Models for explaining human locomotion

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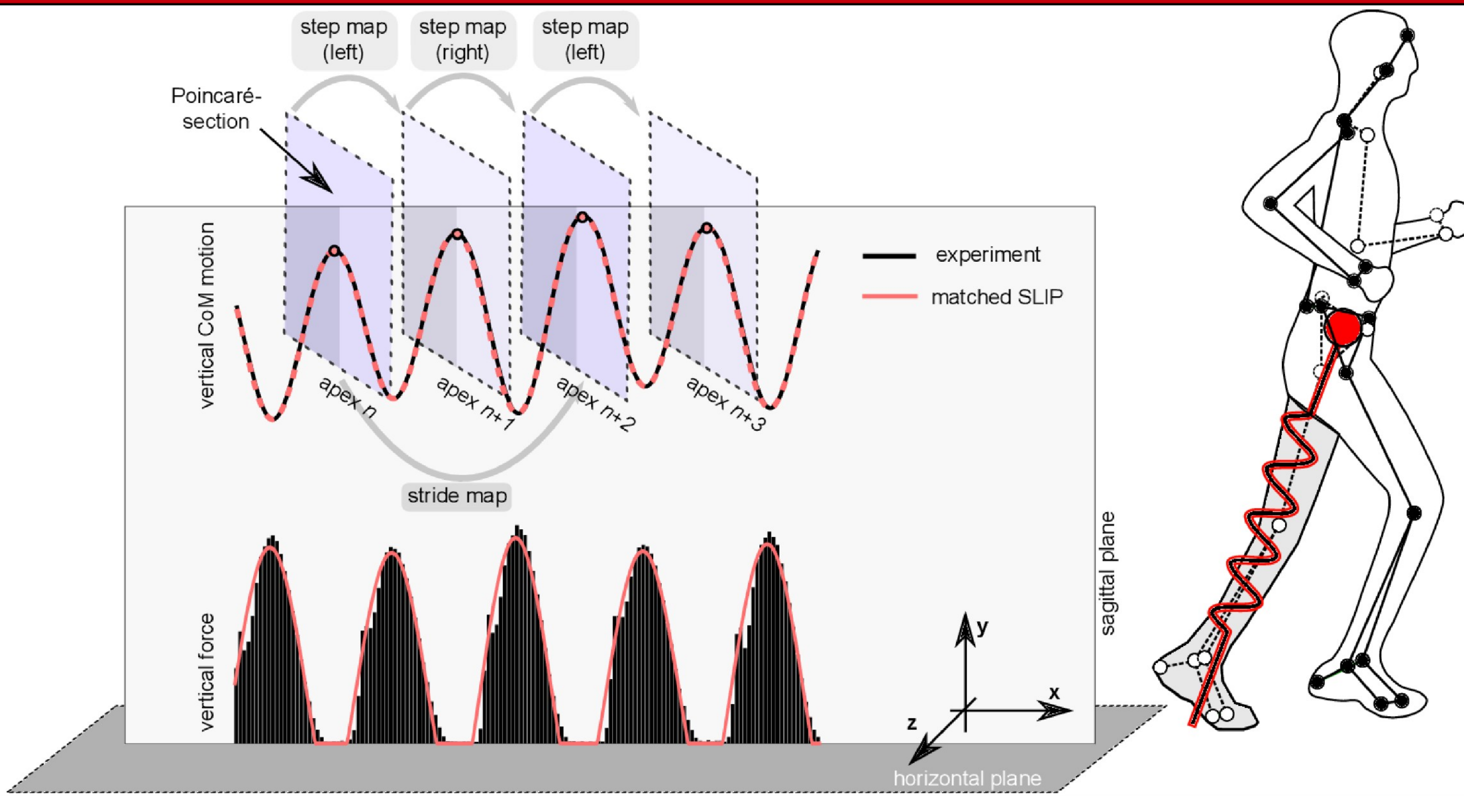

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About Lauflabor

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- Locomotion research since 2003 (Prof. Andre Seyfarth)
- Visit http://www.lauflabor.de
- Focus on **modeling**, but also:
  - Robots
  - Powered protheses
  - Human experiments

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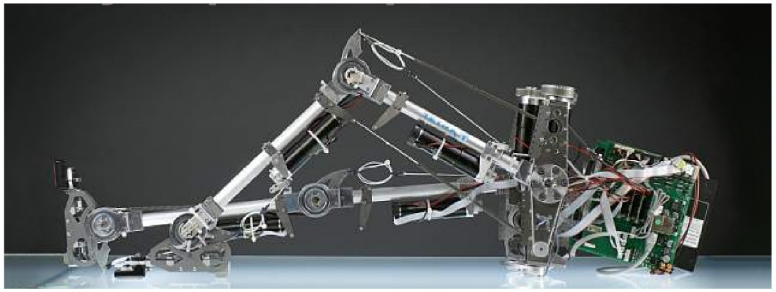

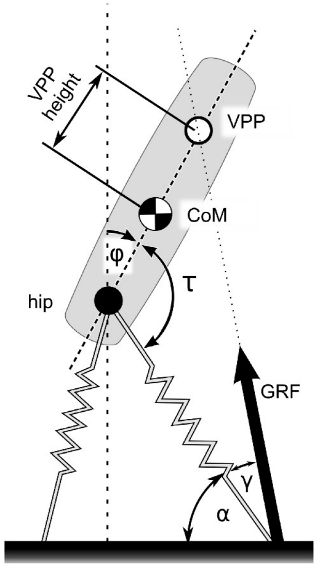

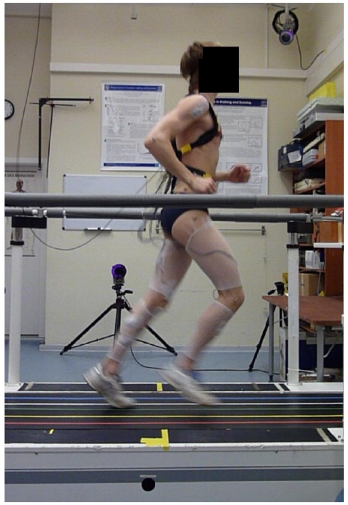

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About me

- Moritz Maus
- Working in biomechanics since 2008
- PhD in control engineering at TU Ilmenau 2012.
  Thesis: "Towards understanding human locomotion"

About this talk

Topic is *human* running

- Introduction
- General characteristics of human treadmill running
- Linear model of “stationary” running
- Explicit mechanical models for locomotion (“templates”)
- Using templates to control robots (*overview)*

Introduction

Why models?

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Everything you can calculate with is a model!

- Multi-body simulation
- Regression from experimental data
- Models of atoms
- Natural numbers: “model of the axioms” (logic)

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A note on complexity

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- Required level of complexity depends on the scientific question.
- More complex is not necessarily better – especially if you know little about the system.
- Example in bipedal robots: Who includes structural deformation of segments in the model?

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Where do we stand?

- Comparison of robot and human performance
- → videos
- Robots can perform comparatively well
- Humans still by far outperform robots in terms of agility, adaptability, efficiency, robustness, …

Where do we stand?

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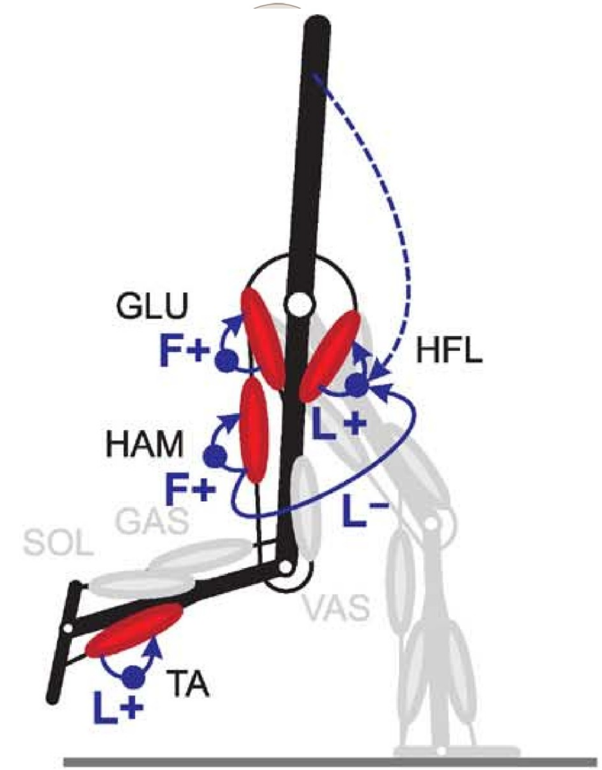
In terms of modeling *human* locomotion:

- Which part can we hope to grasp?
  - exclude “model of brain”
  - reflexes can create “neuro-mechanical oscillators” that walk
- Implicit assumption (in most locomotor research):

  “*There is a comparatively autonomous walking* ***sub****system that is steered by the brain!*”

- → videos



from Geyer and Herr, IEEE T-NSRE 18 (3), 2010

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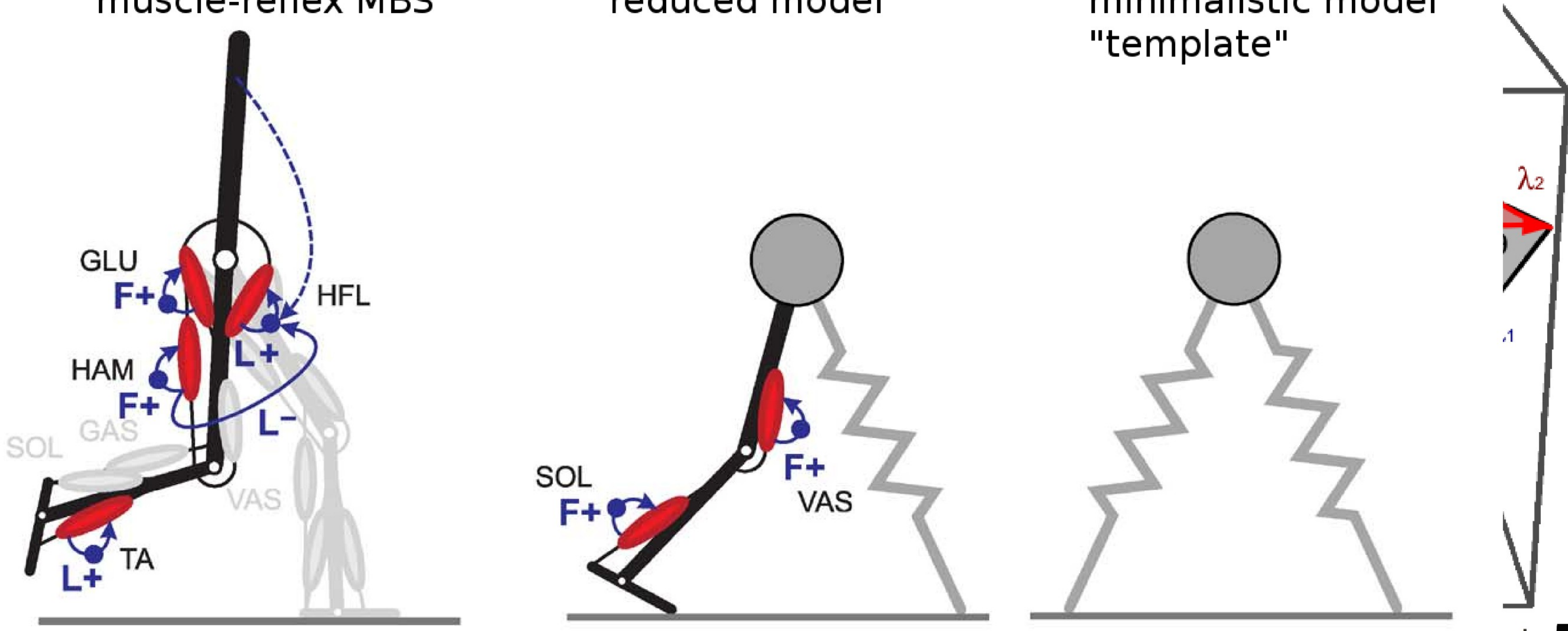
Models used here

Mainly two kind of models:

muscle-reflex MBS | reduced model | minimalistic model "template"



modified from Geyer and Herr, IEEE T-NSRE 18 (3), 2010

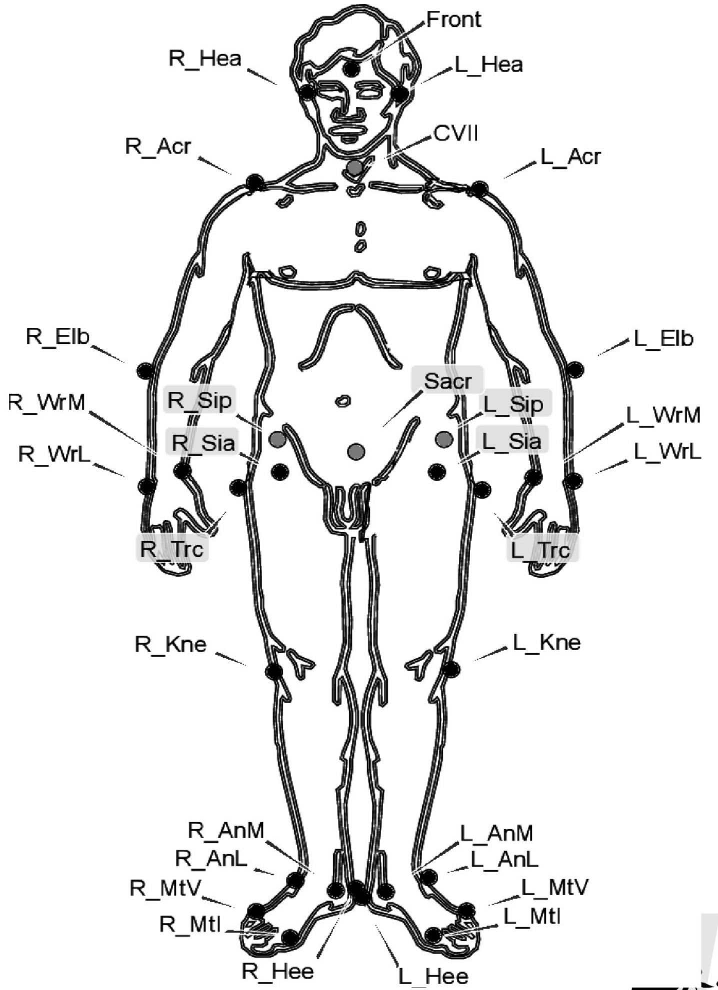
Human treadmill running characteristics

Data overview

- 10 trained subjects, each ~26 min running
- self-selected speed
- ~1800 strides per subject
- MoCap: 31 markers recorded
- (model) **assumption**: motion sufficiently represented by markers

Important processing steps:

- CoM estimation [Maus et al., 2011]
  → required for comparison with templates
- Phase estimation [Revzen et al., 2008]
  → required for continuous prediction



Basic characteristics

- Stationarity?
- Possibly AR(1)-process? (↔ Floquet structure justified)

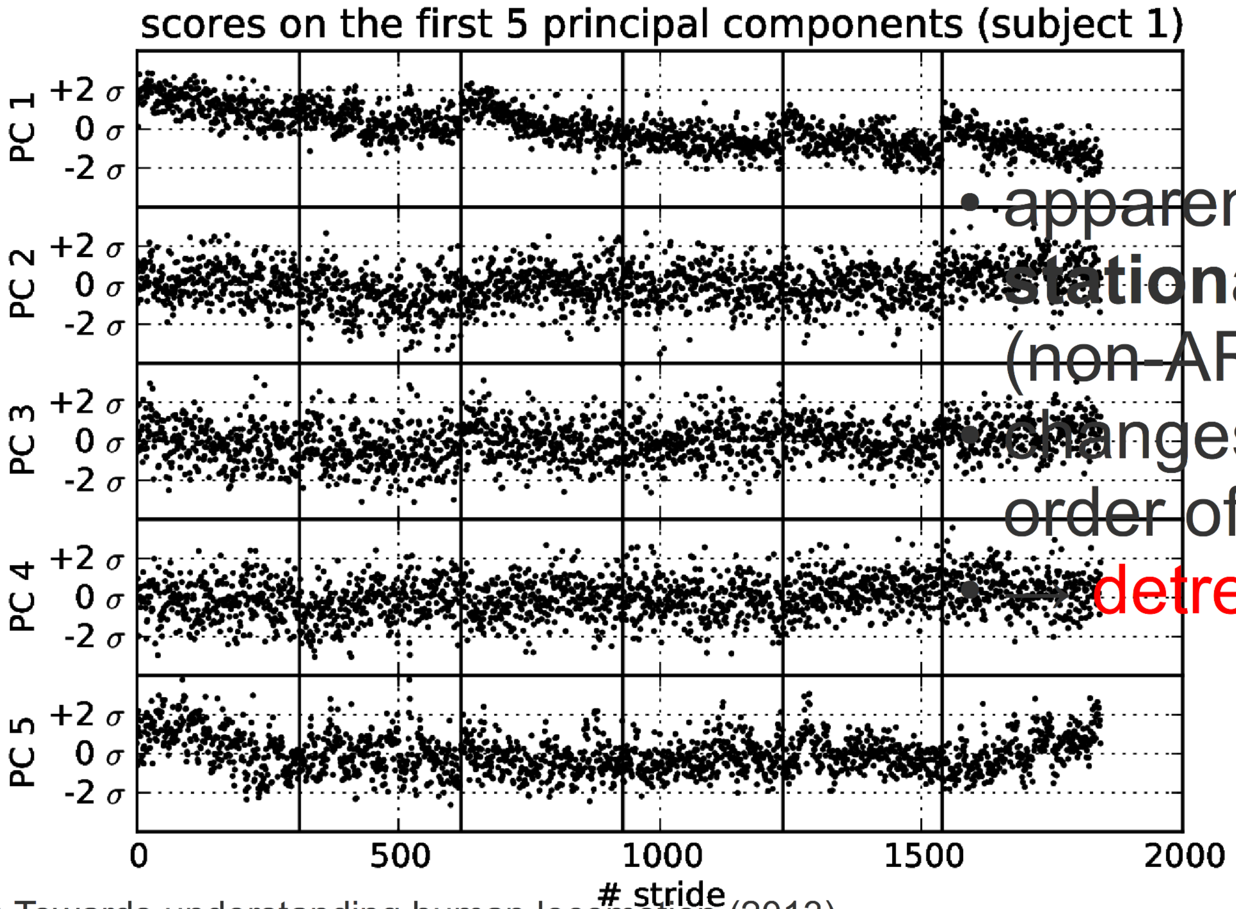
Investigating stationarity

- Procedure:
  - Re-sample data to 50 frames / stride
  - select 15 representative "coordinates" + corresponding velocities = 30 dim.
  - each stride is represented by 1500 numbers

    → stride is **point** in 1500-dim. "stride space"
  - perform PCA:

    → first axes cover most of information about a stride

Stationarity?



- apparently **not stationary** (non-AR(1))
- changes in the order of minutes
- → detrending

Maus: Towards understanding human locomotion (2013)

Summary of data

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- Non-stationary, detrending required
- In lack of a better models, we nevertheless approximate the dynamics with a linear (Floquet) model around a limit cycle.

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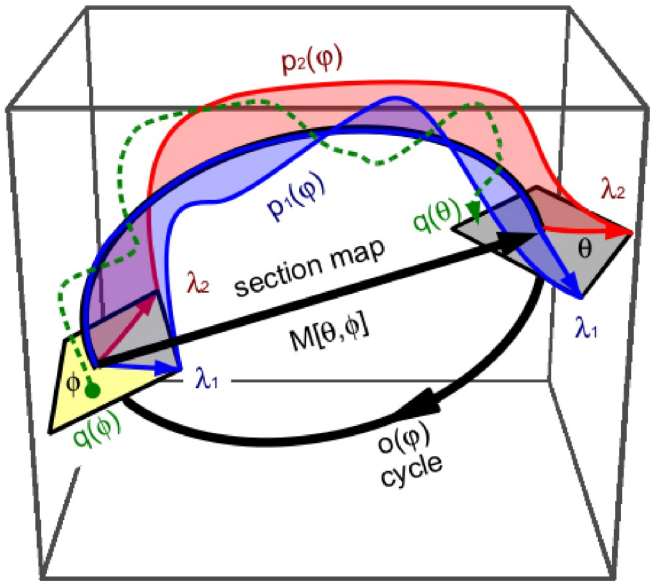
Floquet analysis

Linear approximation to the dynamics around a hypothetical limit cycle

Eigenvalue analysis

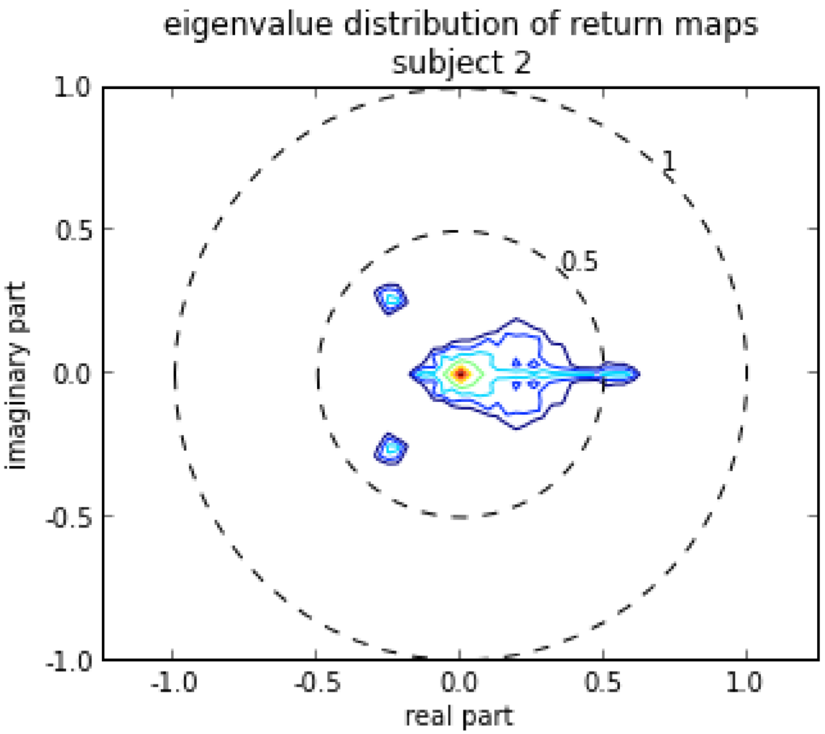
- Analyzing data **around** the limit cycle
- Select Poincaré- section(s)
- Choice of Poincaré- section is arbitrary (in theory)
- Compute mappings from a sectic to the next by OLS
- (for multiple mappings: combine mappings, matrix multiplication)
- For **measured** data: dimension too largy by 1 (tangential direction) → EV 0



from S. Revzen: “Neuromechanical control architectures of arthropod locomotion”, PhD Thesis, Berkeley 2009

Eigenvalues

- The bootstrap (Efron '78):
  - randomly select subset of the data
  - compute quantity of interest (here: return maps and their eigenvalues)
  - repeat for another random subset
- → this results in a *distribution* of eigenvalues, giving a *confidence area* on the eigenvalue distribution
- Here: return map of 45-dim. state (→ 45 eigenvalues)



→ more accurate with multiple sections, but within the original confidence area

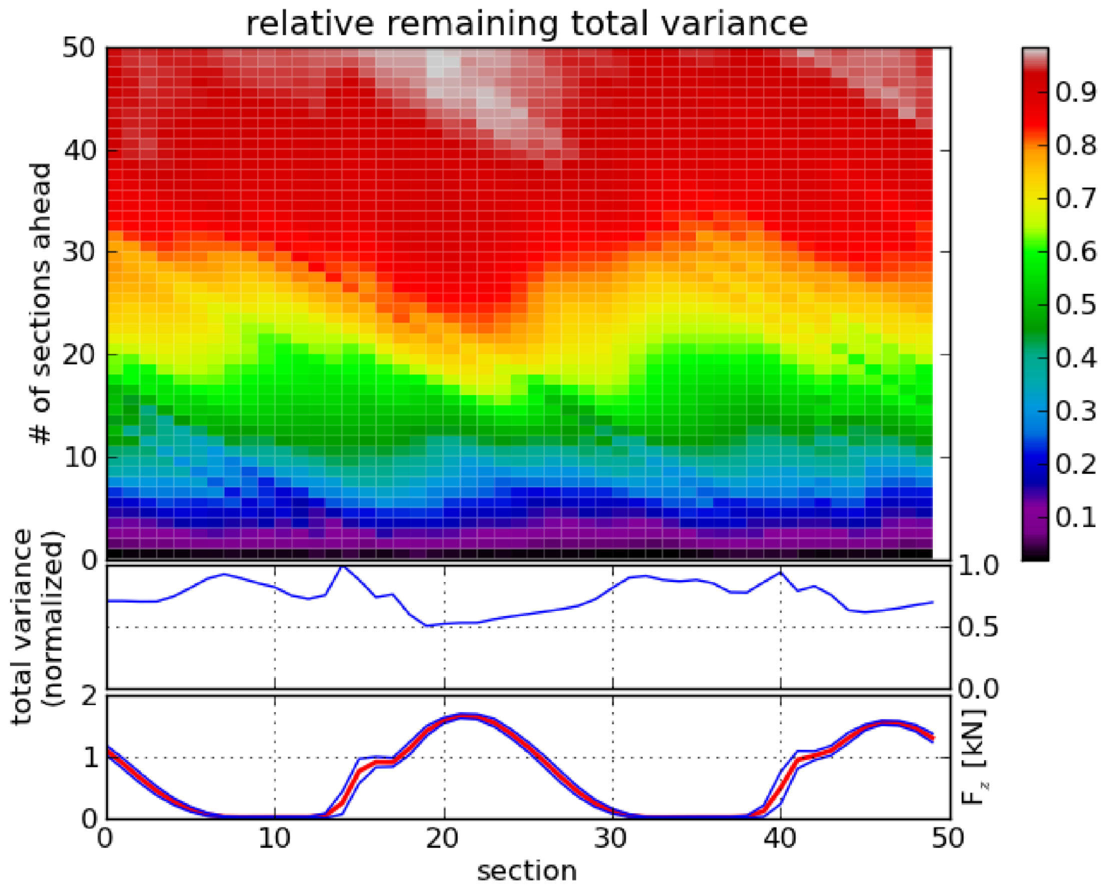
Maus: Towards understanding human locomotion (2013)

Prediction analysis

- Goal: complementary stability analysis:
  "How long is the motion predictable?"
  (stable → *short* prediction (!))
- General linear model: $x(\varphi) = A(\varphi, \phi)\, x(\phi) + \eta$
- Predict state *off* limit cycle
- Compute relative remaining variance:

  var(state – prediction) / var(state)
- Bootstrap → Out-of-sample prediction

Prediction



→ approx. 1-stride deadbeat behavior

Summary

- Linear models predict high stability, approximately 2-step deadbeat
- Explicitly: after 1 step, there is some variance that can be predicted!

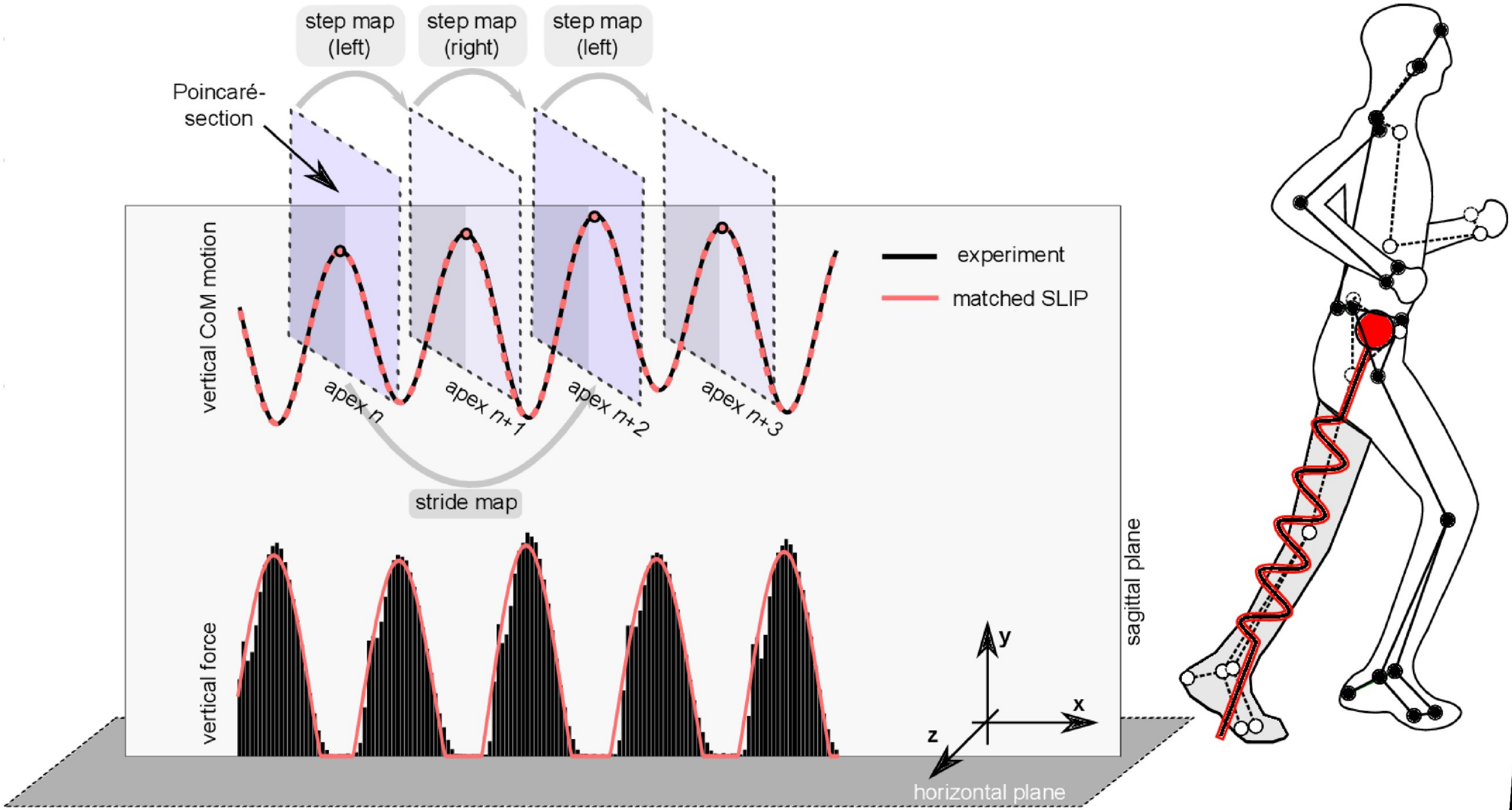
Template models

Explicit minimalistic mechanical models that reproduce human gait

Motivation

- Linear models:
  - don't tell us how the limit cycle is created
  - hardly tells us something about important features of the real system
  - don't give us a hint how to build mechanical analogon
- Idea: explicit **mechanical gait models**
- Requirement: similar behavior

About templates



SLIP model for running

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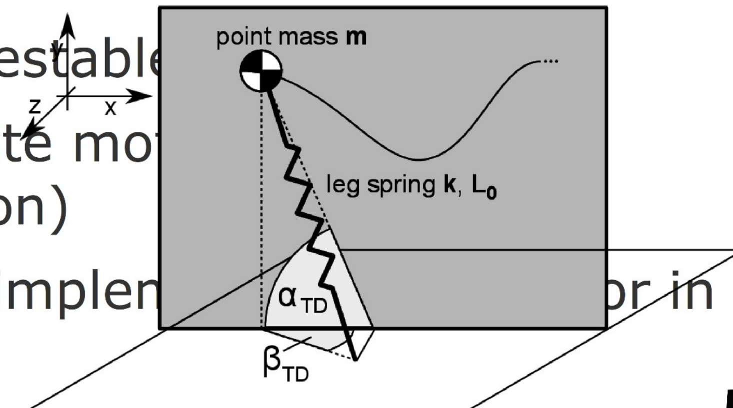
- simple, intuitive, understandable model
- excellent match with experimental CoM dynamics
- complete step dynamics are reduced to a few model parameters
- How to gain insights with this model?
  - investigations on the model → testable
  - analyzing corresponding template mo measurement data (simplification)
  - “anchoring” the model: how to implem or in more complex systems?



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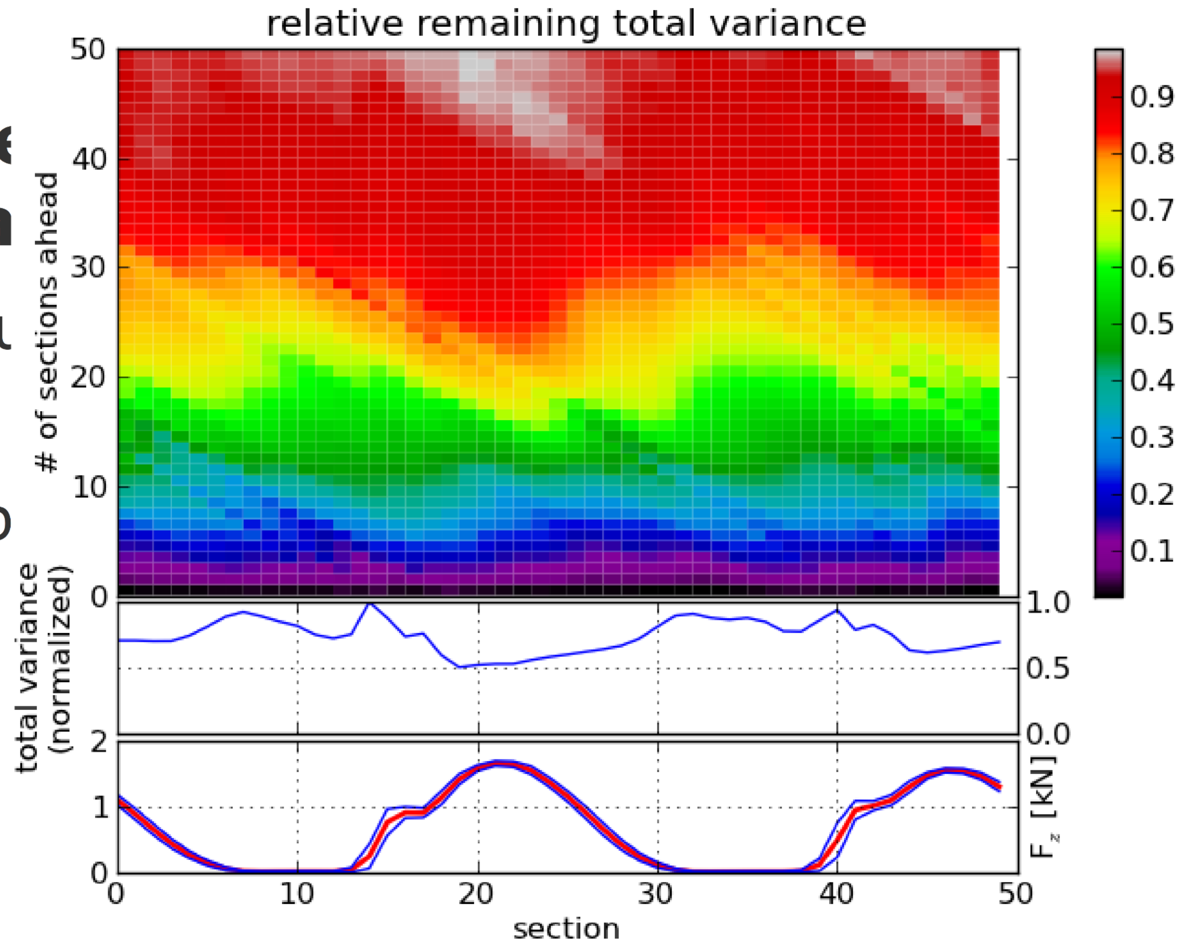
Example of a testable hypothesis

- (Carver, 2009) showed that **de** requires **at lea**
  - argument is qu
  - generalization
  - → testable hyp

→ good agreement with experimental data (2012)

→ NEW: there *is no* controller that could do better!



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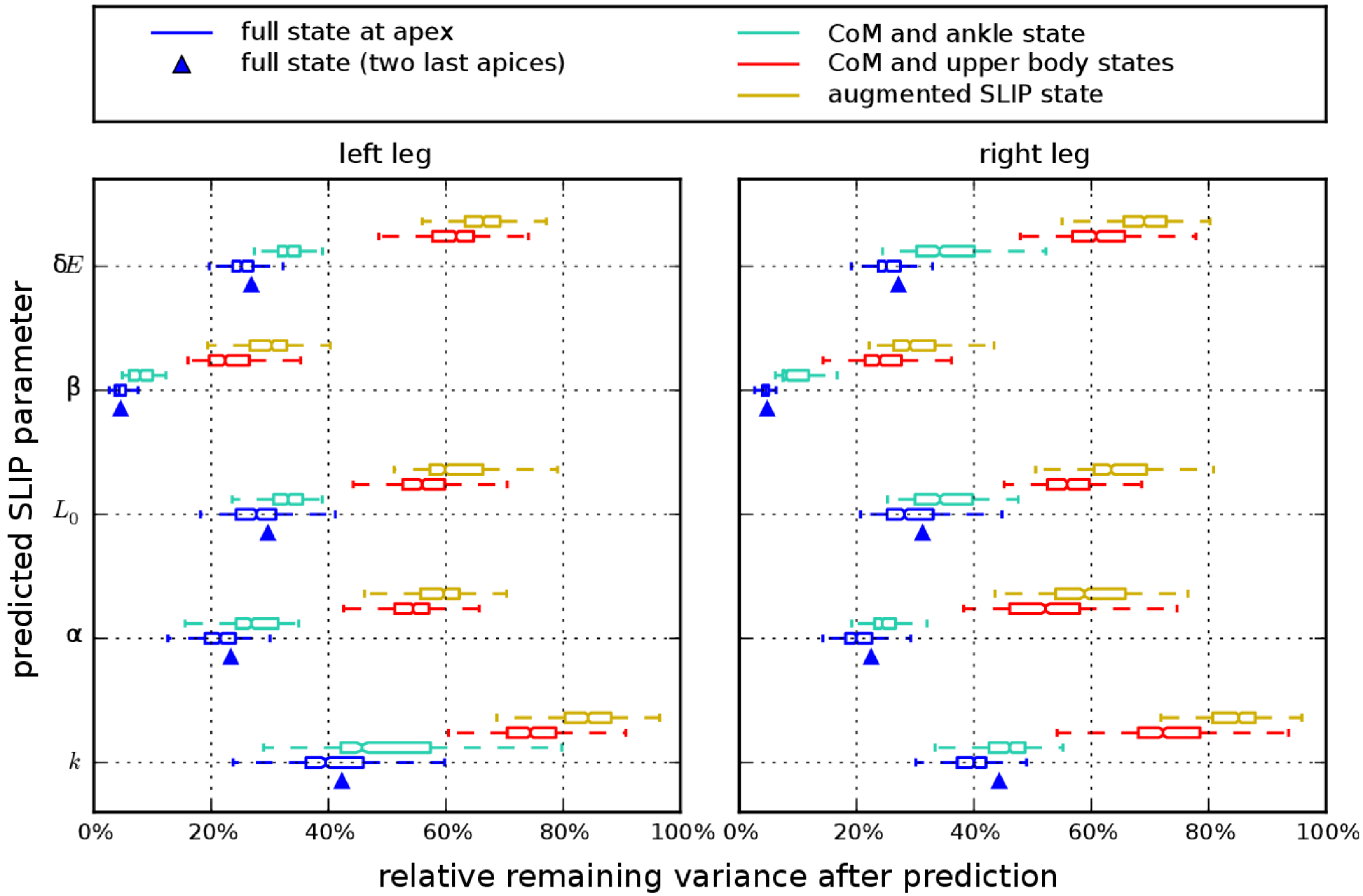
Control input identification



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Autonomous system

- We compute maps:
  [CoM; Ankle] → SLIP parameter

  [CoM; Ankle] → Ankle (n+1)
- This + SLIP yield an autonomous system (9D apex map)
- Compare eigenvalues with 45-dim Floquet model

Comparison of eigenvalues

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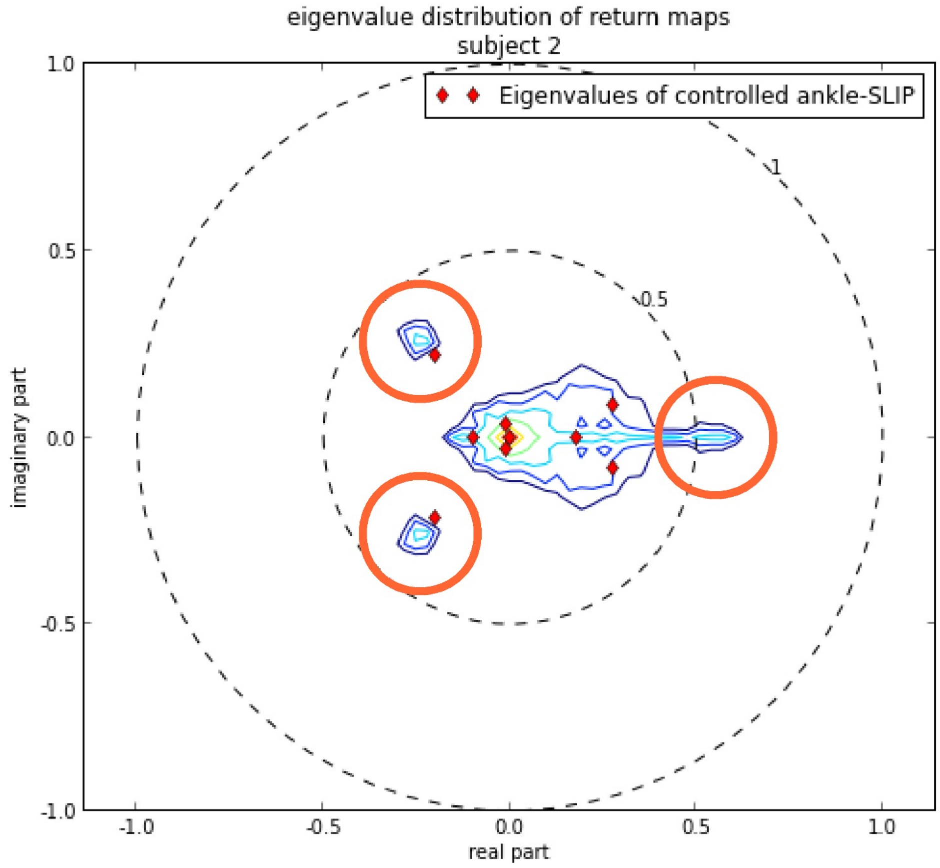
- 45-dim. return map
- 9-dim. "ankle SLIP" return map



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Summary (intermediate)

- Templates generate gaits (“reference” motion)
- SLIP is not self-contained w.r.t. capturing human running
- “SLIP + ankle” is (almost) an autonomous subsystem of human running at jogging speed
- However: not yet a full template: mechanical motion of ankles excluded!

Extending SLIP

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- The bipedal SLIP is able to walk (Geyer, 2006)

  → video

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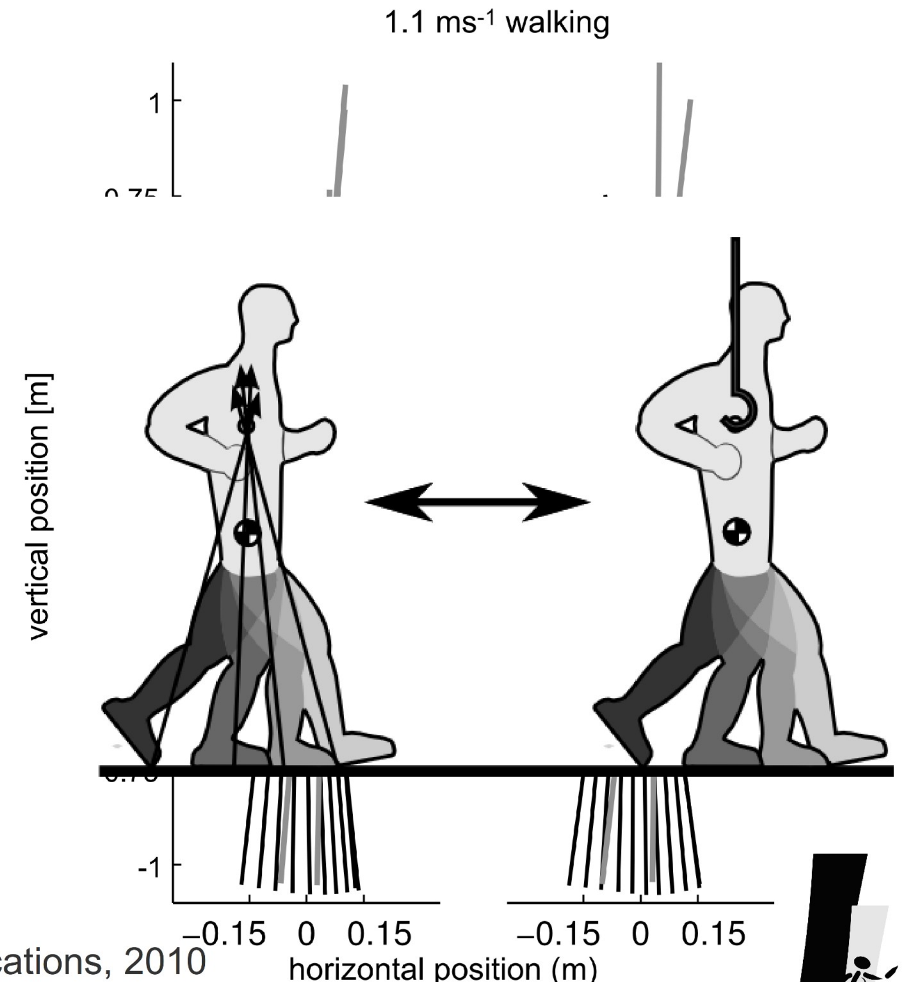
What about the trunk?

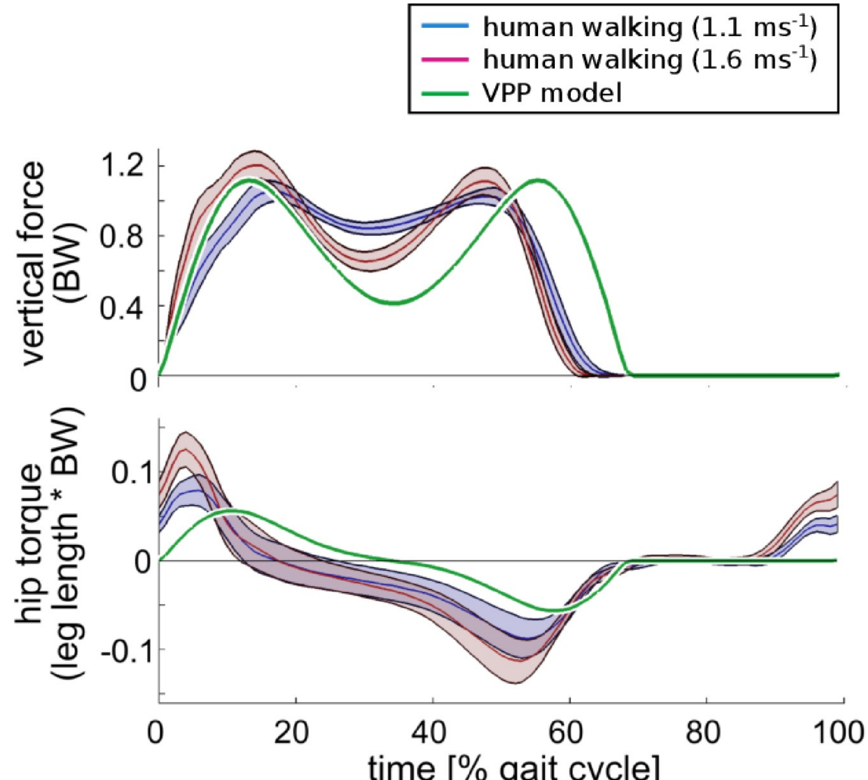
- What about a template for stabilizing the posture?
- Forces intersect → "Virtual pivot point" VPP



Maus et al, Nature Communications, 2010

The VPP model

- based upon bipedal walking SLIP
  → video
- compares well with experiments



Maus et al, Nature Communications, 2010

Summary: Templates

- Templates: highly reduced mechanical models
- Can describe human locomotion
- *Can behave* human-like: Useful for understanding human locomotion
- *Simplicity* allows *generic* investigations
- Attention: don't take too literally

Templates in robot control

(*Overview only*) How templates can be used for robot control

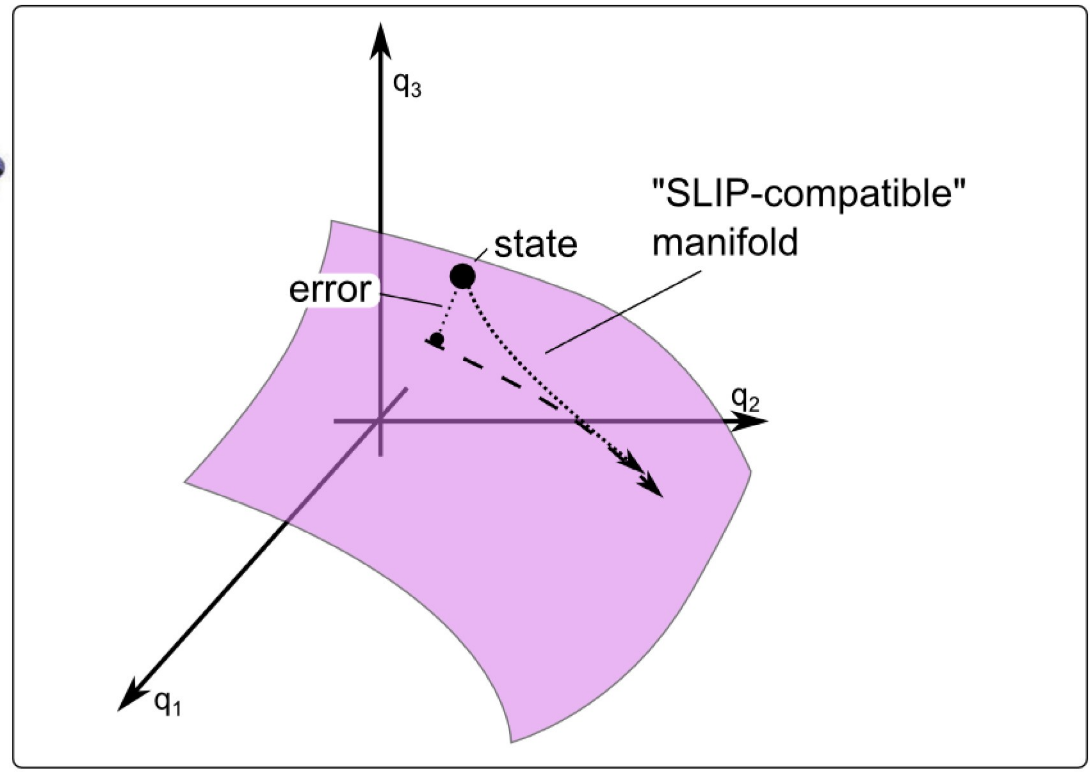
Proof of concept

- "Mable" runs and walks using a **SLIP-embedding** controller

  → video

  Uses "hybrid zero dynamics" (Chevallereau et al., 2002; Poulakakis and Grizzle, 2009; ...)

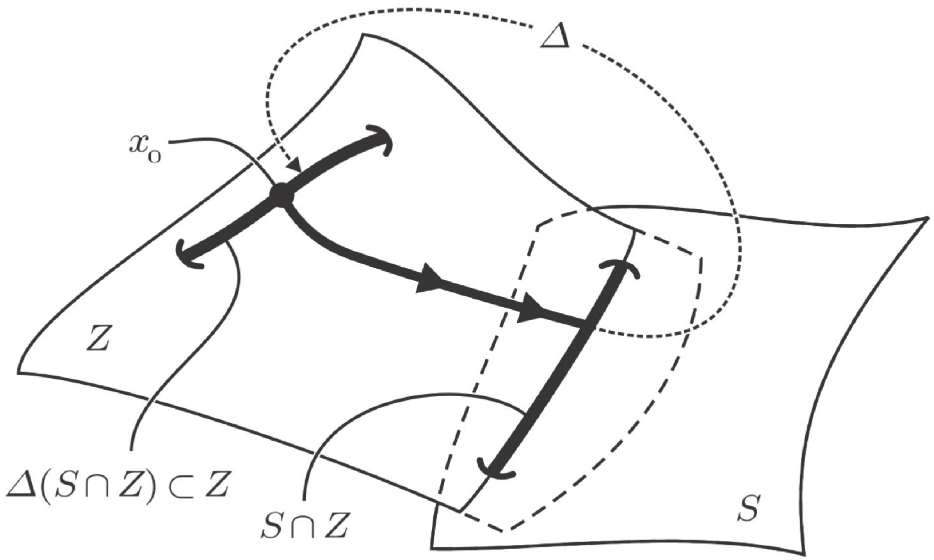
Hybrid zero dynamics



from: Poulakakis and Grizzle, IEEE Transactions on automated control (54), 2009

Hybrid zero dynamics

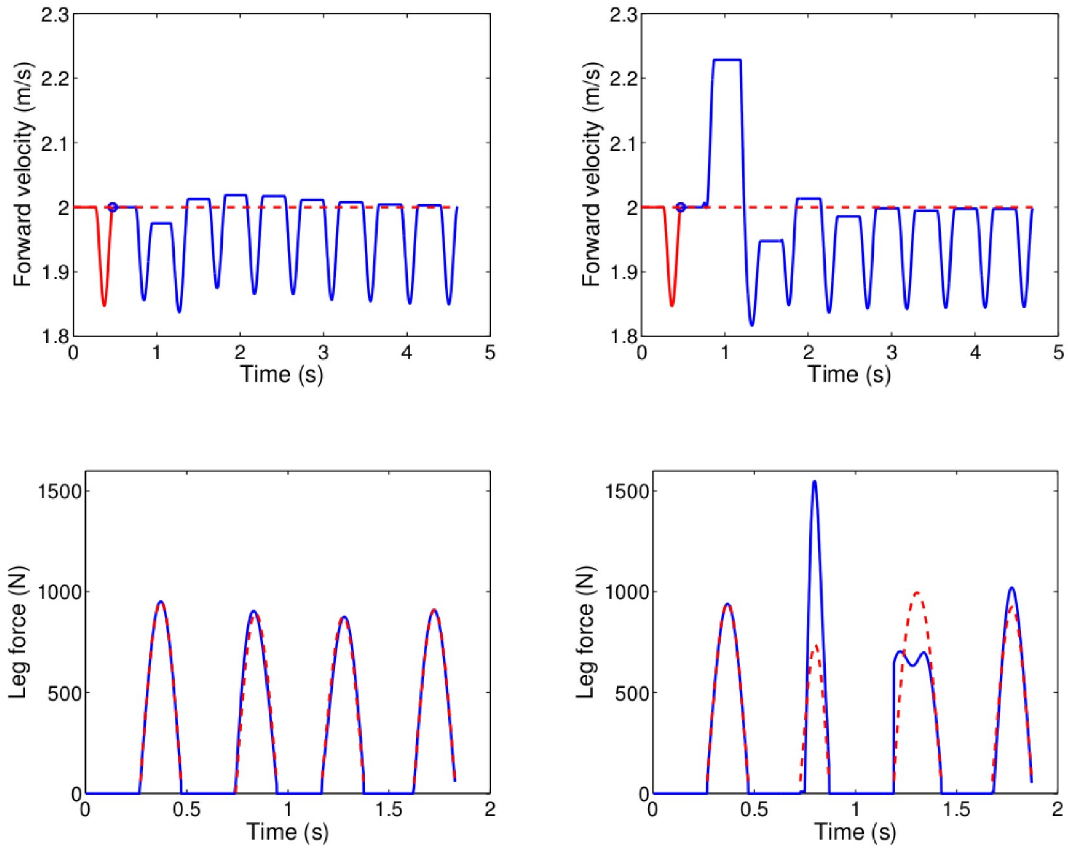
- Needs to take discrete events into account: *impact* maps
- Not necessarily a problem – can be used for control!



From: Chevallereau et. al., IEEE Control Systems Magazine (23), 2003

Comparison

- Here, HZD outperforms reference trajectory based rigid body controller
- Key feature: ignores “SLIP-compatible” errors



HZD based controller

reference trajectory based controller

Poulakakis and Grizzle, IEEE Transactions on automated control (54), 2009

Thank you for your attention!