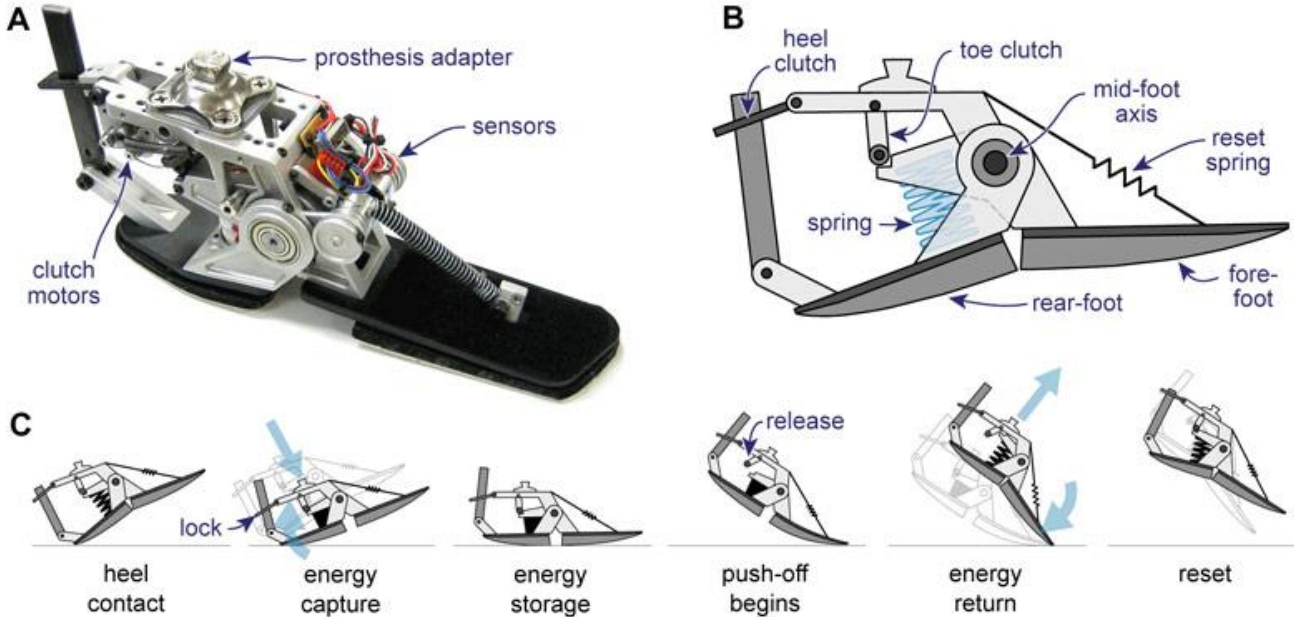


Prosthetic Limbs

Amputees: greatly reduced ankle push-off

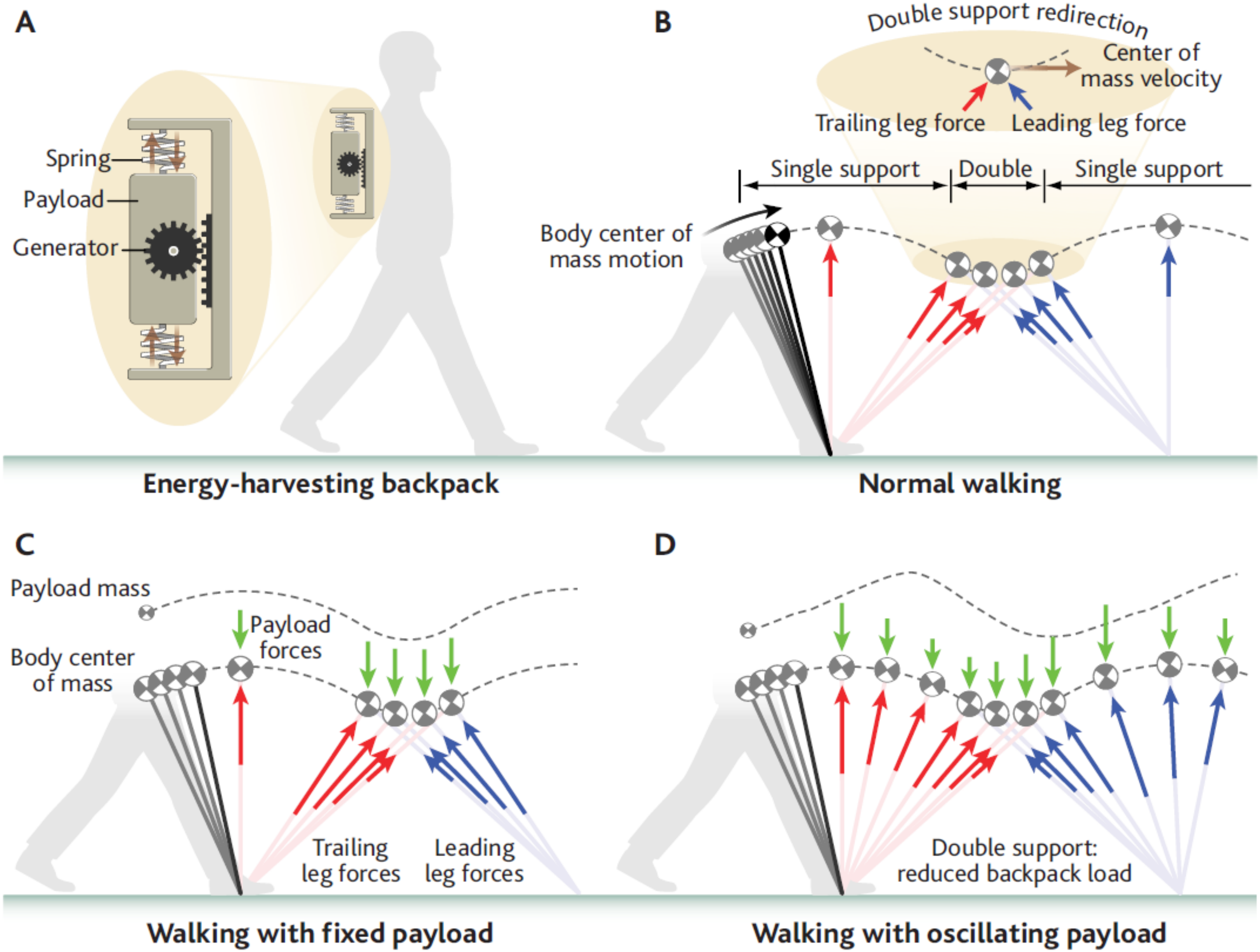






BLUE IN Brief

Artificial Foot



A
Spring
Payload
Generator
Energy-harvesting backpack
B
Double support redirection
Center of mass velocity
Trailing leg force
Leading leg force
Single support
Double
Single support
Body center of mass motion
Normal walking
C
Payload mass
Payload forces
Body center of mass
Trailing leg forces
Leading leg forces
Walking with fixed payload
D
Double support: reduced backpack load
Walking with oscillating payload

Take home message

❶ Model — a hypothetical description of a complex entity or process.

❷ All models are wrong!

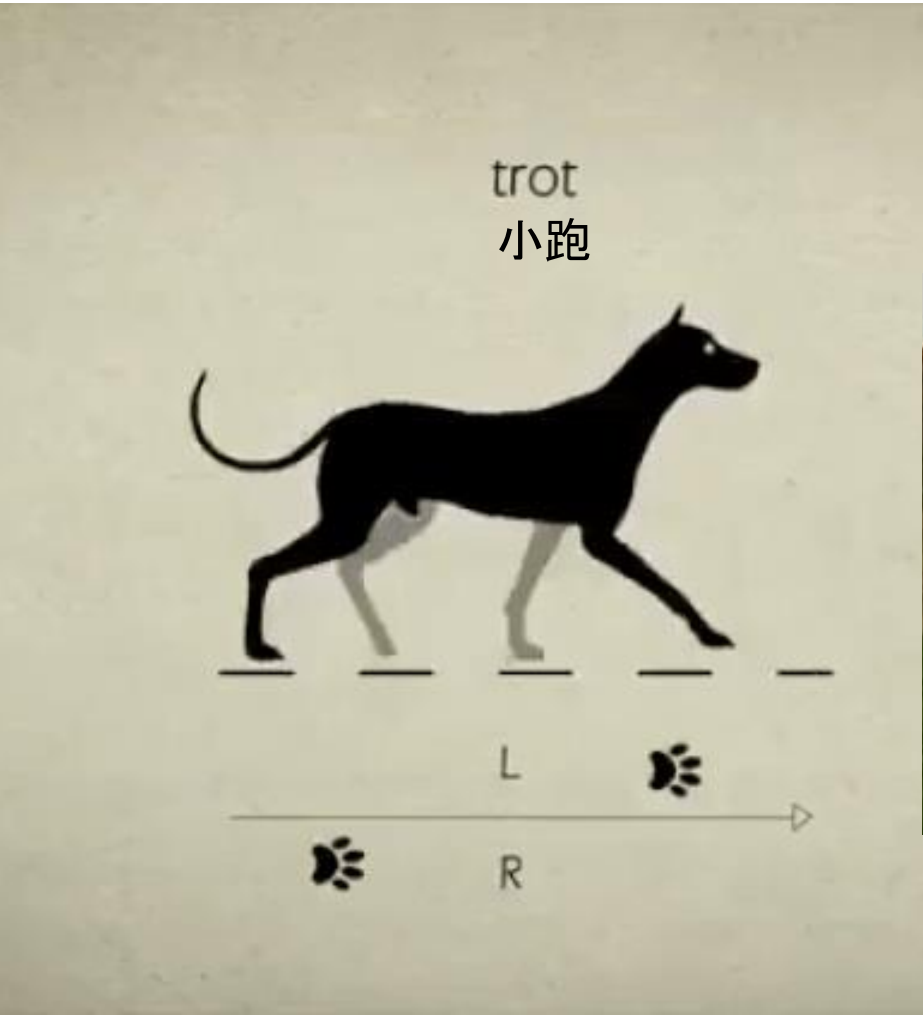
❸ But, some are useful!

❹ Simple model can have powerful insight.

Gaits of legged animals (Quadruped)

Polet DT, Bertram JEA (2019) An inelastic quadrupedal model discovers four-beat walking, two-beat running, and pseudo-elastic actuation as energetically optimal. PLoS Comput Biol 15(11): e1007444. https://doi.org/10.1371/journal.pcbi.1007444

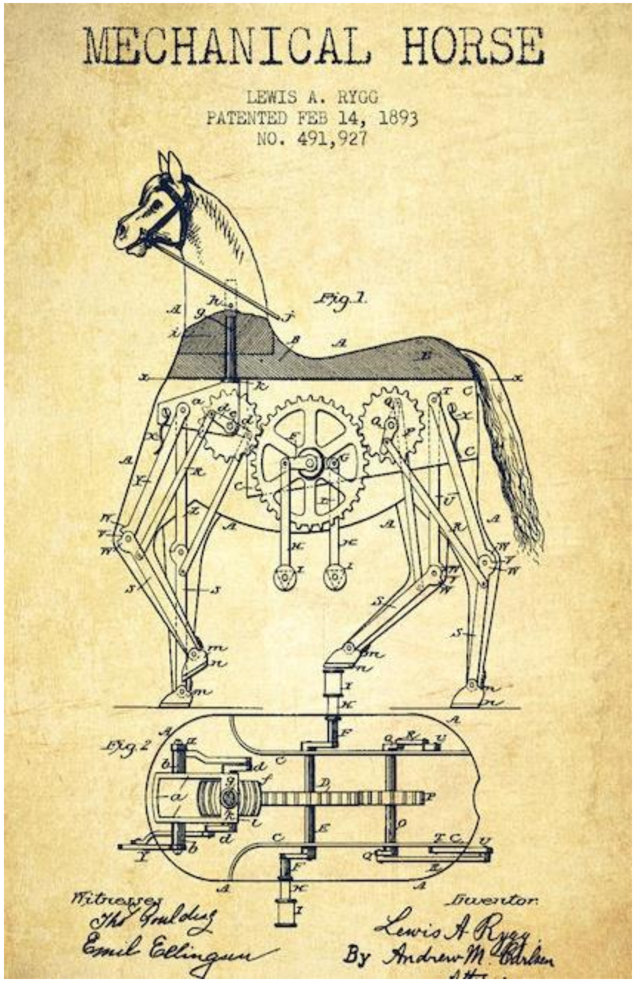
Gaits of legged animals (Quadruped)

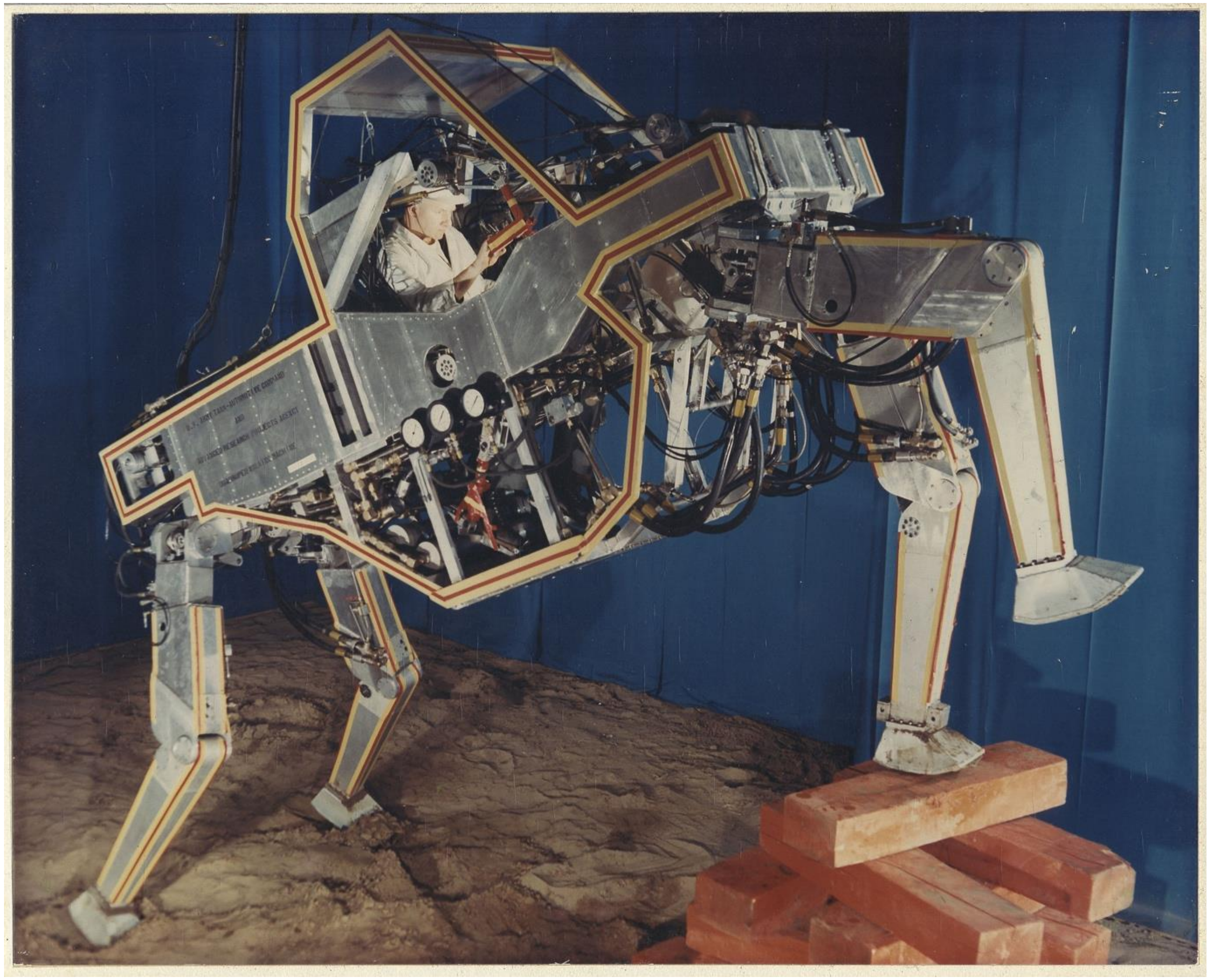


Locomotion: biped walking

Walking toys – passive dynamic walker

History of legged robots



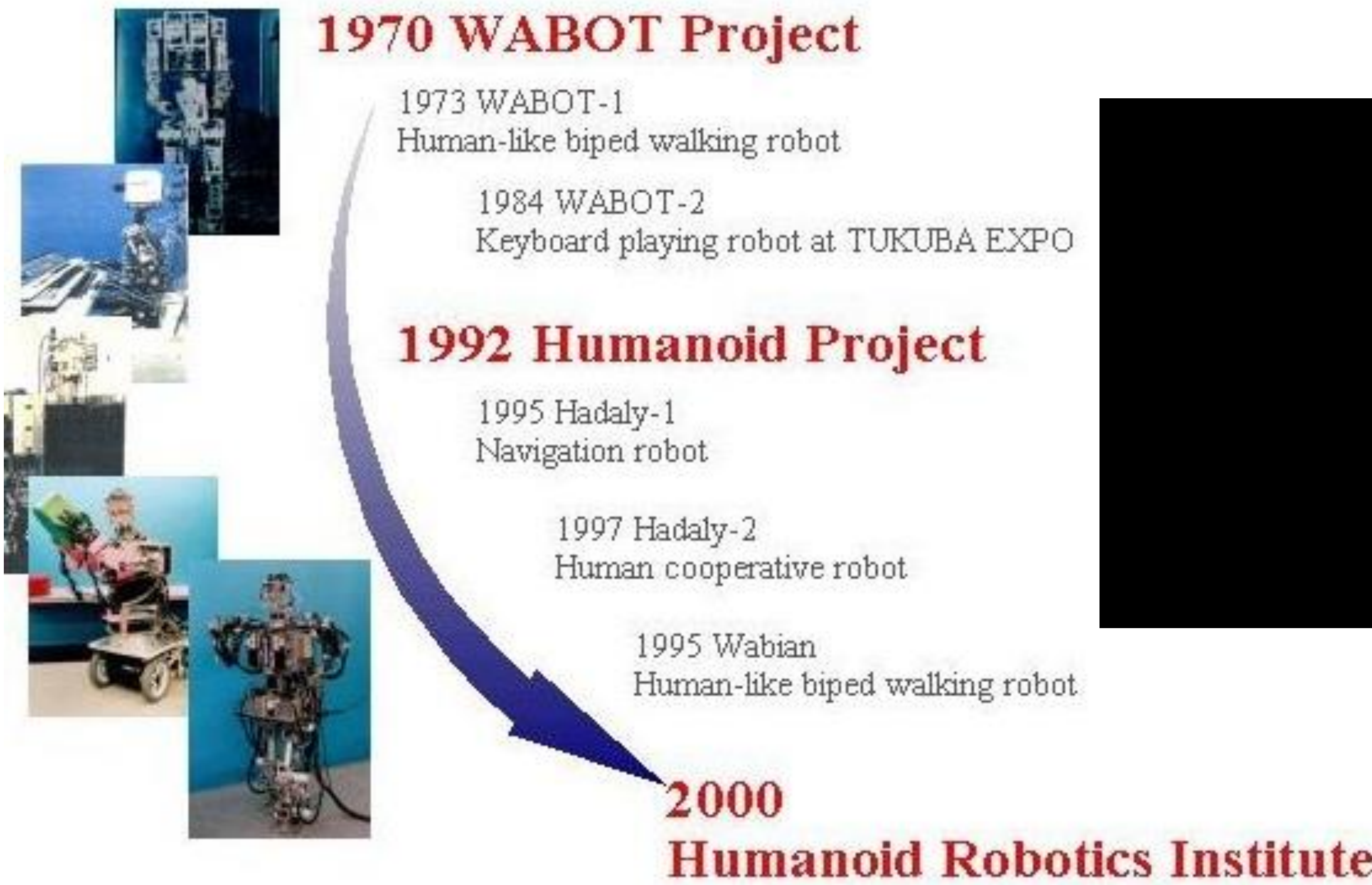


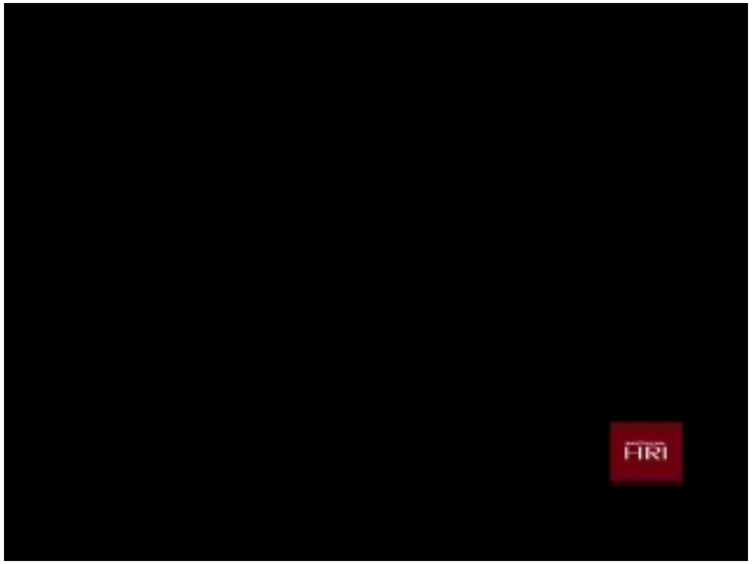
Mechanical horse
patented by Lewis A. Rygg, 1893

Walking truck
developed by GE, 1968

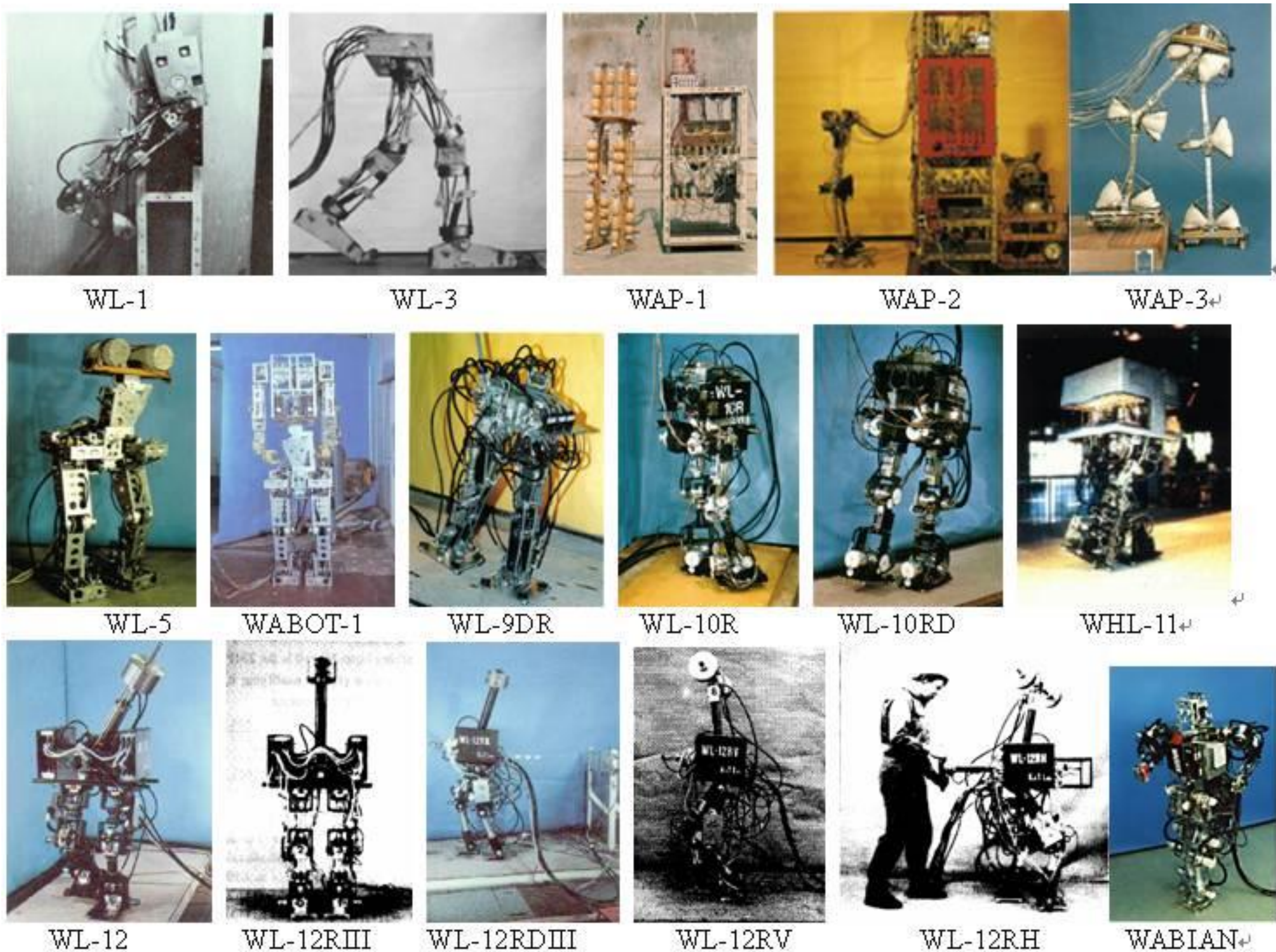
History of legged robots

Waseda (早稲田)



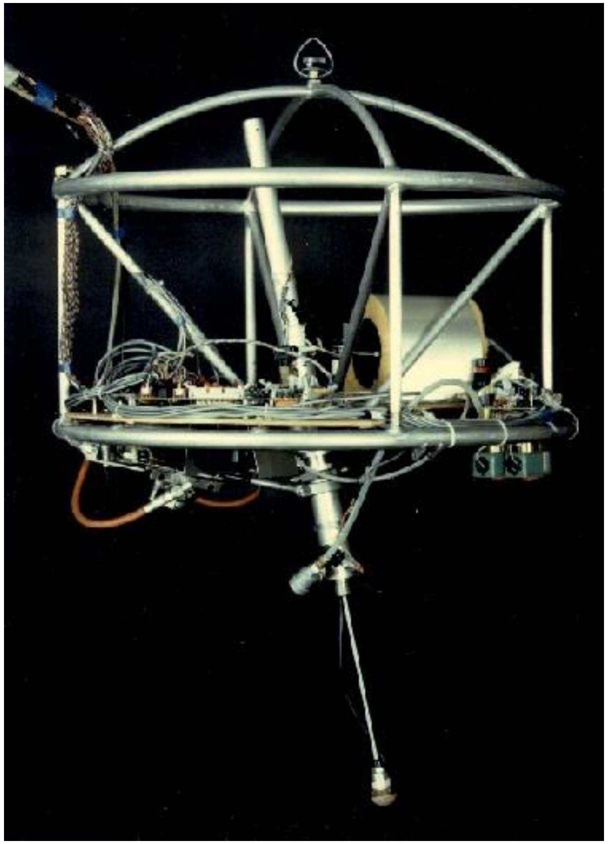


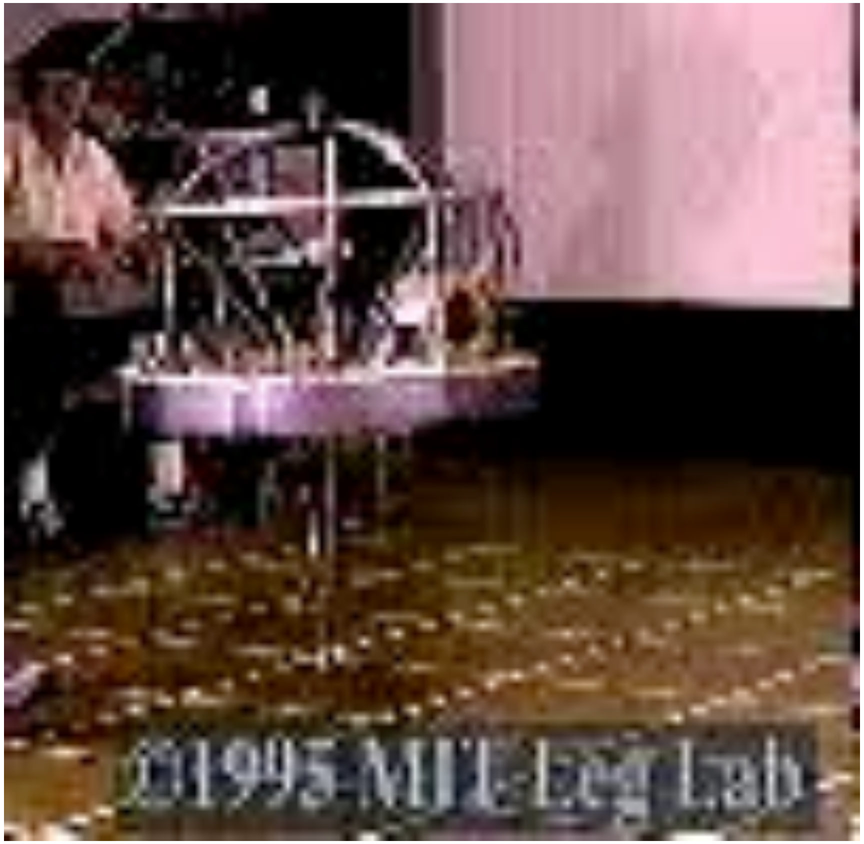
History of legged robots



History of legged robots

MIT Leg Lab

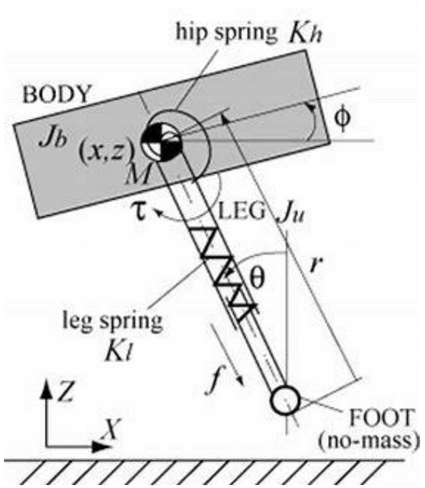




3D One-Leg Hopper (1983-1984)

History of legged robots

MIT Leg Lab



- The control system has three separate parts:
  - ① controlling forward running speed;
  - ② controlling body attitude;
  - ③ controlling hopping height.
- These controllers worked independently, treating any coupling as disturbances. The control system for the Planar One-Leg Hopper did not explicitly program a stepping motion, but allowed the stepping motion to emerge under the constraints of balance and controlled travel.
- The robot hopped in place, travelled at specified rates, and maintained balance when disturbed.
- The simple techniques used for planar one-leg hopper were later generalized for 3D one-leg hopping, bipedal running, and quadruped trotting, pacing, and bounding.

History of legged robots

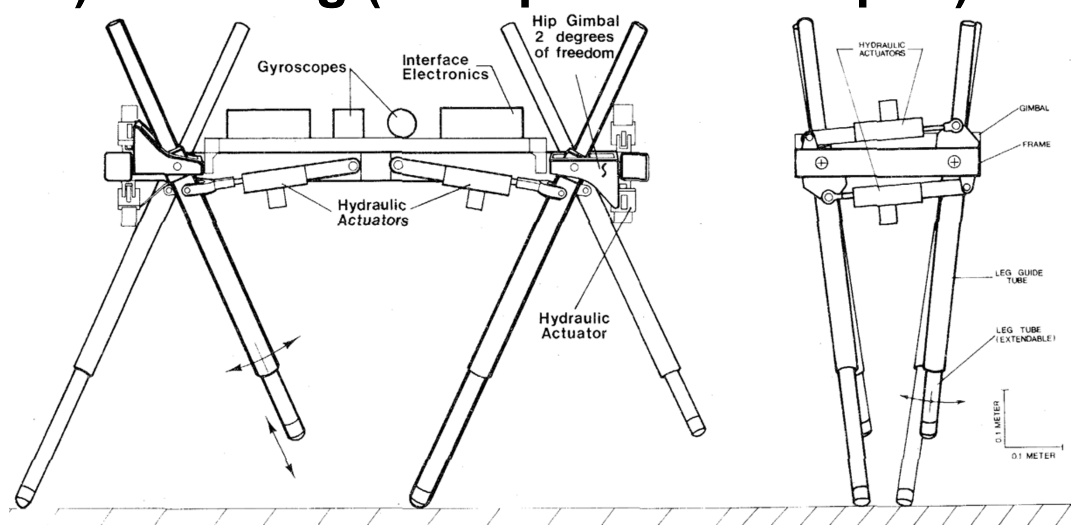
Quadruped (1984-1987)

Quadruped gaits that use the legs in pairs:

1) trotting (diagonal legs as pairs)

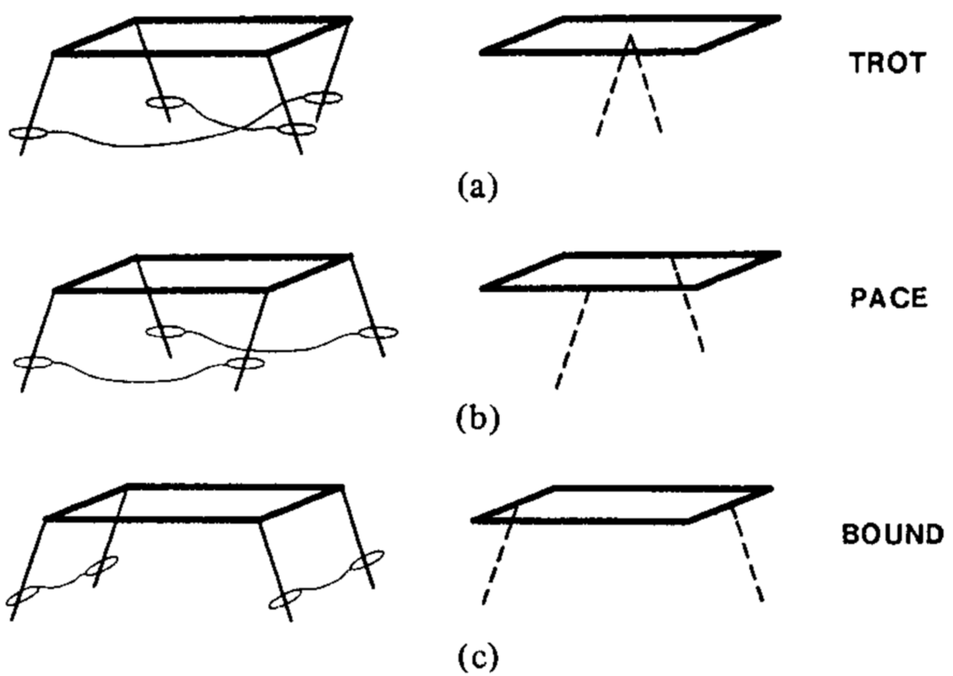
2) pacing (lateral pairs)

3) bounding (front pair and rear pair)



History of legged robots

By restricting consideration to the pair gaits, the control of the Quadruped was reduced to the control of an equivalent virtual biped. Each of the gaits that use the legs in pairs can be transformed into a common underlying gait, a virtual biped gait.

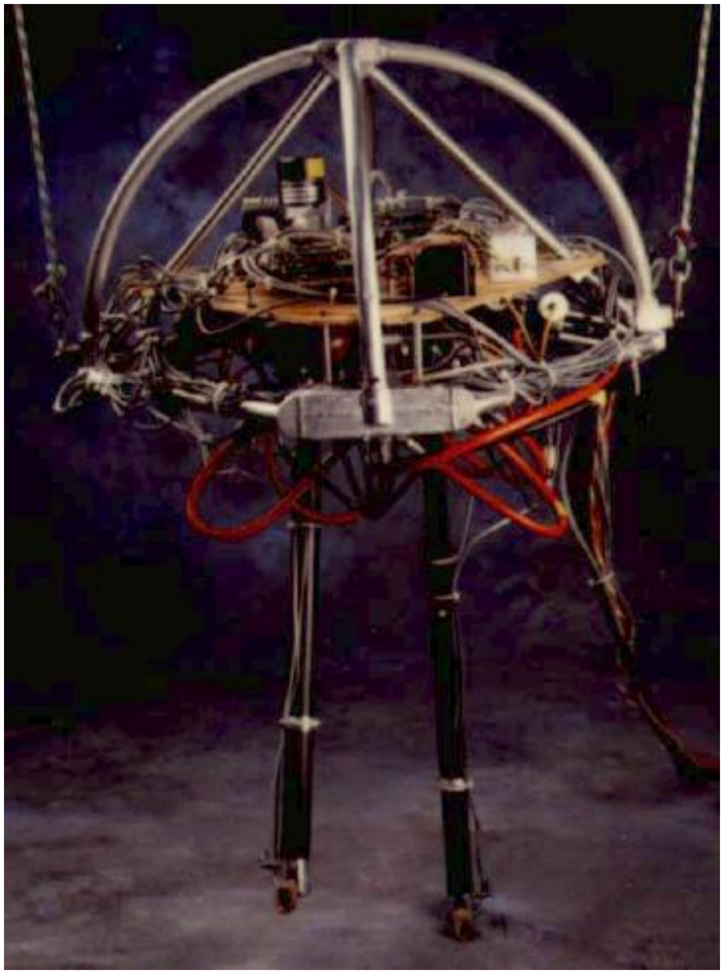


Principles for one-legged hopping are generalized to four-legged running with the addition of a low-level leg coordination mechanism.

Raibert, M. H., Chepponis, M., Brown, H. B. Jr. 1986. Running on four legs as though they were one. IEEE J. Robotics and Automation, 2:70--82.

History of legged robots

MIT Leg Lab



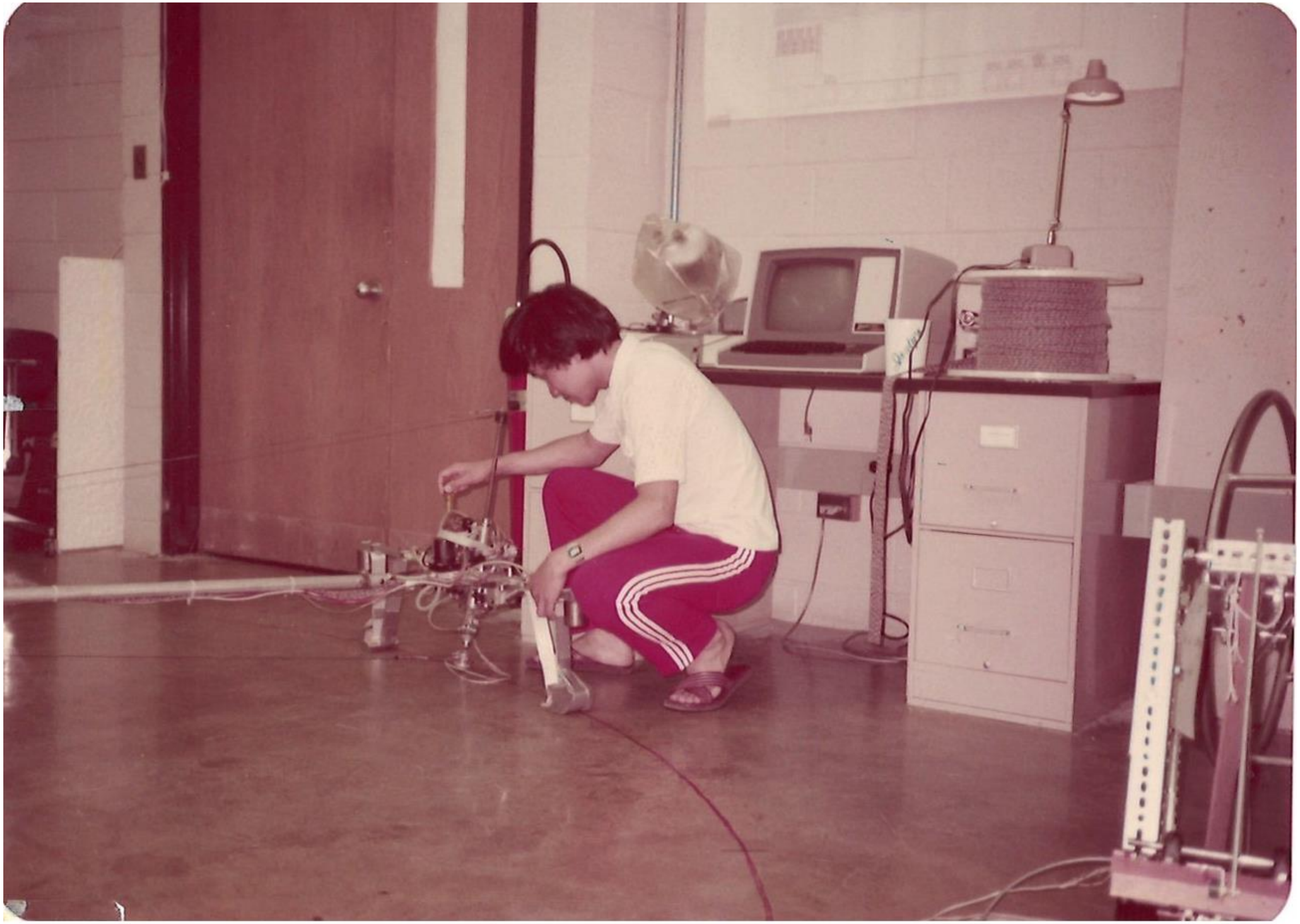
3D Biped (1989-1995)

History of legged robots

MIT Leg Lab

Marc Raibert founded the Leg Laboratory in 1980 and directed it through 1995.

History of legged robots



DYNAMIC BEHAVIOR

Carnegie Mellon Tepper School of Business

Dr. Marc Raibert

Founder and CEO, Boston Dynamics

Abstract: No business plan. No investors. No debt. No MBAs. No PR department. No products (yet). Is it a success?

BIO: Marc Raibert is founder and CEO of Boston Dynamics, a company that creates some of the world's most advanced dynamic robots, such as BigDog, Atlas, Spot and Handle. These robots are inspired by the remarkable ability of animals to move with agility, dexterity, perception and intelligence. A key ingredient of these robots is their dynamic behavior, which contributes to their life-like qualities and their effectiveness in the real-world. Before starting Boston Dynamics, Raibert was Professor of Electrical Engineering and Computer Science at MIT from 1986 to 1995. Prior to that he was Associate Professor of Computer Science and Robotics at Carnegie Mellon from 1980-1986. While at CMU and MIT Raibert founded the Leg Laboratory, a lab that helped establish the scientific basis for highly dynamic robots and that set the stage. for the work done at Boston Dynamics.
Dr. Raibert is a member of the National Academy of Engineering.

Carnegie Mellon University School of Computer Science

PIONEER LECTURE SERIES:
ENTREPRENEURSHIP FOR COMPUTER SCIENCE

NO RECORDING ALLOWED

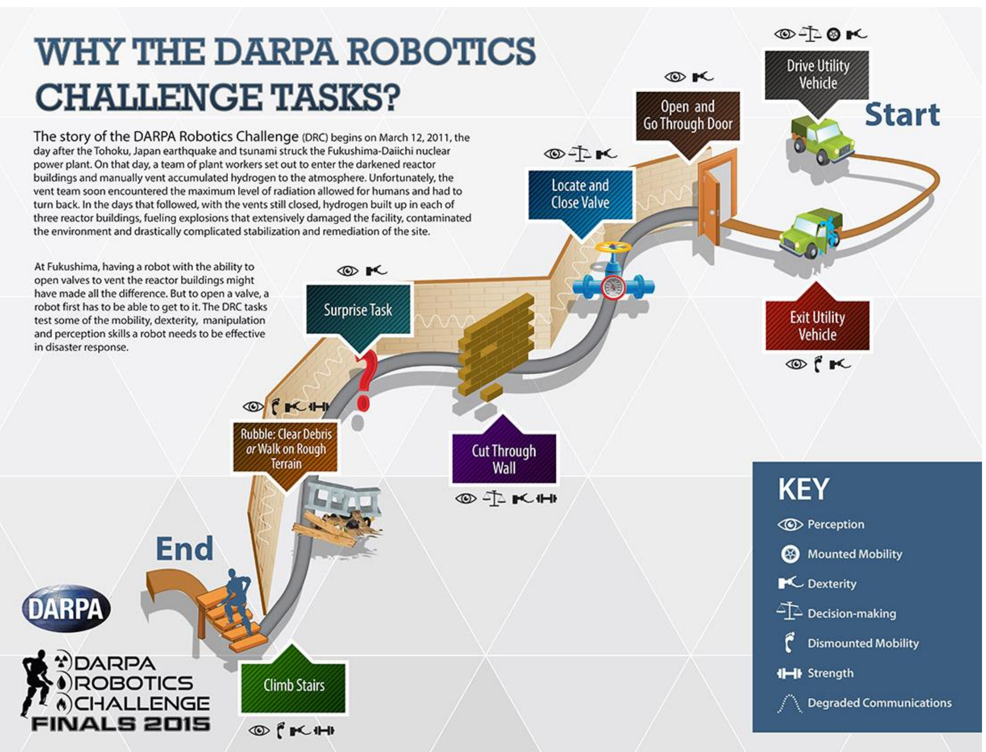
WHEN & WHERE: MARCH 8, 2018 / 6:30 - 7:50 PM / RASHID AUDITORIUM, GHC

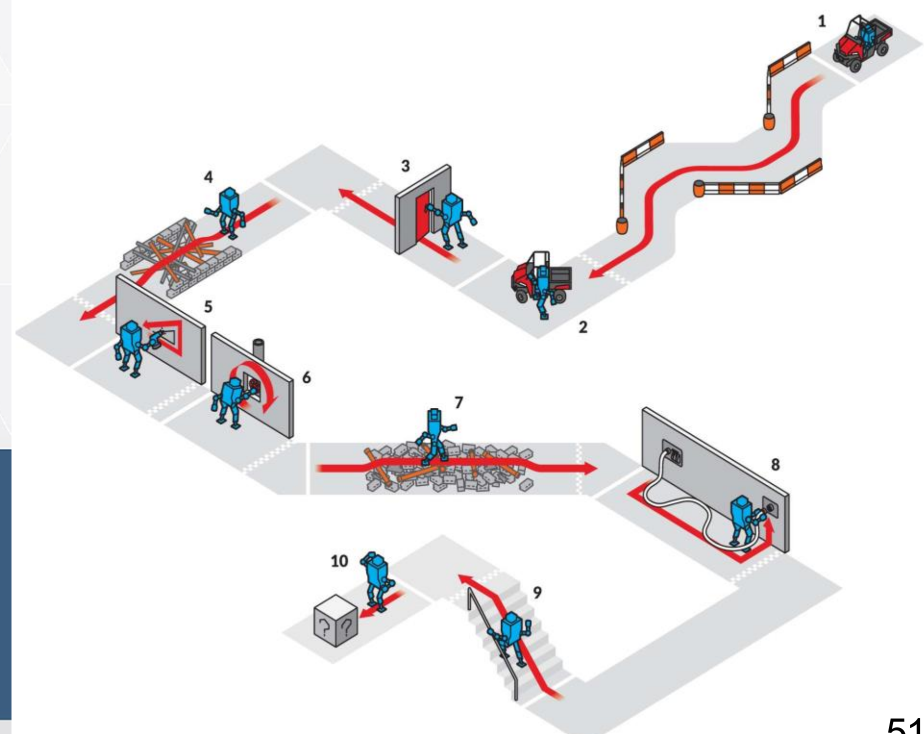
Lecture 8/15

History of legged robots

What we expect from robots?

- Robots can work in the environment for humans as it is.
- Robots can use tools for humans as it is.
- Robots has a human-like shape.





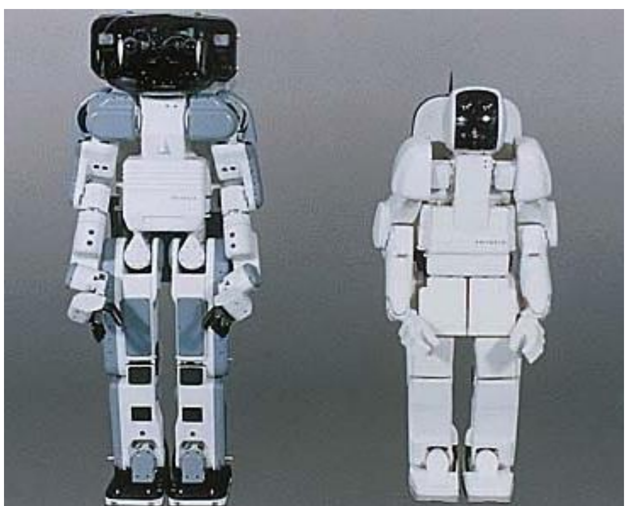
History of legged robots

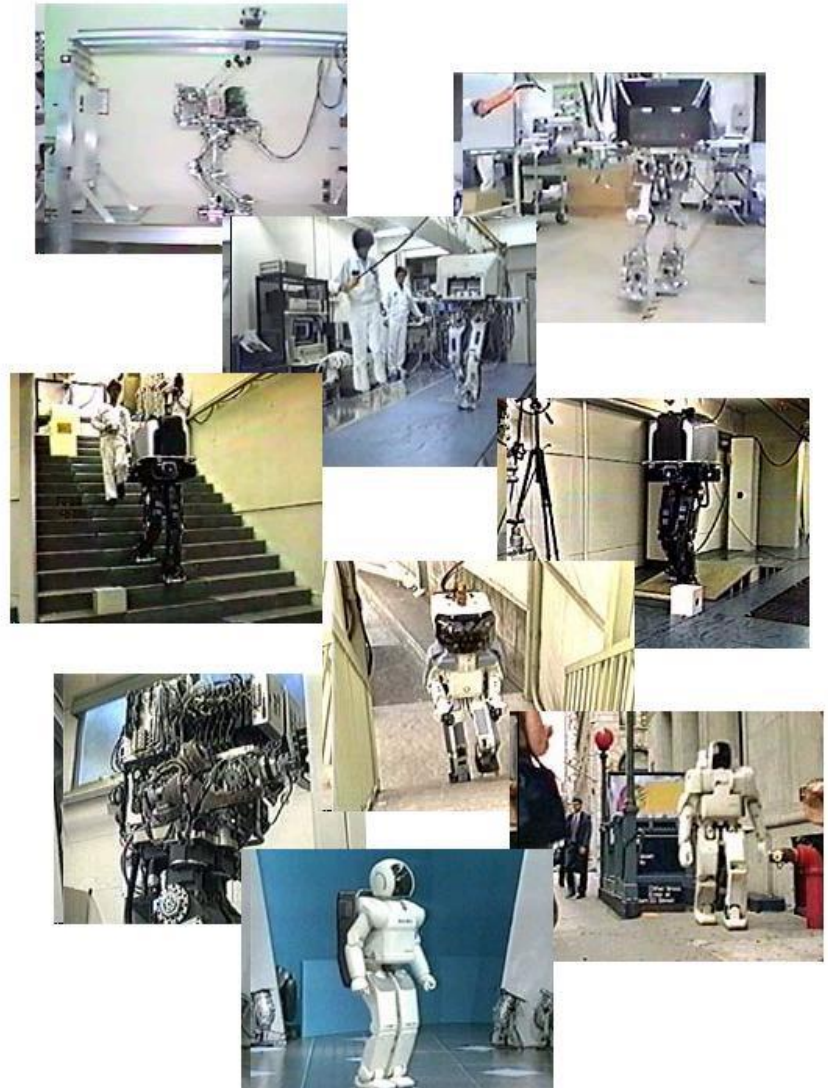
Honda

“十年磨一剑”

P2：世界十大科技进展

MIT（Leg Lab）的评价





1986: E0

1987-1991:
E1, E2, E3

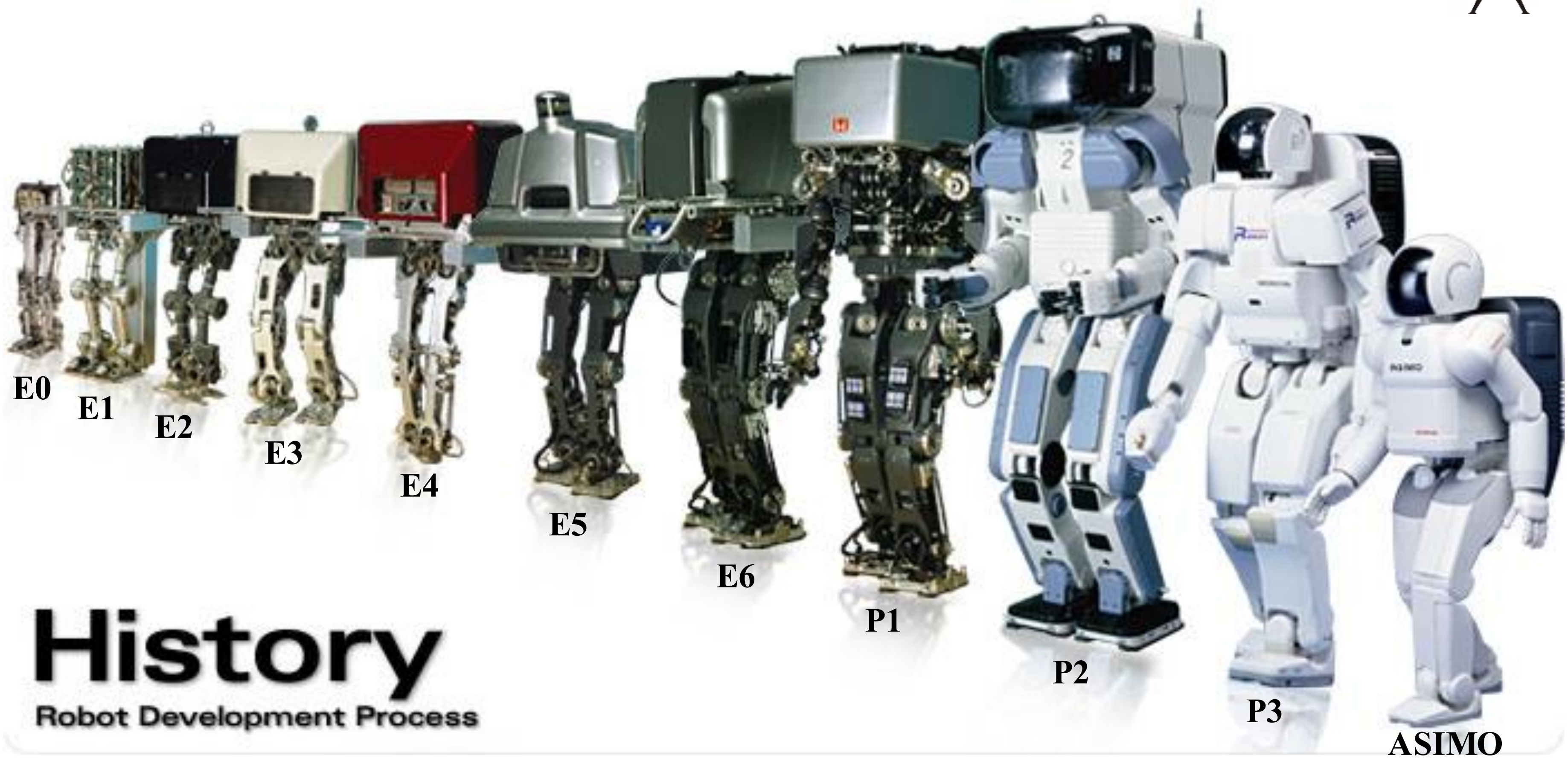
1991-1993:
E4, E5, E6

1994-1997:
P1, P2, P3

2000: ASIMO

History of legged robots

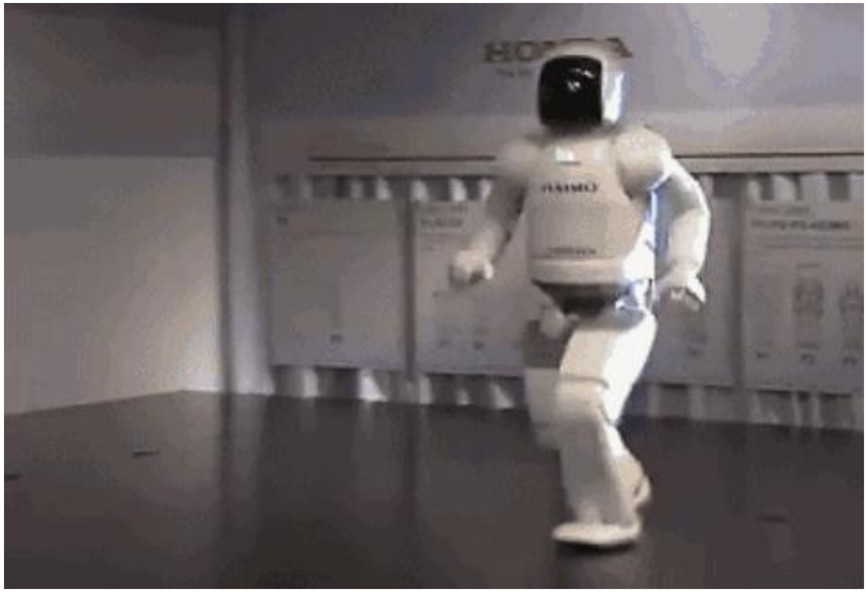
Honda

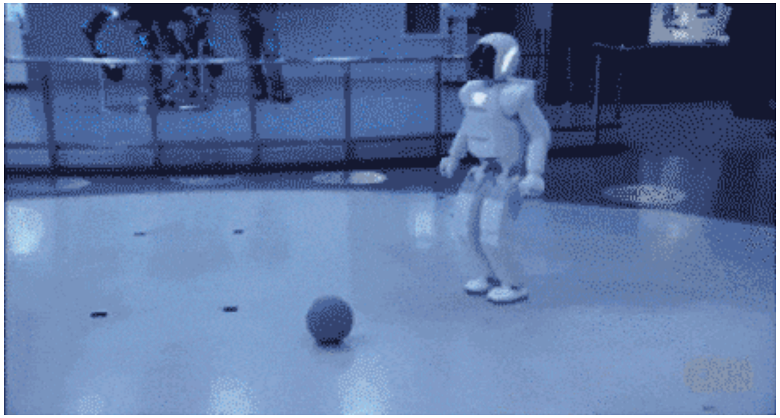


History of legged robots

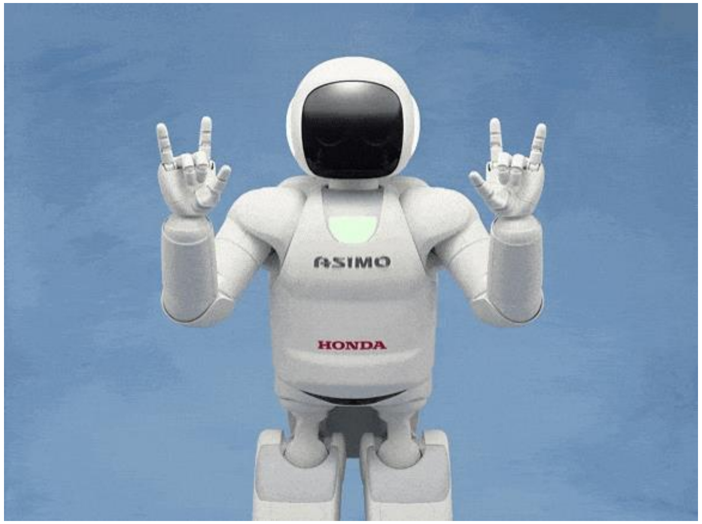
ASIMO (2000)

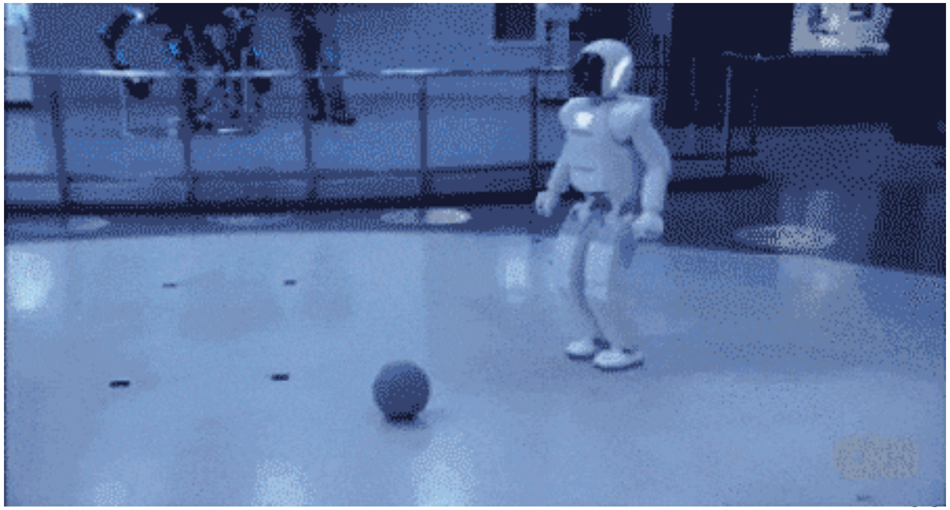
Advanced --- New Era
Step in --- Stepping
Innovative --- Innovation
Mobility --- Mobility



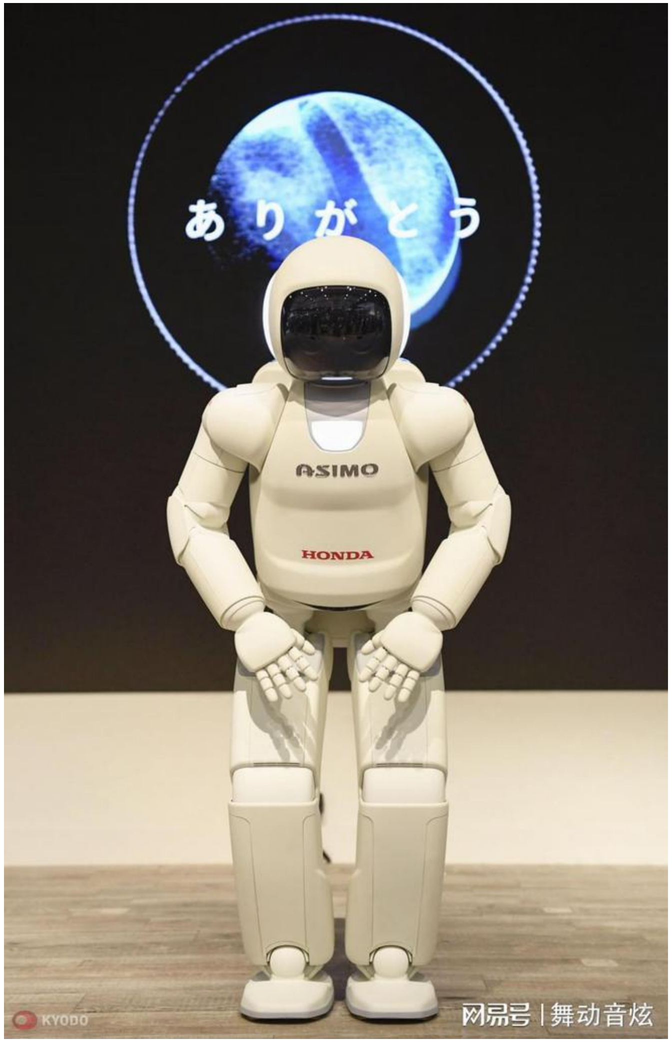


History of legged robots





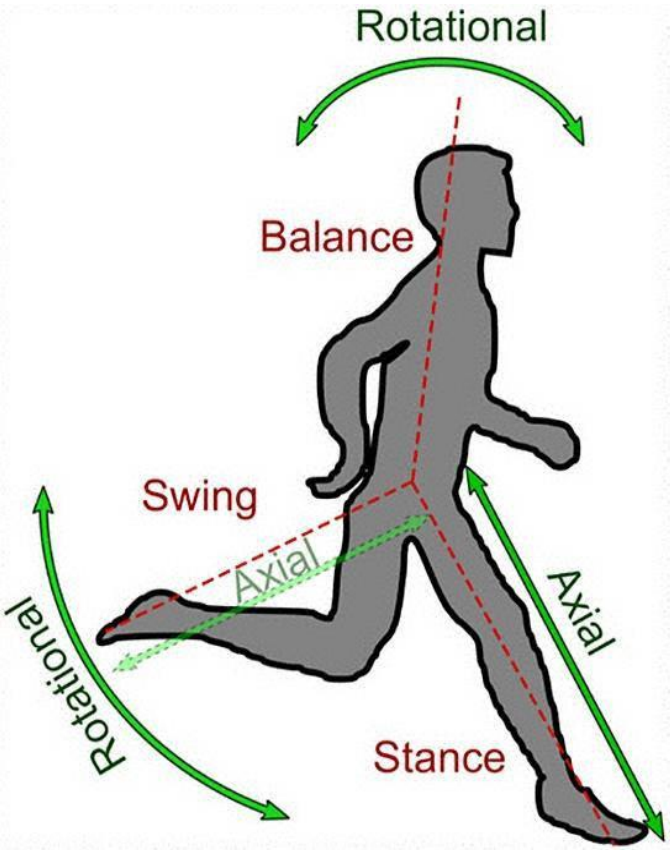
History of legged robots



History of legged robots

Tesla　　马斯克：2026年特斯拉人形机器人产量将达到5万台

Locomotion: biped walking



Main locomotion **sub-functions**:

(1) axial **stance** leg function

(the repulsive function of the stance leg to counteract gravity)

(2) rotational **swing** leg function

(an additional axial leg function of the swing leg is used for ground clearance)

(3) balance for maintaining posture.

(an inherently unstable system)

- the concepts behind the design and control of legged systems.
- the insight obtained from biology that can be adapted to engineered systems

Final Project Presentation

Date: May 28, 2025

1. **8 minutes for Group Presentation + 3 minutes for Q&A;**
2. **The presentation needs to clarify the specific contribution of each group member to the project;**
3. **Use podium desktop PC (make sure video can be played), or your own laptop (HDMI interface);**
4. **PPT, WORD report and other attachments (programs, data, videos, etc.). Please submit them in BB system before June 11, 2025 (submission as a group ZIP file).**