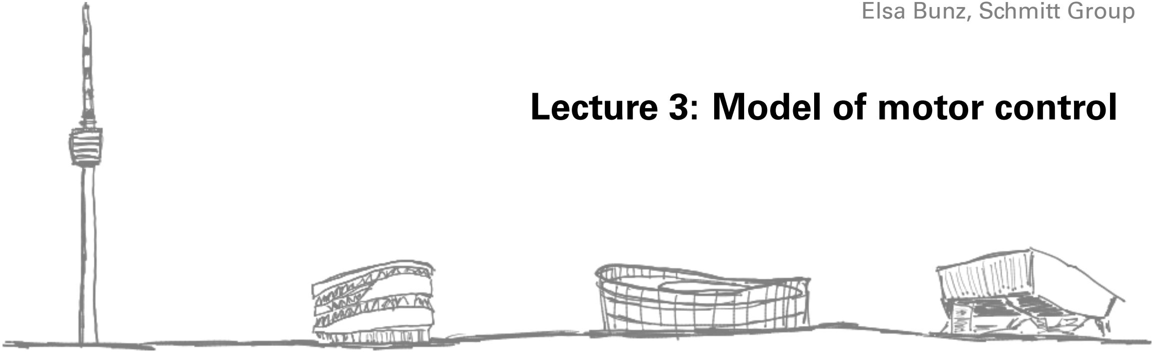
Data-Integrated Simulation Science A

Elsa Bunz, Schmitt Group

Lecture 3: Model of motor control

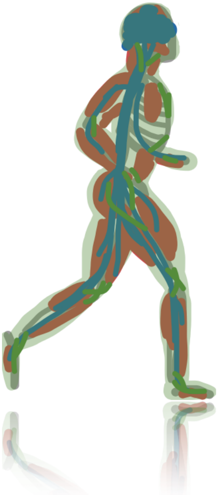


University of Stuttgart
Institute for Modelling and Simulation
of Biomechanical Systems

SimTech

cbb Computational
Biophysics
and Biorobotics

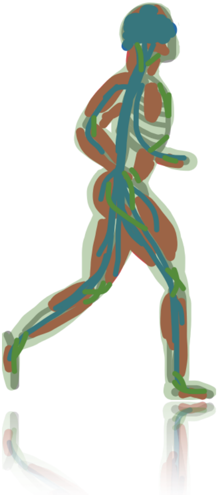
What is required for such a model?



	Bones Structure	Rigid bodies
	Ligaments, cartilage, fat Springs	Passive force
	Muscles Motors	Active force
	Neurons Wires, CPU	Reflexes, commands

Lecture 1

What is required for such a model?



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Lecture 2

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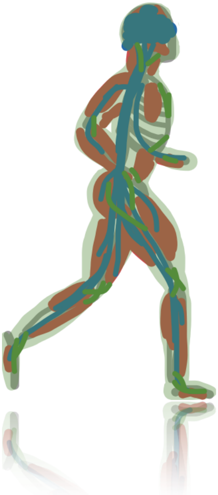

	Bones Structure	Rigid bodies
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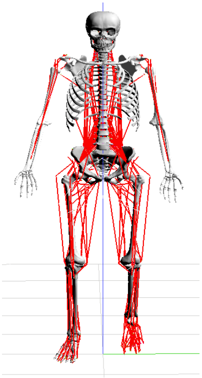
Lecture 3

Overview



Nervous system / Brain

$u(t)$

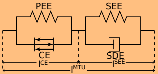
Body

Activation dynamics

$$a(t) = f_a(\gamma(t), l^{CE}(t))$$
$$\dot{\gamma} = f_\gamma(\gamma(t), u(t))$$

$a(t)$

Muscle model



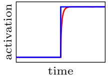
$f_{\mathrm{MTU}}(t)$

Skeletal system

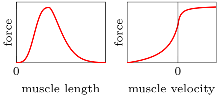
$$\mathcal{F}^{\mathrm{MTU}} = \frac{\partial L^{\mathrm{MTU}}}{\partial \mathcal{Q}} \cdot F^{\mathrm{MTU}}$$
$$\mathbf{M}(\mathcal{Q})\ddot{\mathcal{Q}} + C(\mathcal{Q}, \dot{\mathcal{Q}}) = \mathcal{F}_{\mathrm{ext}} + \mathcal{F}^{\mathrm{MTU}}$$

$\mathcal{Q}(t)$

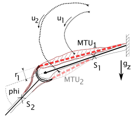
Resulting joint angle trajectory



Biochemical processes act as low-pass filter



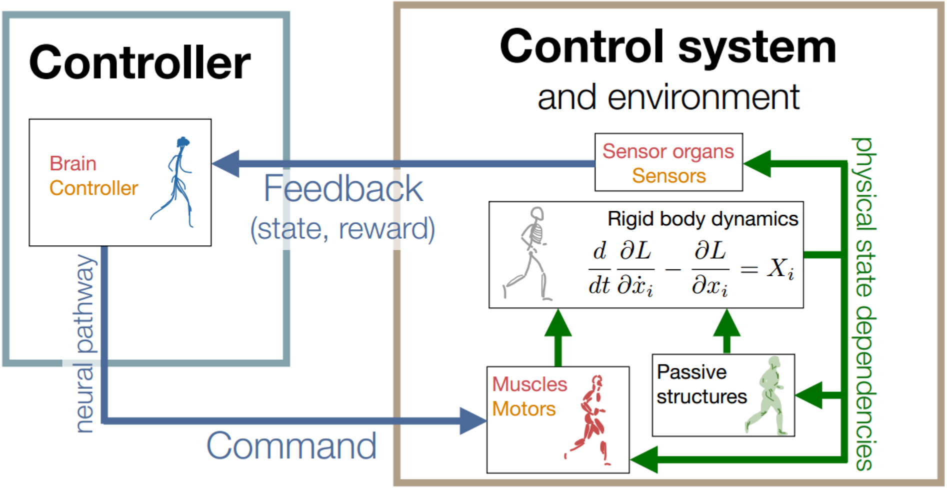
Muscle model incorporates nonlinear force-length and force-velocity relation



Nonlinear muscle routing translates muscle forces to torques

Wochner [11]

What is required for such a model?

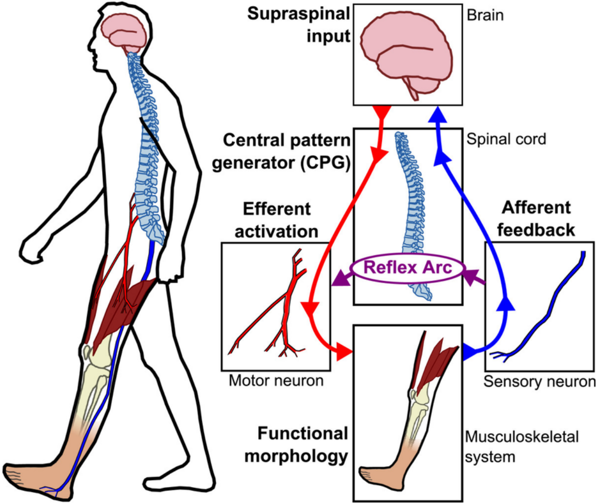


Overview

Overall problem: Generate motor command for each muscle based on control goal and current state of the system (sensor signals)

- Human motor control
- Motor control theories
- Control approaches
  - Feedback + Feedforward control
  - Equilibrium point control
  - Reflex control
  - Learning
- Summary
- Overview work @CBB

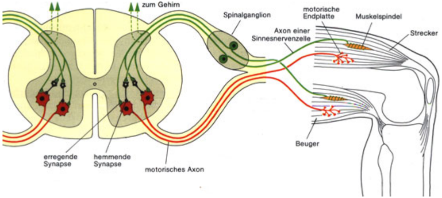
Human motor control



Tucker et al. [1]

Motor control theories

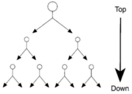
Reflex Theory
* Sherrington 1906
* Movement is controlled by stimulus-response
* Reflexes are combined into actions that create behaviour



Goll/Schwoerbel [2]

Motor Program Theory
* Adaptive and generalised motor programs exist to control actions that have common characteristics (Schmidt 1976)

Internal Model Theory
* CNS contains knowledge about properties of the body and of the external world [3]



Shumway-Cook and Woollacott [4]

Hierarchical theory
* Cortical centers control movement in a top-down manner
* Sensory feedback needed and used to control the movement (Adams 1971)

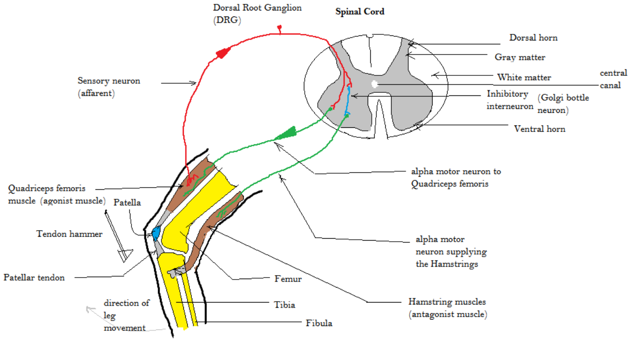
Dynamical Systems Theory
* Movement emerges to control degrees of freedom
* Movement patterns self-organise within the environmental conditions
* Functional synergies are developed
(Bernstein 1967, Turvey 1977, Kelso & Tuller 1984)

others...

Sources: [5] and Shumway-Cook and Woollacott [4]

Reflex Theory

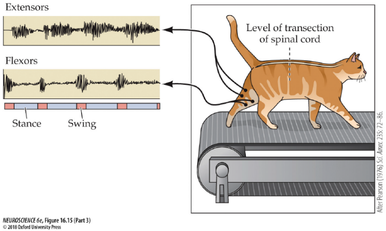
- Formulated by Sir Charles Sherrington 1906
- Assumption: reflexes are basic elements of complex movement and behavioral pattern
- Simplest reflexes are mono-synaptic reflexes
- Example: Patellar reflex



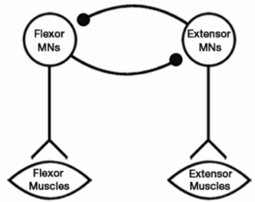
Sarkar [6]

Central Pattern Generator (CPG)

- Neural circuit that produces rhythmic outputs in the absence of rhythmic input
- Located in the spinal cord
- Does not require sensory input
- Thomas Graham Brown 1914: Half-centre model



Tia [7]

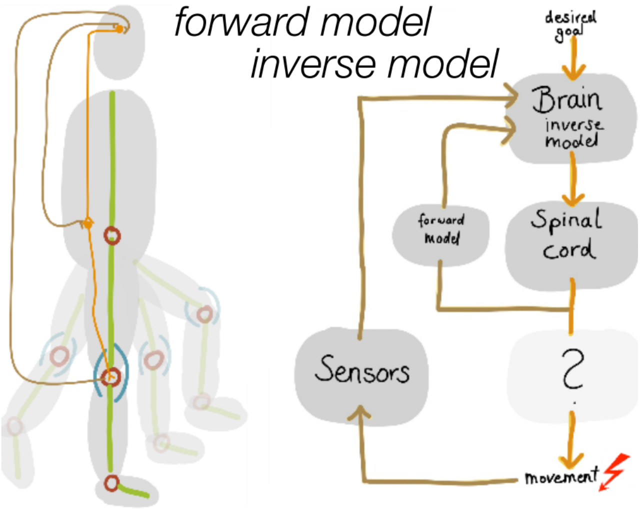


Olsen [8]

Internal Model Theory

Forward model: Predicts consequence of given action

Inverse model: Computes required motor commands that can produce desired outcome



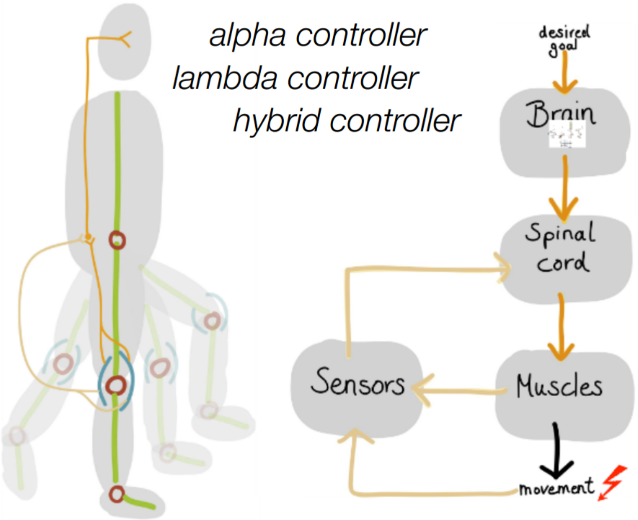
Equilibrium Point Control

Movements are generated through a gradual transition of equilibrium points along a desired trajectory

alpha controller

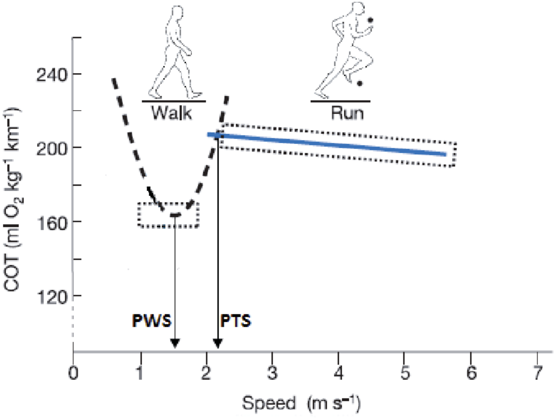
lambda controller

hybrid controller



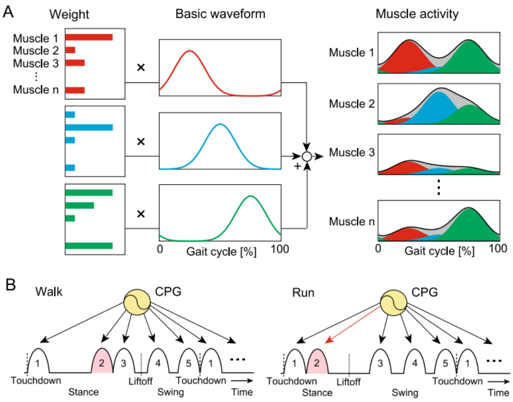
Degrees of freedom problem

Optimal Control hypothesis



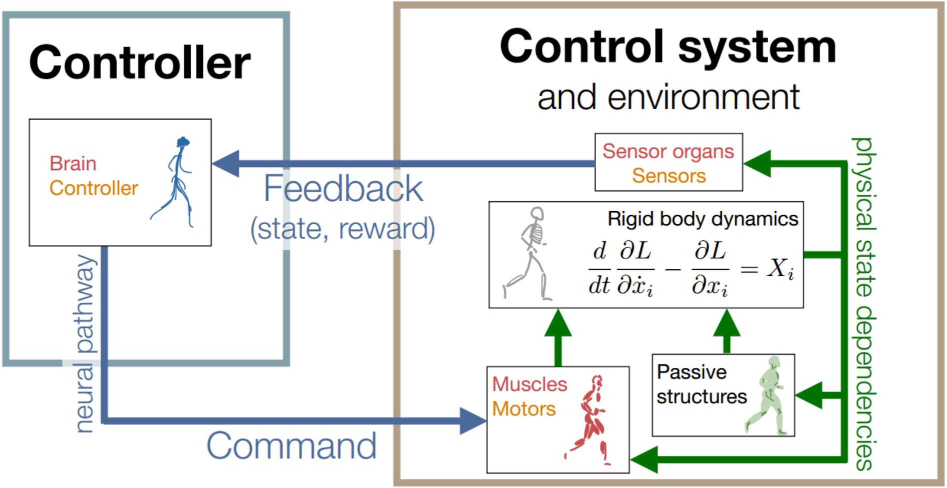
Majed et al. [9]

Muscle Synergy hypothesis



Aoi et al. [10]

What is required for such a model?



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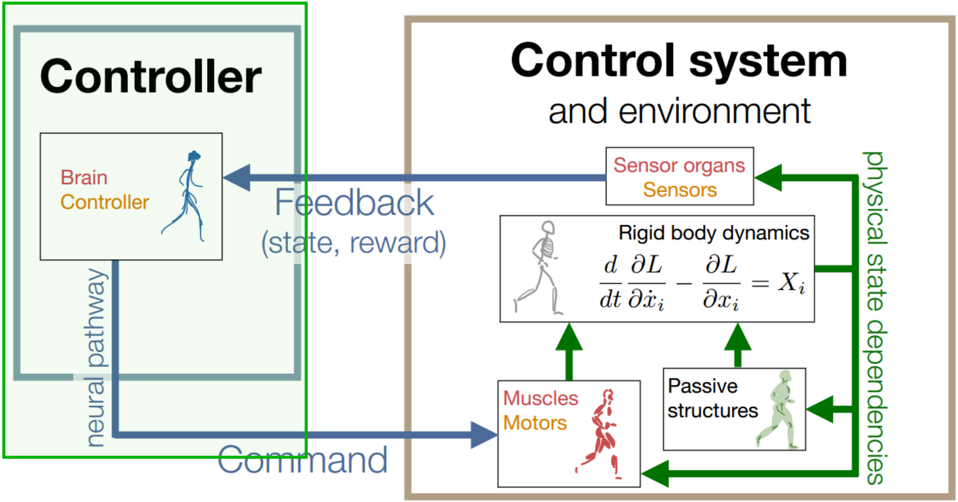
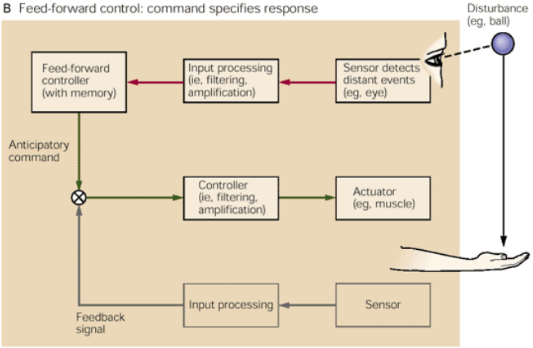
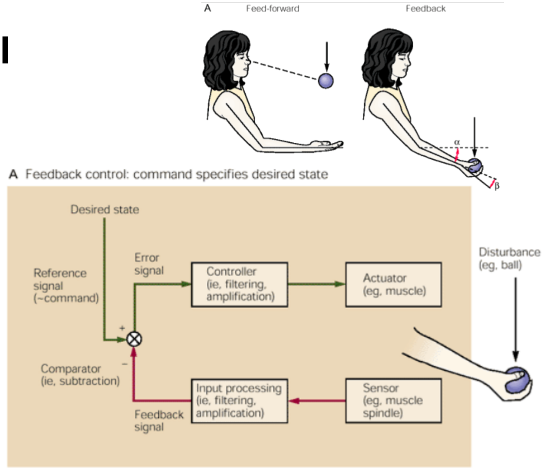


Feedback + Feedforward Control



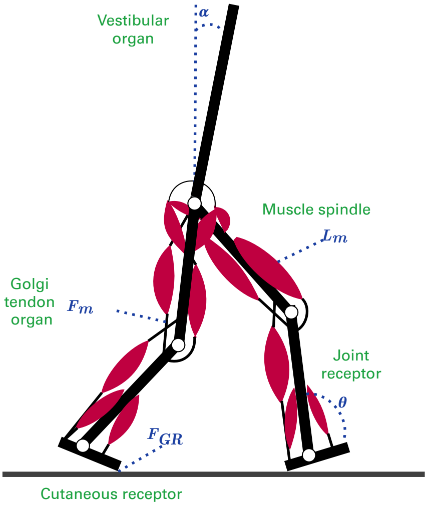


Ghez and Krakauer [12]

Feedforward: Anticipatory control, muscle activities are predefined

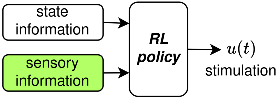
Feedback: Comparison of actual signals with set point and error signal

What kind of sensory information?



How to use sensory information?

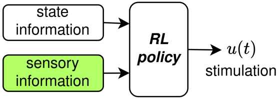
Reinforcement learning



Use sensory information as
input to a black-box controller

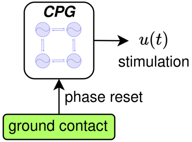
How to use sensory information?

Reinforcement learning



Use sensory information as input to a black-box controller

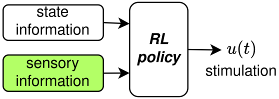
Central Pattern Generator



Use sensory information to modulate feed-forward signal

How to use sensory information?

Reinforcement learning



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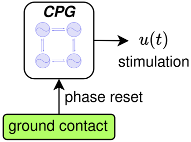
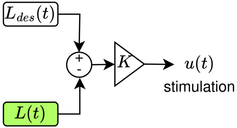


Use sensory information to modulate feed-forward signal

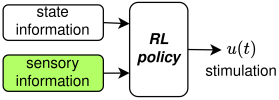
λ-Controller



Compare sensor information to desired sensor signal

How to use sensory information?

Reinforcement learning



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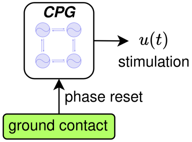

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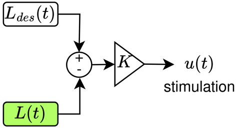
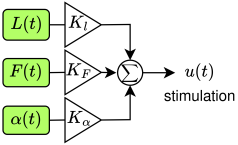


Compare sensor information to desired sensor signal

Reflex Controller



Use sensor signals to directly generate stimulation

A simple model of "low level" motor control

Sought-after: a relation between "brain" and "lower level" sensorimotor processing units and the motor command (neural excitation) **u**

$$\boxed{u_j^{\text{closed}} = f_u(\kappa, \lambda_j^{\text{CE}}, l_j^{\text{CE}})}$$

$$\boxed{u_j^{\text{closed}} = \frac{\kappa}{l_{j,\text{opt}}^{\text{CE}}} \cdot (l_j^{\text{CE}}(t - \delta t) - \lambda_{j,i}^{\text{CE}}) + \sigma \cdot \dot{l}_j^{\text{CE}}}$$

monosynaptic reflex

Simple "high level" - control

$$\boxed{u_{\mathrm{j}} = \cancel{u_{\mathrm{j}}^{\mathrm{open}}} + u_{\mathrm{j}}^{\mathrm{closed}}}$$

motor (control) command **u**

$$u_{\mathrm{j}}^{\mathrm{closed}} = \frac{\kappa}{l_{\mathrm{j,opt}}^{\mathrm{CE}}} \cdot (l_{\mathrm{j}}^{\mathrm{CE}}(t - \delta t) - \lambda_{\mathrm{j,i}}^{\mathrm{CE}})$$

using

$$\vec{\lambda}_{\mathrm{i}}^{\mathrm{CE}} = [\lambda_{\mathrm{1,i}}^{\mathrm{CE}}, ..., \lambda_{\mathrm{j,i}}^{\mathrm{CE}}, ..., \lambda_{\mathrm{n,i}}^{\mathrm{CE}}]^T$$

n: number of muscles

i: ith desired state

with m=i target vectors (TV) to achieve a certain movement.

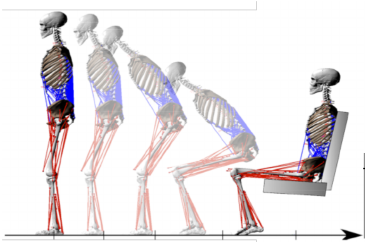
TVs depend on the systems state and not on time.

The simplest possible **"high level" control is a rule** to switch between a finite (and low) number **of target vectors depending on the state of the system.**

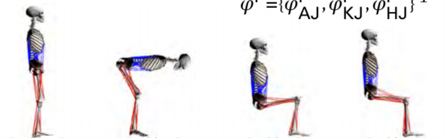
Equilibrium point control

EP idea: $\varphi^{\mathsf{P}} \in \mathbb{R}^{\mathsf{ndof}}$; $L^{\mathsf{P}} \in \mathbb{R}^{\mathsf{nmusc}}$; L^{P}=$\{l_1^{\mathsf{CE}}, l_2^{\mathsf{CE}}, \ldots, l_m^{\mathsf{CE}}\}$; $\boxed{\varphi^{\mathsf{P}} \to L^{\mathsf{P}}}$; P=$\mathsf{P}_1, \mathsf{P}_2, \ldots, \mathsf{P}_j$

$\Rightarrow$ intermittent sequence of EP to generate motion: $\Psi \in \mathbb{R}^{\mathsf{npos}}$; $\Psi = \{\varphi^{\mathsf{P}_1}, \varphi^{\mathsf{P}_2}, \ldots, \varphi^{\mathsf{P}_j}\}^T$



φ^{P}=$\{\varphi_{\mathsf{AJ}}^{\mathsf{P}}, \varphi_{\mathsf{KJ}}^{\mathsf{P}}, \varphi_{\mathsf{HJ}}^{\mathsf{P}}\}^T$



	Position P_1	Position P_2	Position P_3	Position P_4
AJ	5°	5°	5°	5°
KJ	12°	40°	110°	83°
HJ	13°	120°	103°	82°

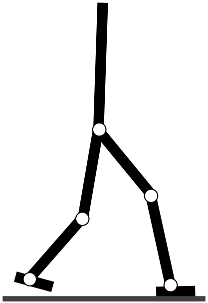
Exemplary task: Learn stand-to-sit movement *using heuristic method*

- Find EPs: P1, P2, P3, P4;
- Find switching times between EPs: $\boxed{\text{P1 if t < 0.1s}}$; $\boxed{\text{P2 if 0.1s} \leq \text{t < 0.15s}}$

$\boxed{\text{P3 if 0.15s} \leq \text{t < 0.55s}}$; $\boxed{\text{P4 if 0.55s} \leq \text{t}}$

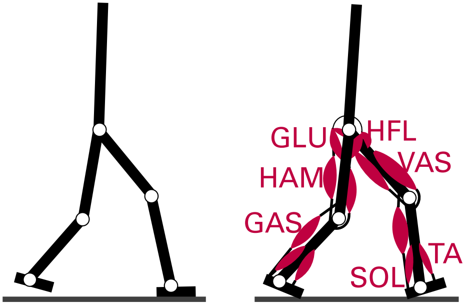
Equilibrium point control

Reflex control: walking model



Geyer and Herr [13]

Reflex control: walking model



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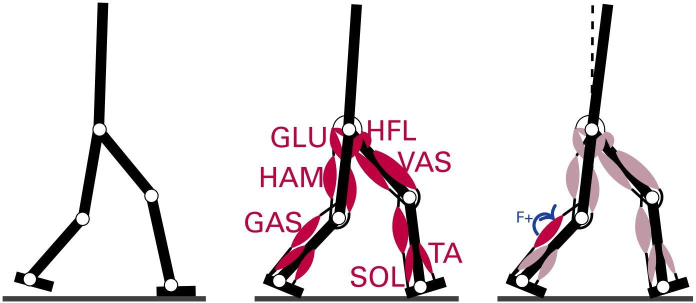

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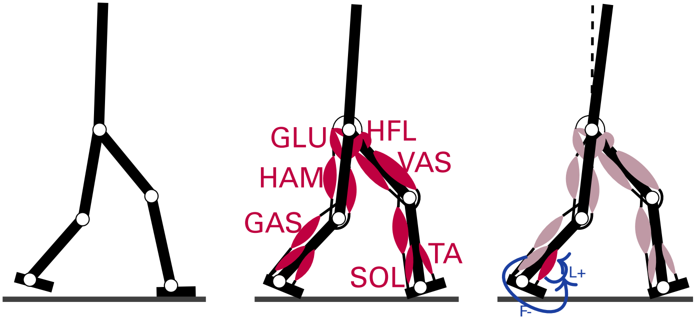

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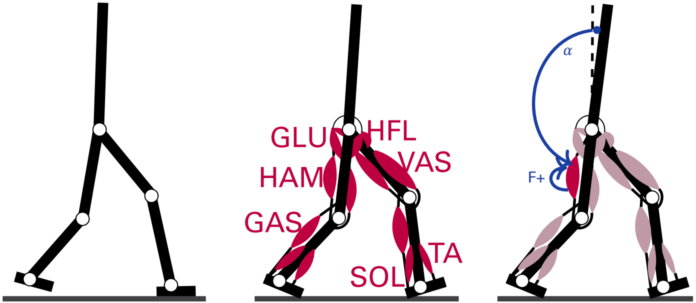

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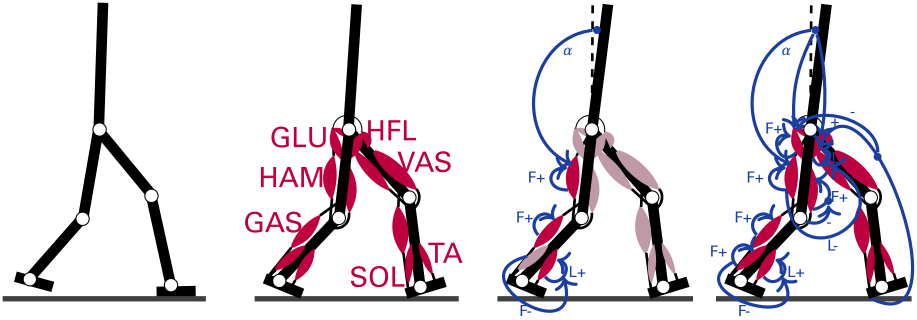

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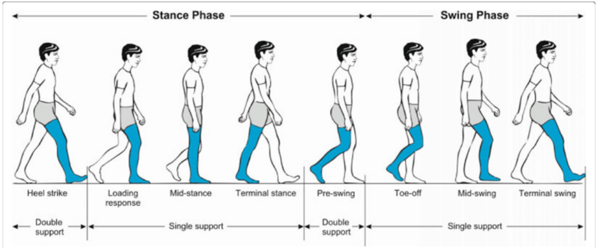
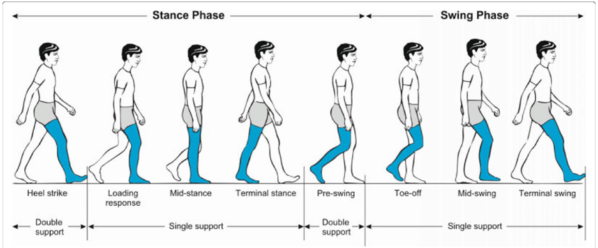


From Moltedo et al. [14]

- Two states: Stance and swing
- Two sets of reflexes, switch depending on ground contact

[13]

Reflex control: walking model



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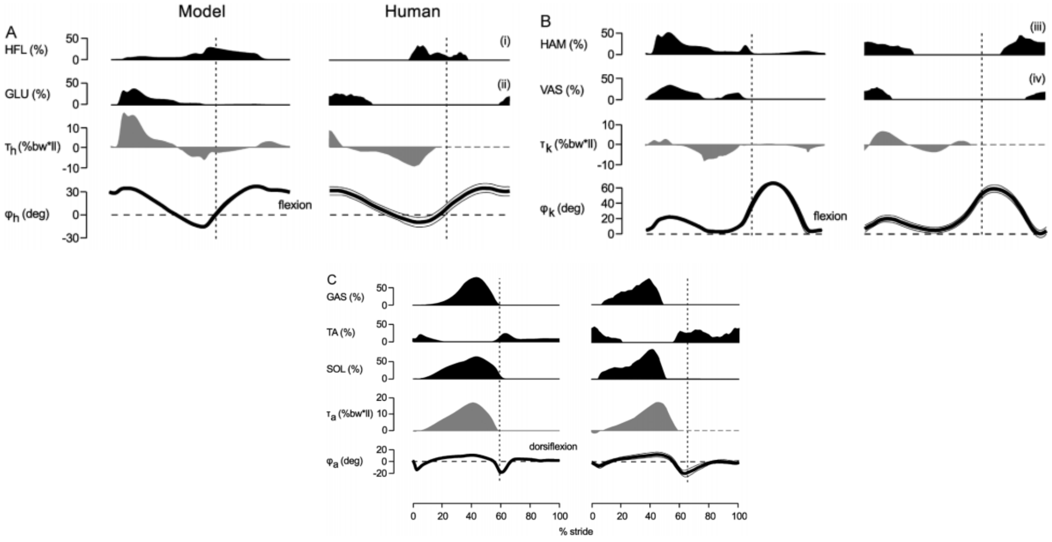


Geyer and Herr [13]

Reflex control

Work in progress: Extension to further movements

Reflex control

Learning

Given a specific control idea, learning is ...

- Finding appropriate **muscle stimulation pattern**, time to **change pattern**, etc.
- Optimising **controller gains**
- **Balancing feedforward and feedback** contributions
- Autonomously learning the **control policy**

Schumacher et al. [15]

Summary

Overall problem: Generate motor command for each muscle based on control goal and current state of the system (sensor signals)

- Human motor control not completely unravelled, variety of motor control theories exist
- Discussed approaches that are commonly used: Internal model, Equilibrium Point Control, CPG, Muscle Synergies, Reflex control
- Goal of learning/ optimization depends on the control approach used

What is required for such a model?

Model of high-level motor control

EP control $\Lambda_i^{\text{move}} = \{\vec{\lambda}_1, \vec{\lambda}_2, \vec{\lambda}_3, \ldots, \vec{\lambda}_n\}$

Joint space control

- continuous vs. intermittent
- ***model-based control***
- ***learning-based control***

Model of skeletal muscle

Hill-type model

$$F_j^{\text{MTU}} = f_f(l_j^{\text{MTU}}, \dot{l}_j^{\text{MTU}}, l_j^{\text{CE}}, a_j)$$

$$\dot{l}_j^{\text{CE}} = f_v(l_j^{\text{MTU}}, \dot{l}_j^{\text{MTU}}, l_j^{\text{CE}}, a_j)$$

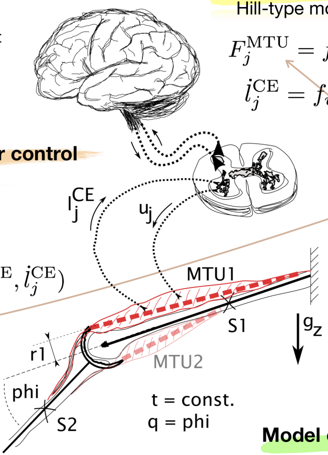
$$\dot{a}_j = f_a(a_j, l_j^{\text{CE}}, u_j)$$

Model of low-level motor control

- monosynaptic reflex
- alpha-gamma co-activation

$$u_j = u_j^{\text{open}} + u_j^{\text{closed}}$$

$$u_j^{\text{closed}} = f_n(\kappa, \lambda_j^{\text{CE}}, l_j^{\text{CE}}, \dot{l}_j^{\text{CE}})$$



Numerical solution

$$\vec{q}(t) = ?$$

Parameters

Initial conditions

Model of skeletal structure

$$M(q)\ddot{q} = C(q)\dot{q}^2 + E(q, \dot{q}) + G(q) + R(q)F^{\text{MTU}}$$

Schmitt et al. [16]

Work @CBB Stuttgart

References

[1] Michael Tucker et al. “Control Strategies for Active Lower Extremity Prosthetics and Orthotics: A Review”. Jan. 2015.

[2] Goll/Schwoerbel. *Sinne, Nerven, Hormone*. Cornelsen-Velhagen & Klasing. URL: \https://bio.vobs.at/physiologie/a-neuro-5.php.

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