EESC · USP
Escola de Engenharia de São Carlos
Universidade de São Paulo

ARC Lab
Laboratório de Controle de Robótica Avancada

SEM5950 - SEM0586
Legged Robots

Aula #1: Princípios de locomoção com pernas

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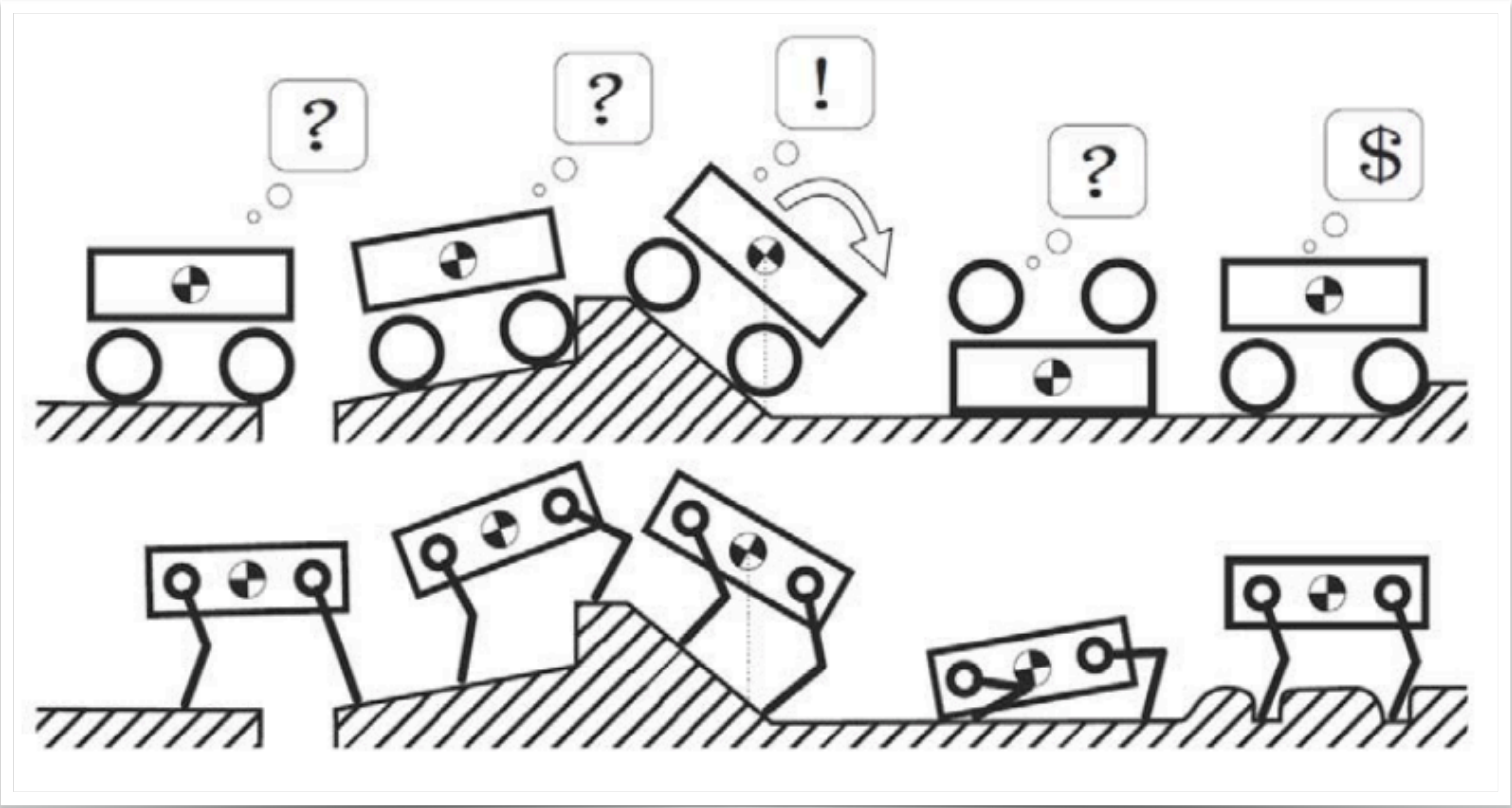
São Carlos, 27/05/19

Por que pernas?

Por que não rodas?

Perna vs. Rodas



Conteúdo

Conteúdo

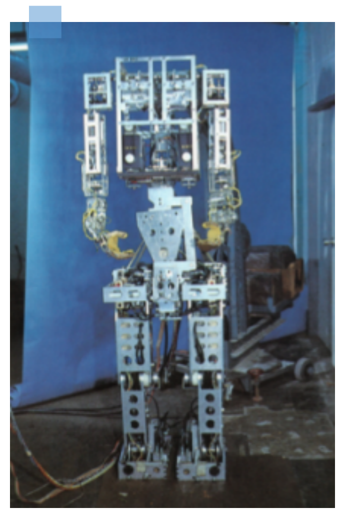
Histórico (resumido) de robôs com pernas

First computer-controller robot (Raiber, 70s – 80s)

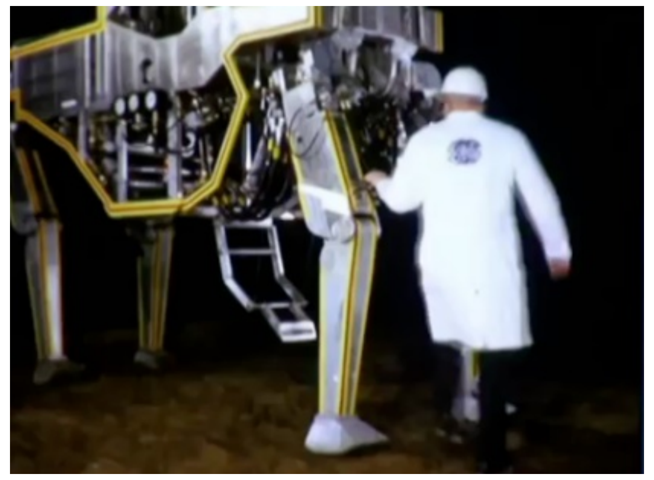
P2
(Honda, 1996)

ZMP concept
(Vukobratovic, 1972)

1970 — 1980 — 1990 — 2000



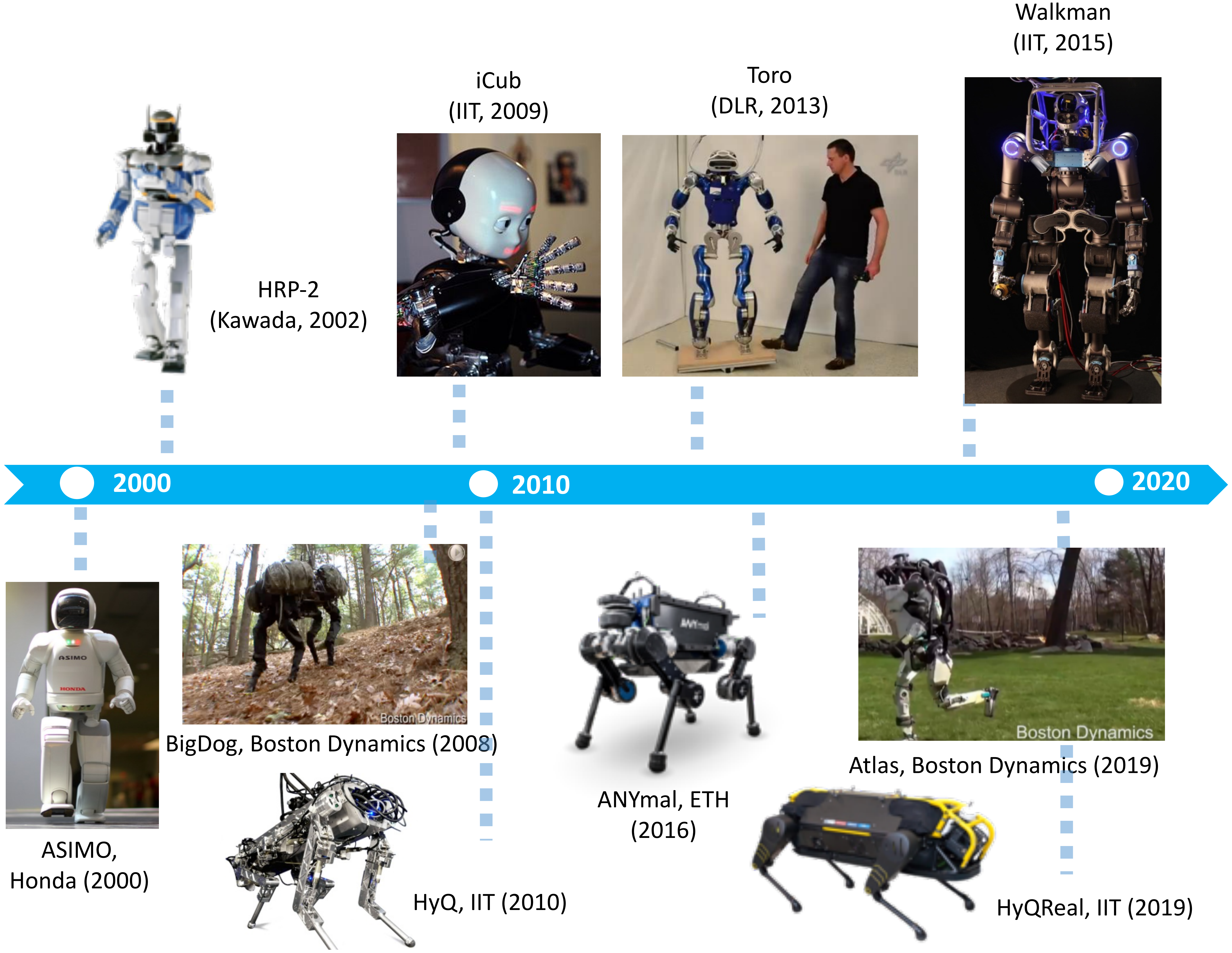
First Humanoid Robot
(1973 - Waseda University, Japan)



The pre-robotic period
First walking machines were tele-operated by humans: GE Walking Truck (~1960s)

Purely passive dynamics
(McGeer, 1990)

Histórico (resumido) de robôs com pernas



1957 — Walking Machines by Joseph Shigley

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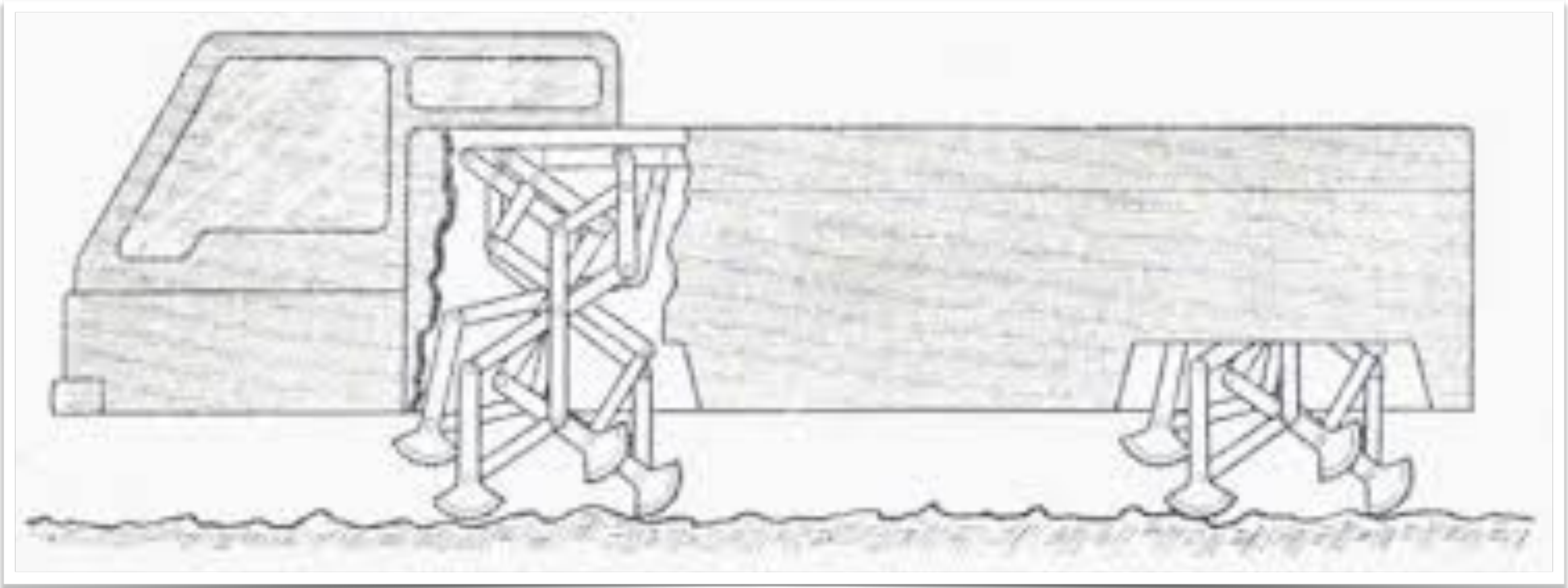
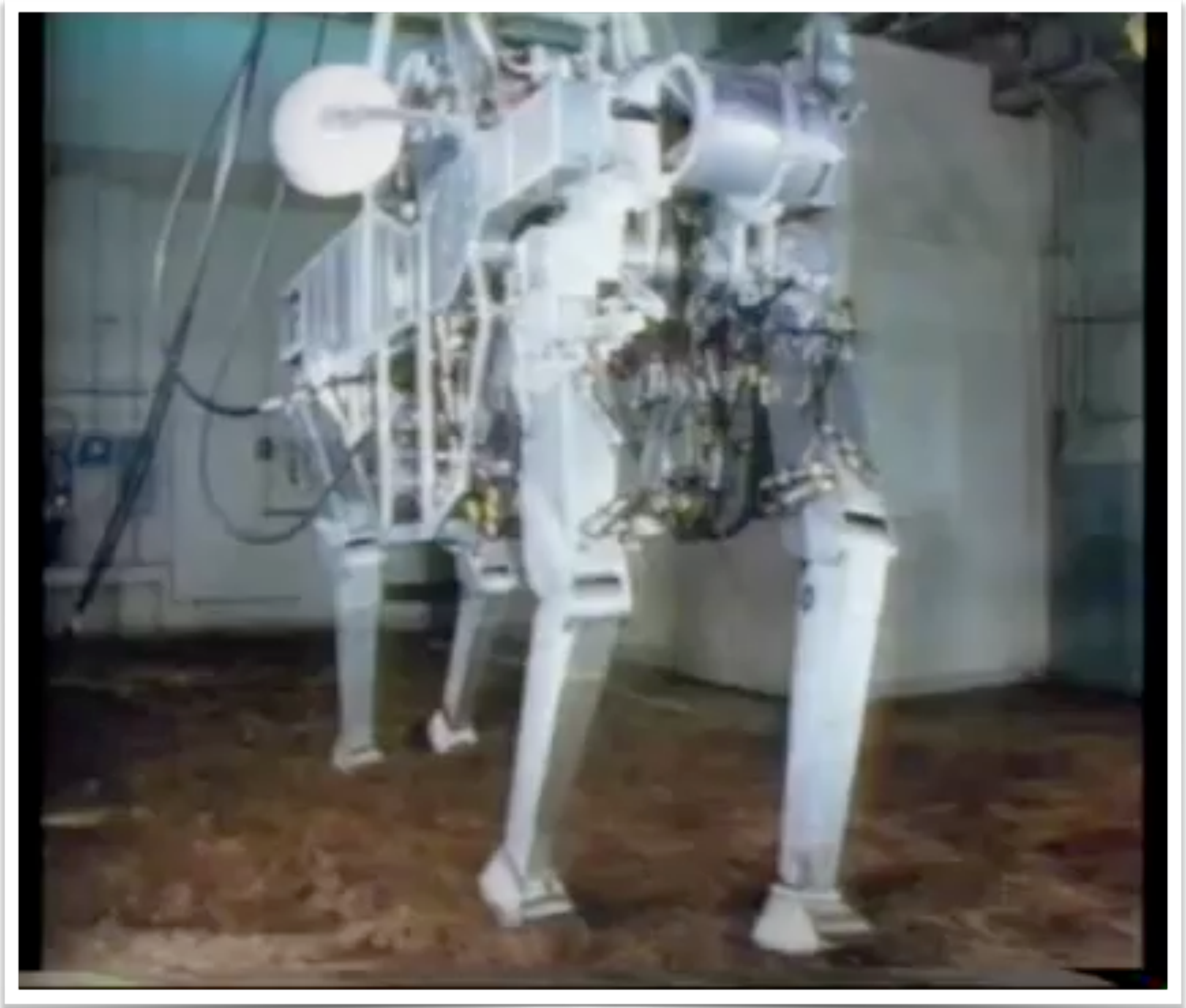
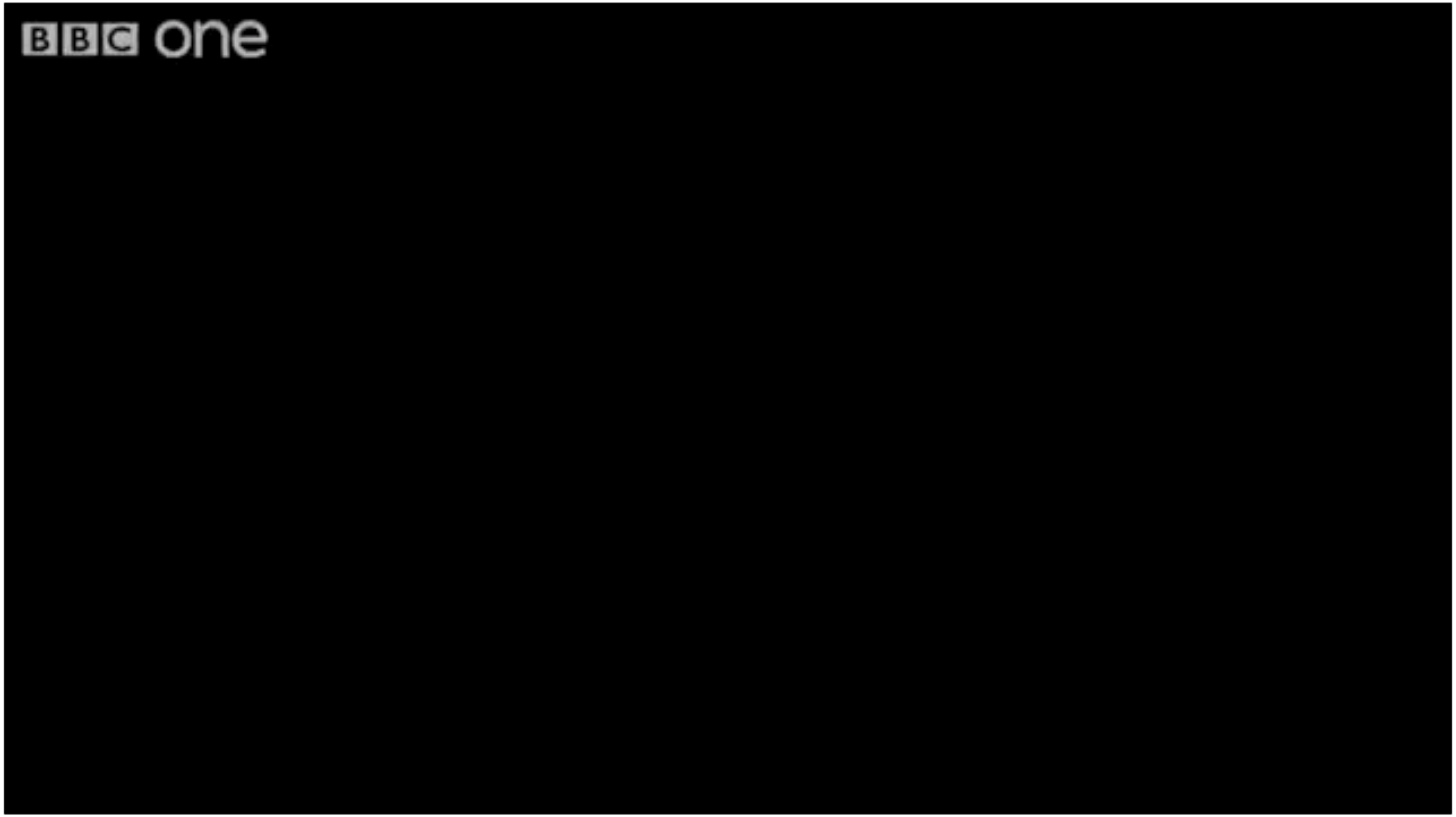


1969 — Walking truck by General Electric



1984 — The OSU Adaptive Suspension Vehicle

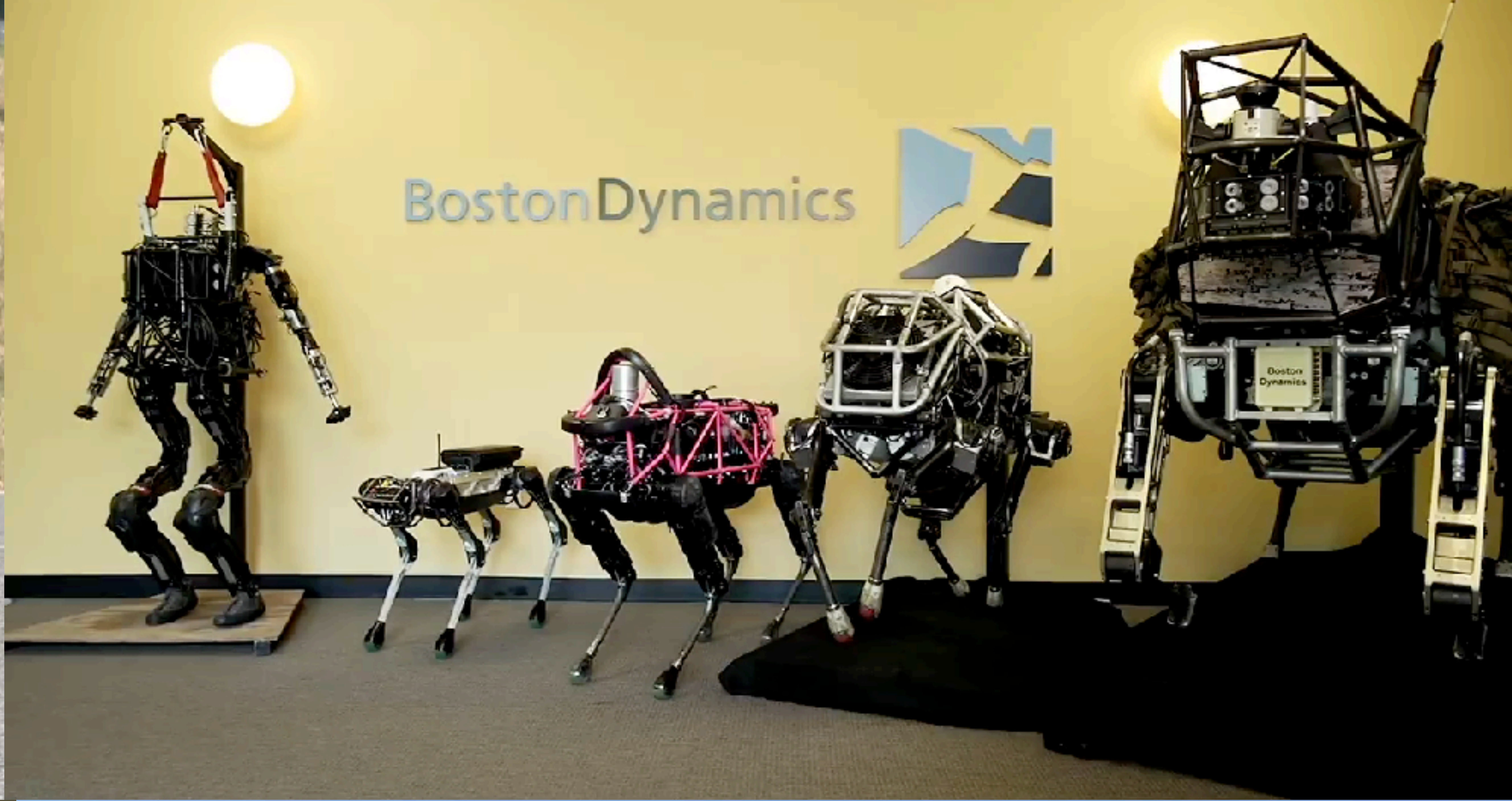
Theo Jansen's walking mechanism




Boston Dynamics
Meet Atlas, the latest humanoid robot from
Alphabet Inc.'s Boston Dynamics.
WSJ
Boston Dynamics
Boston Dynamics


Boston Dynamics


Boston Dynamics


BostonDynamics


Boston Dynamics


Boston Dynamics


BOSTON DYNAMICS — SEPTEMBER 2019

Massachusetts Institute of Technology

Autonomous Running Jumps Over Obstacles in the MIT Cheetah 2

Hae-Won Park, Patrick Wensing, and Sangbae Kim

MITMECHE

BIOMIMETIC ROBOTICS LAB


iit
ADVR


ANYmal

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Introdução

- **Base de suporte**
- CoP
- ZMP
- Capture point

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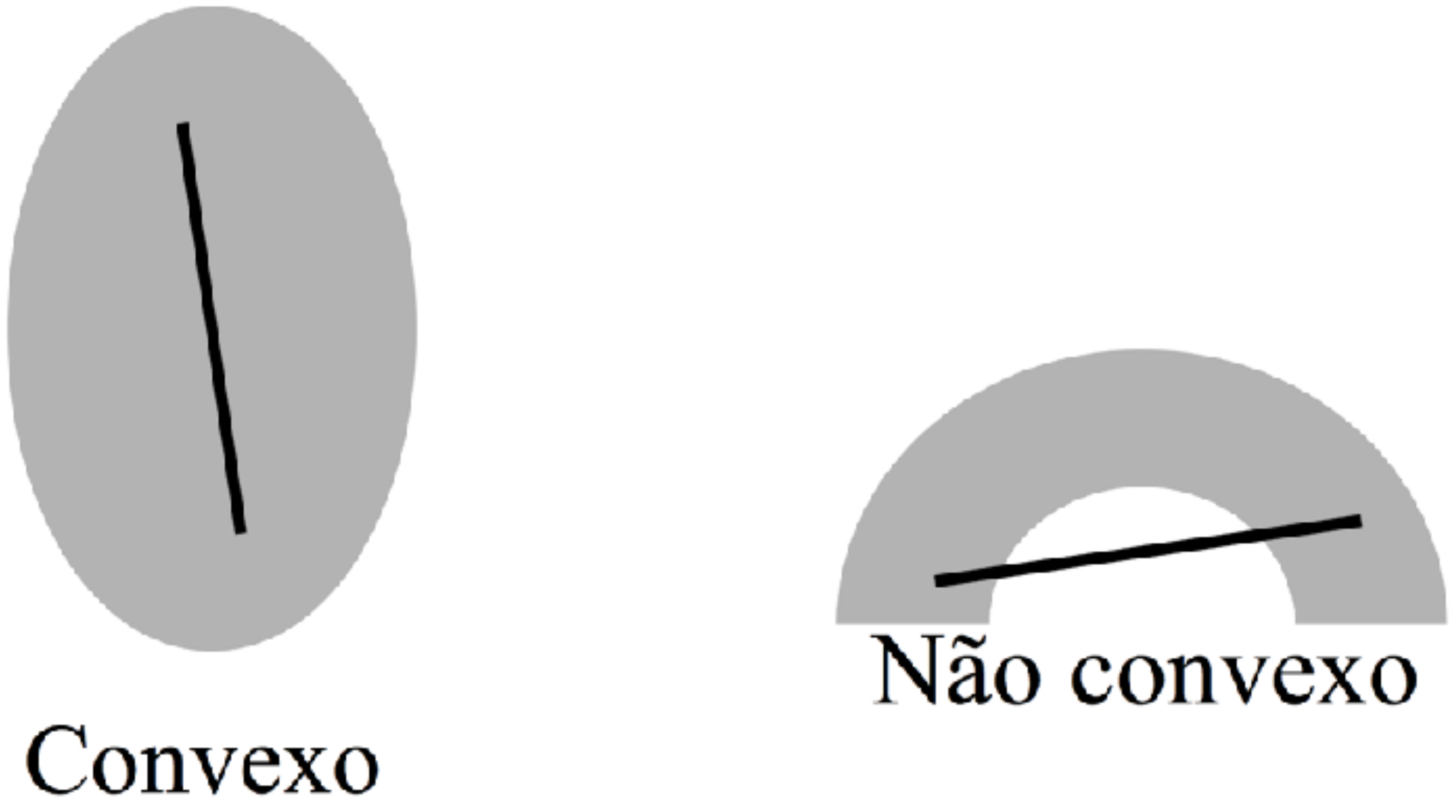
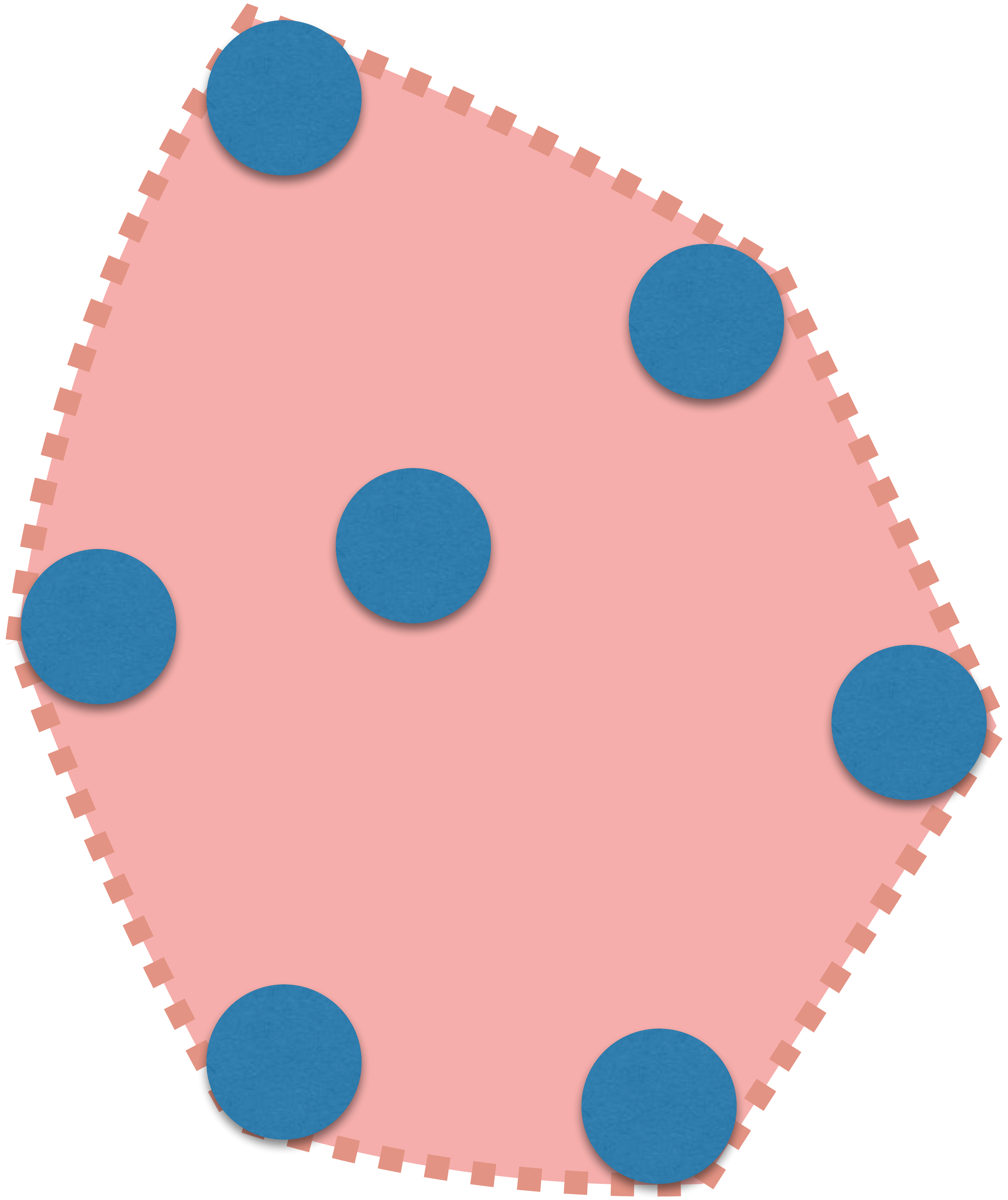
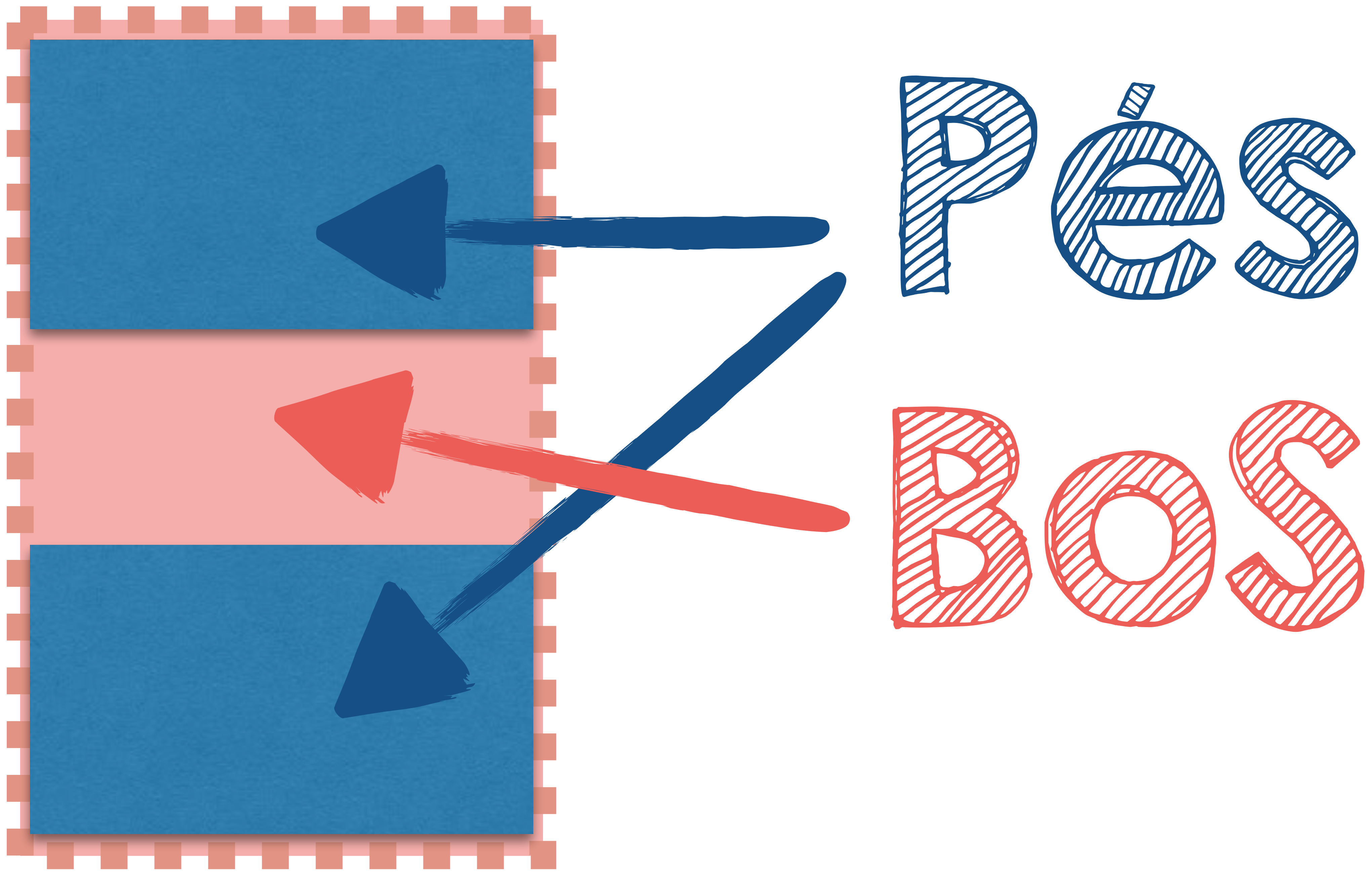
Envoltória convexa (Complex hull)



Menor polígono convexo que contém uma coleção de objetos (pontos)

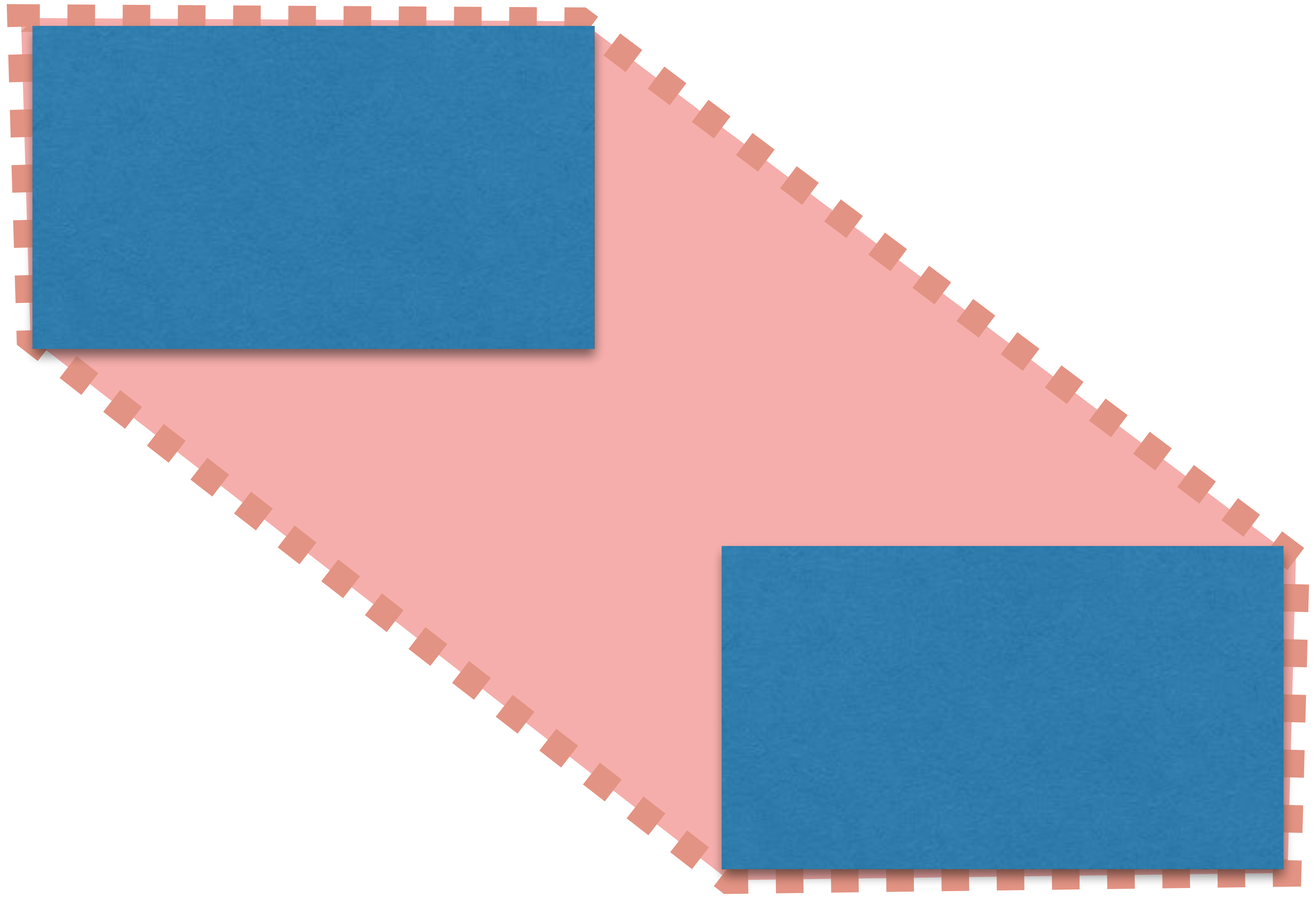


Base de suporte (BoS)



Polígono formado pela **envoltória convexa** dos **pontos de contato** com o ambiente

Base de suporte (BoS)



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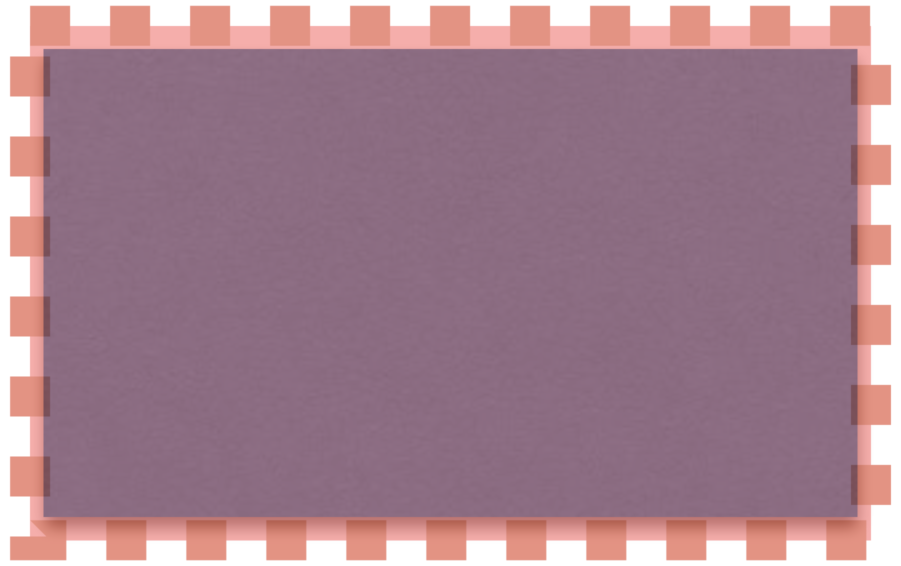
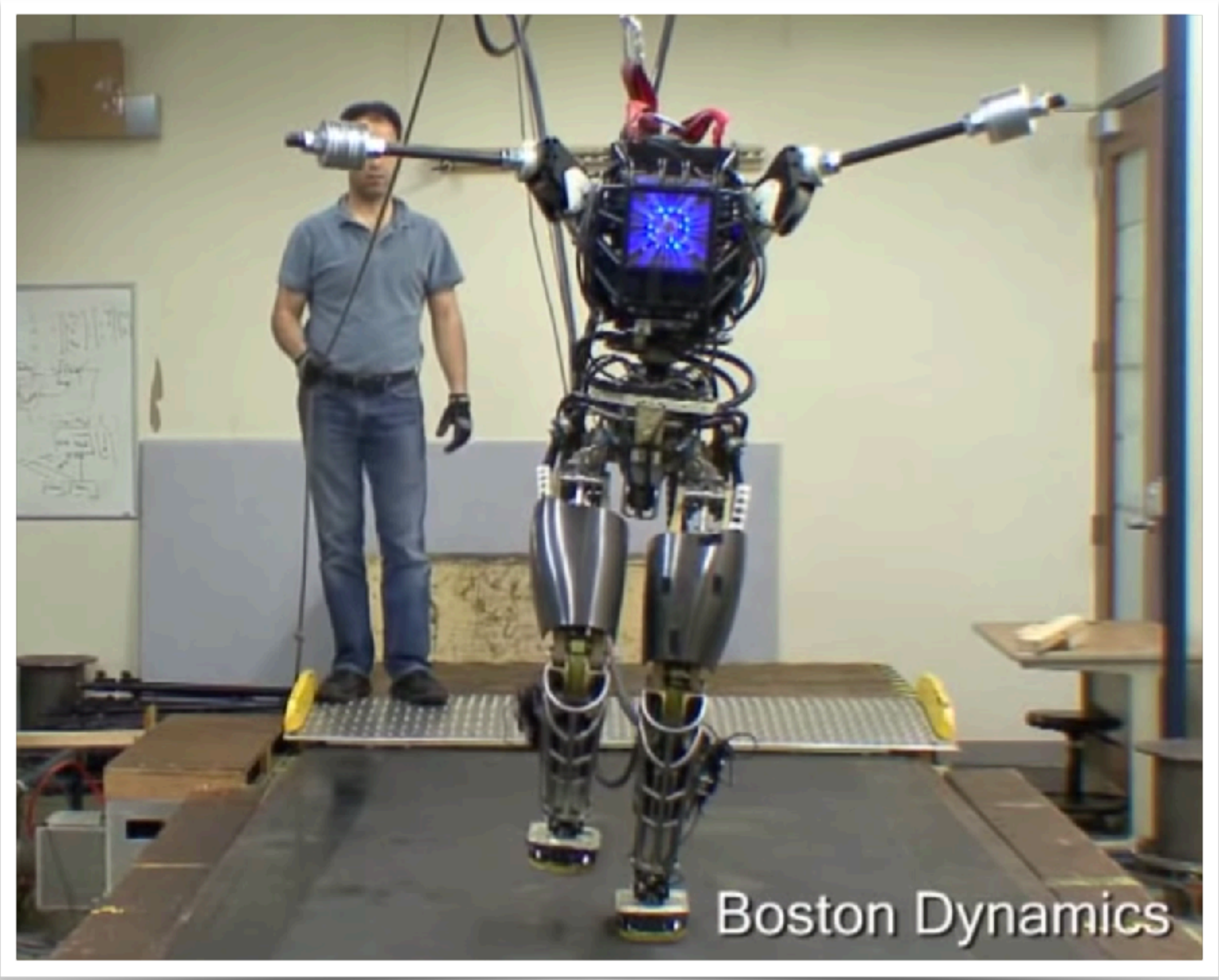
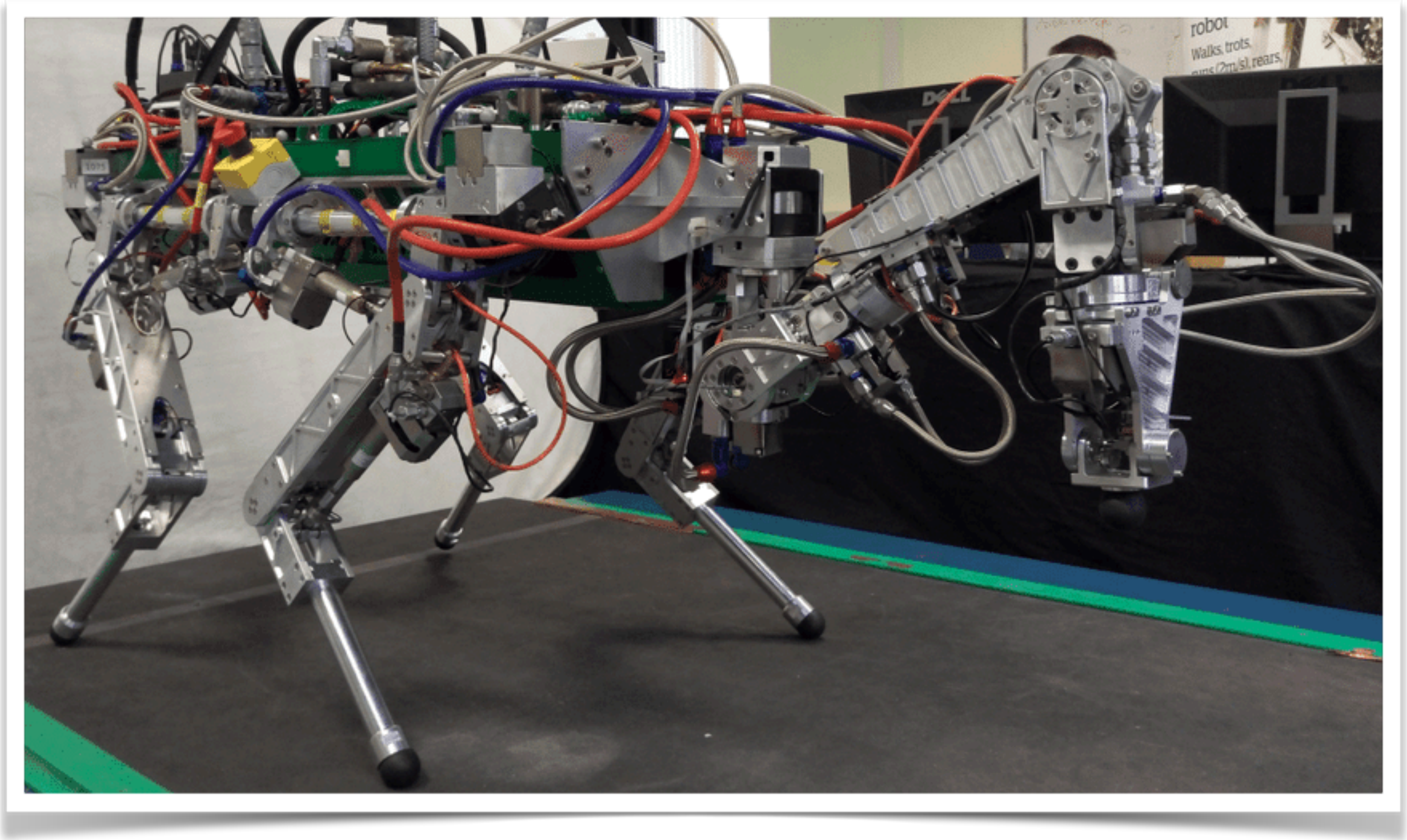
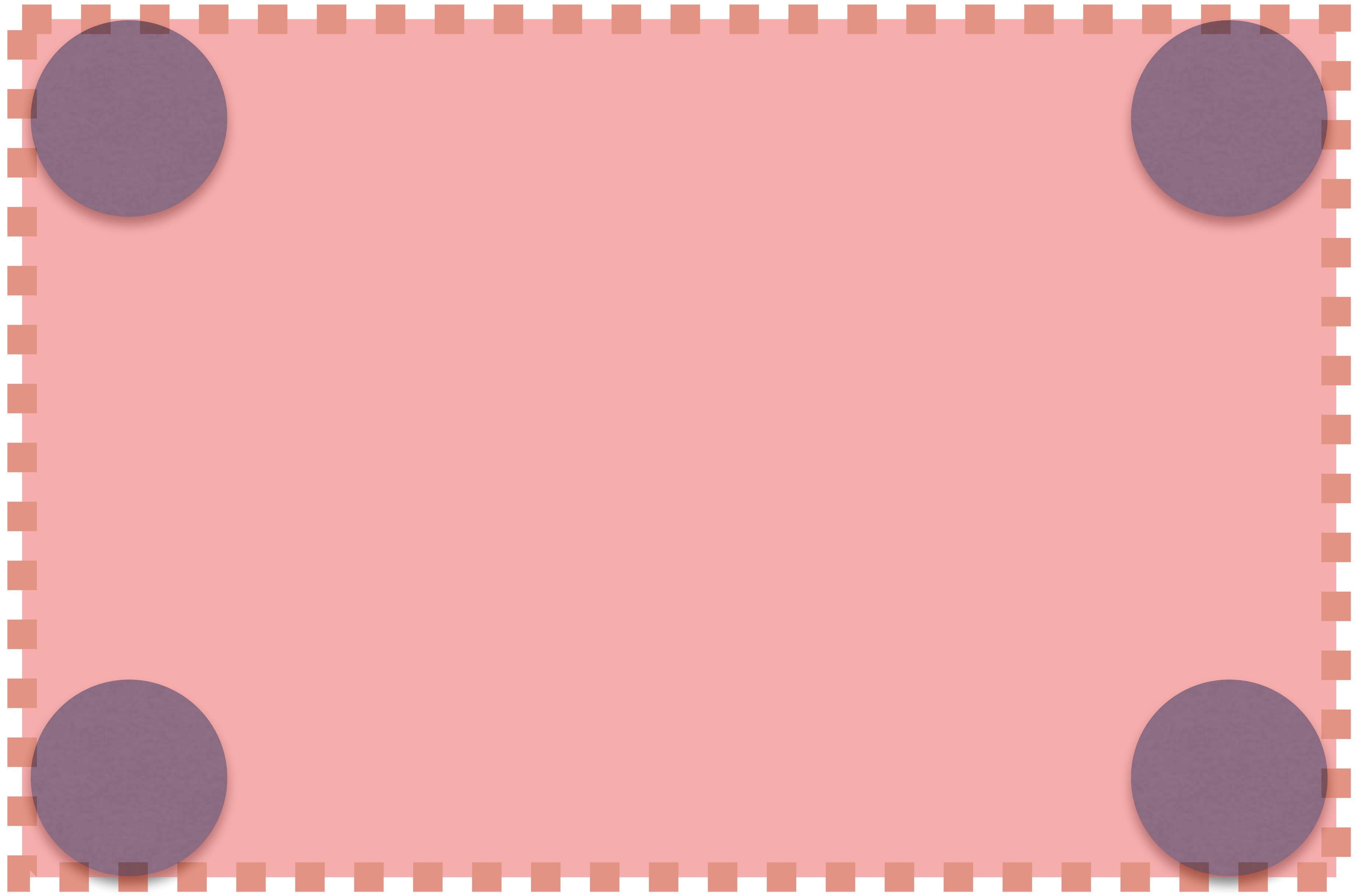


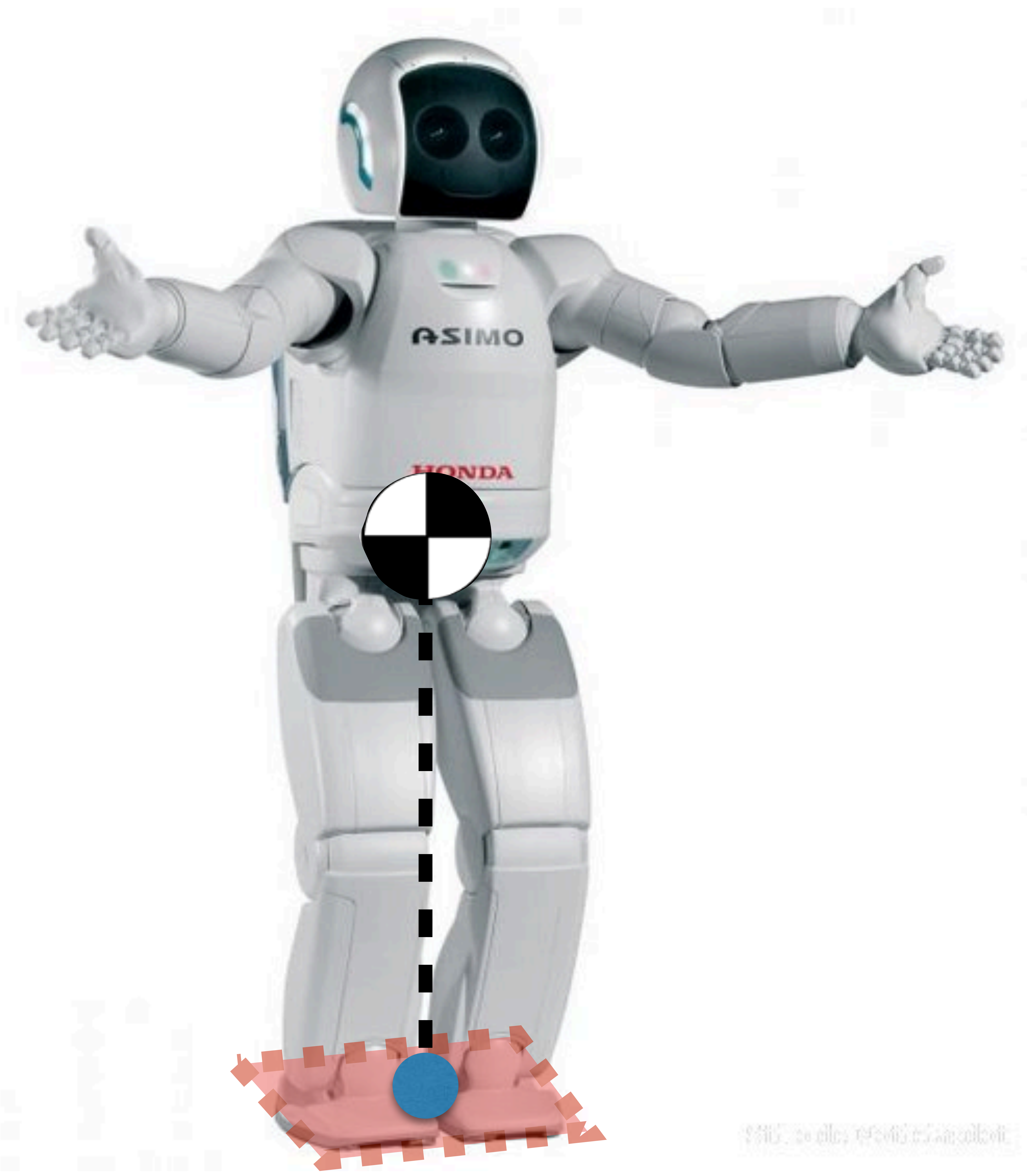


Base de suporte (BoS)

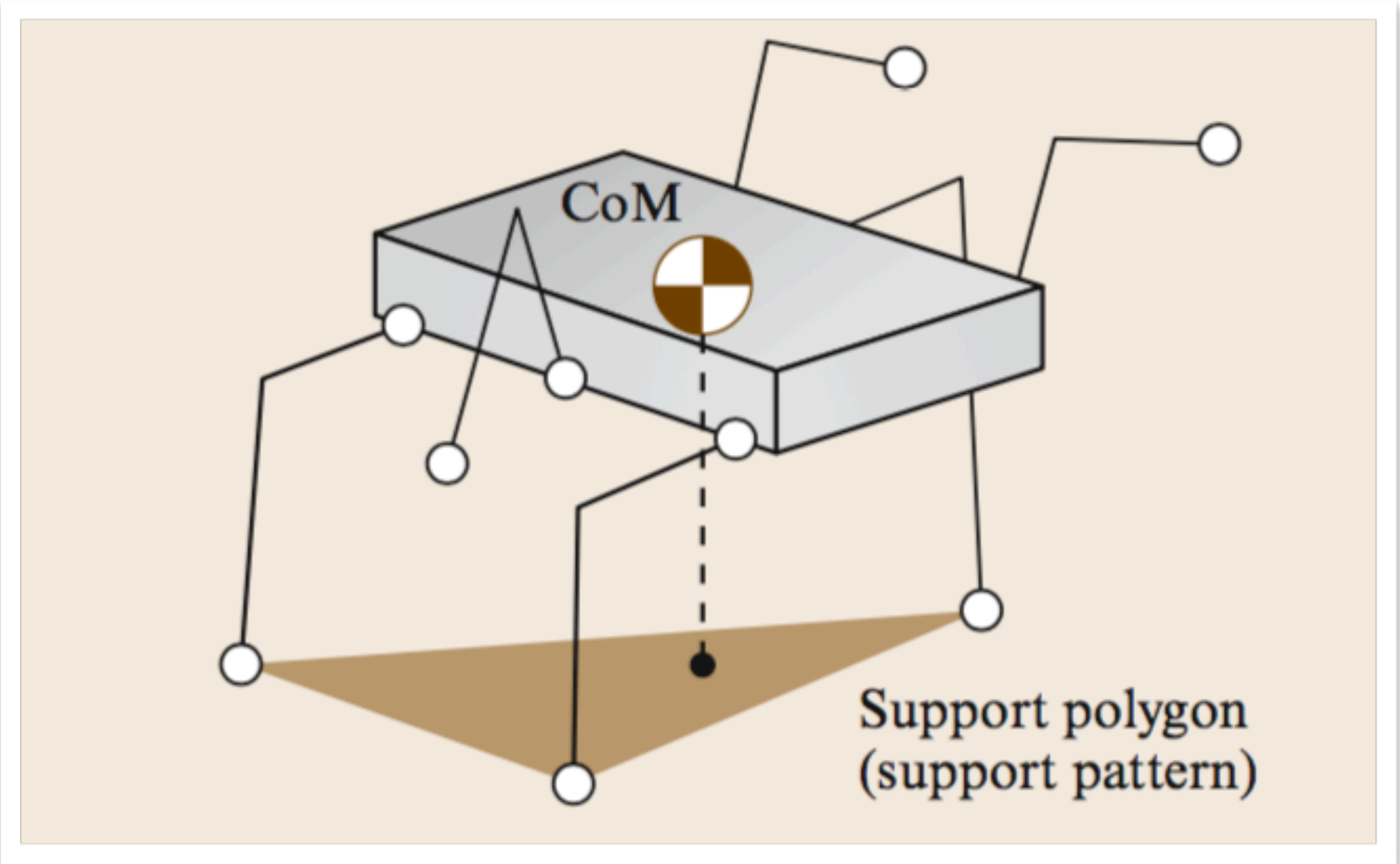


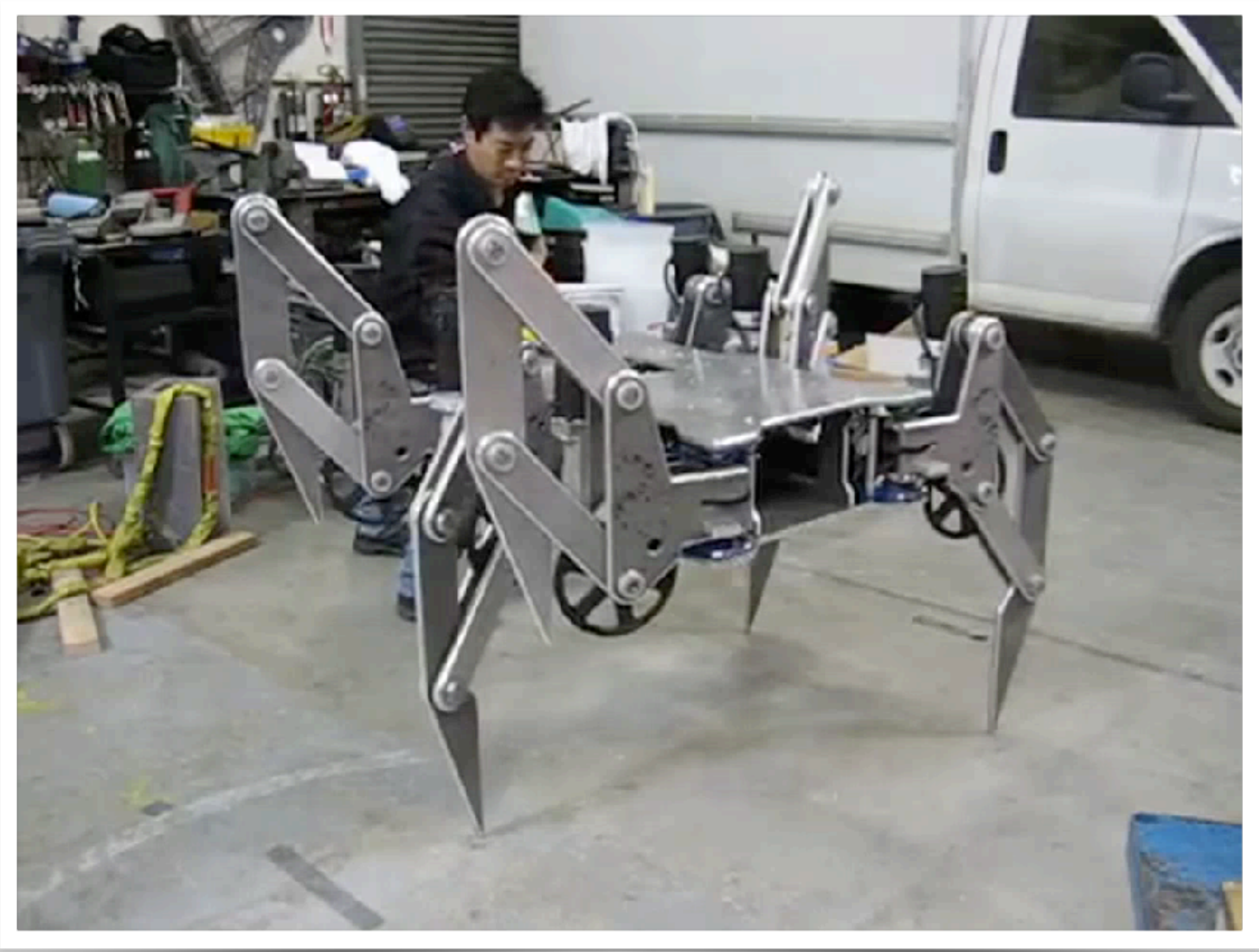


Estabilidade estática



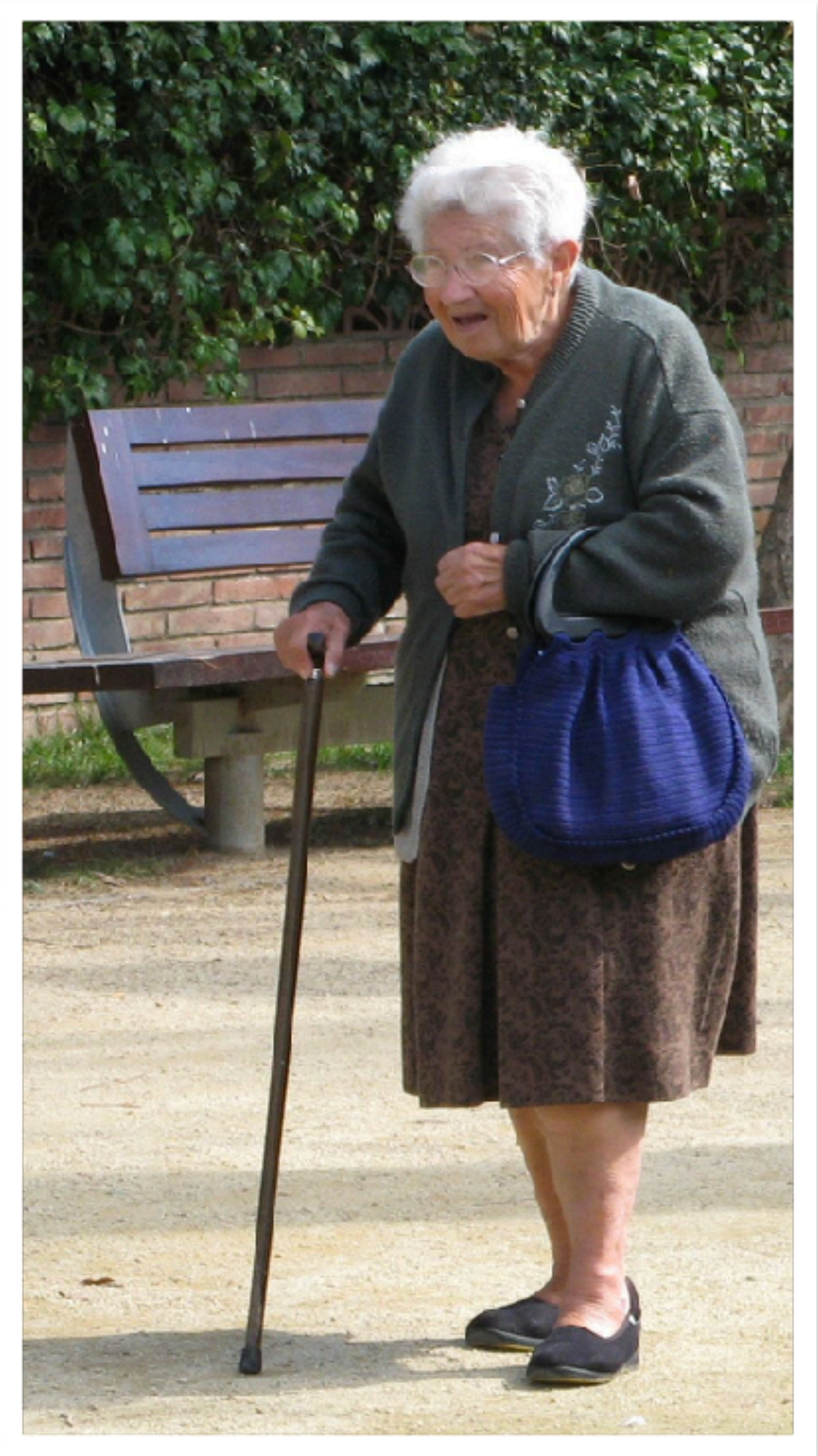
Estabilidade estática





Estabilidade estática

Estabilidade estática

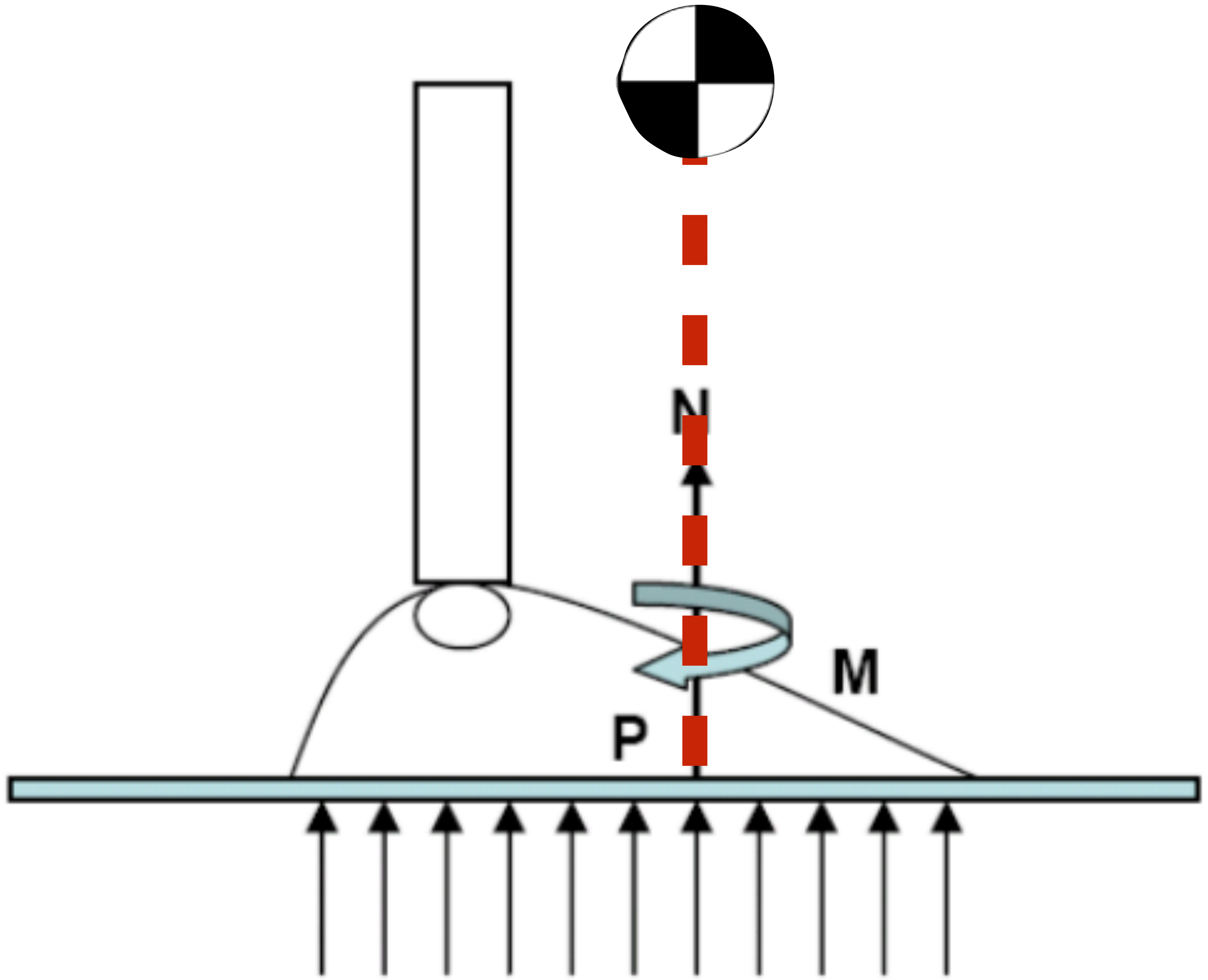


Estabilidade estática

Conteúdo

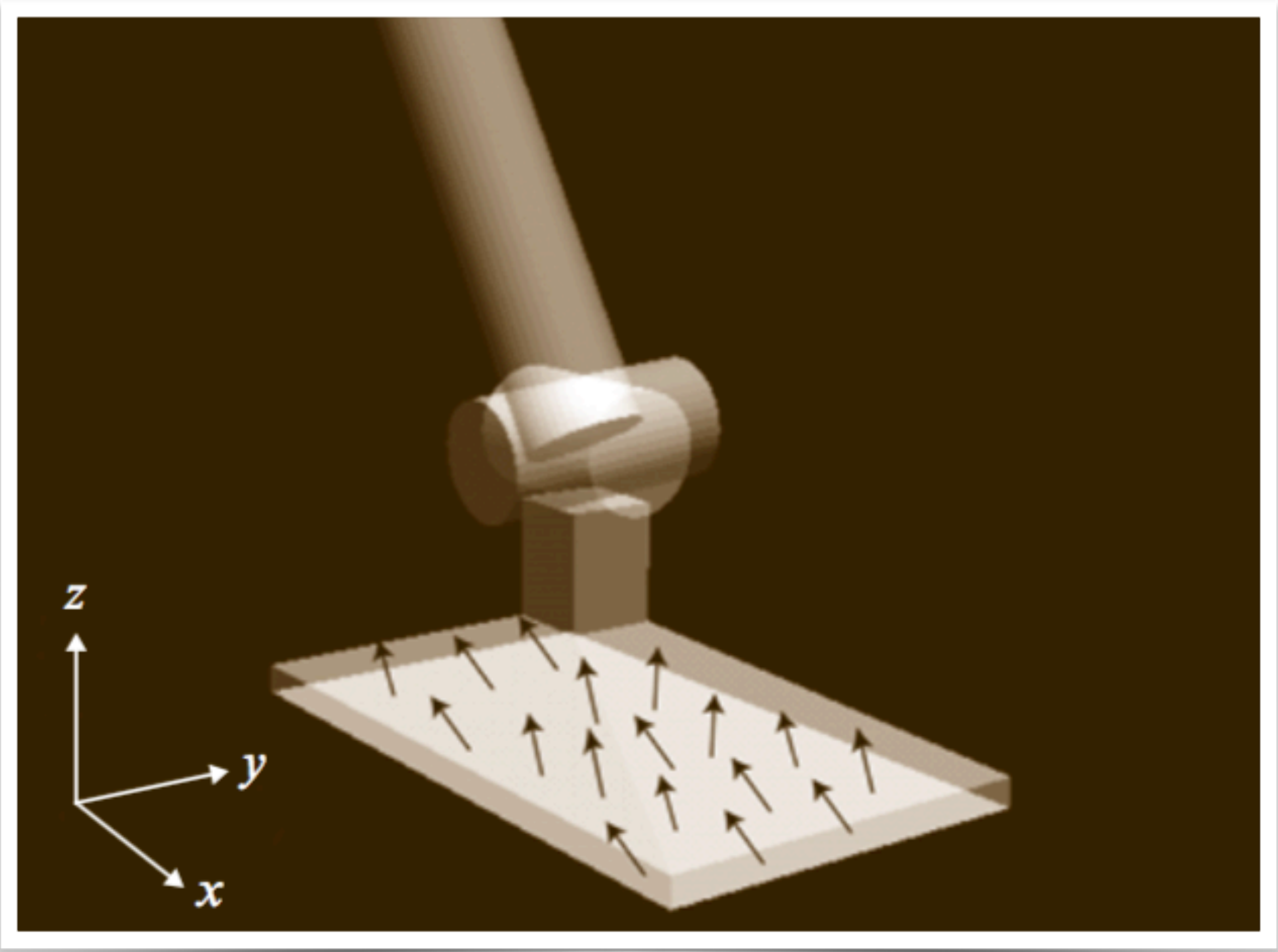
Centro de Pressão (CoP)

Introdução
Princípios básicos
Conclusão



Ponto por onde passa a **força resultante** das forças de interação

Centro de Pressão (CoP)



N Pontos de contato:

$$\boldsymbol{p}_i (i = 1, \ldots, N)$$

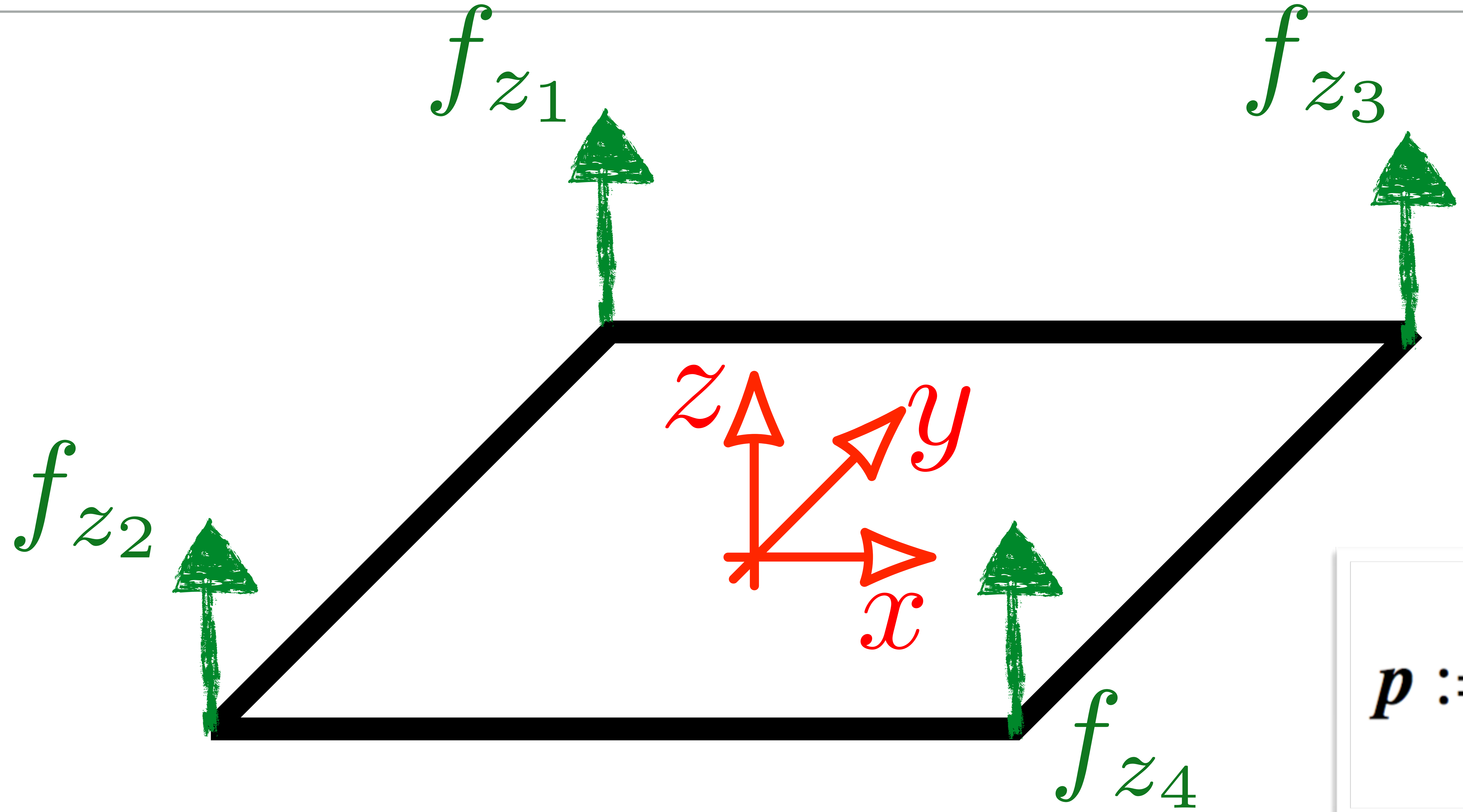
Forças de reação

$$\boldsymbol{f}_i := [f_{ix}\, f_{iy}\, f_{iz}]^\top$$

CoP:

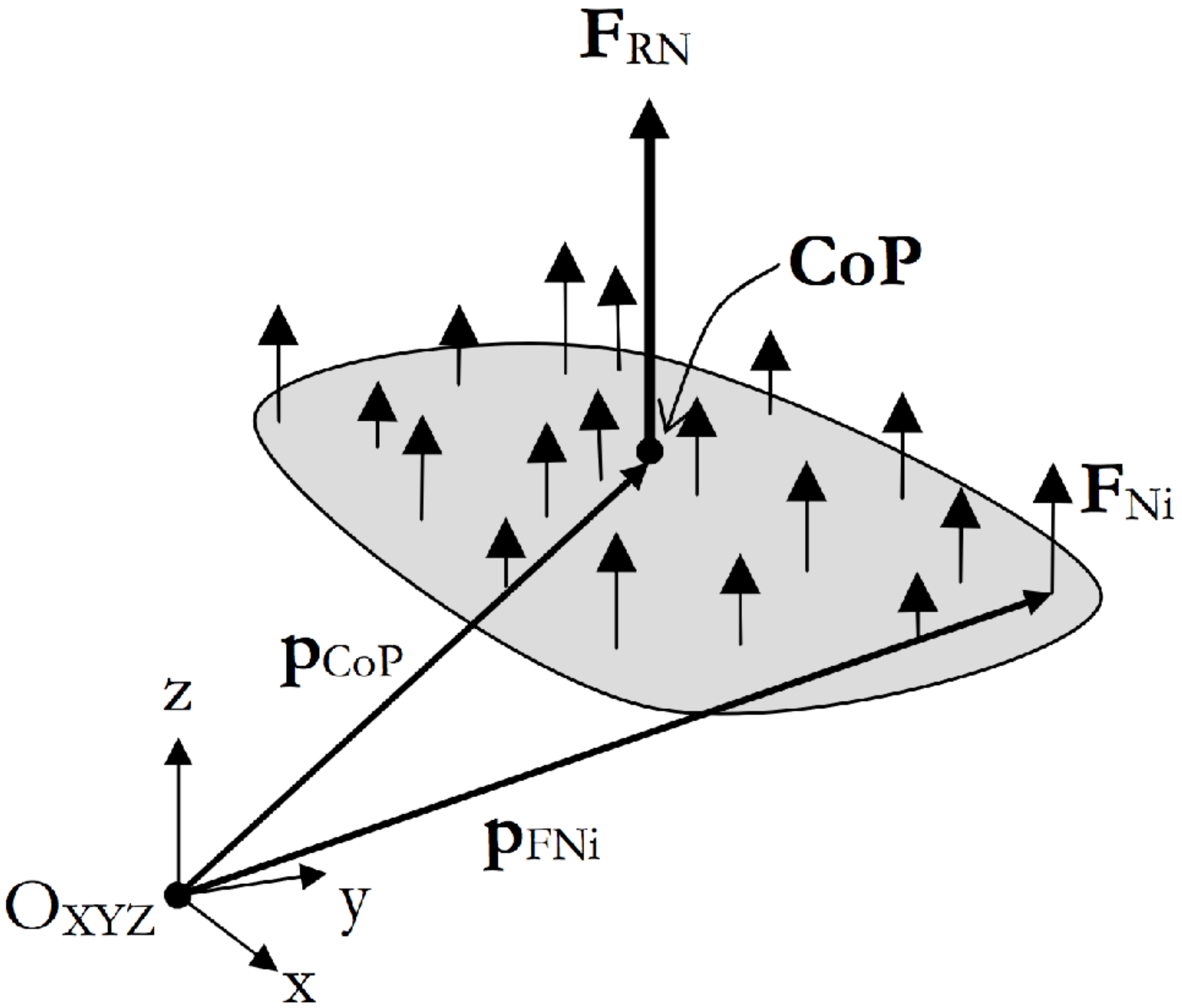
$$\boldsymbol{p} := \frac{\sum_{i=1}^{N} \boldsymbol{p}_i f_{iz}}{\sum_{i=1}^{N} f_{iz}}$$

Centro de Pressão (CoP)

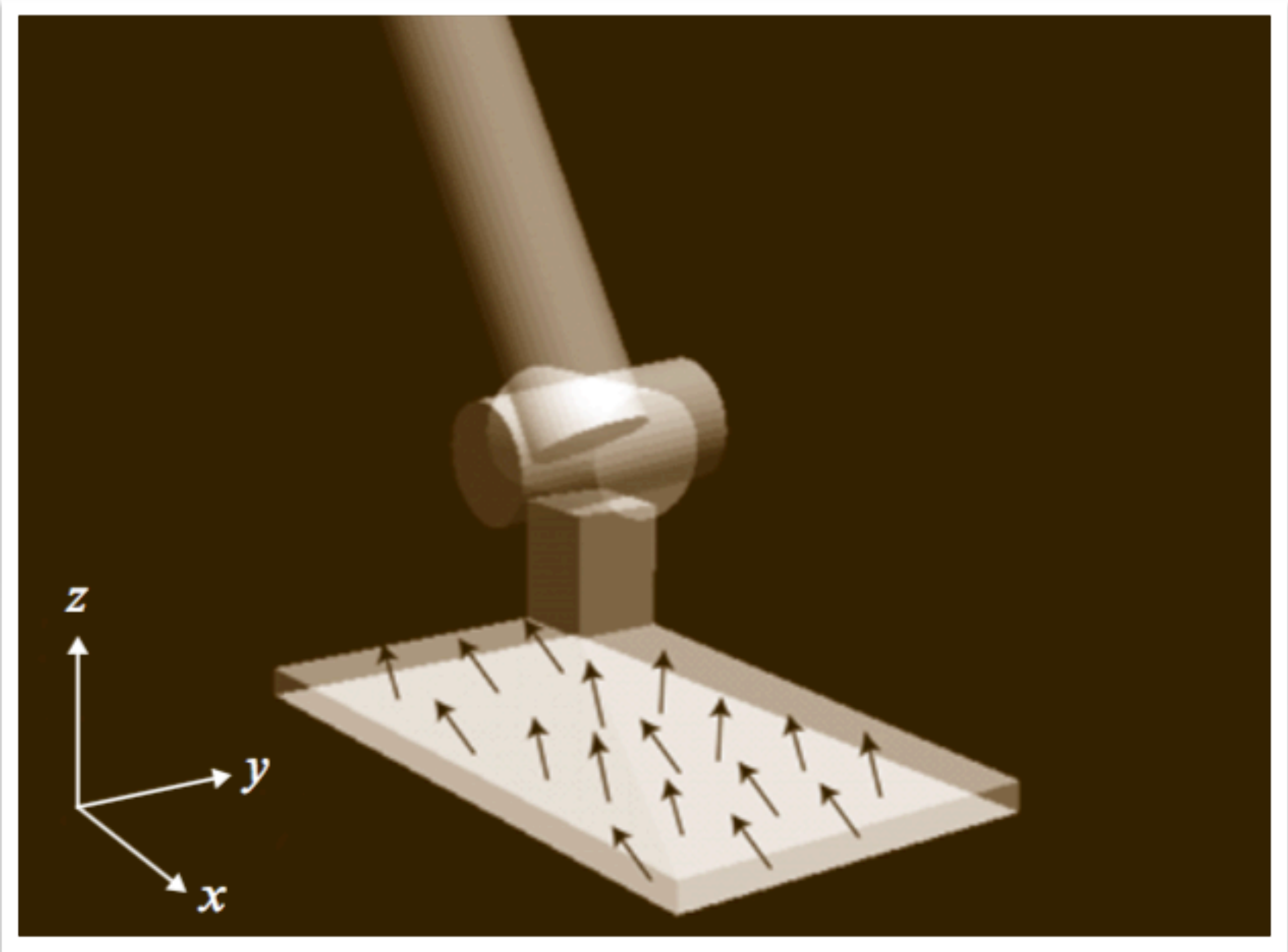


$$\boldsymbol{p} := \frac{\sum_{i=1}^{N} \boldsymbol{p}_i f_{iz}}{\sum_{i=1}^{N} f_{iz}}$$

Centro de Pressão (CoP)



Centro de Pressão (CoP)



Também pode ser definido por:

$$\boldsymbol{p} = \sum_{i=1}^{N} \alpha_i \boldsymbol{p}_i \, ,$$

$$\alpha_i := f_{iz} / f_z \, ,$$

$$f_z := \sum_{i=1}^{N} f_{iz} \, .$$

CoP: Center of Pressure

Robô pode somente empurrar contra o chão:

$$f_{iz} \geq 0 \qquad (i = 1, \ldots, N)$$

Então:

$$\begin{cases} \alpha_i \geq 0 & (i = 1, \ldots, N) \\ \sum_{i=1}^{N} \alpha_i = 1 \,. \end{cases}$$

Logo...

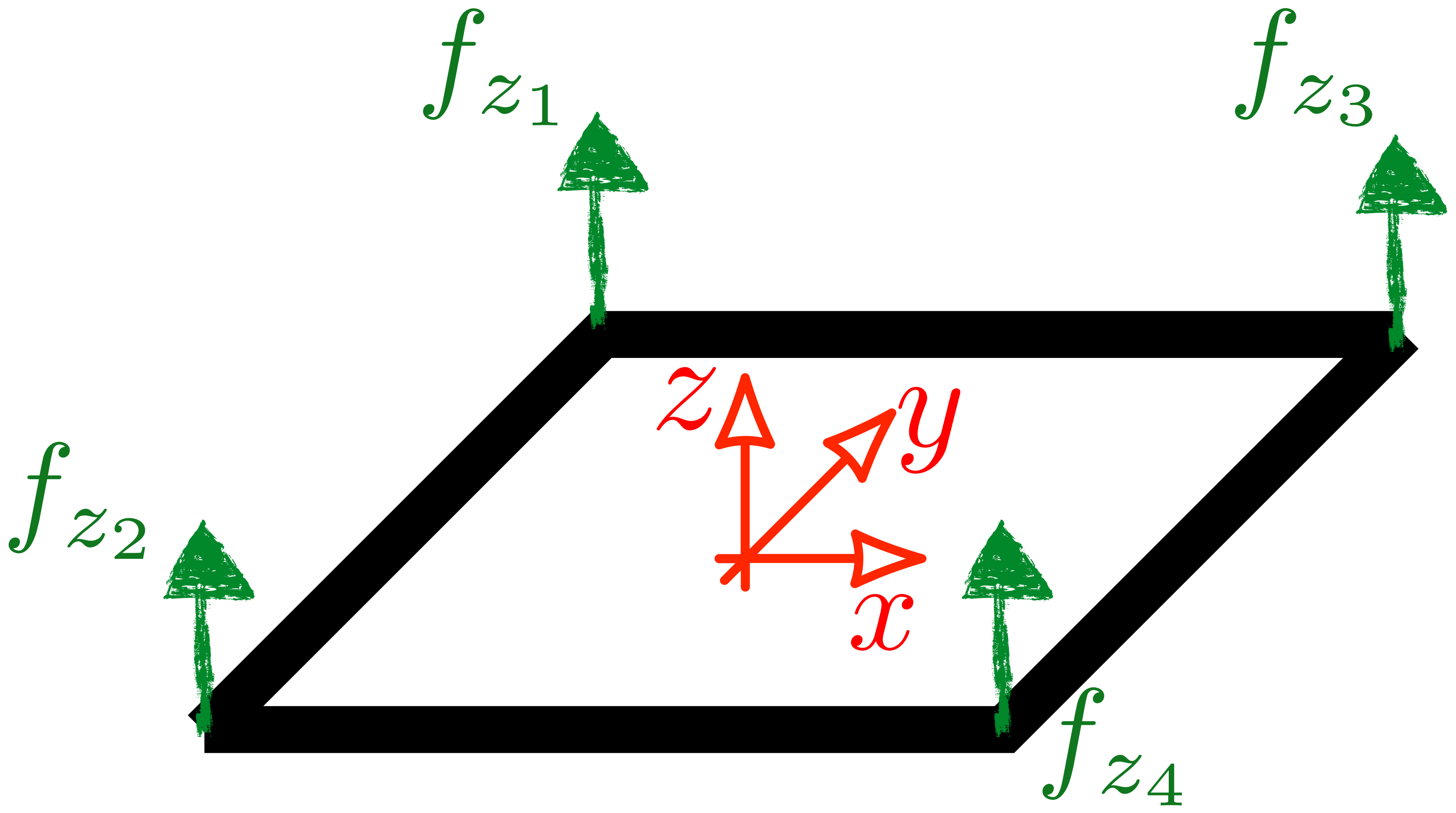
O CoP nunca deixa o polígono de suporte!

$$\boldsymbol{p} = \sum_{i=1}^{N} \alpha_i \boldsymbol{p}_i \,,$$

$$\alpha_i := f_{iz} / f_z \,,$$

$$f_z := \sum_{i=1}^{N} f_{iz} \,.$$

Torques no CoP



Superfície horizontal:

$$p_{iz} = p_z$$

$$\boldsymbol{p} := \frac{\sum_{i=1}^{N} \boldsymbol{p}_i f_{iz}}{\sum_{i=1}^{N} f_{iz}}$$

$$\tau_x = \tau_y = 0$$

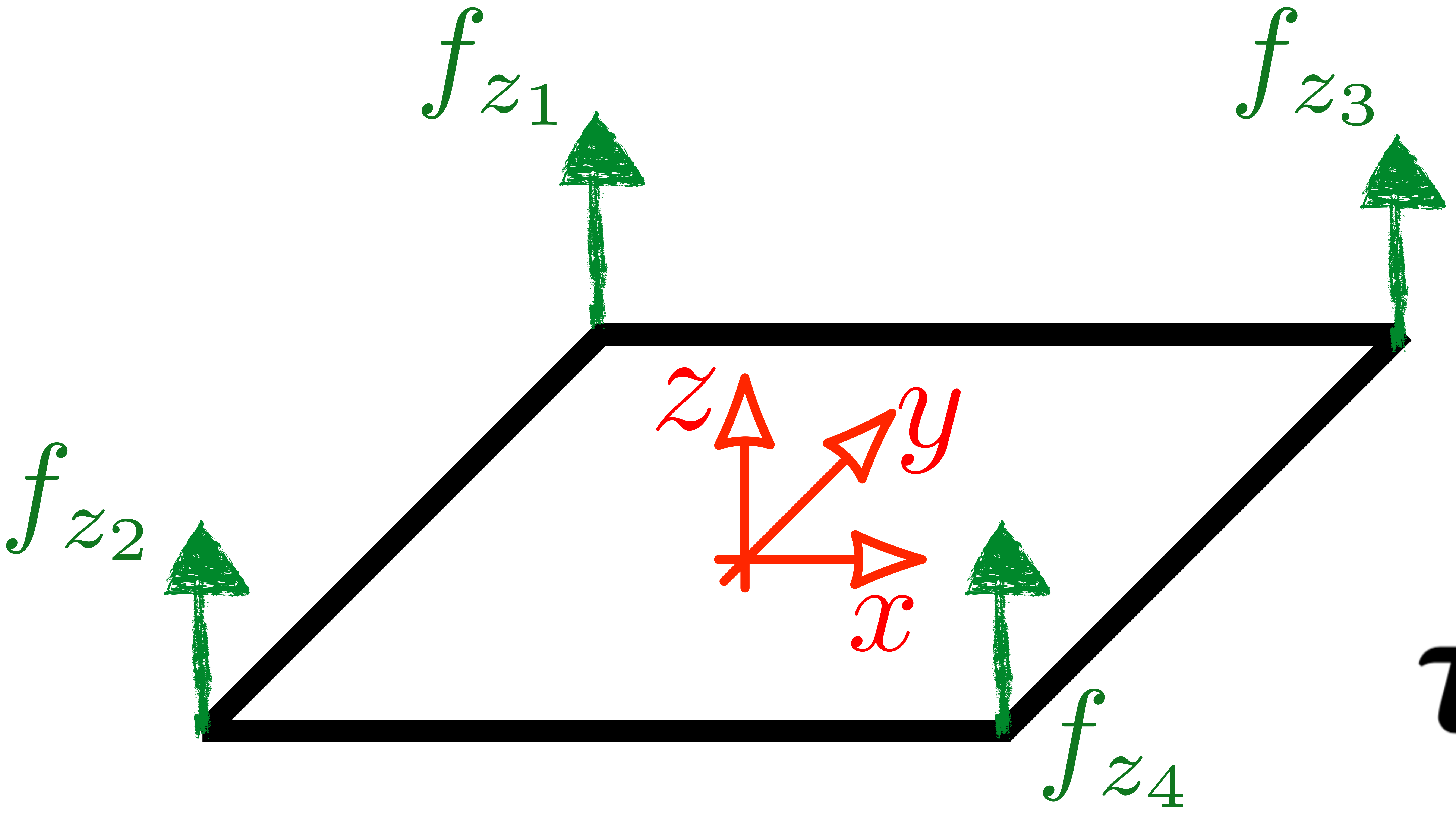
$$\boldsymbol{\tau} = \sum_{i=1}^{N} (\boldsymbol{p}_i - \boldsymbol{p}) \times \boldsymbol{f}_i$$

$$\tau_x = \sum_{i=1}^{N} (p_{iy} - p_y) f_{iz} - \sum_{i=1}^{N} (p_{iz} - p_z) f_{iy}$$

$$\tau_y = \sum_{i=1}^{N} (p_{iz} - p_z) f_{ix} - \sum_{i=1}^{N} (p_{ix} - p_x) f_{iz}$$

$$\tau_z = \sum_{i=1}^{N} (p_{ix} - p_x) f_{iy} - \sum_{i=1}^{N} (p_{iy} - p_y) f_{ix}$$

Torques no CoP



$$\boldsymbol{\tau}_z \neq 0$$

equivalente ao CoP, mas nem sempre

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- Base de suporte
- CoP
- **ZMP**
- Capture point

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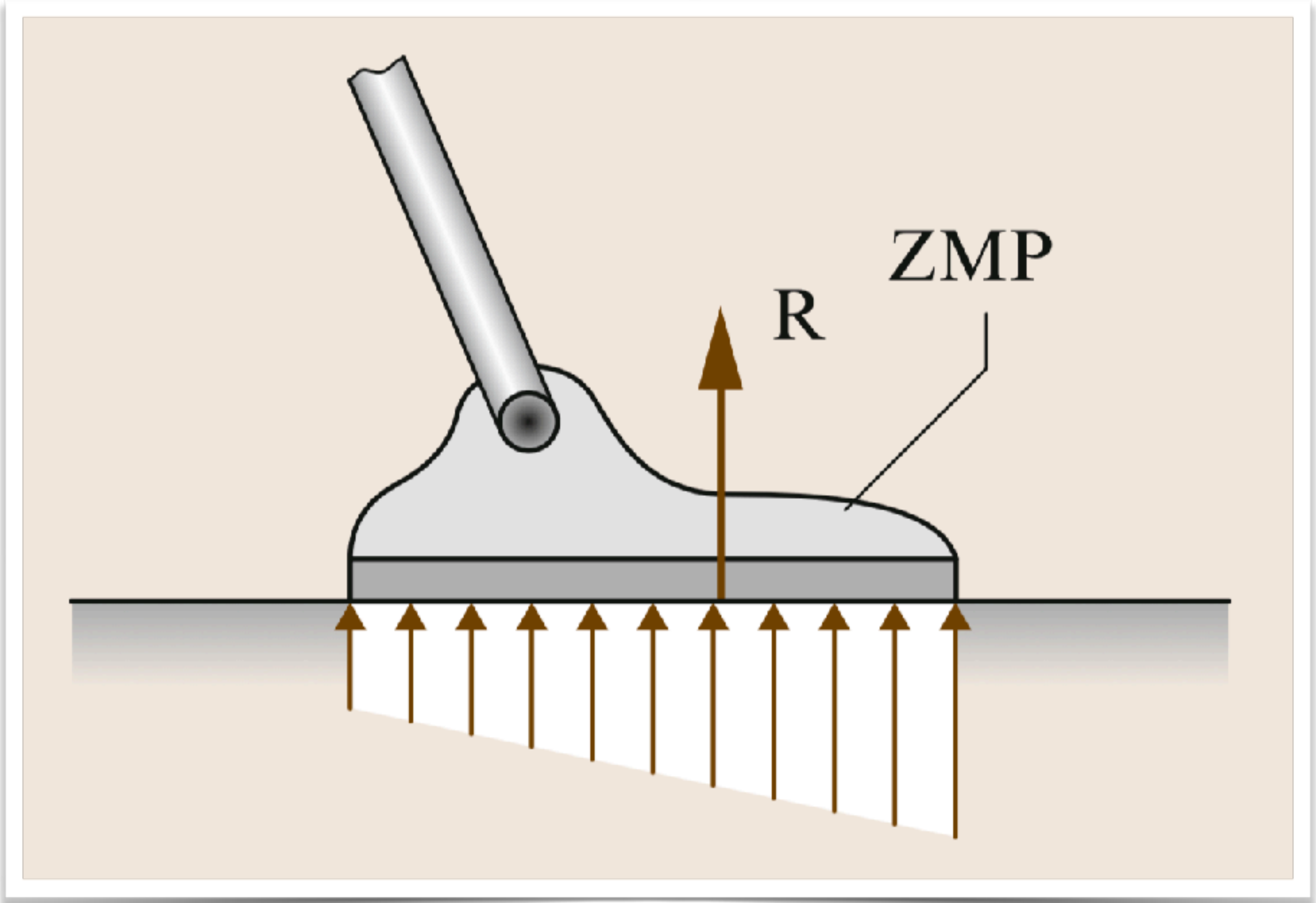
ZMP: Zero moment point

(praticamente) **Equivalente ao CoP**



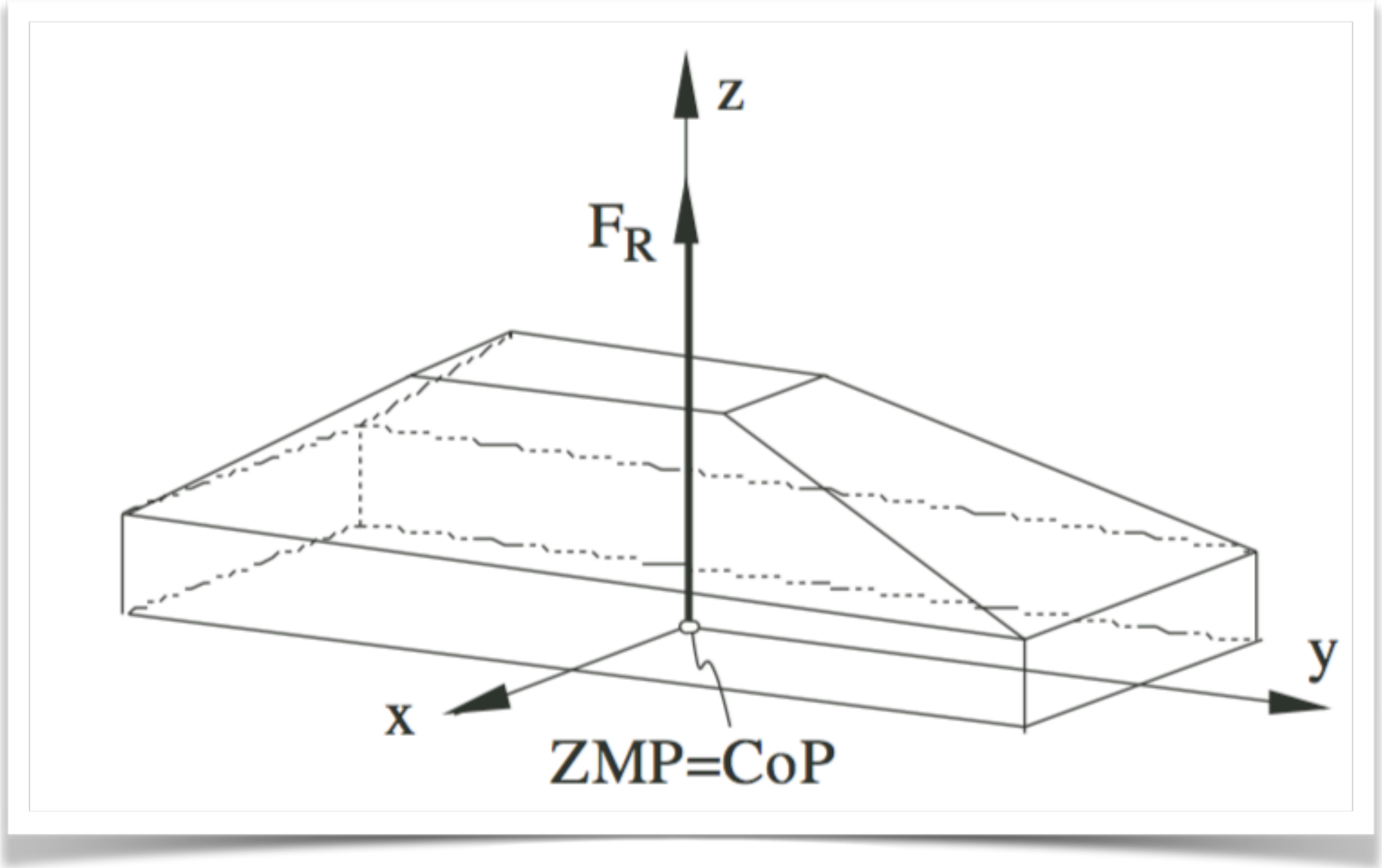
Nomenclatura não é muito precisa:

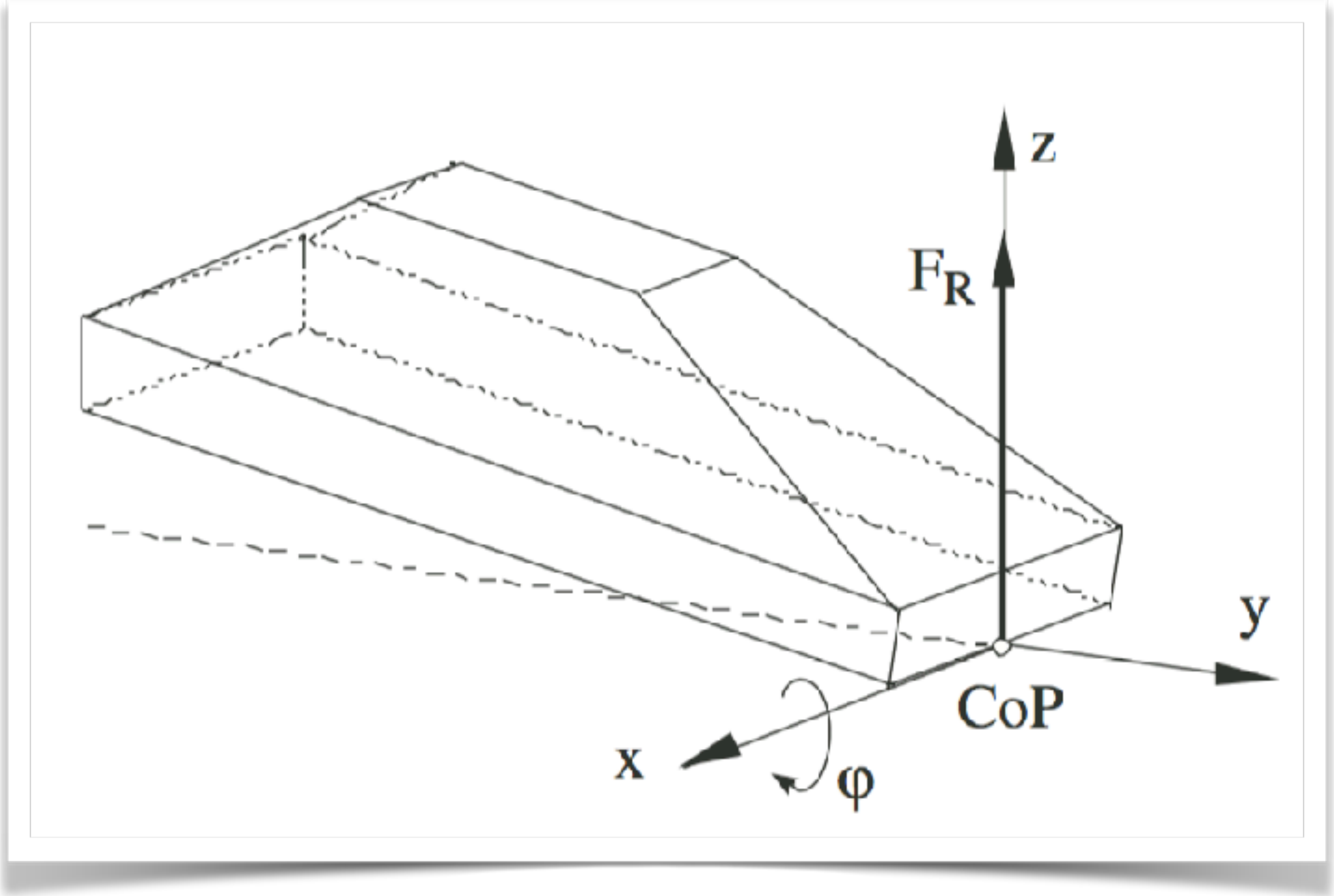
$$\tau_x = \tau_y = 0$$

$$\tau_z \neq 0$$

ZMP: Zero moment point

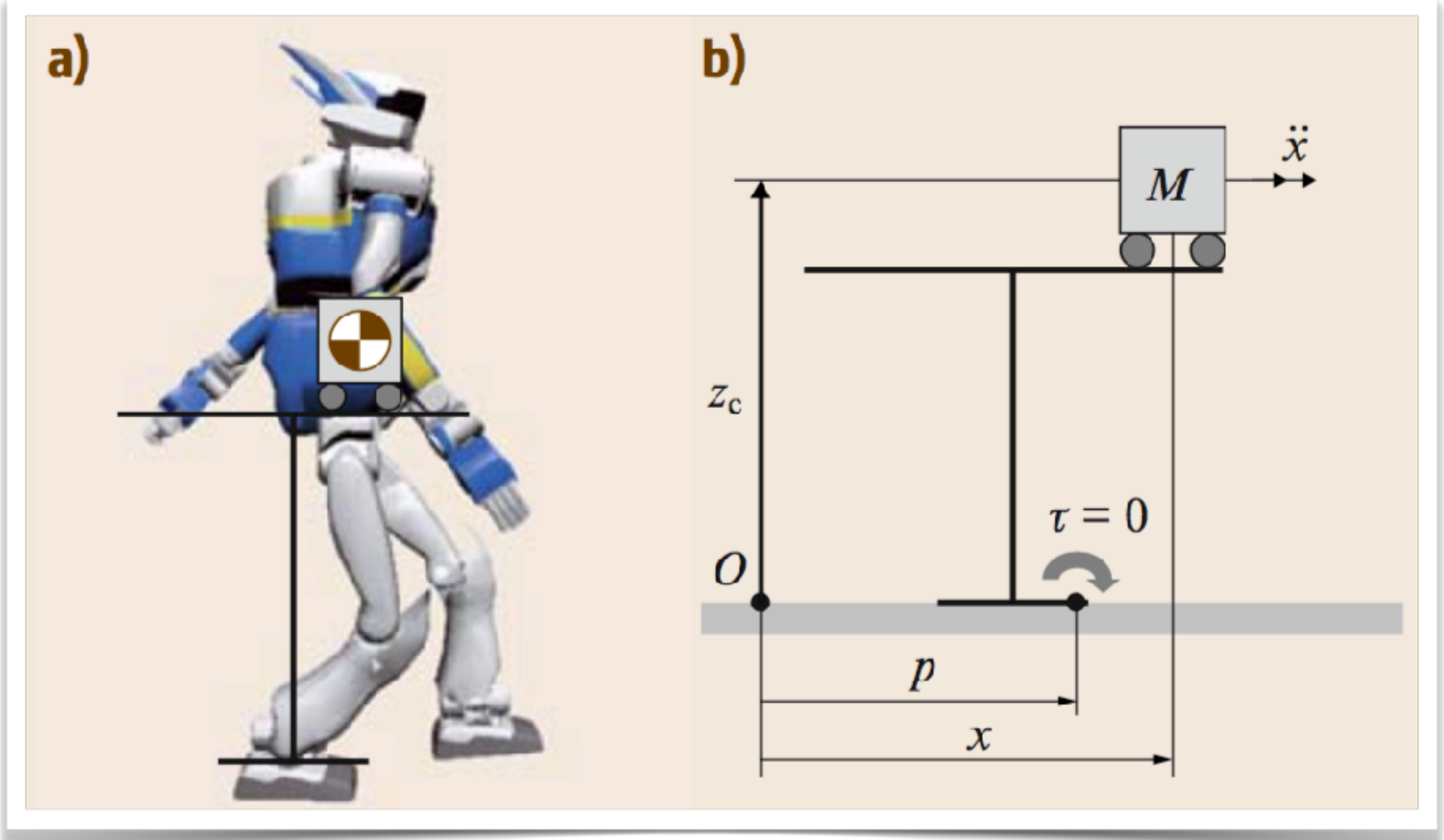
(praticamente) **Equivalente ao CoP**





Computed ZMP

Leva em consideração o **movimento** do robô



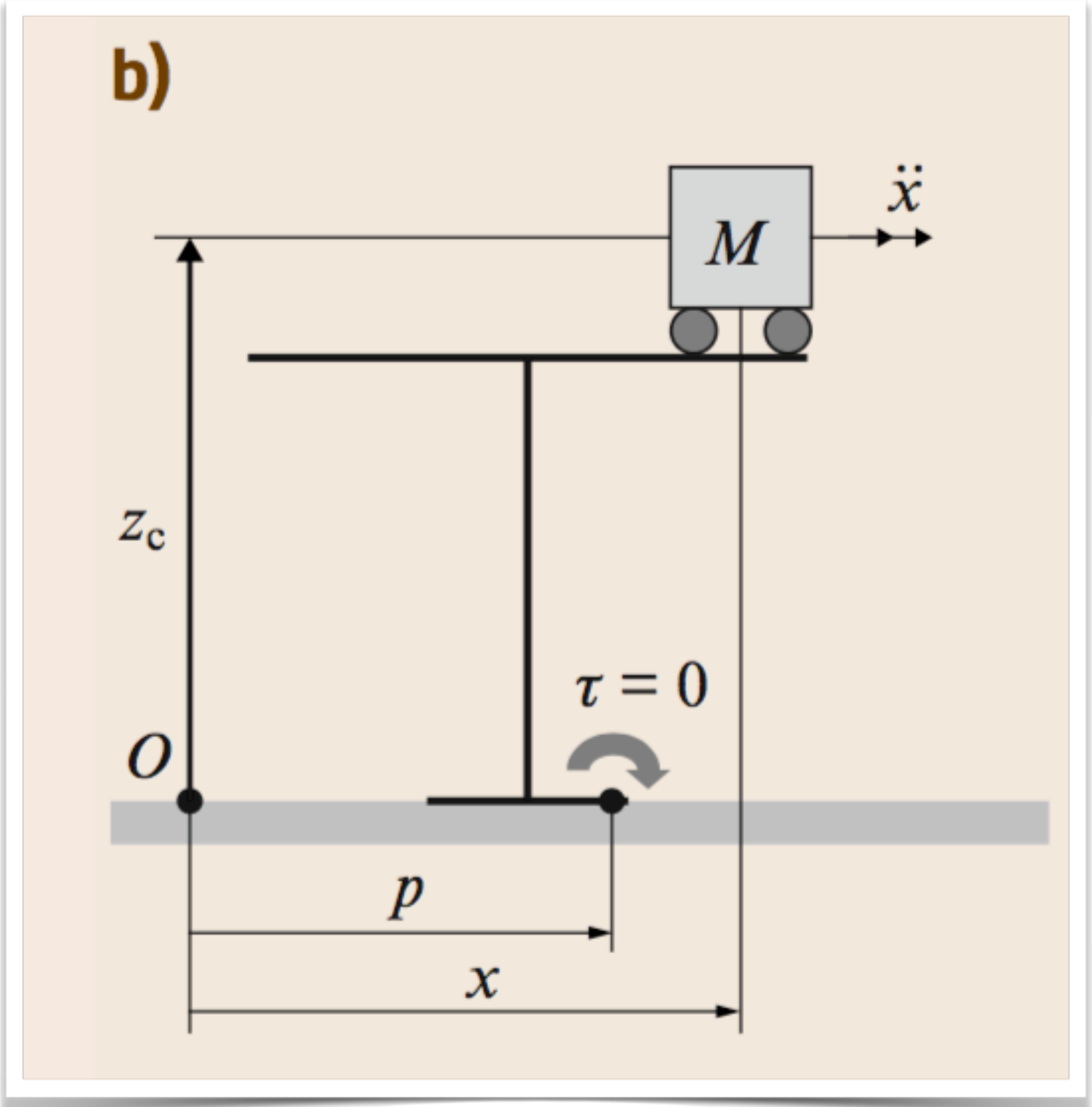
Computed ZMP

$$\tau = -Mg(x - p) + M\ddot{x}z_c$$

ZMP: $\tau = 0$

$$p = x - \frac{z_c}{g}\ddot{x}$$

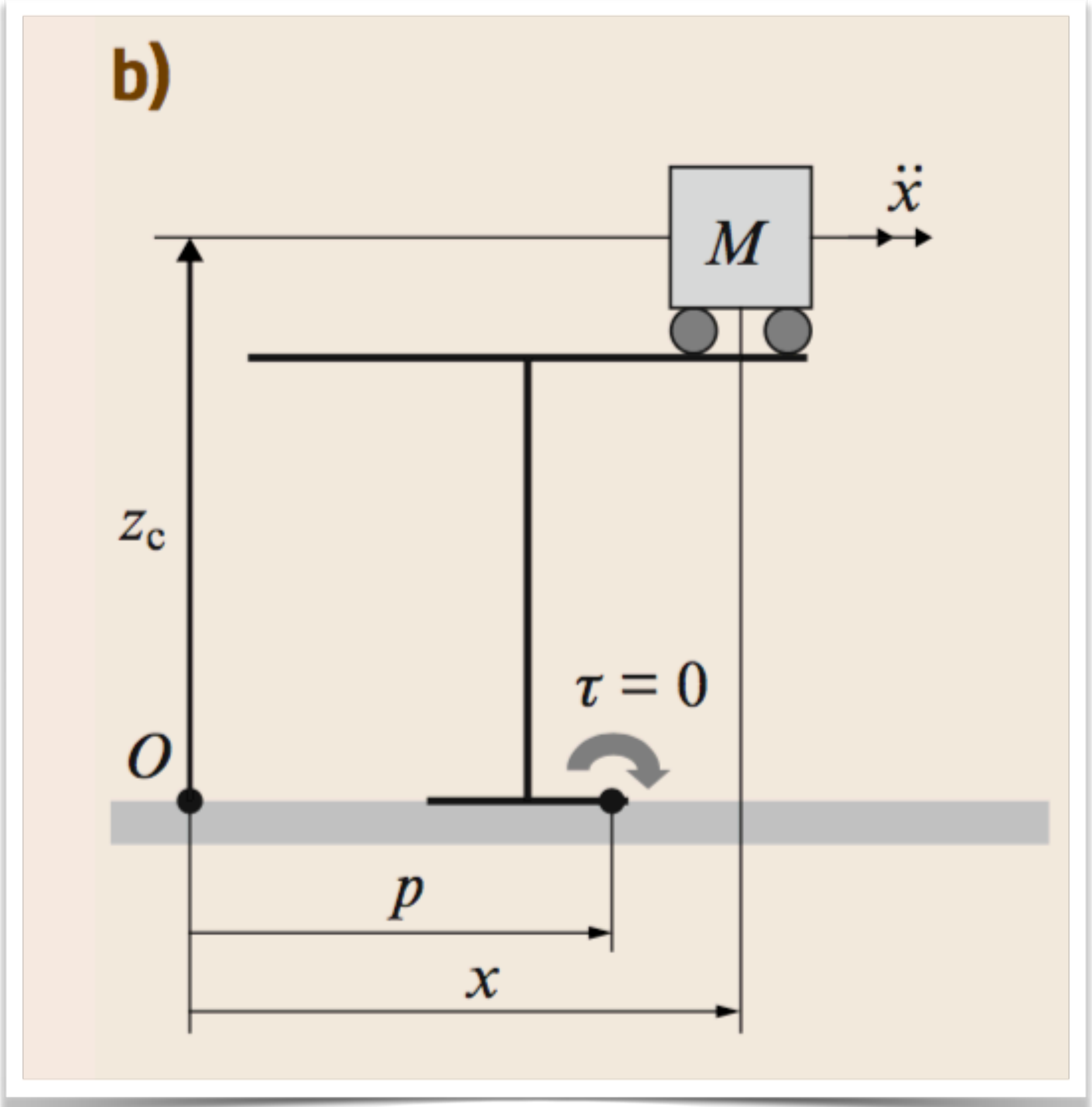
$$p := \frac{\sum_{i=1}^{N} p_i f_{iz}}{\sum_{i=1}^{N} f_{iz}}$$



Computed ZMP

$$p = x - \frac{z_c}{g}\ddot{x}$$

Para acelerações nulas, o **ZMP coincide** com a projeção do **CoM**



Computed ZMP

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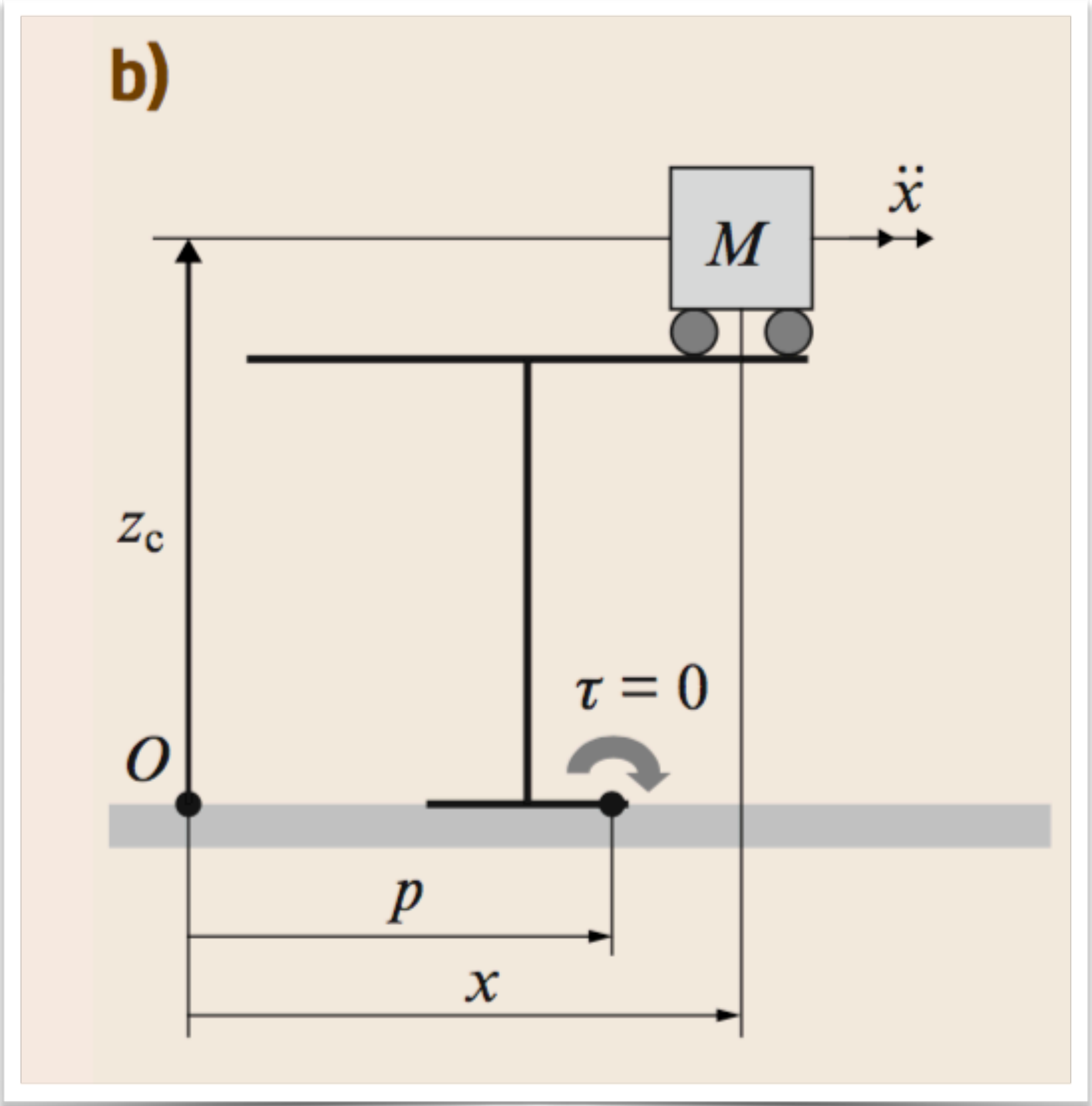
$$p = x - \frac{z_c}{g}\ddot{x}$$

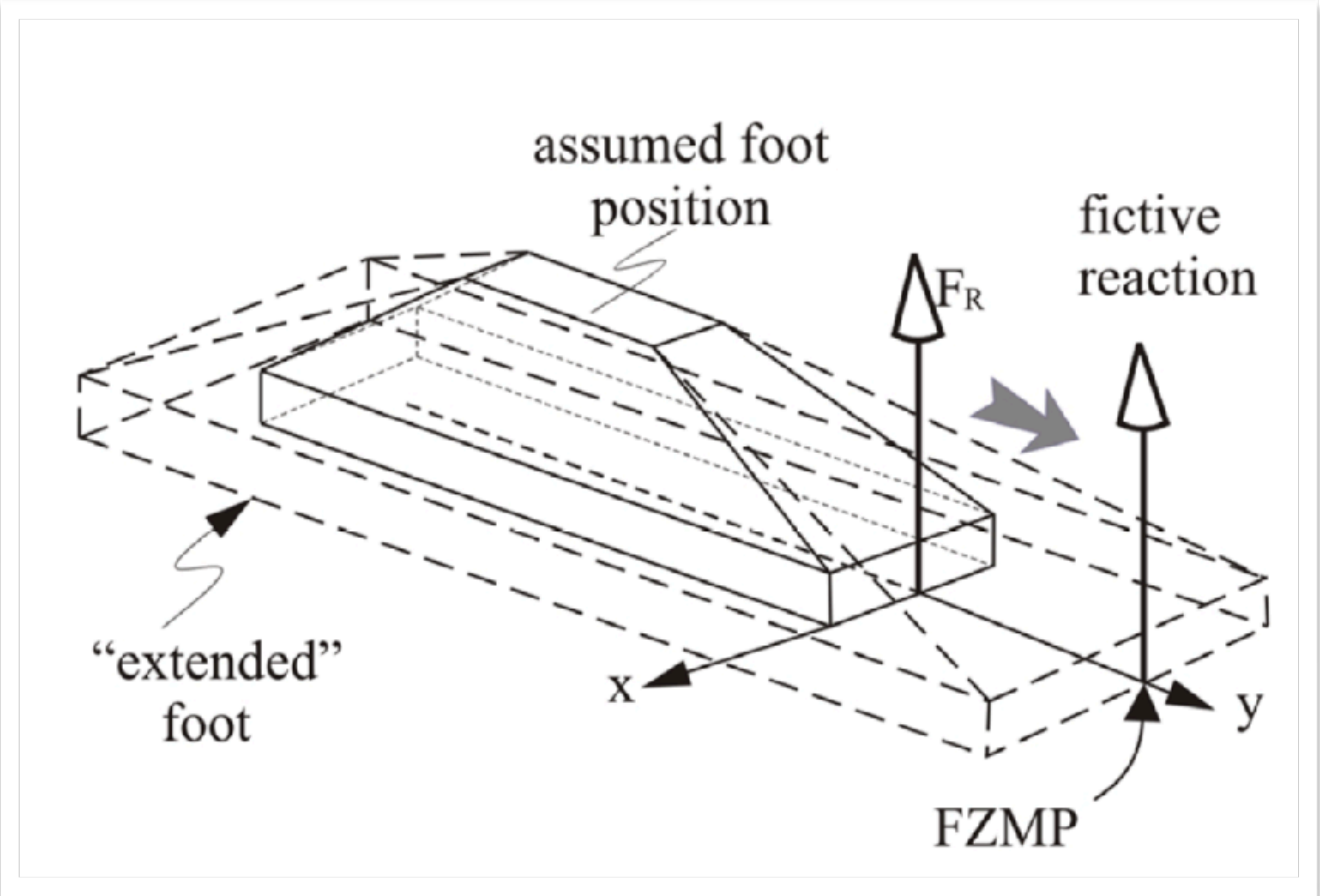
Não é limitado pela base de suporte

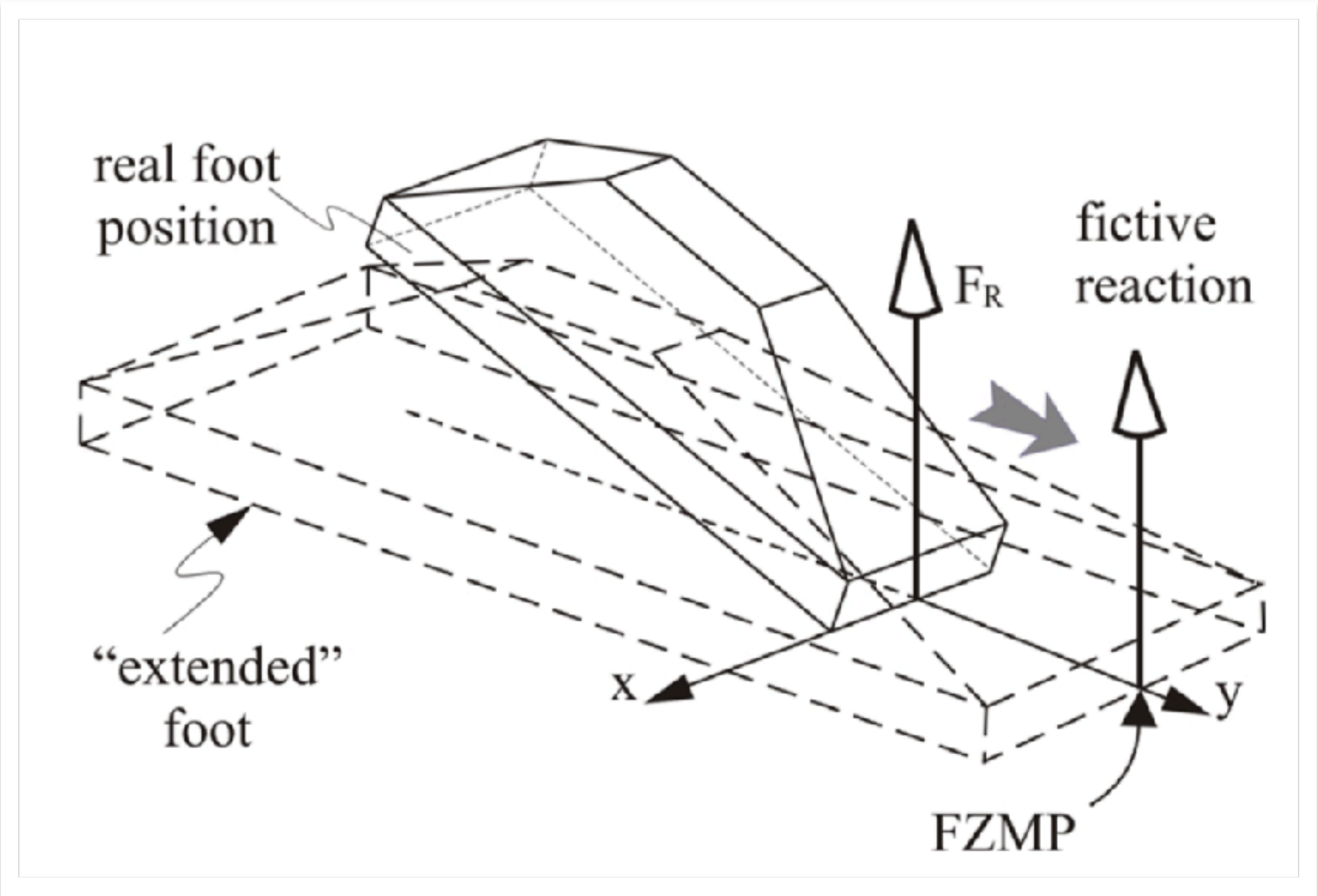
Caso o ZMP saia da área de suporte, ele é chamado '**Fictitious ZMP**' (FZMP) ou '**Foot Rotation Indicator**' (FRI)



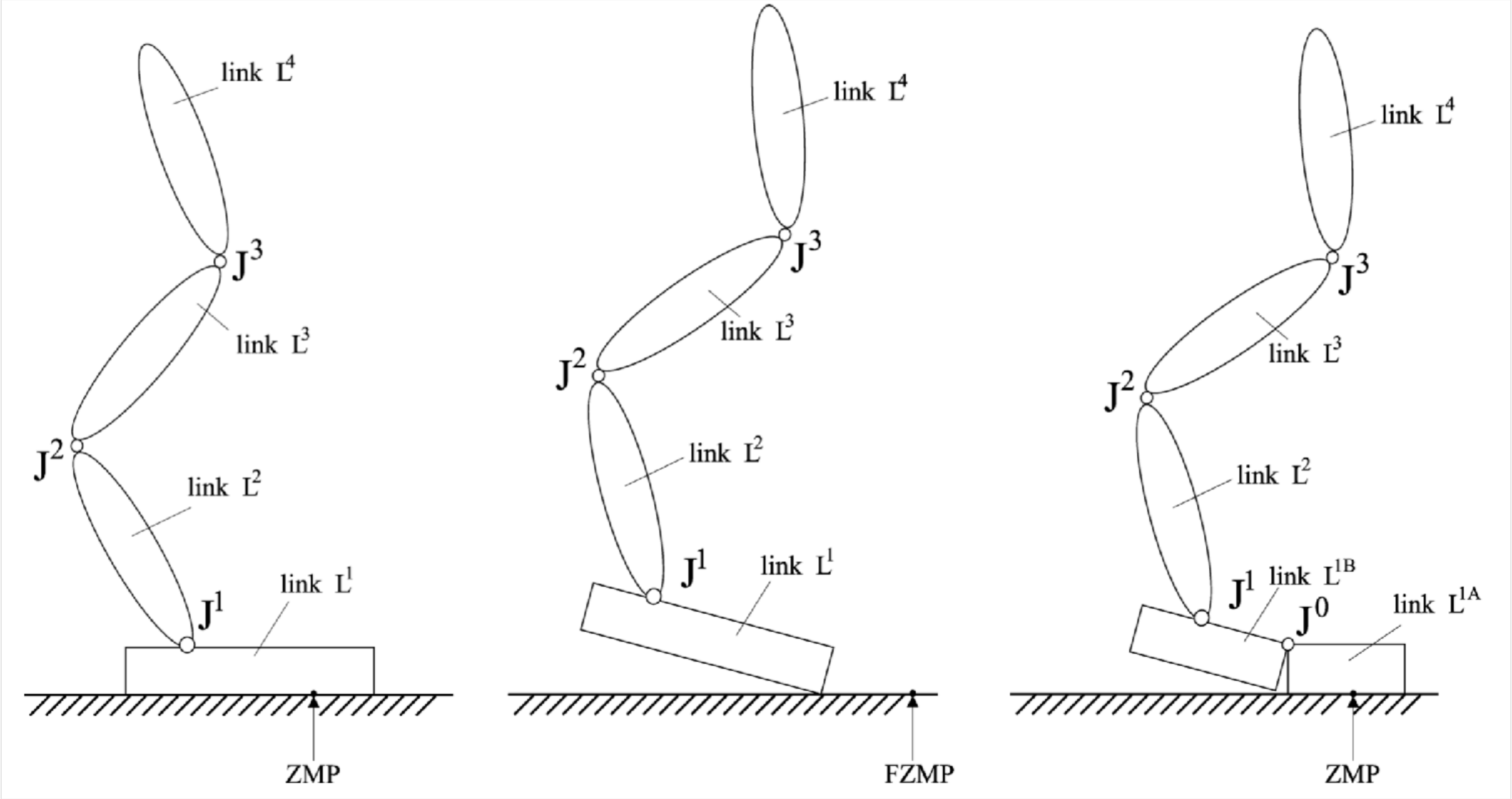

Boston Dynamics

FZMP

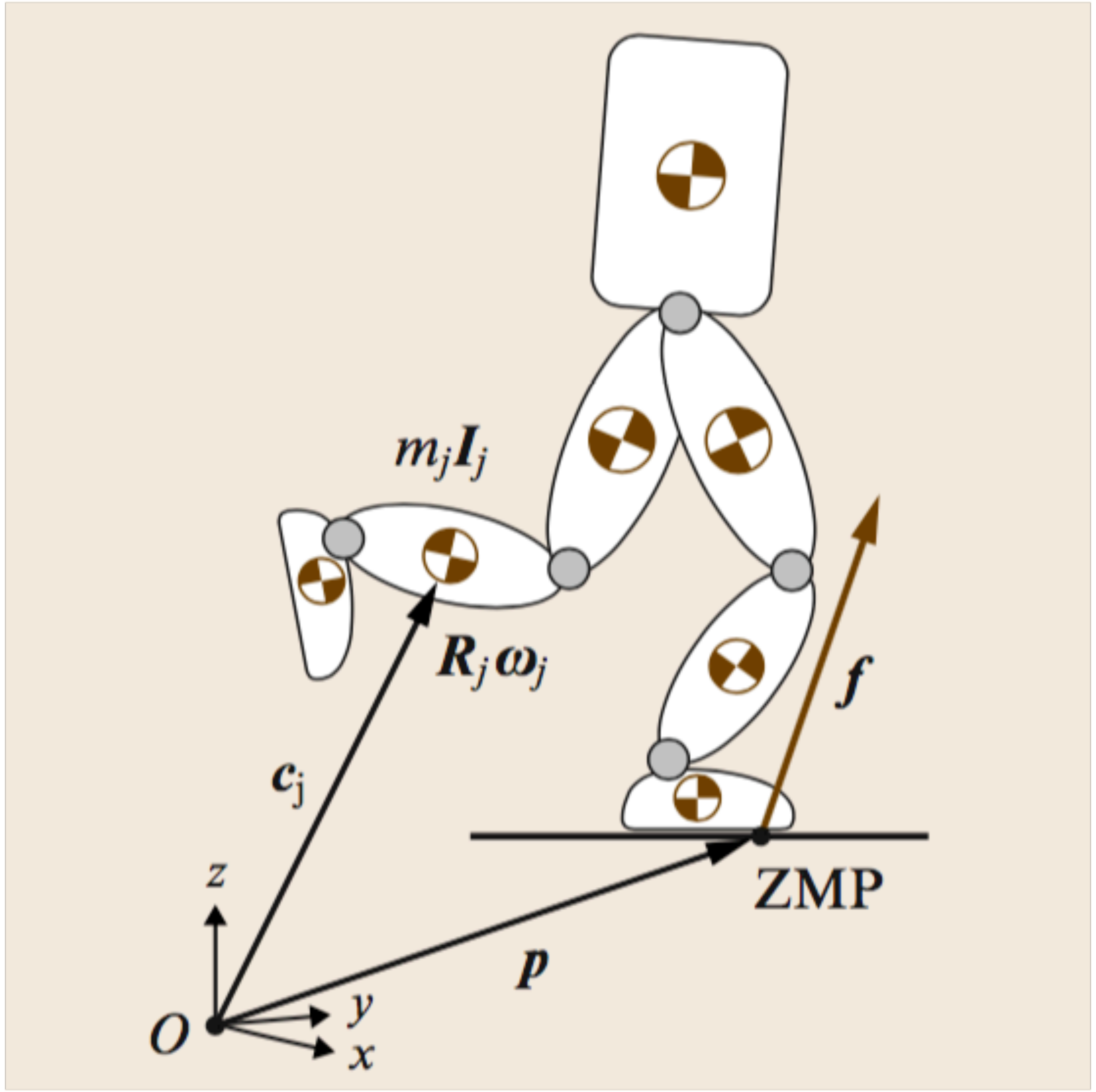

assumed foot position
fictive reaction
FR
"extended" foot
x
y
FZMP


real foot position
fictive reaction
FR
"extended" foot
x
y
FZMP

FZMP


link L4
J3
link L3
J2
link L2
J1
link L1
ZMP
link L4
J3
link L3
J2
link L2
J1
link L1
FZMP
link L4
J3
link L3
J2
link L2
J1
link L1B
J0
link L1A
ZMP

ZMP em 3D



Momento linear:

$$\mathcal{P} = \sum_{j=1}^{N} m_j \dot{\boldsymbol{c}}_j$$

Momento angular:

$$\mathcal{L} = \sum_{j=1}^{N} [\boldsymbol{c}_j \times (m_j \dot{\boldsymbol{c}}_j) + \boldsymbol{R}_j \boldsymbol{I}_j \boldsymbol{R}_j^\top \boldsymbol{\omega}_j]$$

ZMP:

$$p_x = \frac{Mgx + p_z \dot{\mathcal{P}}_x - \dot{\mathcal{L}}_y}{Mg + \dot{\mathcal{P}}_z},$$

$$p_y = \frac{Mgy + p_z \dot{\mathcal{P}}_y + \dot{\mathcal{L}}_x}{Mg + \dot{\mathcal{P}}_z},$$

Conteúdo

Capture point

Ponto no chão onde o robô deve posicionar o **ZMP** para **parar** o movimento de seu **CoM**

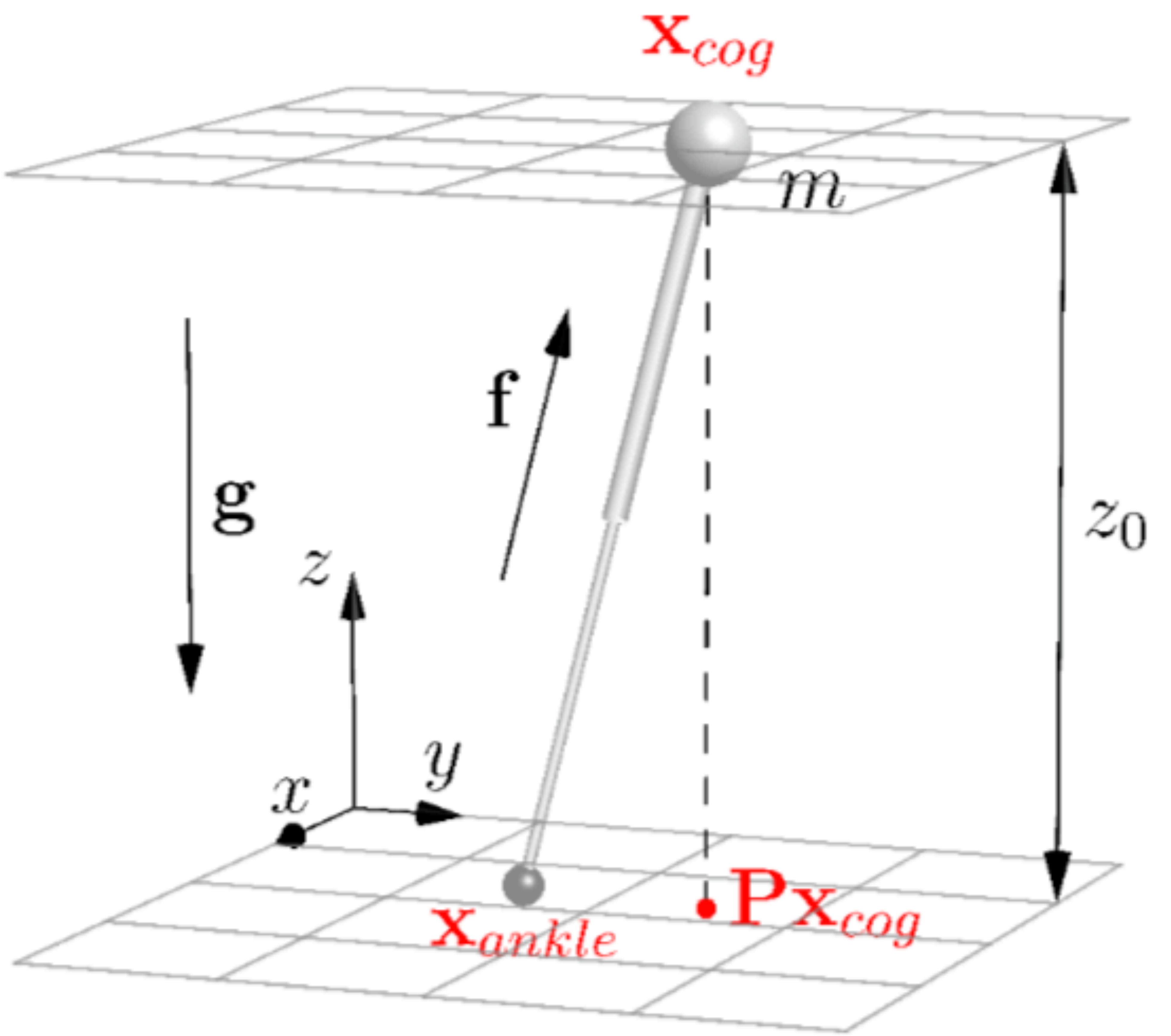
Também chamado de **Extrapolated Center of Mass (XCoM)**

[Hof, A. L. (2008). The 'extrapolated center of mass' concept suggests a simple control of balance in walking. Human movement science, 27(1), 112-125.]

Capture point

Baseado no modelo do **pêndulo invertido linear**

[Pratt, J., et al. (2006). Capture point: A step toward humanoid push recovery]



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Kajita, S., & Espiau, B. (2008). Legged robots. In Springer handbook of robotics (pp. 361-389). Springer Berlin Heidelberg.

Wieber, P. B., Tedrake, R., & Kuindersma, S. (2016). Modeling and control of legged robots. In Springer handbook of robotics (pp. 1203-1234). Springer, Cham.

Vukobratović, M., Borovac, B., & Potkonjak, V. (2006). ZMP: A review of some basic misunderstandings. International Journal of Humanoid Robotics, 3(02), 153-175.

Pratt, J., et al. (2006). Capture point: A step toward humanoid push recovery. In Humanoid Robots, 2006 6th IEEE-RAS International Conference on (pp. 200-207). IEEE.


That's all Folks!