ISEK

# An Introduction into the analysis of stabilizing feedback control of walking

**Jaap van Dieën, Sjoerd Bruijn, Maarten Afschrift**

**Department of Human Movement Sciences**
**Vrije Universiteit Amsterdam**
**Amsterdam Movement Sciences**

# Speakers and Titles

Jaap van Dieën

Fall risk, gait stability, and feedback control
15 min + 5 min Q&A

Sjoerd Bruijn

Mechanisms to stabilize steady-state gait
25 min + 10 min Q&A

Maarten Afschrift

Feedback control after gait perturbations
25 min + 10 min Q&A

Vrije Universiteit Amsterdam

Chair: Minoru "Shino" Shinohara (Georgia Institute of Technology, USA)

Note: Please type your questions into the **Q&A box**, not the Chat box

# Fall risk, gait stability, and feedback control

**Jaap van Dieën, dept of Human Movement Sciences, VU Amsterdam**

# fall risk in older adults, annual statistics in the Netherlands

**108.000**

treatments in emergency dept

3320 per 100.000 inhabitants > 65 yrs

# walking a risk for falls

most falls occur while walking

in community dwelling elderly and

*Berg et al. Age & Ageing 1997*

in residents in long-term care

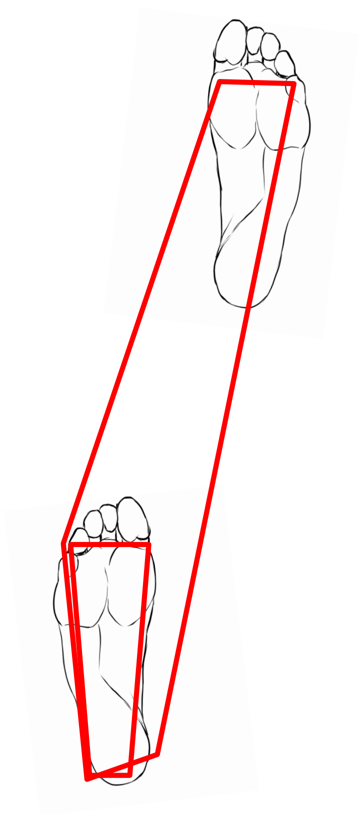
*Robinovitch et al. Lancet 2013*

many of these falls occur without major external perturbations

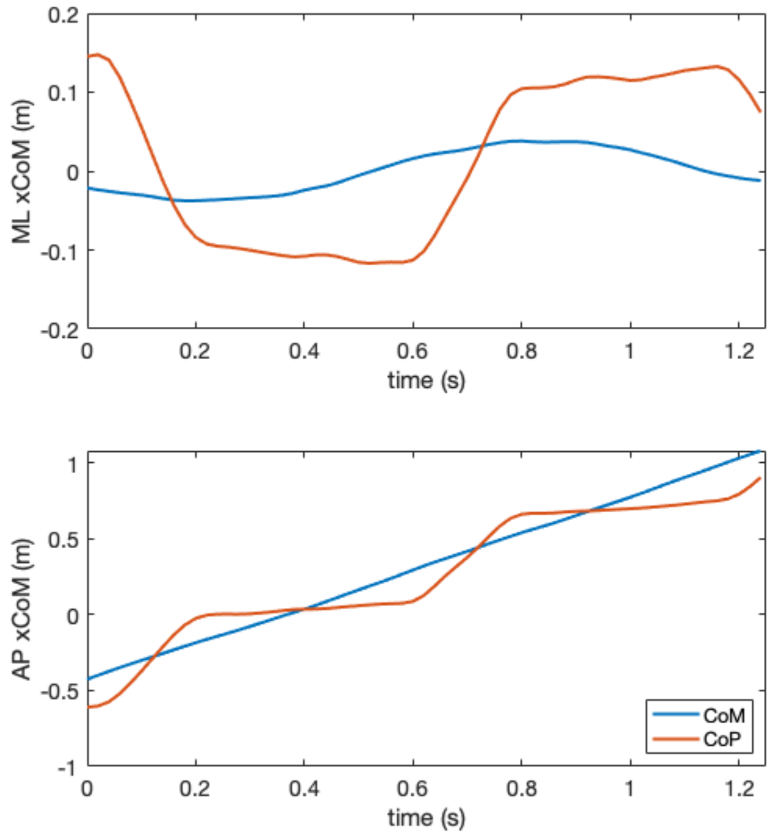
*Robinovitch et al. Lancet 2013*

# gait stability

CoM moves high above small BoS



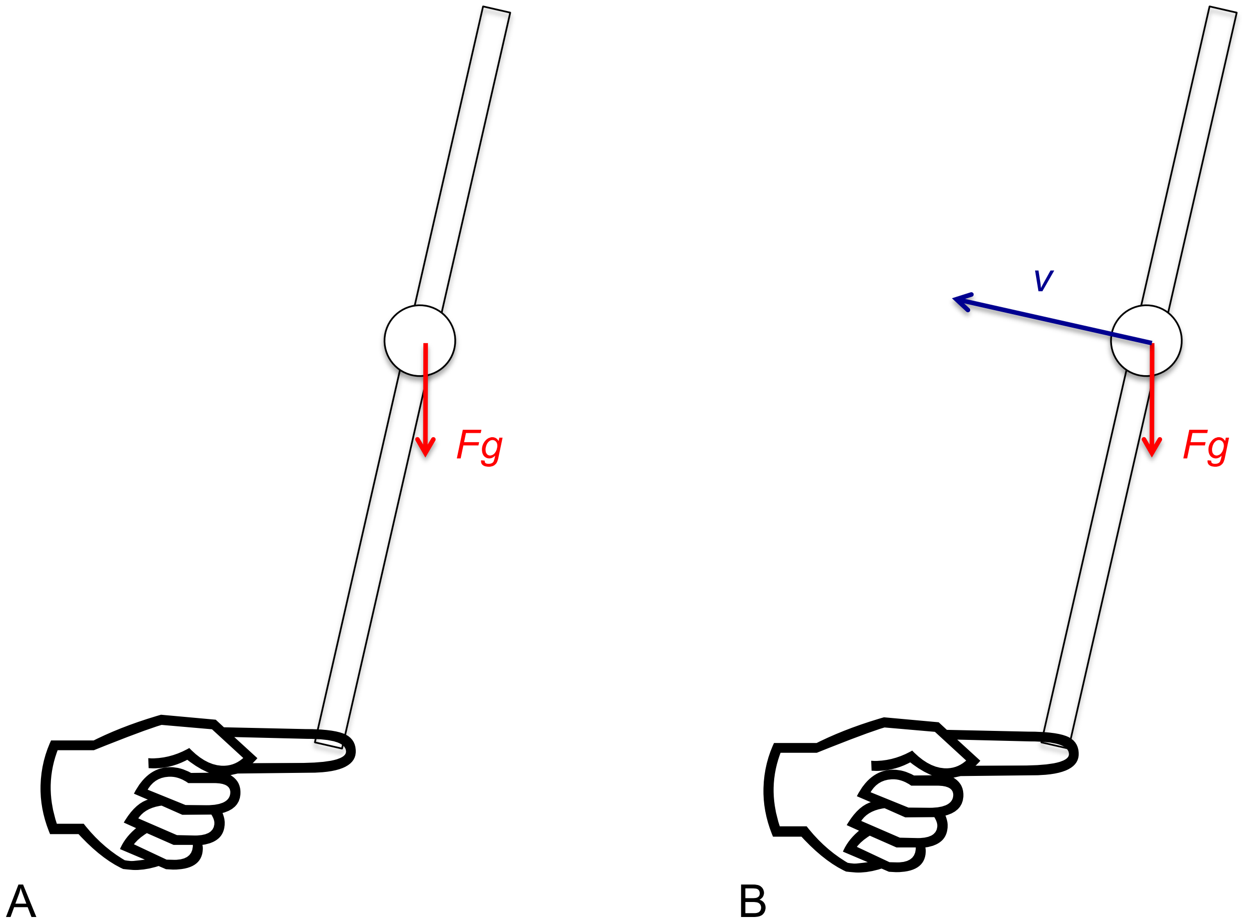
CoM moves toward and beyond stance foot




modeling suggests that feedback control is needed

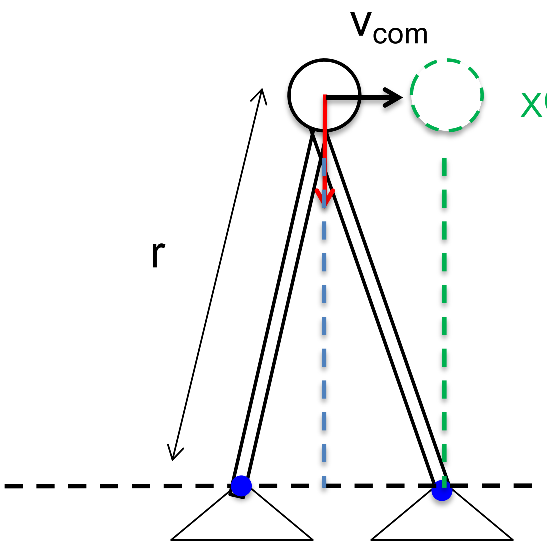
*Bauby & Kuo J Biomech 2000*

# CoM state feedback




position and velocity feedback are needed

# CoM state



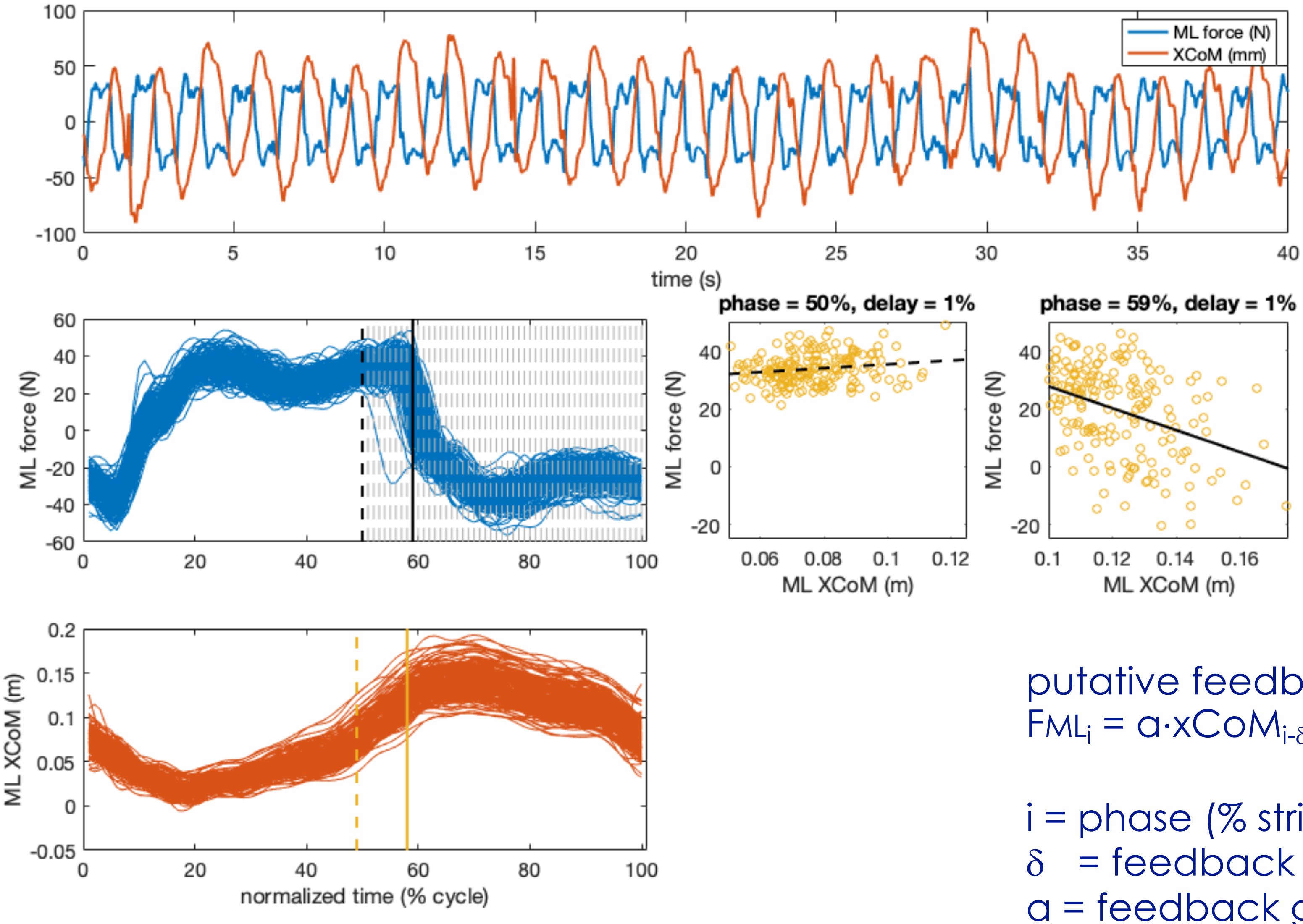

xCoM = CoM + dCoM/dt/ω

ω=√(g/r)

extrapolated center of mass (xCoM)

predicts where foot should be placed to control CoM velocity


*Townsend J Biomech 1985*
*Hof et al. J Biomech 2005*
*Hof Hum Mov Sci 20008*



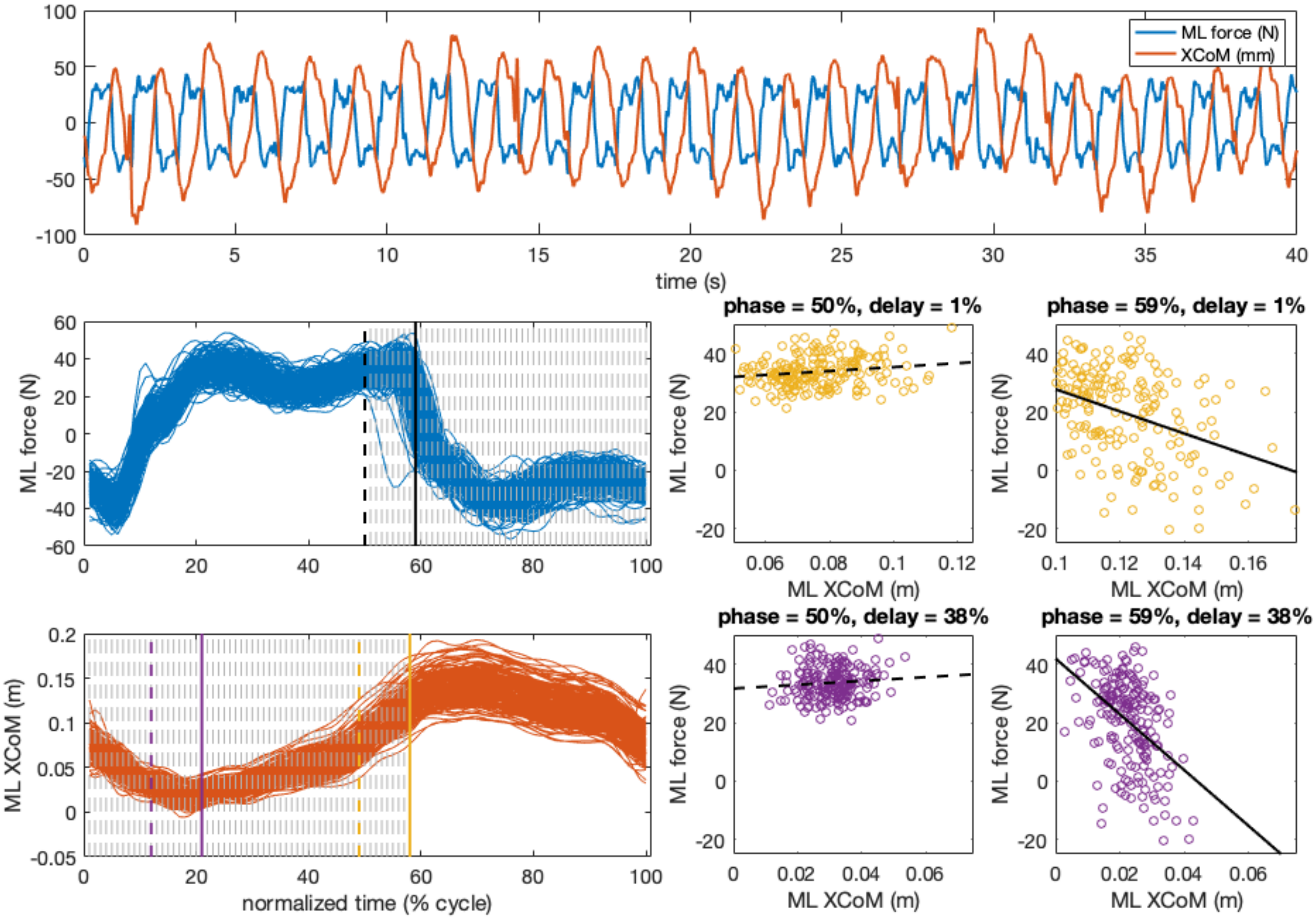

putative feedback model:

$F_{ML_i} = a \cdot xCoM_{i-\delta} + b$

i = phase (% stride)

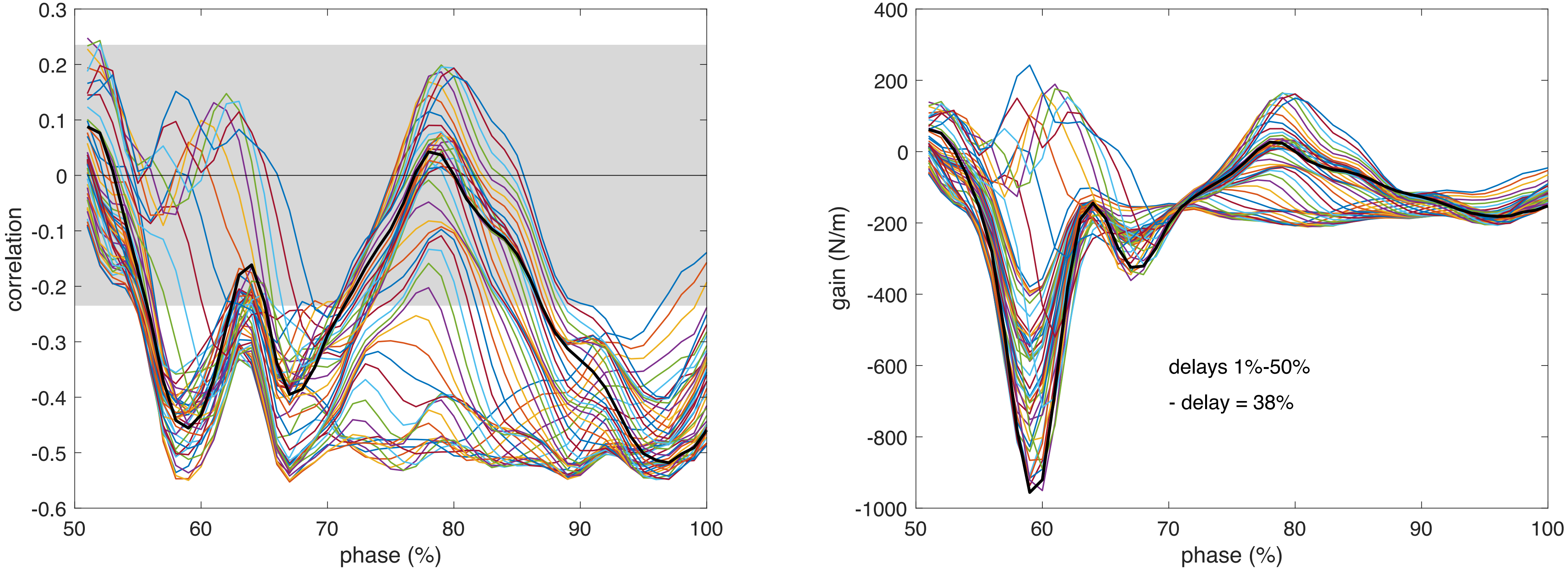
$\delta$ = feedback delay (% stride)

a = feedback gain




$$F_{ML_i} = a \cdot xCoM_{i-\delta} + b$$

# mediolateral stabilization, typical example



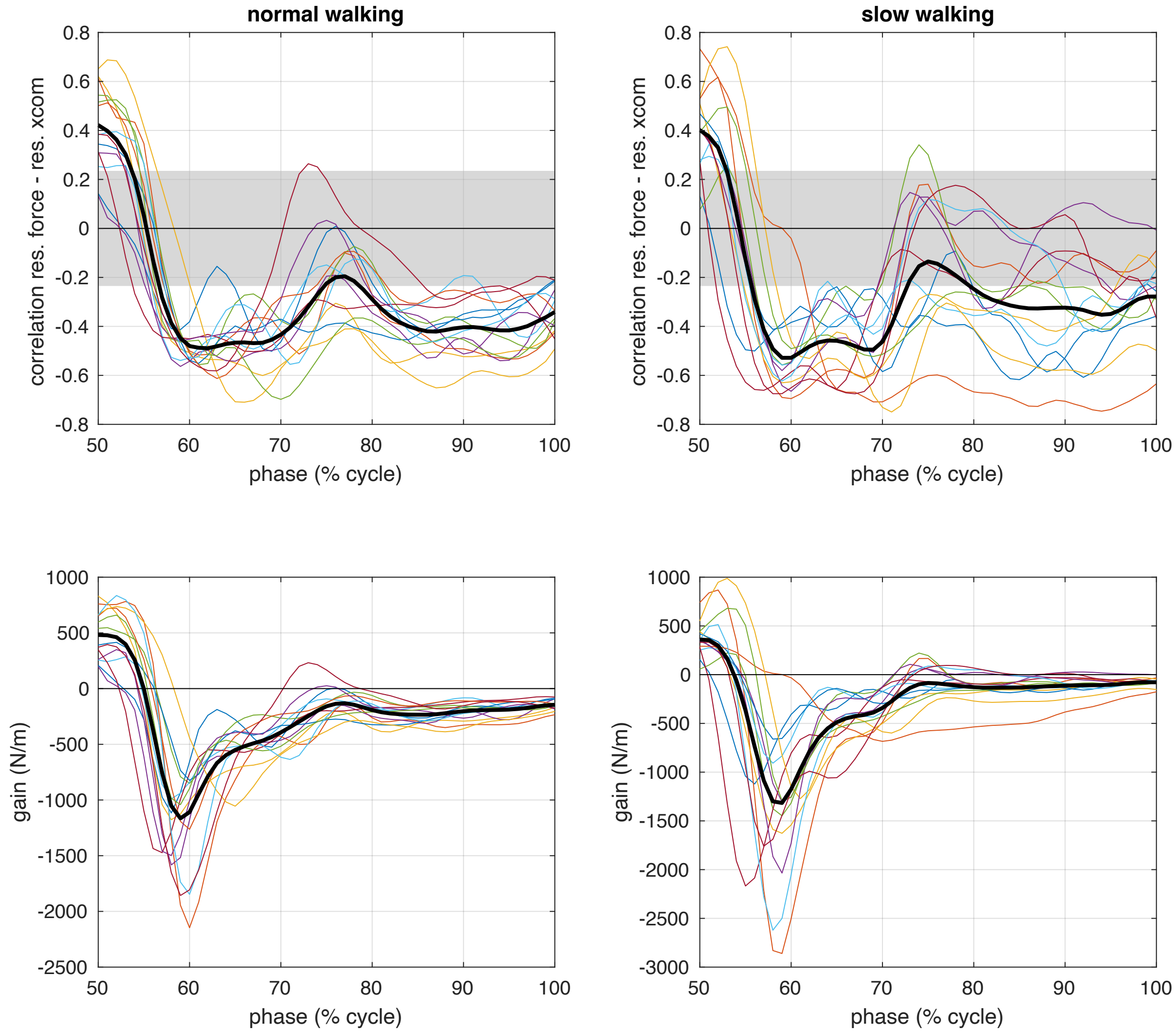

delay yielding largest negative gain selected

# mediolateral stabilization, group results

normal and slow
treadmill walking

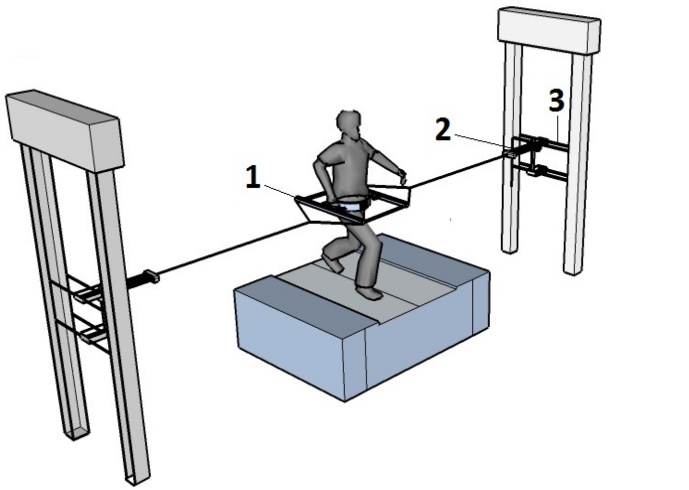
n = 14
normalized speed =
1.25 and 0.63

*data from van Leeuwen et al. PONE 2020*



# effects of stabilization demands

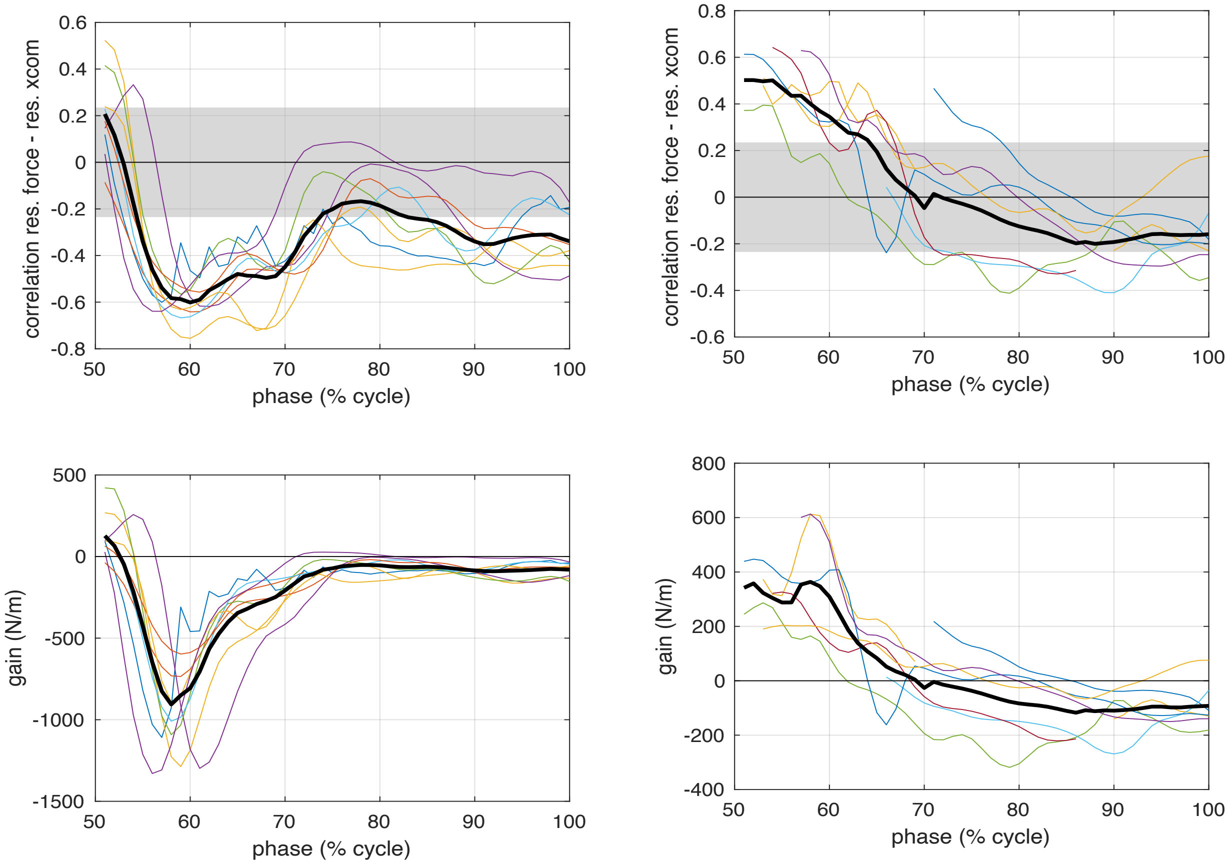
normal and stabilized treadmill walking




n = 8
speed = 0.8 m/s

*data from Magnani et al. Sci Rep 2021*

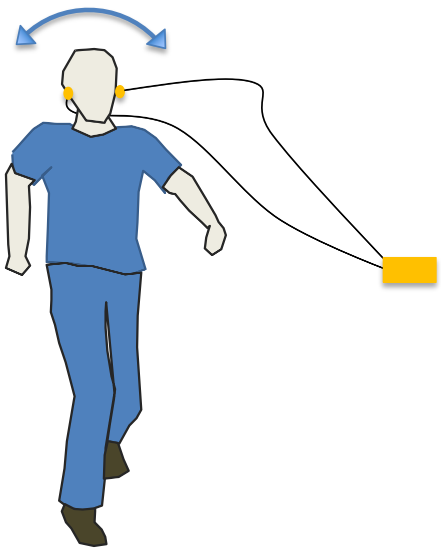
normal | stabilized



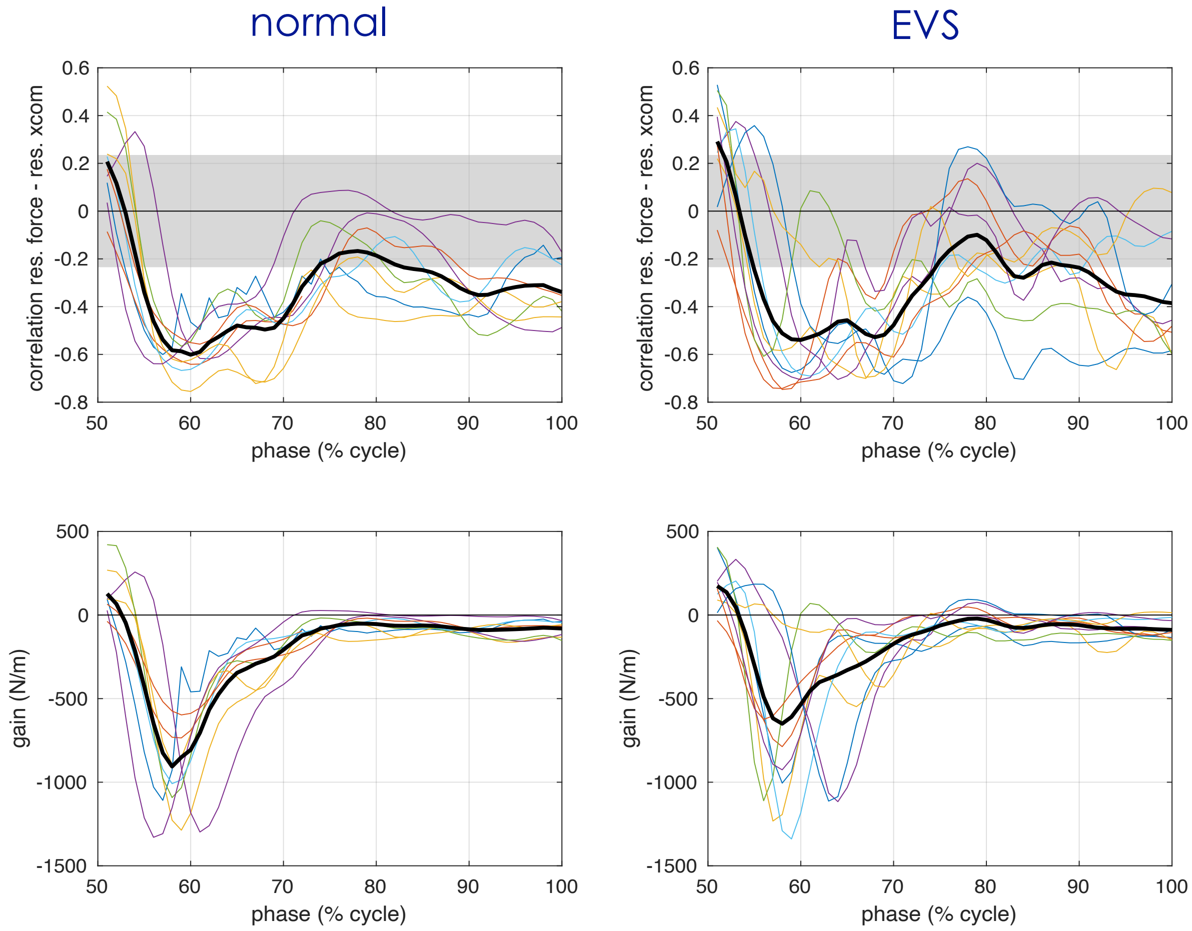

decreased correlation and gain indicate role in stabilization

# effects of sensory perturbations

normal and perturbed treadmill walking



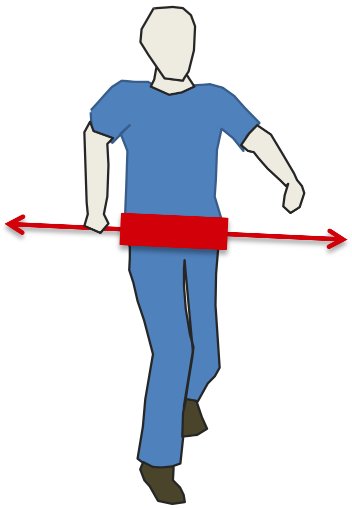
n = 8
speed = 0.8 m/s
*data from Magnani et al. Sci Rep 2021*




decreased correlation with EVS indicates feedback

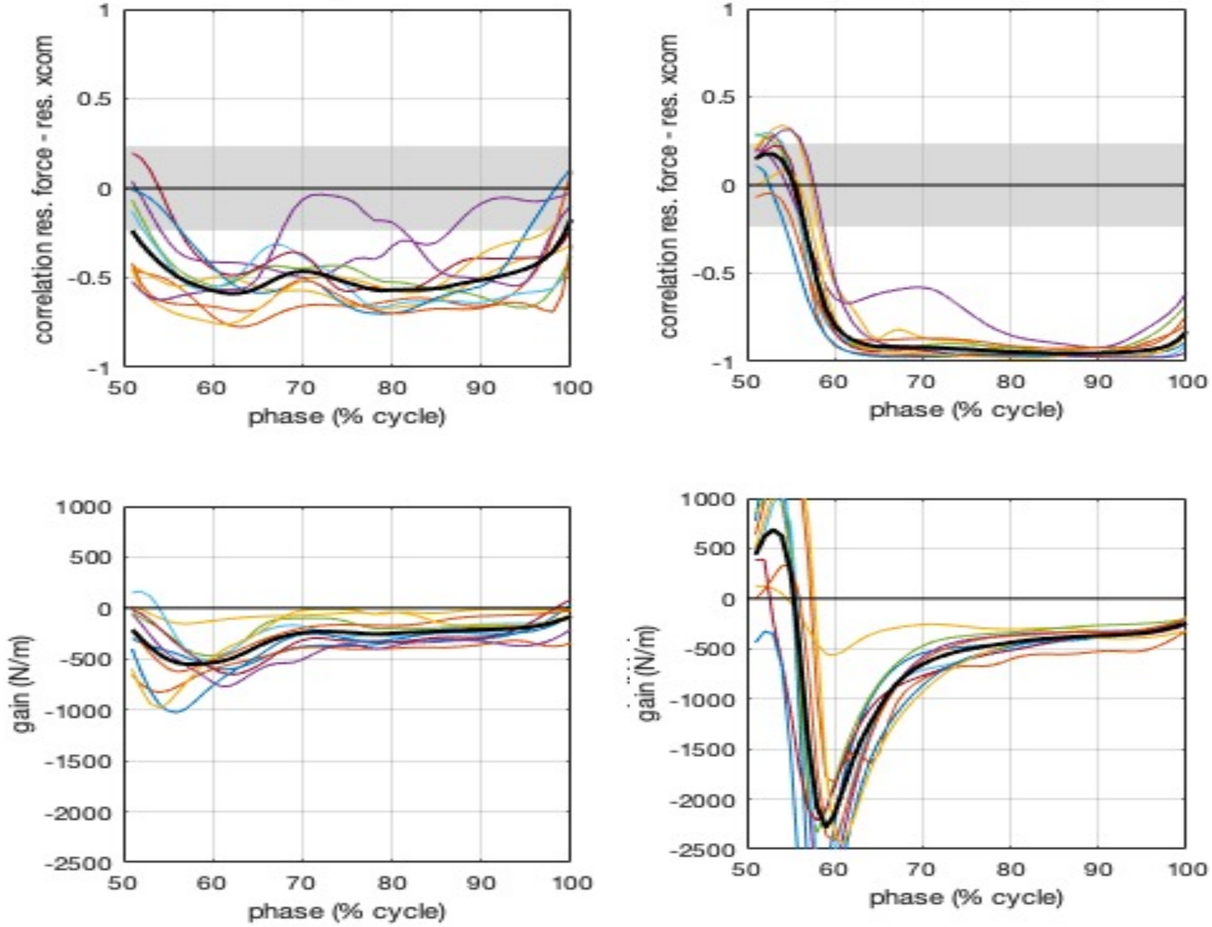
# effects of mechanical perturbations

normal and perturbed treadmill walking



n = 9
speed = 1.25 m/s
*data from Vlutters et al. Sci Rep 2018*

steady-state | waist pulls




increased correlation and gain in perturbed gait

# conclusions

phase dependent CoM state (xCoM) feedback

- affected by stabilization demands
- impaired by electrical vestibular stimulation
- used in steady-state and enhanced in perturbed gait

NB results for anteroposterior control are very similar

goodness of fit, residual error, and gain characterize stabilizing feedback control and may have diagnostic value

mocap of pelvis marker (CoM proxy) on an instrumented treadmill allows assessment of stabilizing feedback control

Amsterdam Movement Sciences

VU Vrije Universiteit Amsterdam

Amsterdam UMC University Medical Centers

# Thanks for your attention

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Maarten Afschrift, Mina Arvin, Sjoerd Bruijn, Jaak Duysens, Marco Hoozemans, Moira van Leeuwen, Rina Magnani, Mohammadreza Mahaki, Mirjam Pijnappels, Sabine Verschueren

KEEP CONTROL
HORIZON 2020
EUROPEAN EARLY STAGE RESEARCHER NETWORK

MOVE AGE

eurobench
European robotic framework for bipedal locomotion benchmarking

Motek a DIH brand

NWO Netherlands Organisation for Scientific Research

# Mechanisms to stabilize steady-state gait

**Sjoerd Bruijn, Department of Human Movement Sciences**
**Vrije Universiteit Amsterdam**
**Amsterdam Movement Sciences**

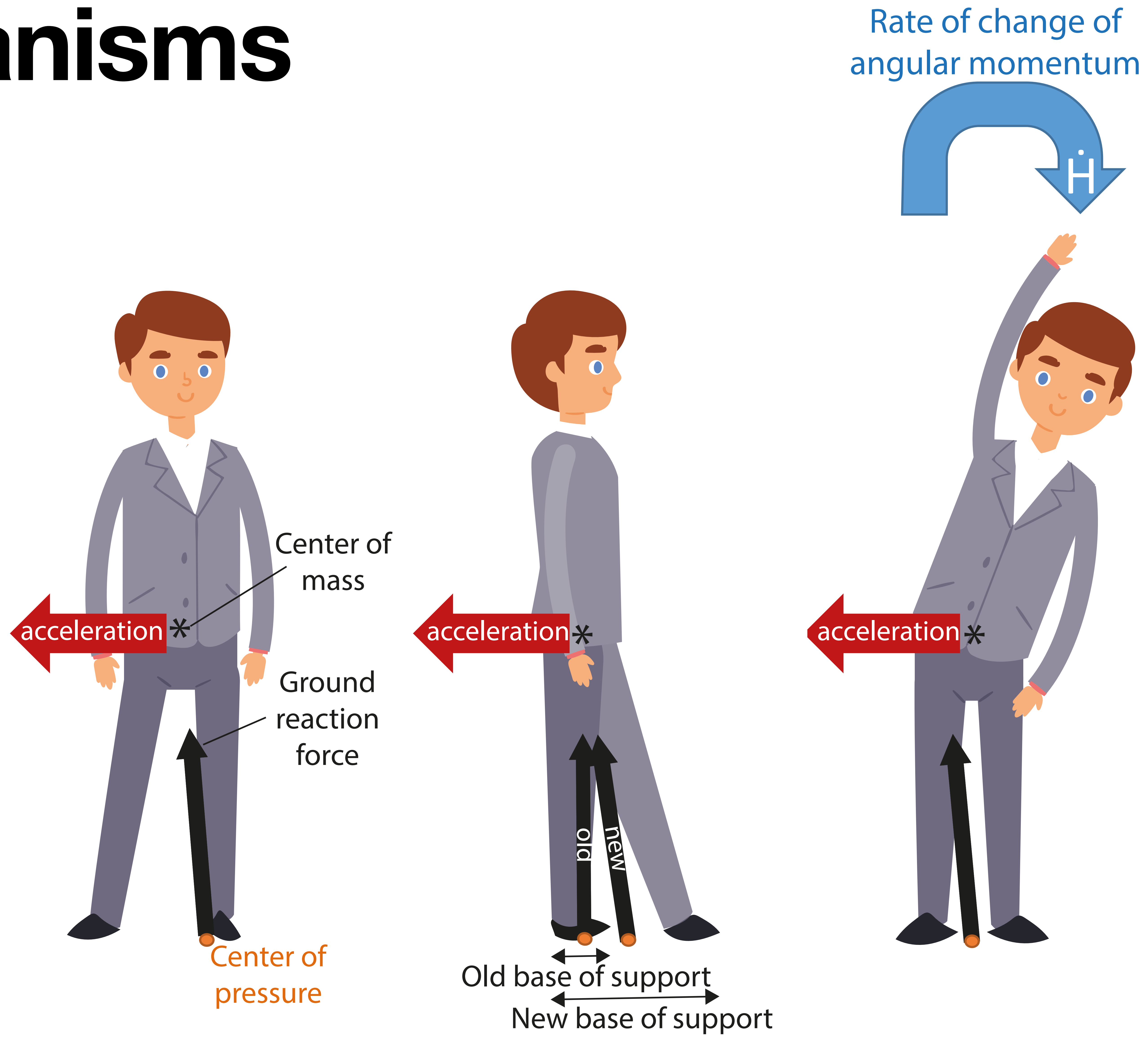
# Acknowledgements

Jaap van Dieën, Andreas Daffertshofer, Mirjam Pijnappels, Mohammadrezah Mahaki, Jian Jin, Moira van Leeuwen, Maarten Afschrift, Hendrik Reimann, and several others

Vidi Grant
016.Vidi.178.014

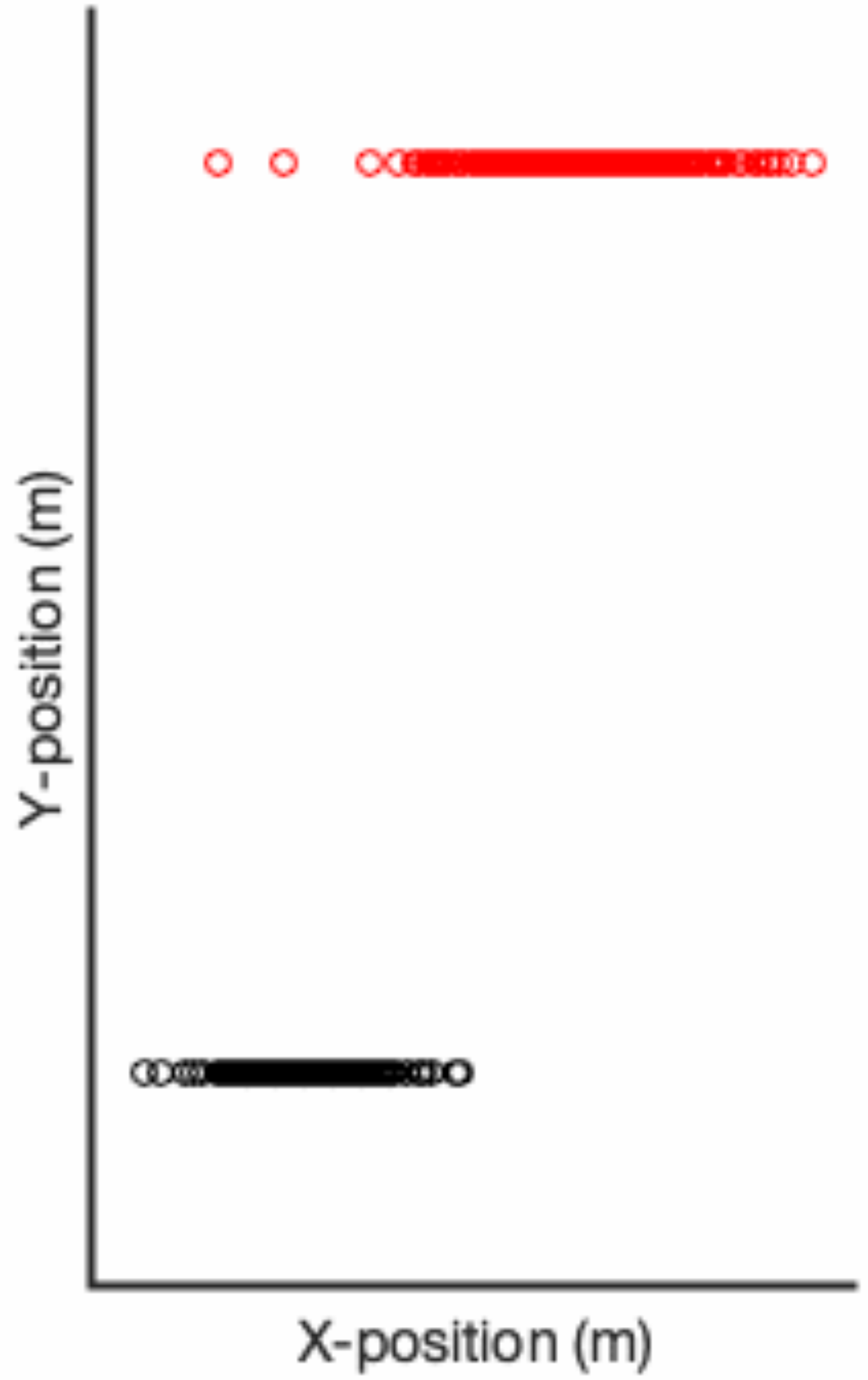
Amsterdam
Movement Sciences

# 3 mechanisms




Hof (2008) Hum Mov Sci

# Foot placement: linear models



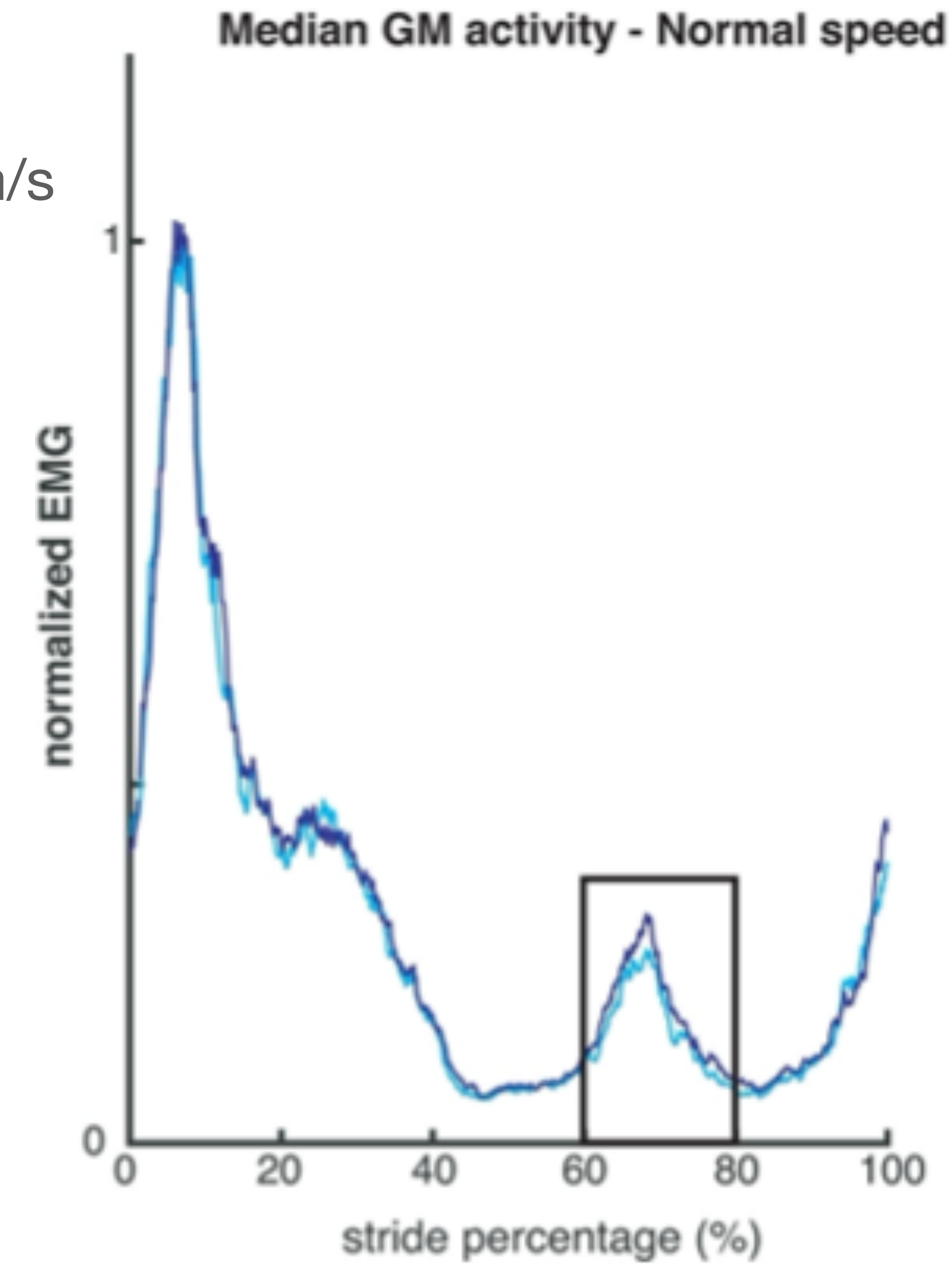

$$FP = \beta_{vel} \cdot C\dot{o}M(i) + \beta_{pos} \cdot CoM(i) + \varepsilon(i)$$

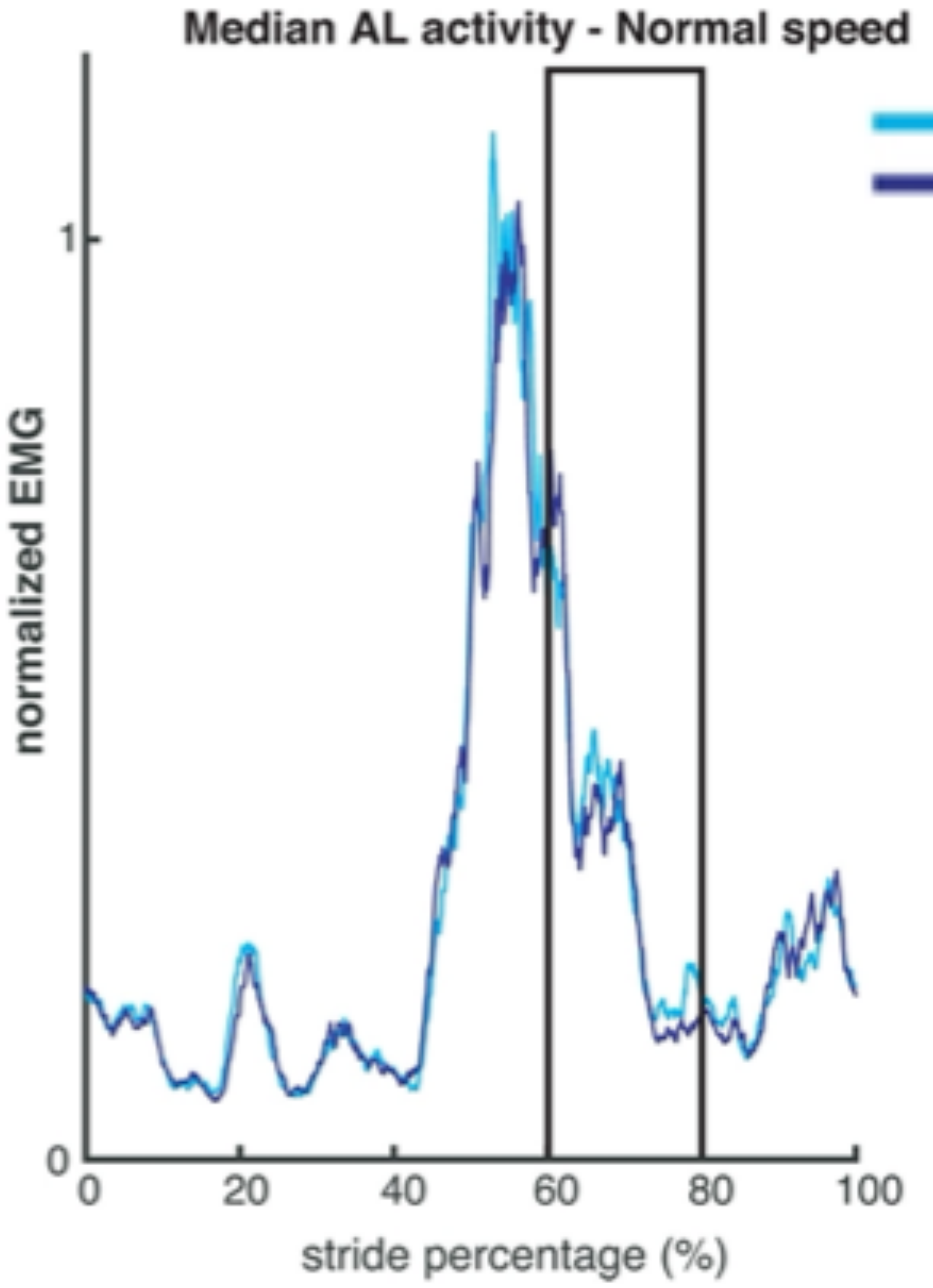
Wang & Srinivasan (2014) Biol Let

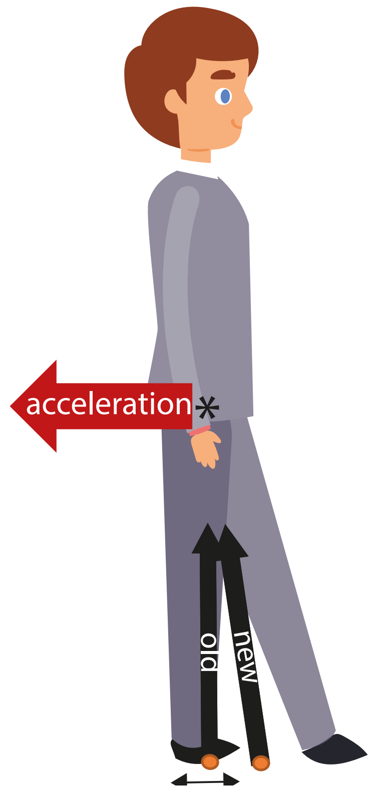
https://github.com/SjoerdBruijn/FootPlacement

# Foot placement: Active control!

n=30
V=1.25 × sqrt(L) m/s



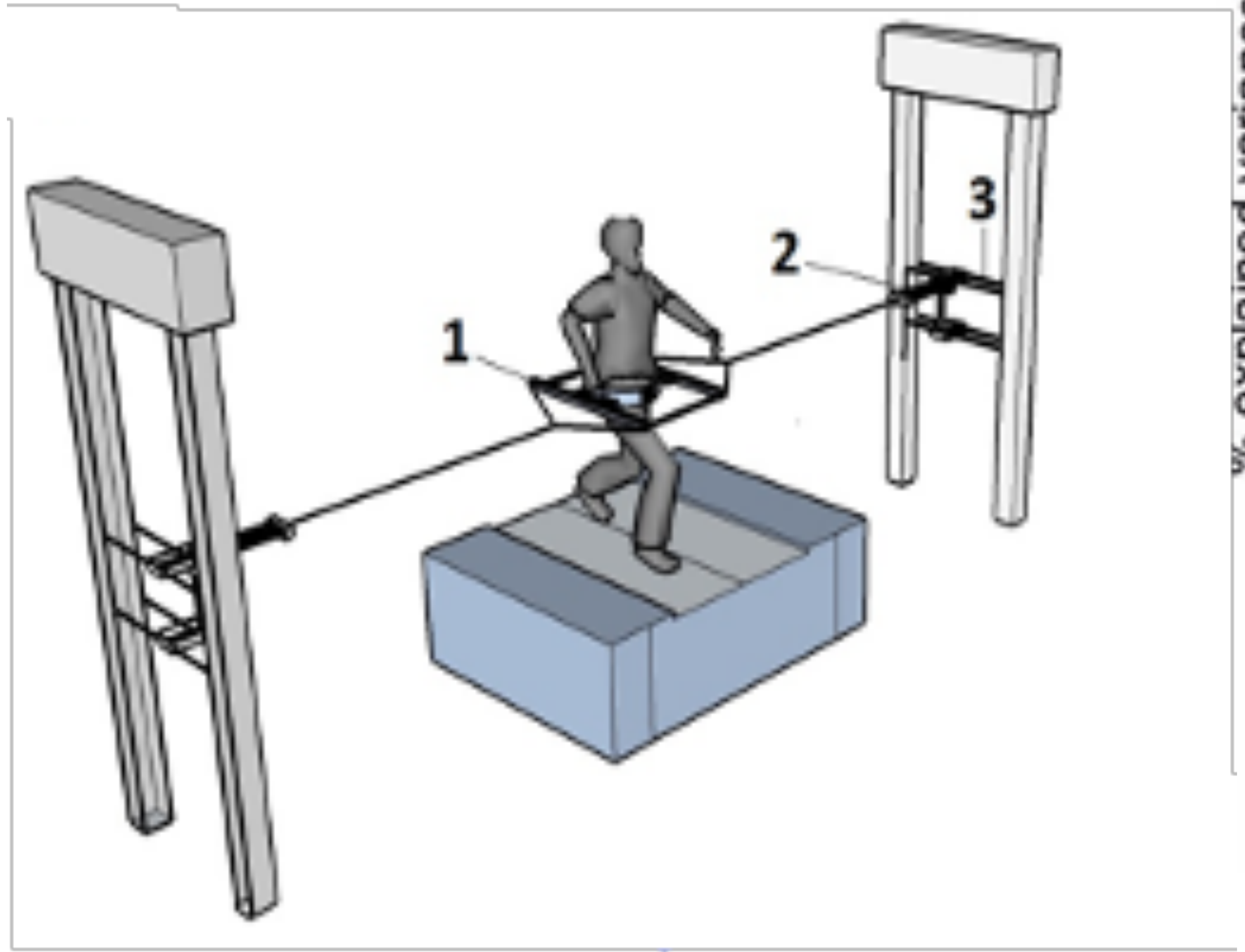



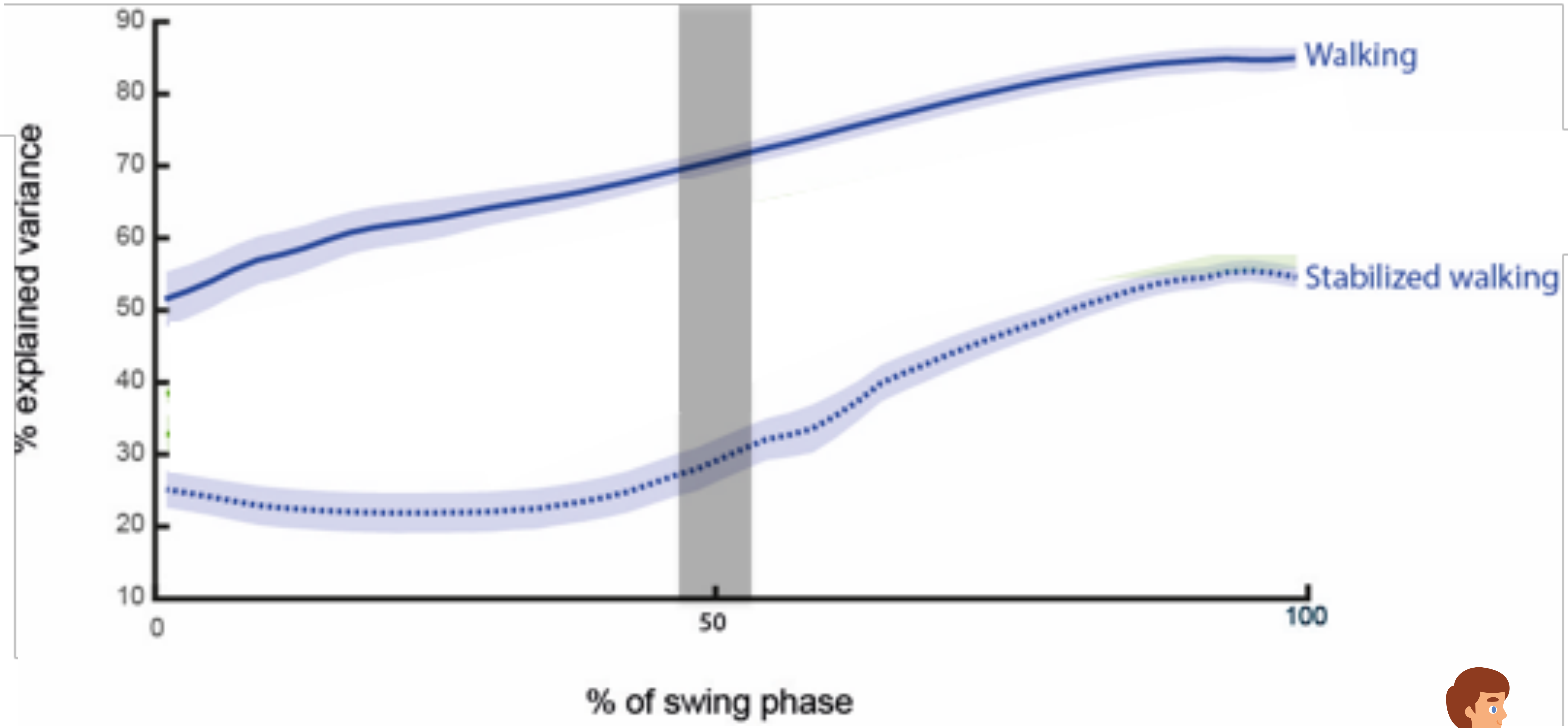

Ranking et al (2014) J Neurophysiol; Van Leeuwen et al (2020) PLoS One

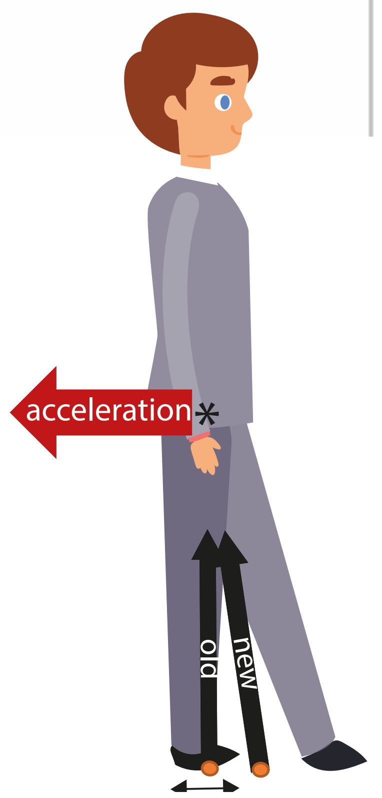
# Foot placement: Stabilisation

normal and ML
stabilized walking




n = 10
speed = 1.25 m/s

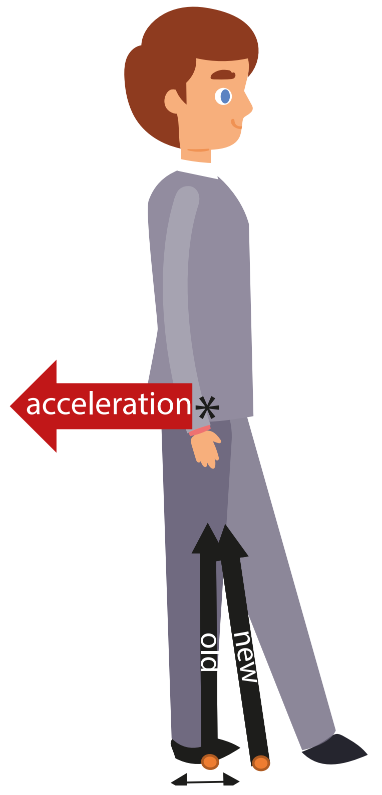



Mahaki et al (2019) PeerJ

# Foot placement

- Foot placement relative to CoM can be described using linear models
- Foot placement relative to the CoM is actively controlled
- Foot placement is used to control gait stability



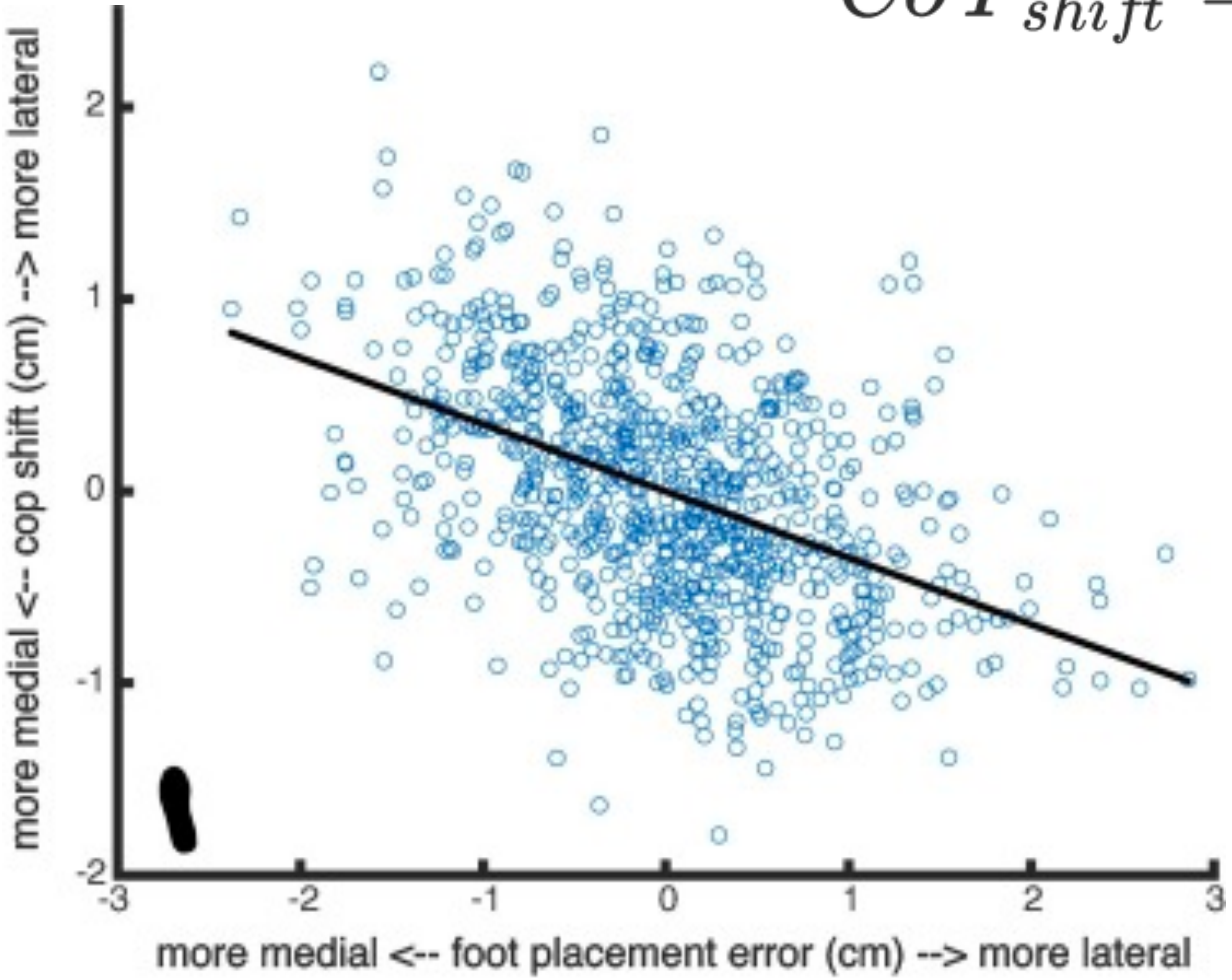
# Error term

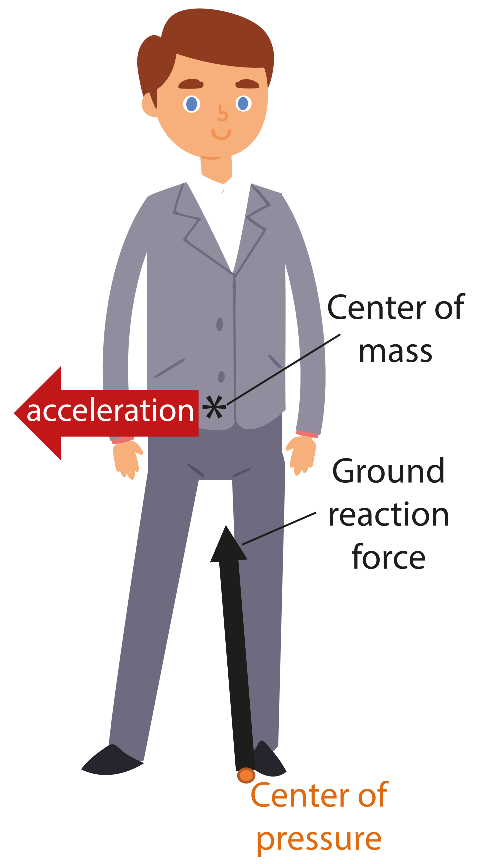
$$FP = \beta_{vel} \cdot C\dot{o}M(i) + \beta_{pos} \cdot CoM(i) + \varepsilon(i)$$

# Ankle moment control

$$CoP_{shift} = \beta_{fp\_error} \cdot \varepsilon_{fp} + \varepsilon_{am}$$

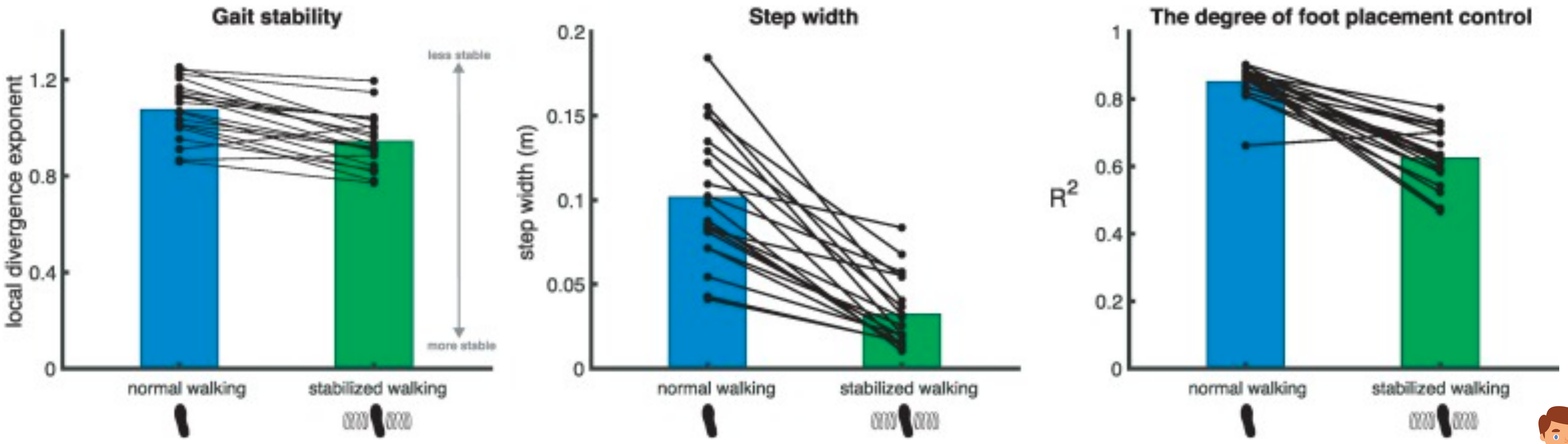
n=20
V=1.25 × sqrt(L) m/s

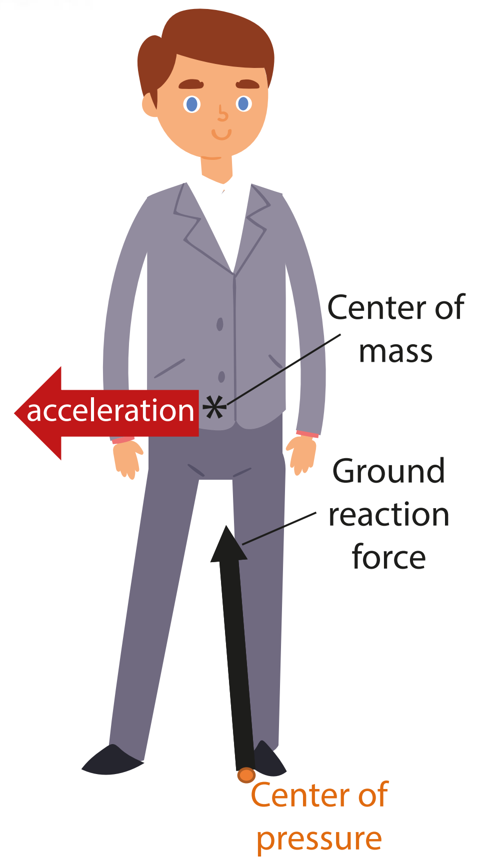



Van Leeuwen et al (2022 ) J Biomech

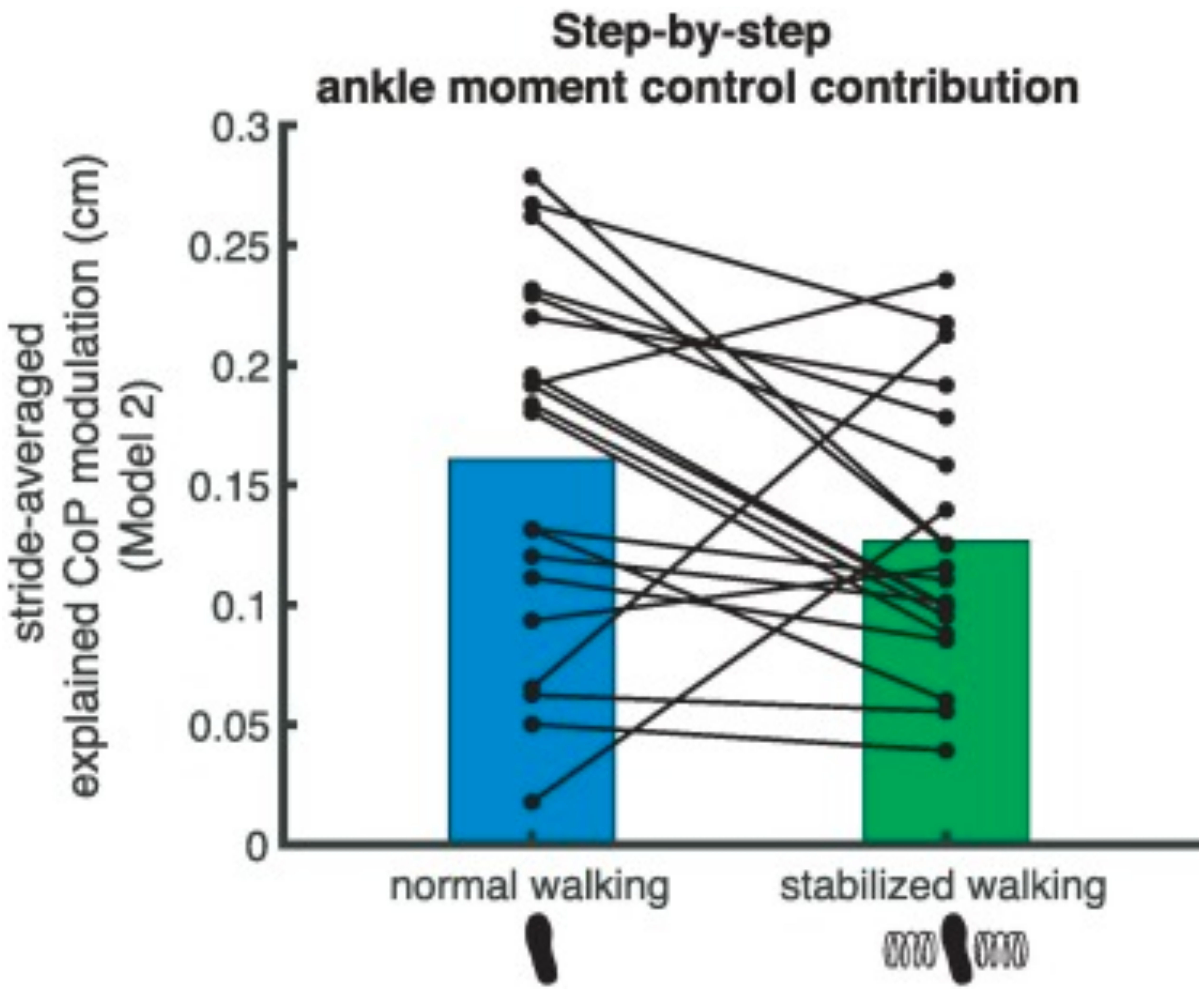
# Ankle moment control: Stabilisation

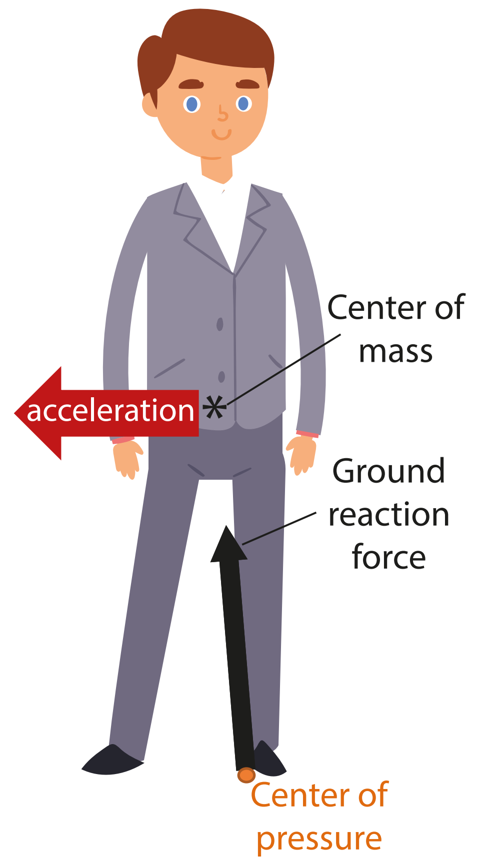



Van Leeuwen et al (2022 ) J Biomech

# Ankle moment control: Stabilisation

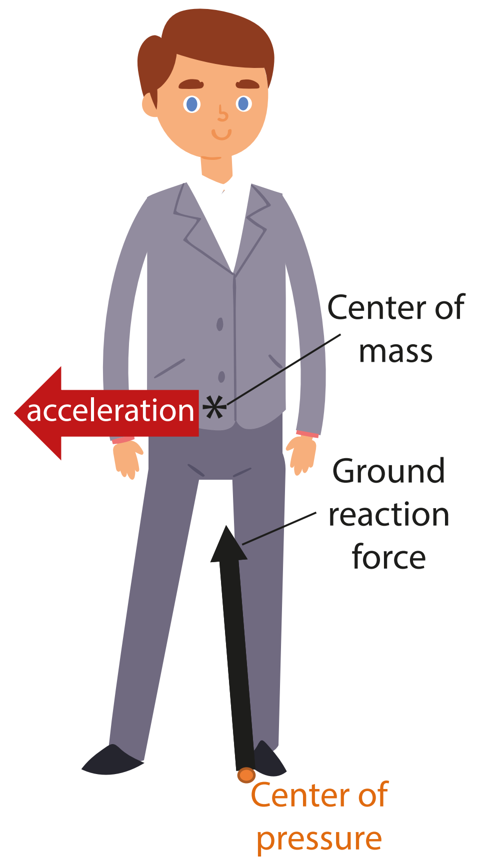



Van Leeuwen et al (2022 ) J Biomech

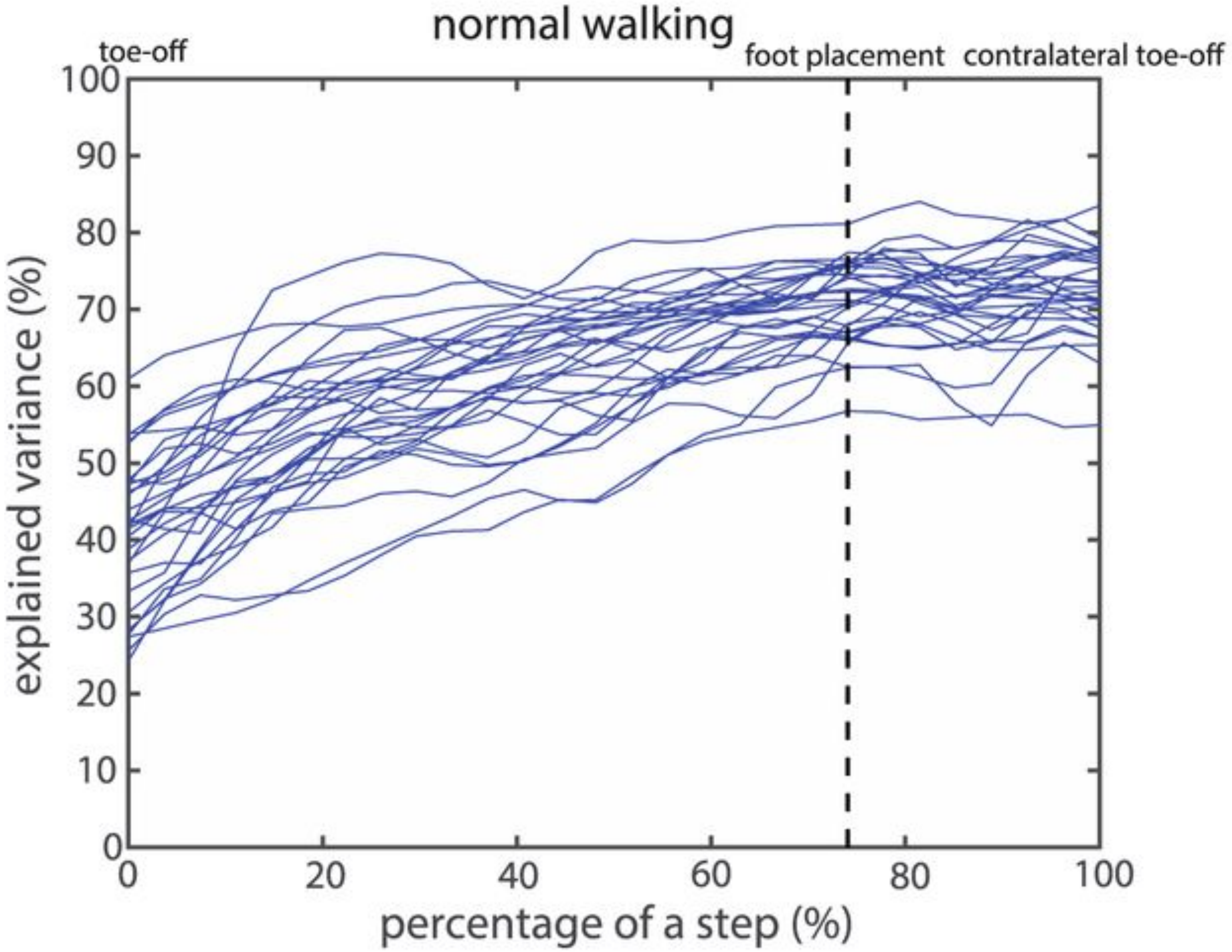
# Ankle moment control

- Errors in ML foot placement are corrected by ankle moment control
- Which is also partly active (results not shown)



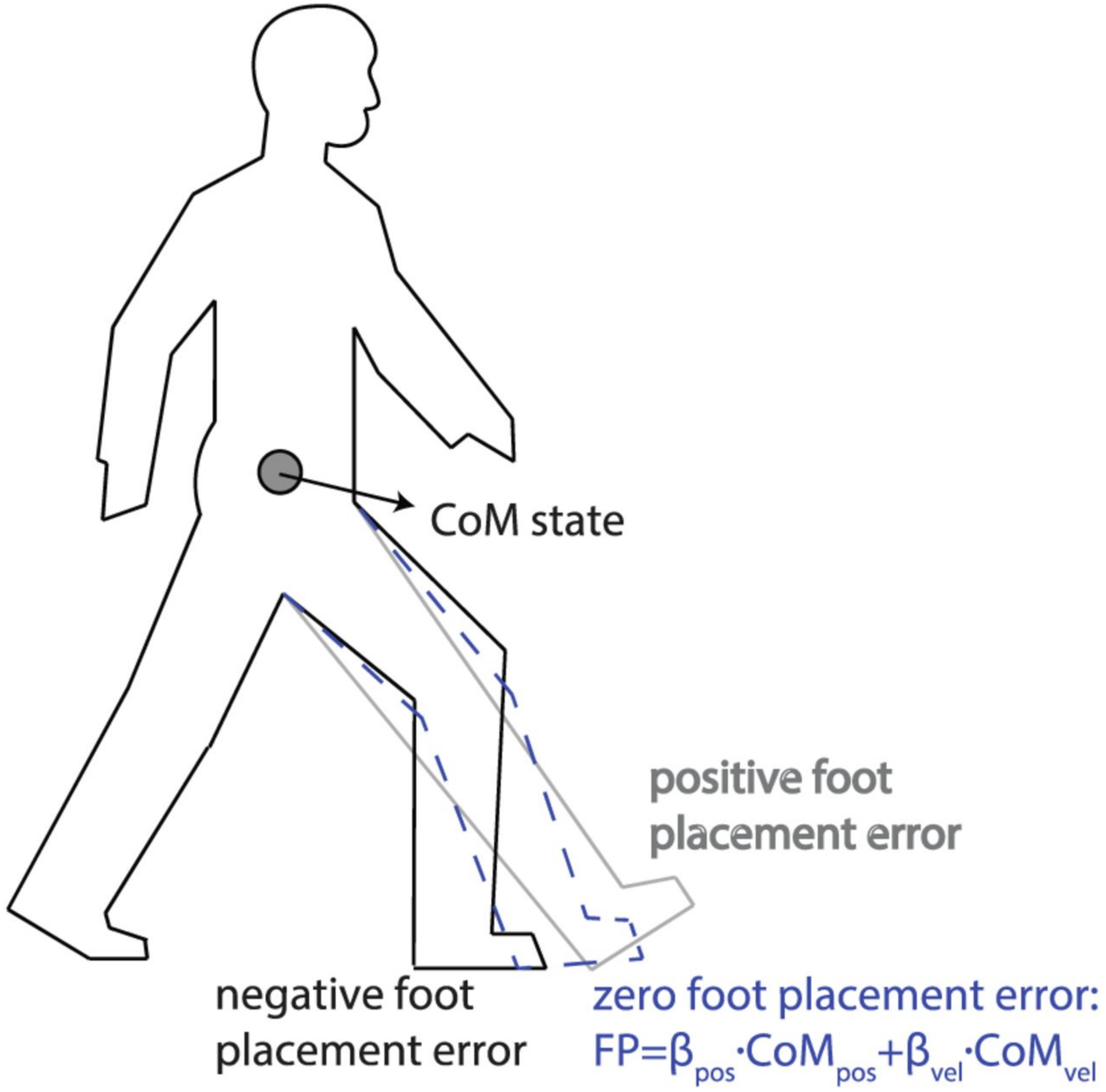
# Foot placement (AP)

n=30
V=1.25 × sqrt(L) m/s



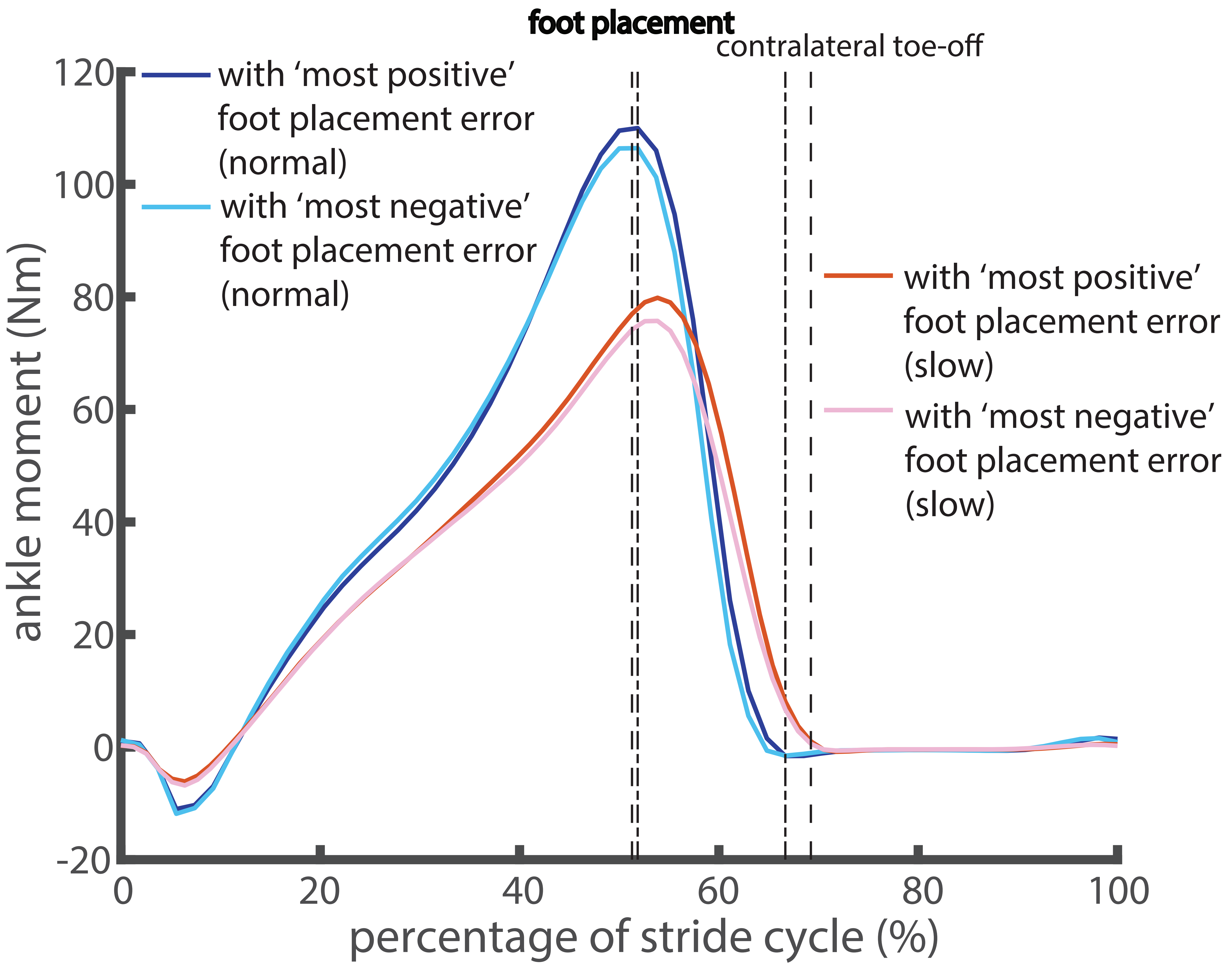

Jin et al (2022 ) BioRxiv

# Push off as correction for foot placement (AP)



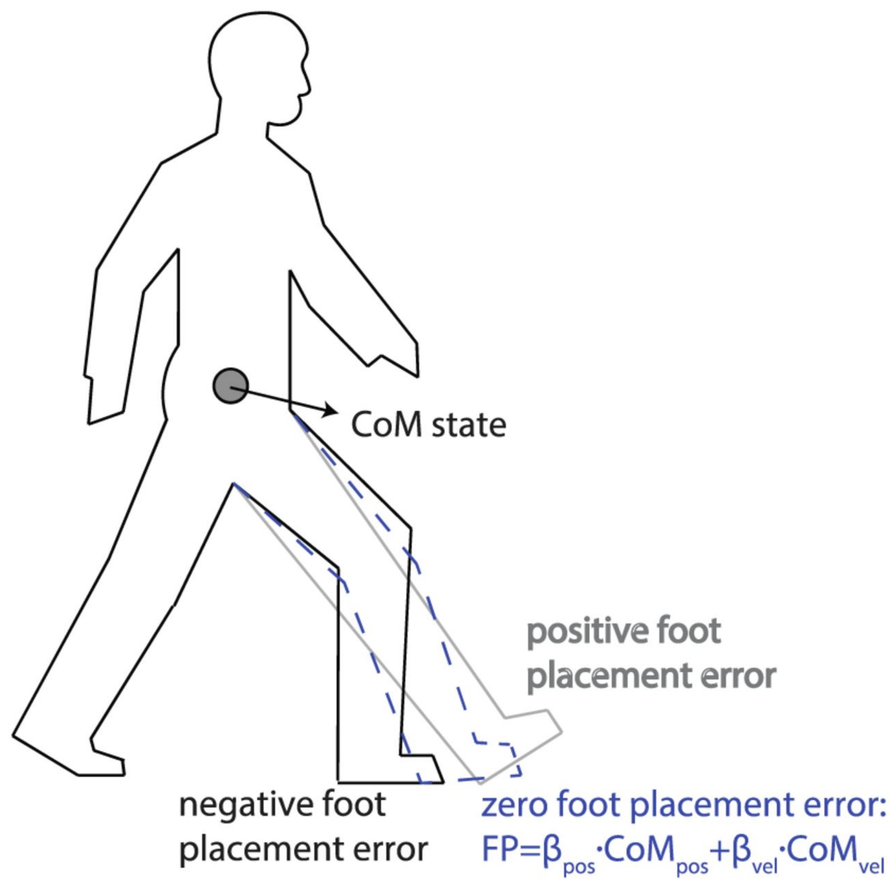

Jin et al (2022 ) BioRxiv

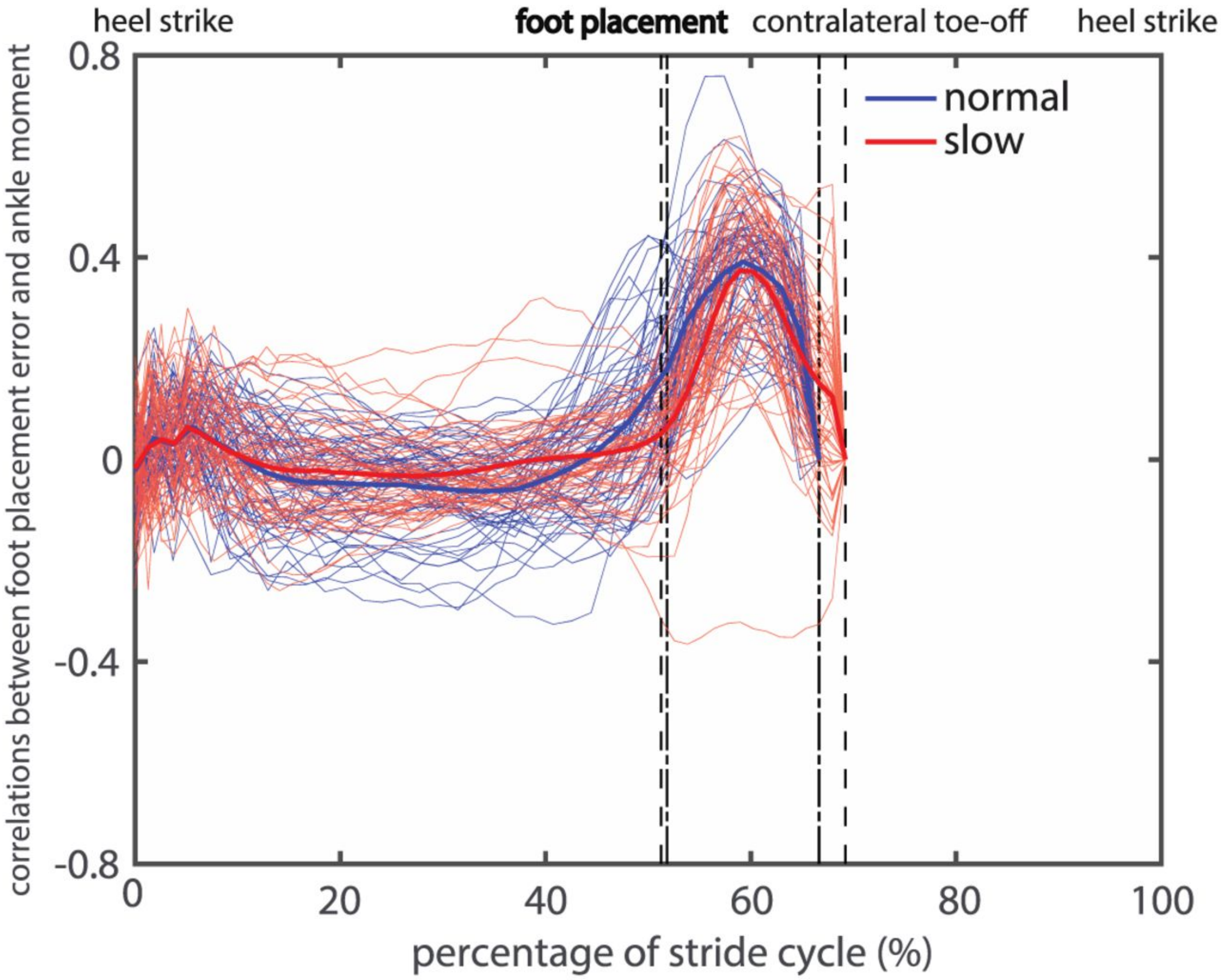
# Push off as correction for foot placement (AP)




Jin et al (2022 ) BioRxiv

# Push off as correction for foot placement (AP)




Jin et al (2022 ) BioRxiv

# Conclusions

- Foot placement relative to CoM can be described using linear models
- Foot placement relative to the CoM is actively controlled
- Foot placement is used to control gait stability
- Errors in ML foot placement are corrected by ankle moment control
- Errors in AP foot placement are correcte by push off

https://github.com/SjoerdBruijn/FootPlacement

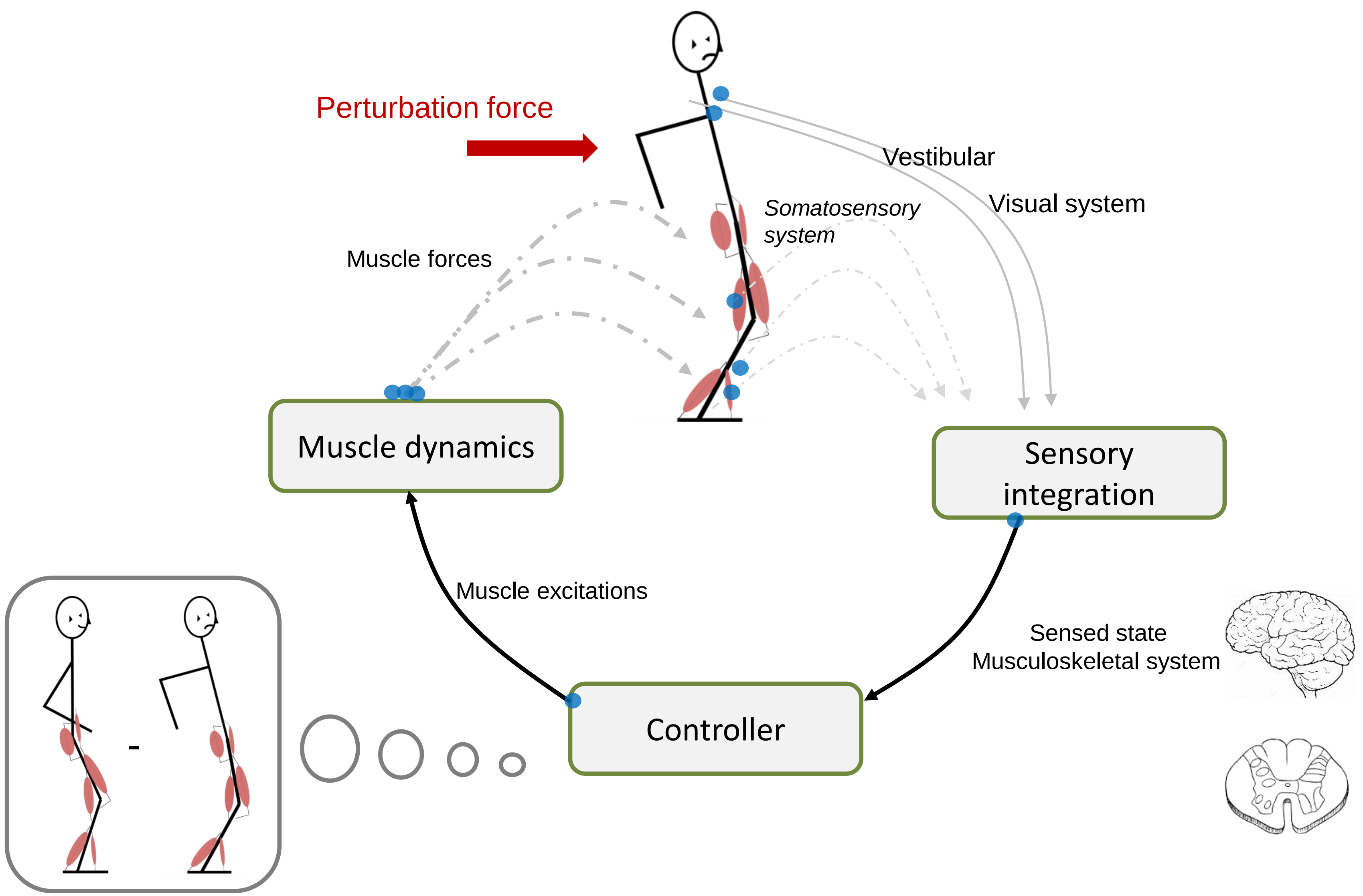
# Bonus slide

- Part of what I described is most likely passive (Patil et al); However,  a part is CERTAINLY active control; evidence:
  - Muscle activity correlated to foot placement (Rankin et al, van Leeuwen et al)
  - Walking on Lesschuh (van Leeuwen et al)
  - Sensory perturbations, such as GVS (Reimann et al, Magnani et al), Vibration (Arvin et al., Roden-Reynolds et al.)
  - (After) effects of walking in a (perturbing) force field (Rankin et al)

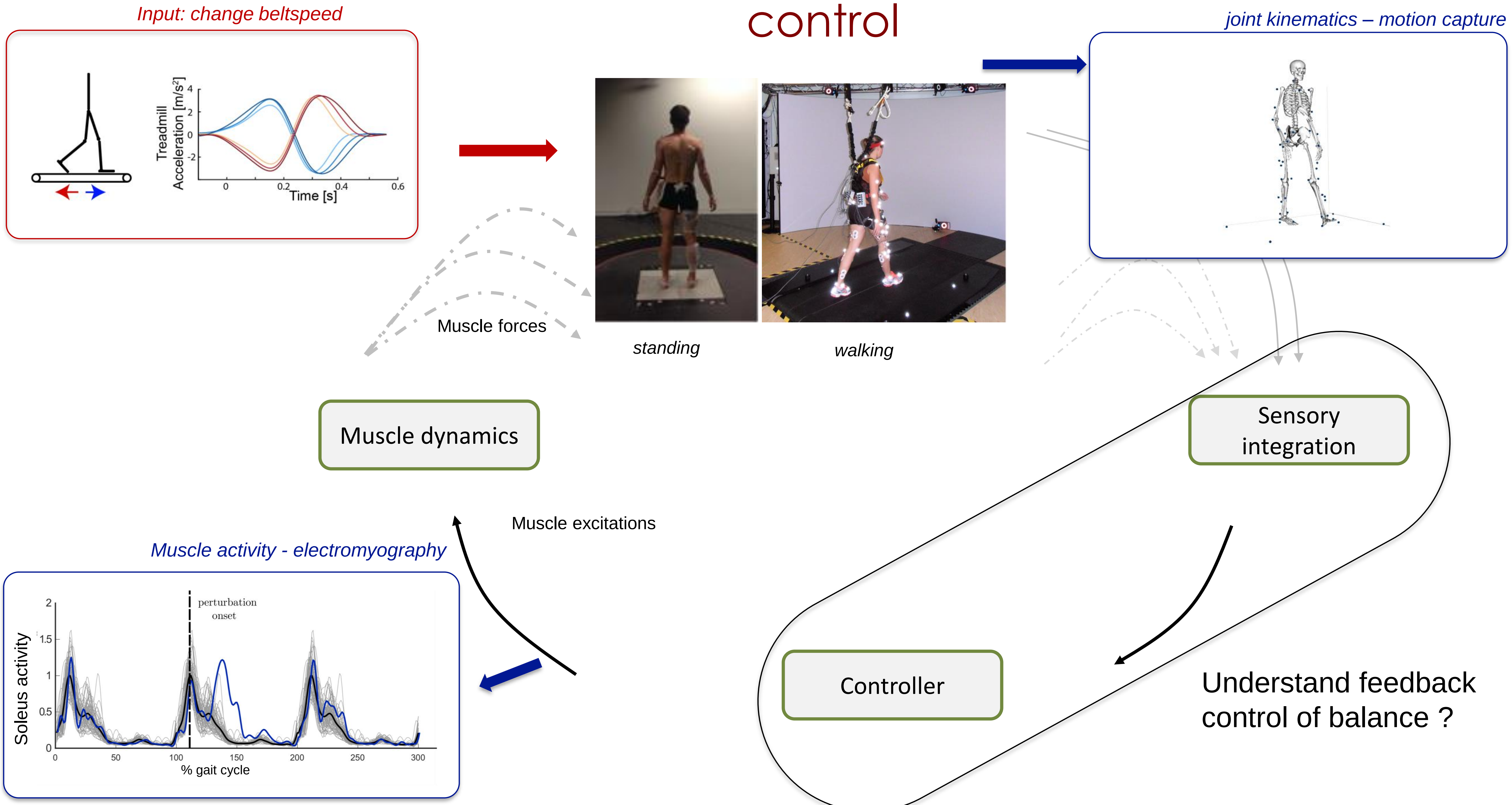
# Feedback control after gait perturbations

**Maarten Afschrift, VU Amsterdam**

# Perturbations to gain insight in reactive balance control

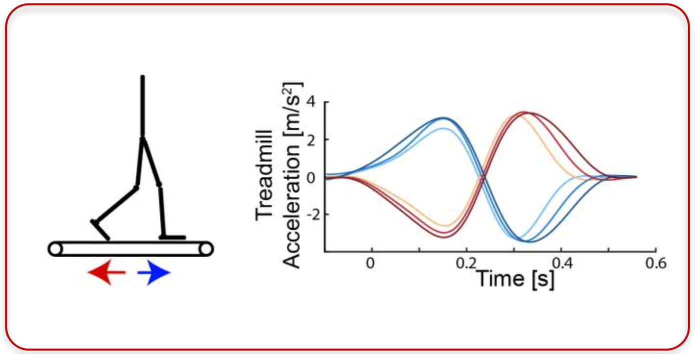


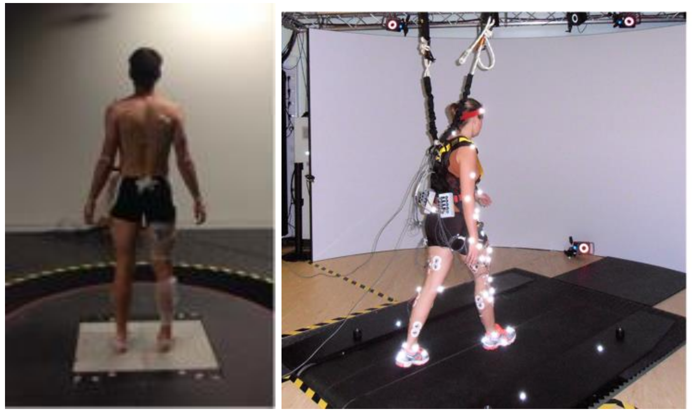
# Perturb walking to gain insight in reactive balance control



# Perturb walking to gain insight in reactive balance control

*Input: change beltspeed*

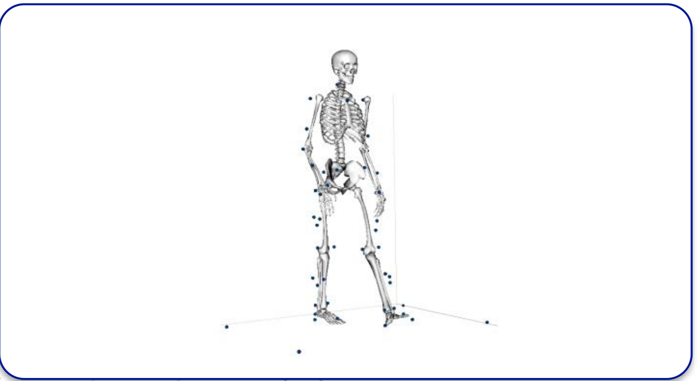


*standing*

*walking*

*joint kinematics – motion capture*

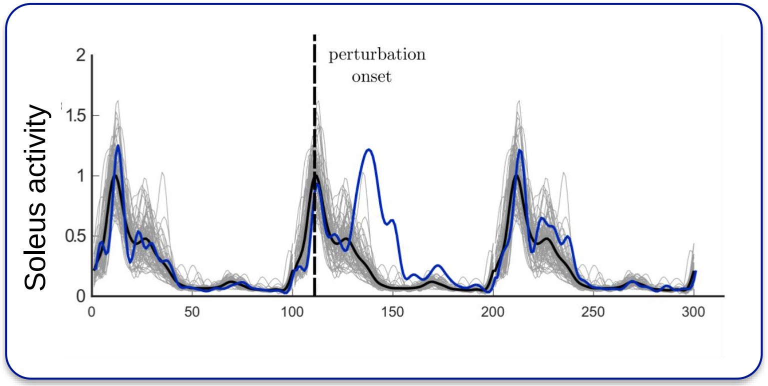


Muscle forces

Muscle dynamics

Muscle excitations

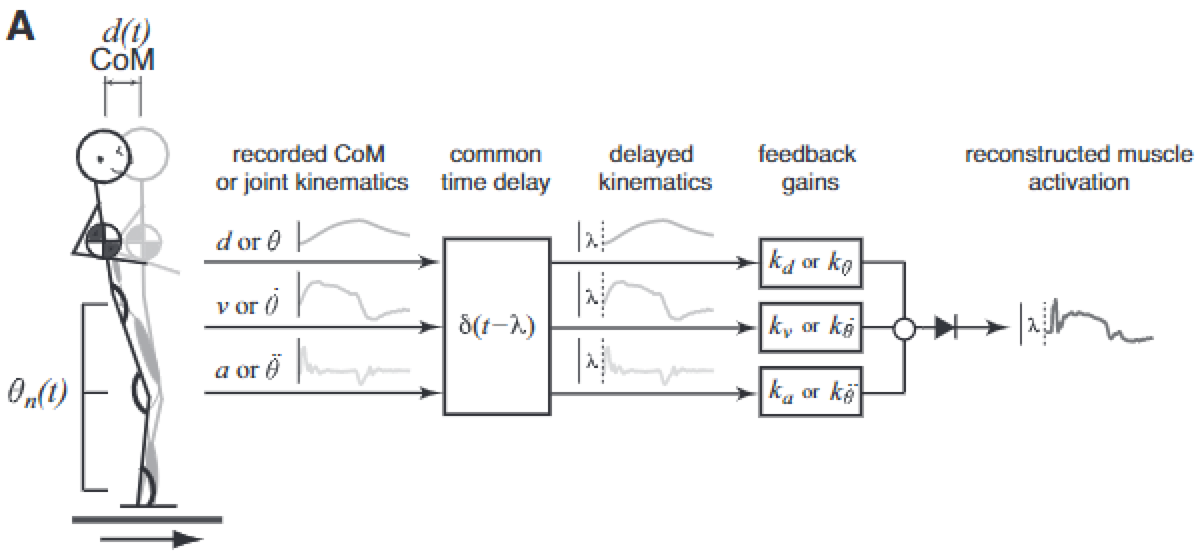
*Muscle activity - electromyography*




Delayed feedback
of deviations in
COM kinematics

Understand feedback
control of balance ?

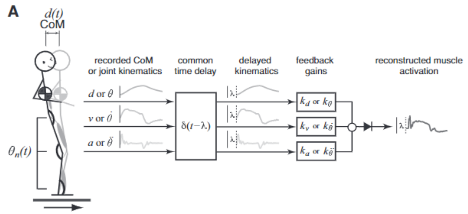
# Feedback of whole body-center of mass kinematics can explain change in muscle activity after perturabation




$$EMG(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta C\dot{O}M(t-\tau) + K_a \cdot \Delta C\ddot{O}M(t-\tau)$$

*S. Safavynia and L. Ting (J. Neurophysiol. 2013)*

# Feedback of whole body-center of mass kinematics can explain change in muscle activity after perturabation

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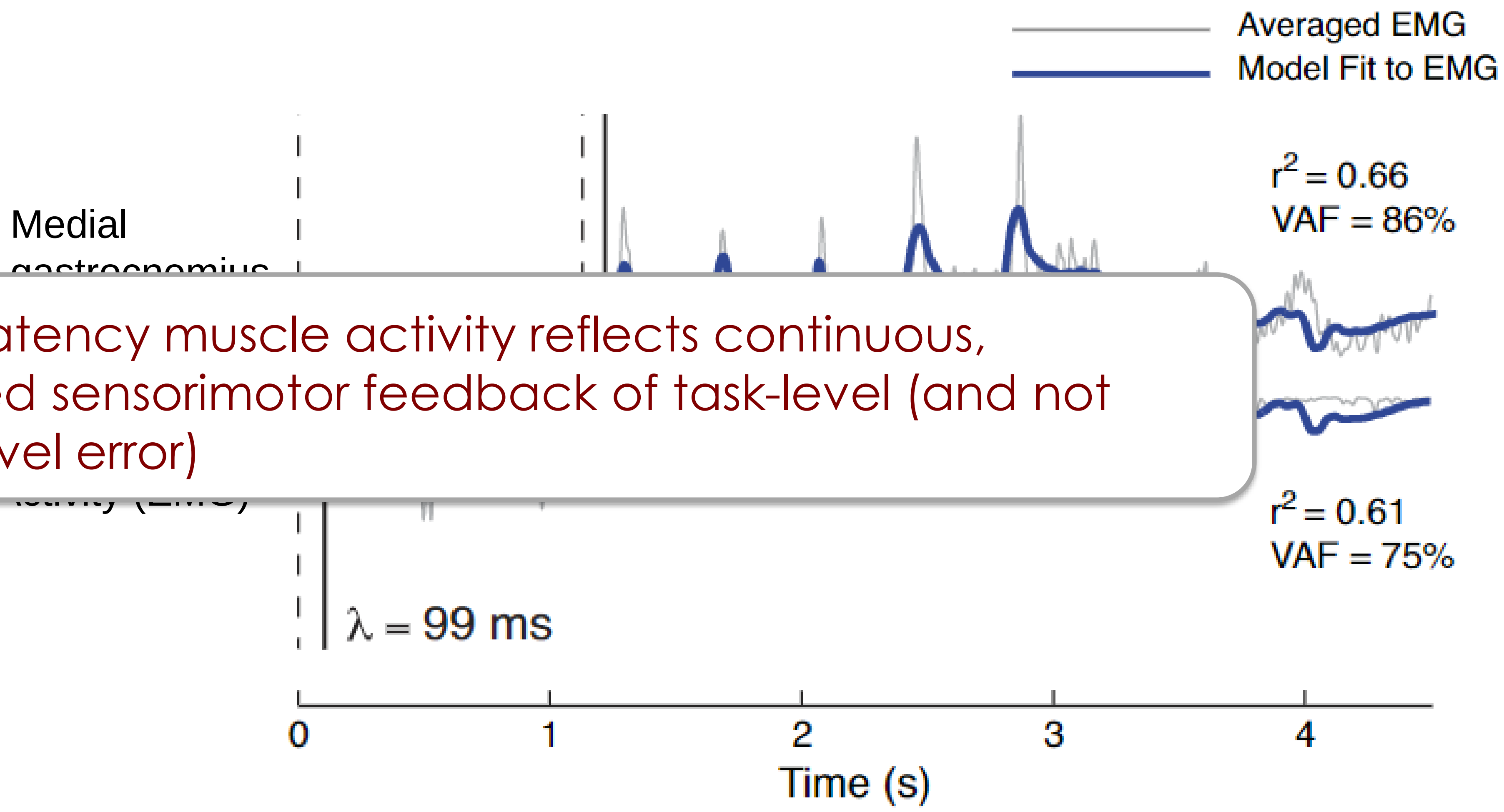
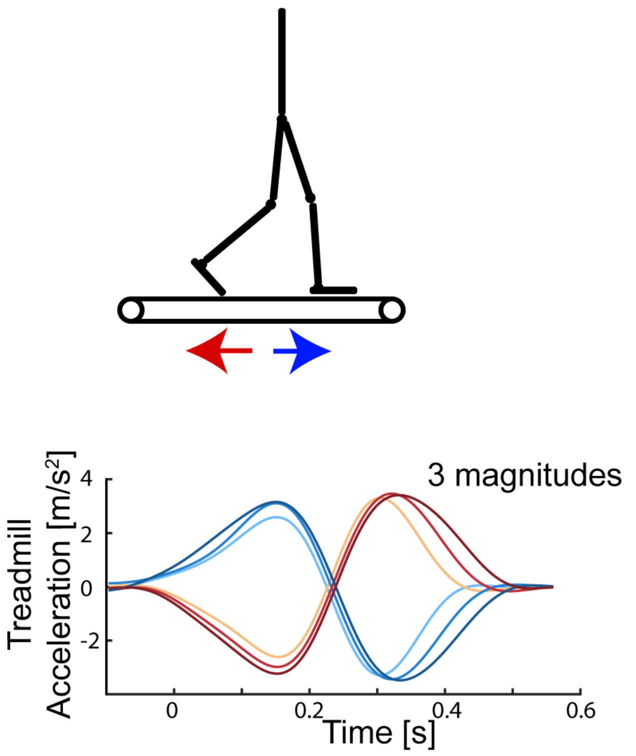



Long-latency muscle activity reflects continuous, delayed sensorimotor feedback of task-level (and not joint-level error)

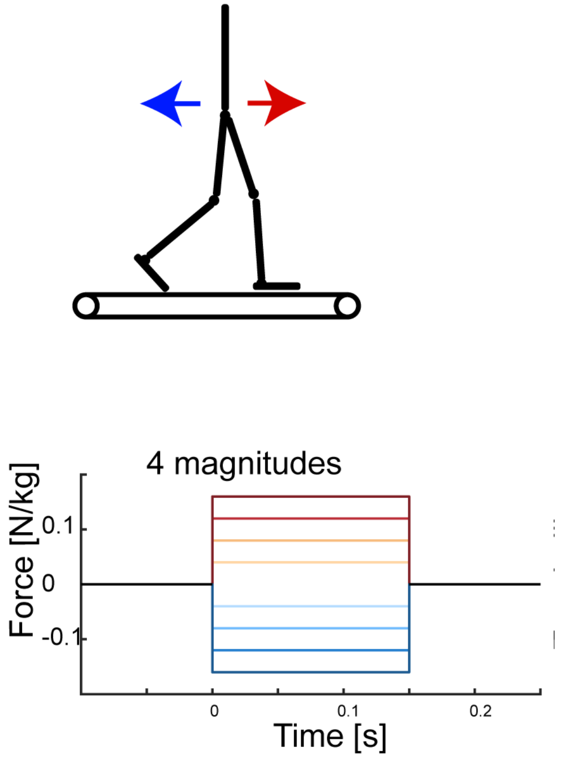
$$EMG(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta C\dot{O}M(t-\tau) + K_a \cdot \Delta C\ddot{O}M(t-\tau)$$

# Task level (COM feedback) in perturbed walking ?

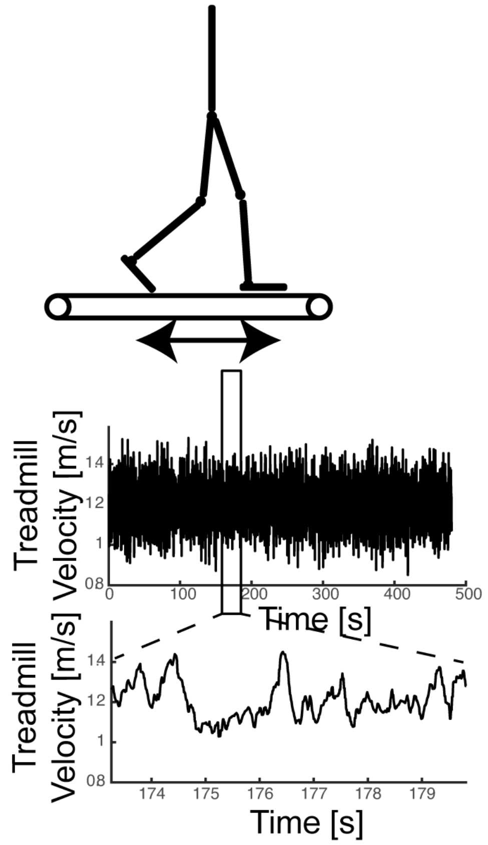
Discrete translation walking




Discrete push walking




Continuous translation walking

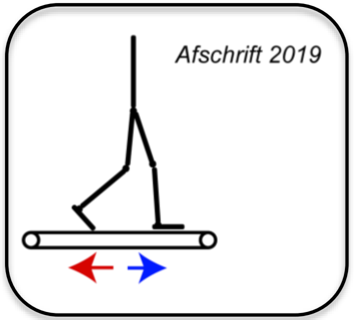


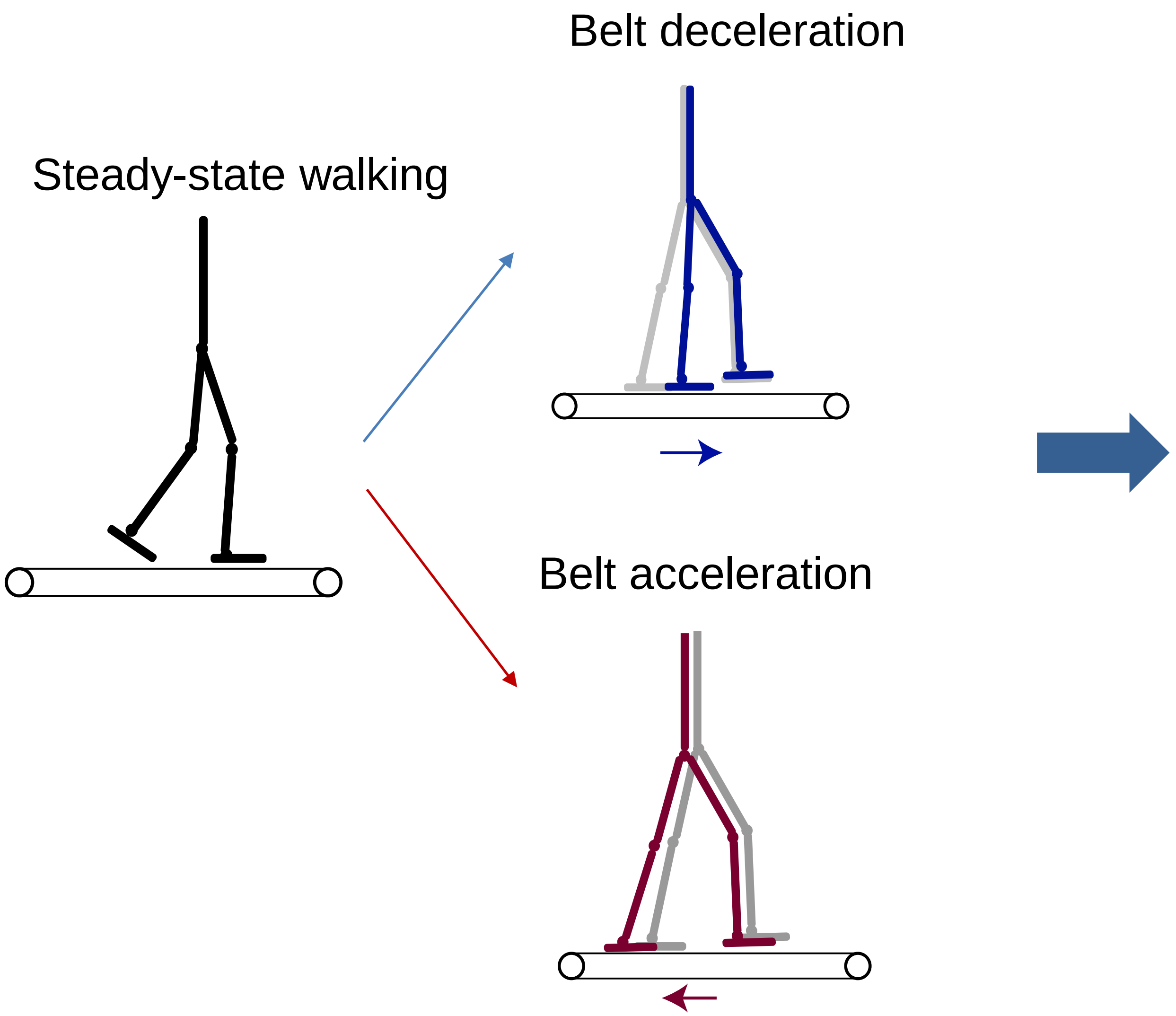

Afschrift et al, Gait and Posture. 68 (2019)

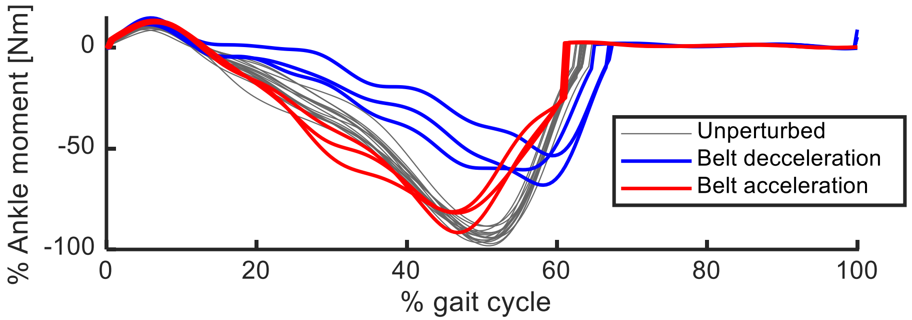
M. Vlutters, et al. Scientific Reports. 8, 14621–14621 (2018).

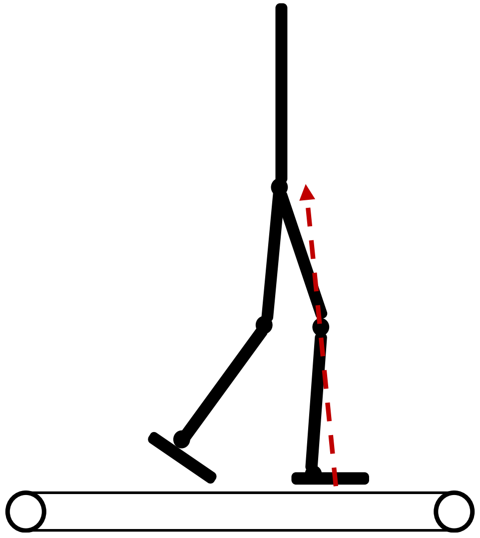
J. K. Moore et al., *PeerJ*. **3**, e918–e918 (2015).

# Ankle strategy in perturbed walking

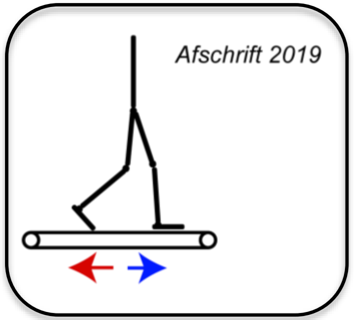


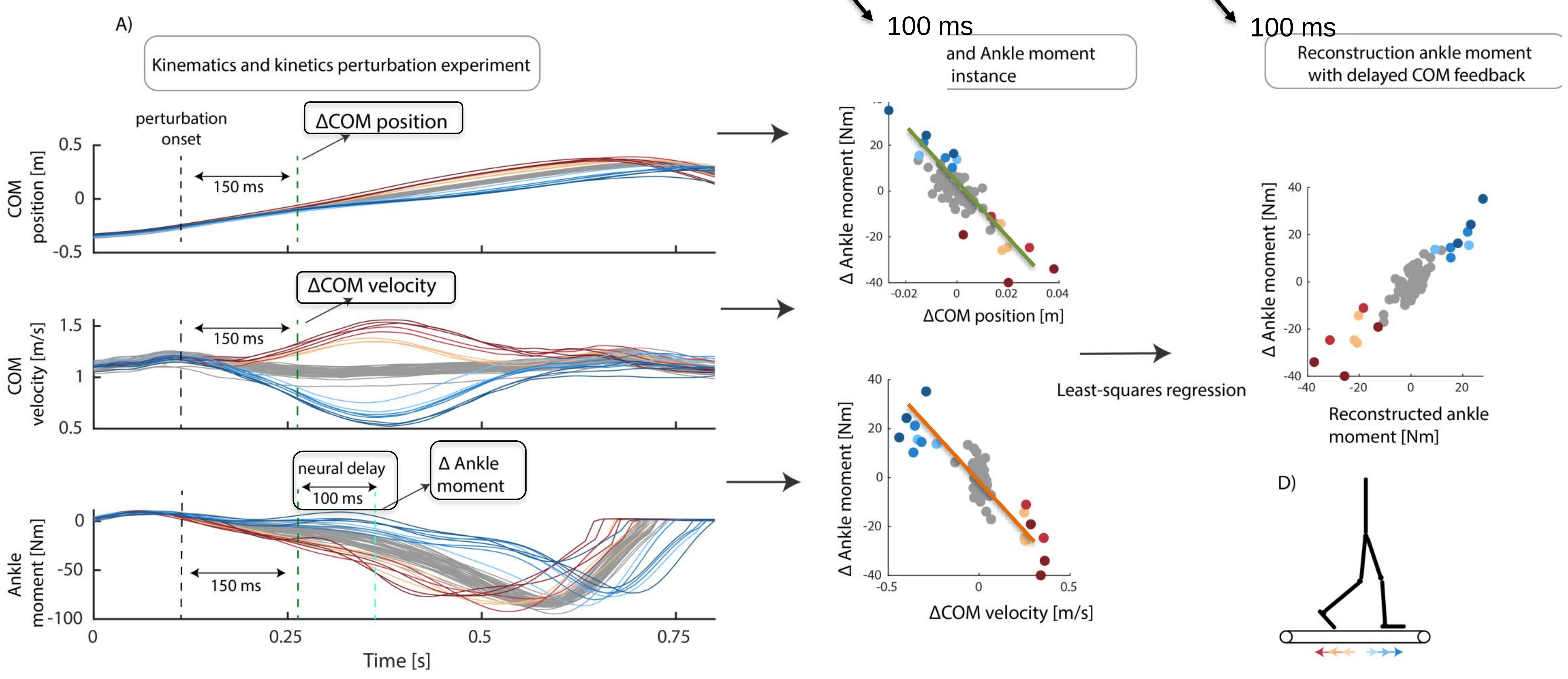



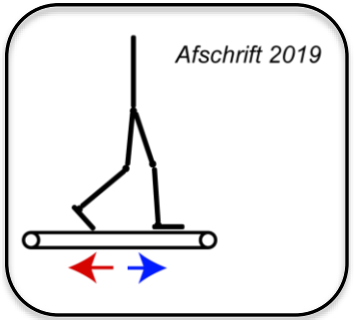
# Ankle strategy driven by COM feedback ?



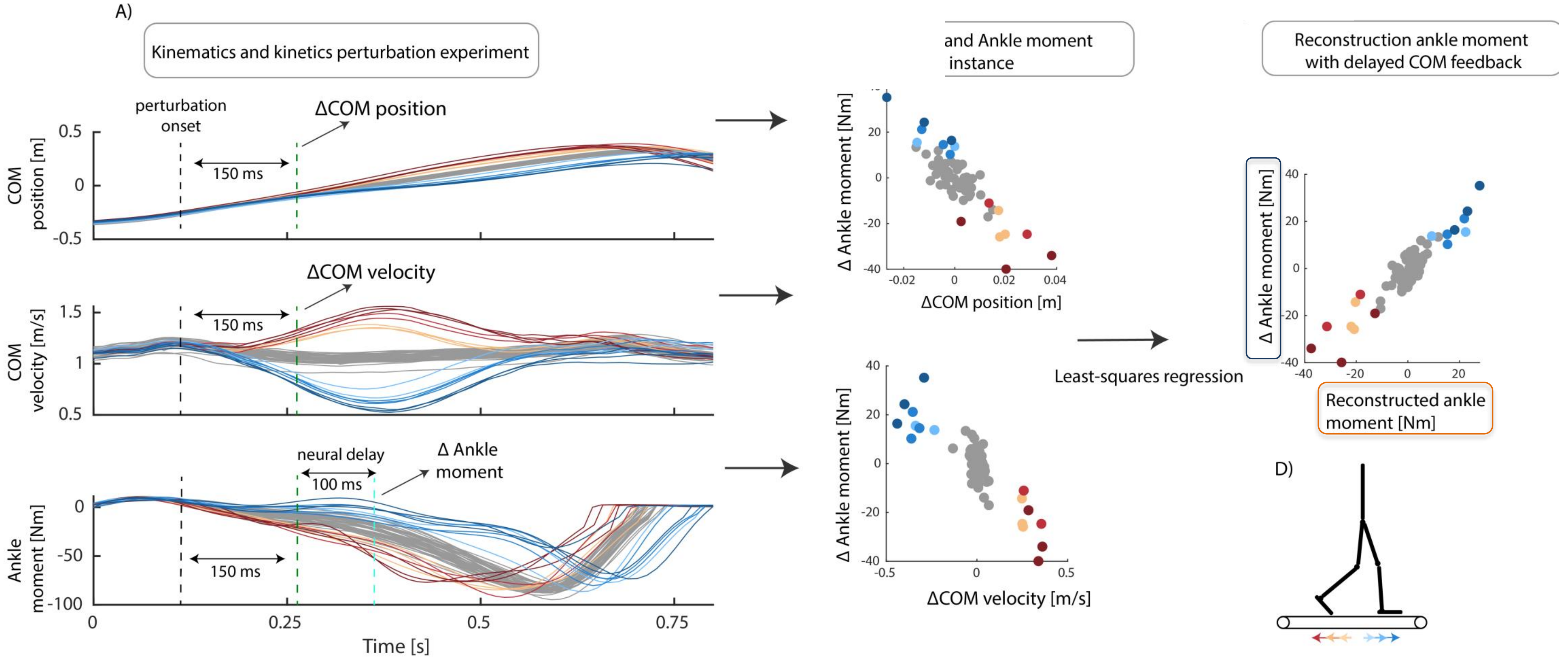

$$T_{ankle}(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta \dot{COM}(t-\tau)$$



# Ankle strategy driven by COM feedback ?

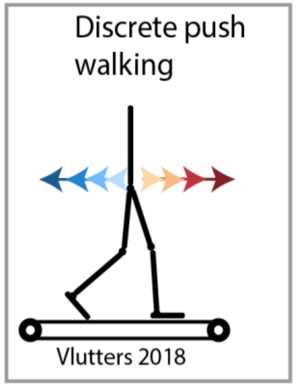


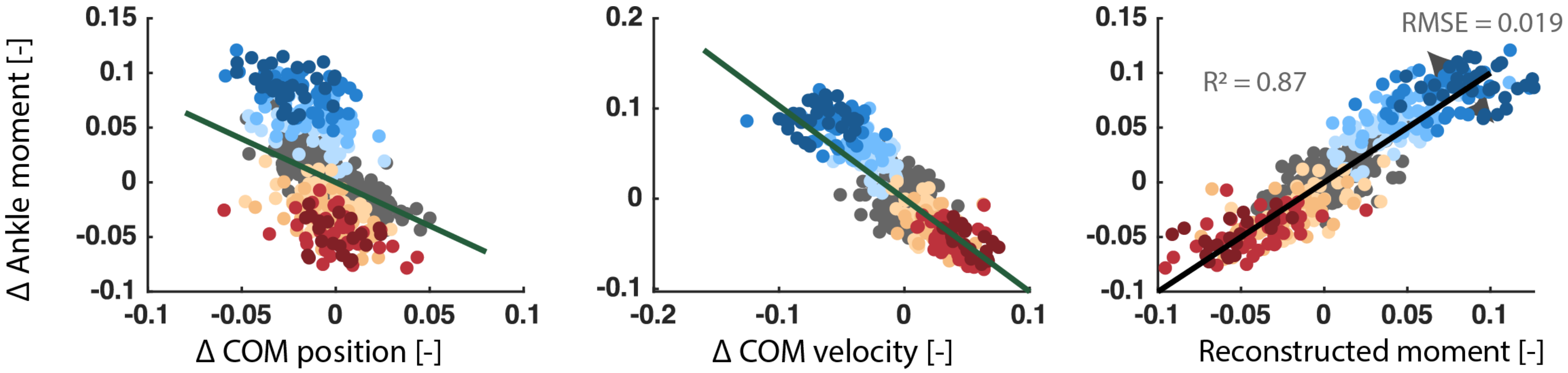

$$T_{ankle}(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta \dot{COM}(t-\tau) + \epsilon$$

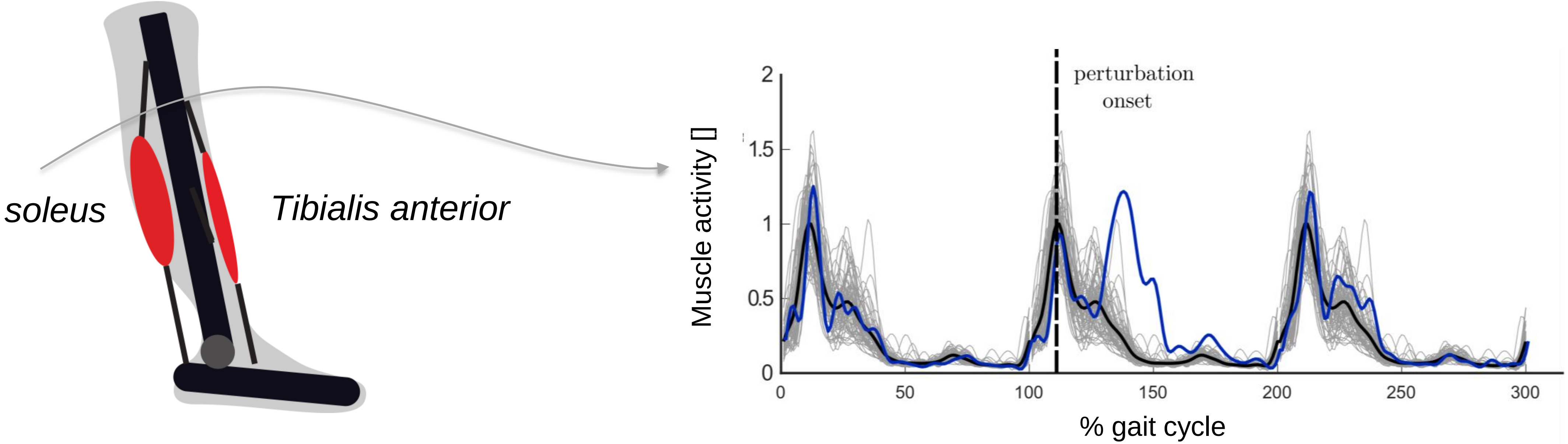


# COM feedback explains changes in ankle moment in perturbed walking

$$T_{ankle}(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta C\dot{O}M(t-\tau) + \epsilon$$

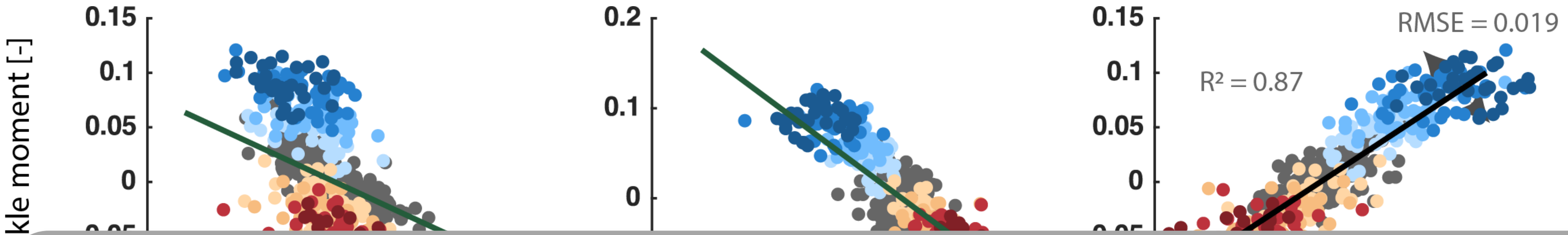


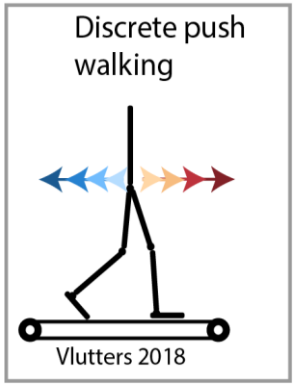



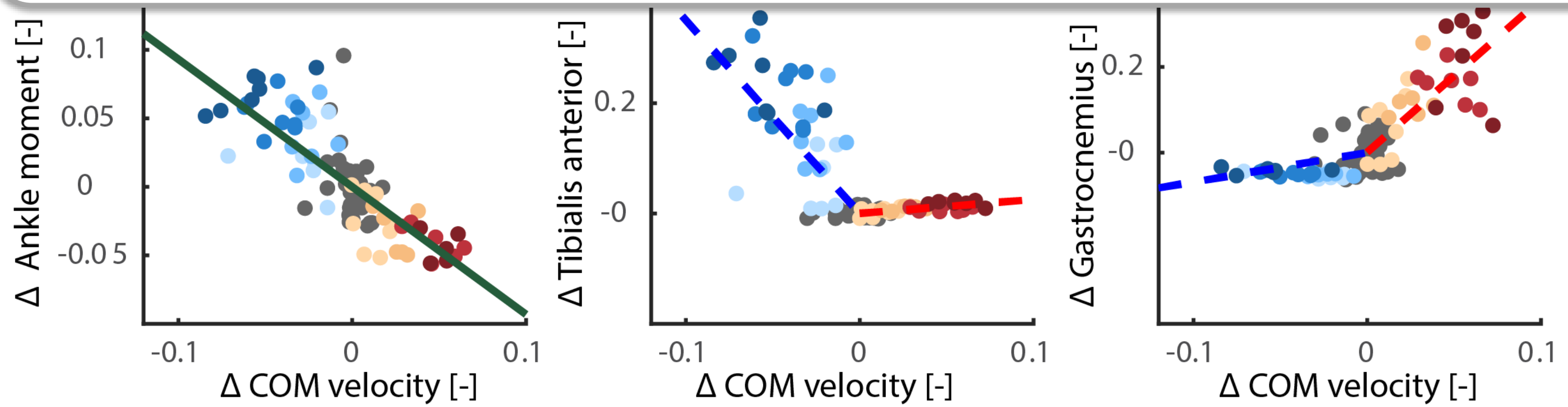
# COM feedback explains changes in ankle moment in perturbed walking

$$T_{ankle}(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta C\dot{O}M(t-\tau) + \epsilon$$

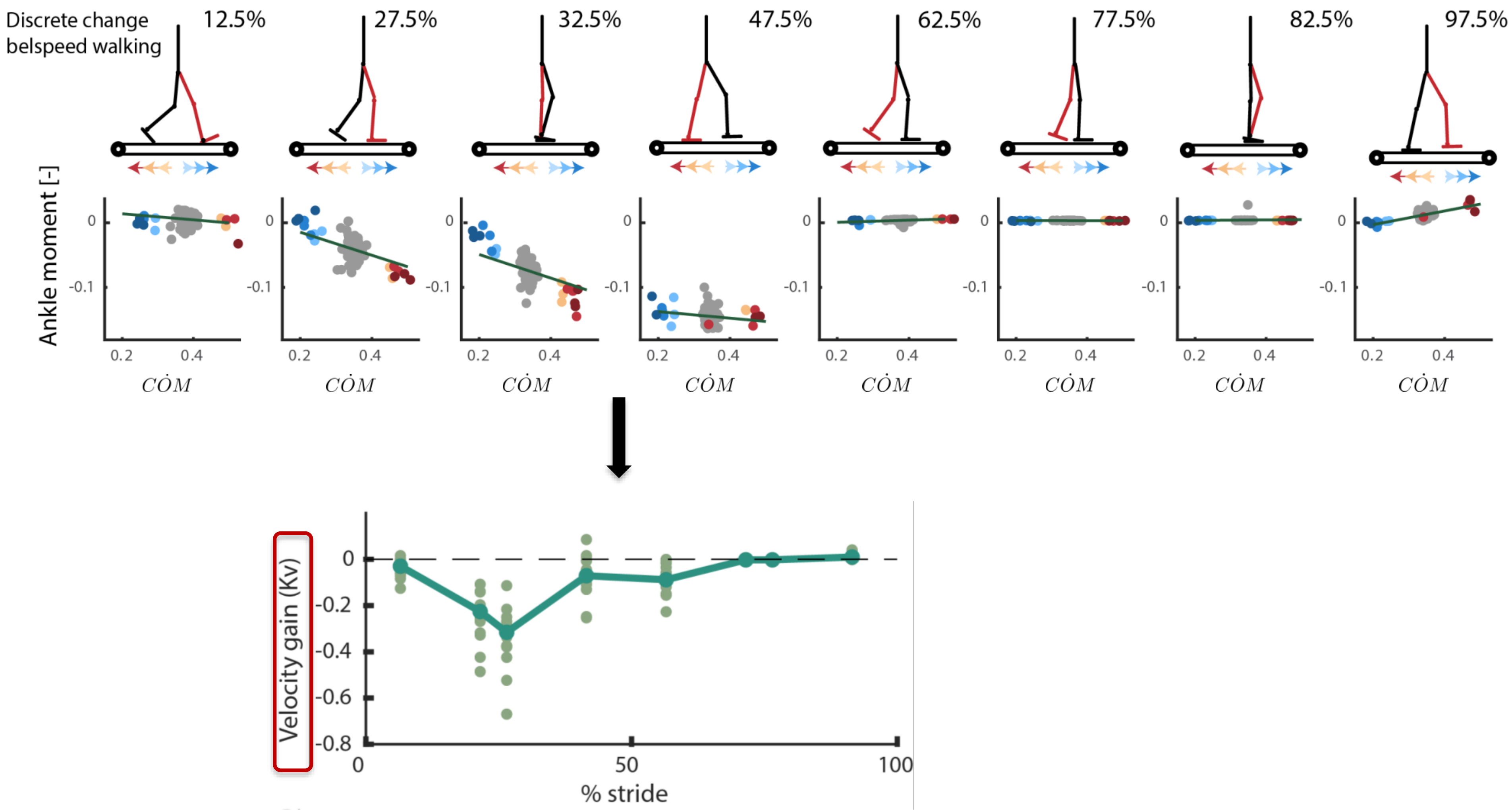



Delayed COM feedback explains changes in ankle moment in response to pelvis push and pulll perturbations

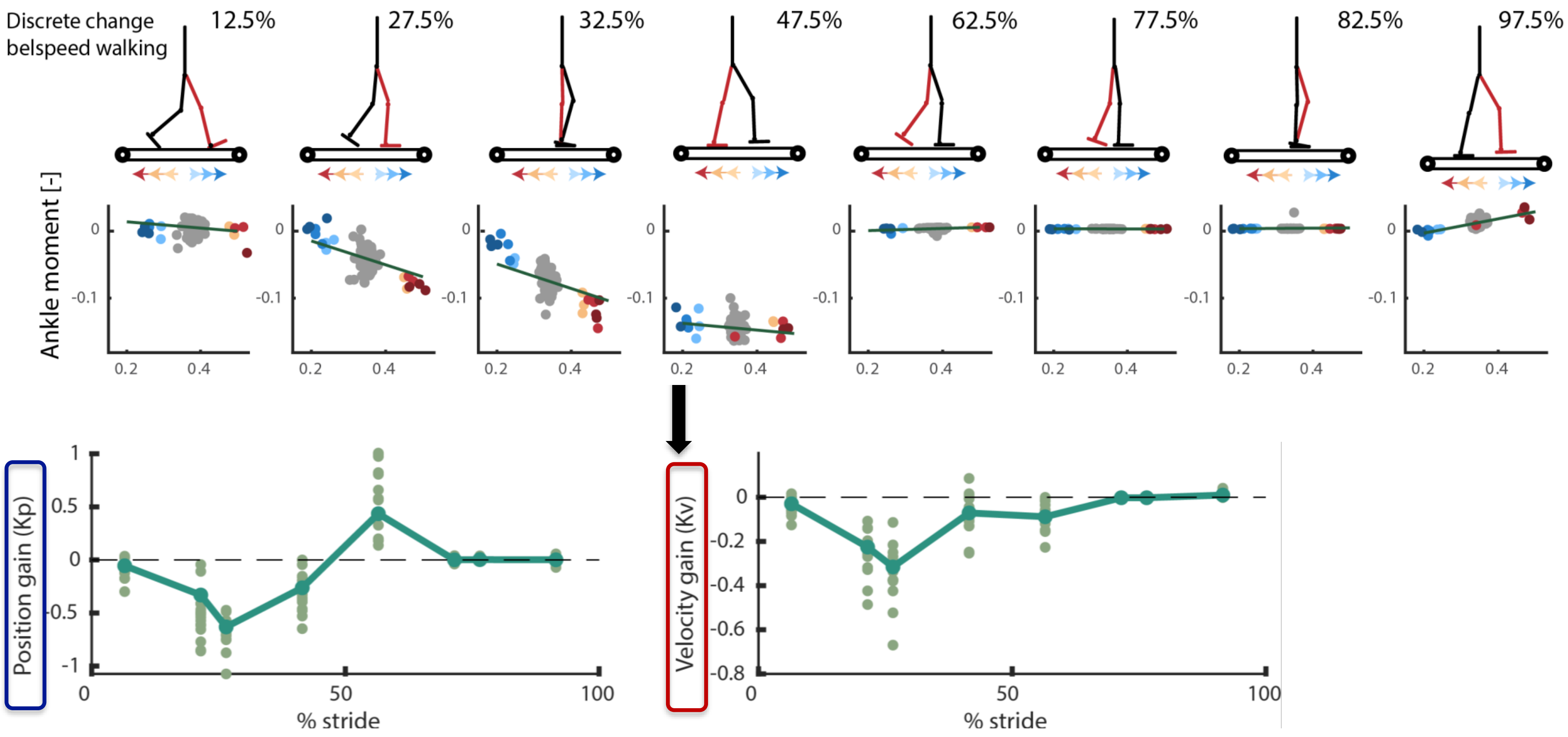


# Modulation of COM feedback during the gait cycle



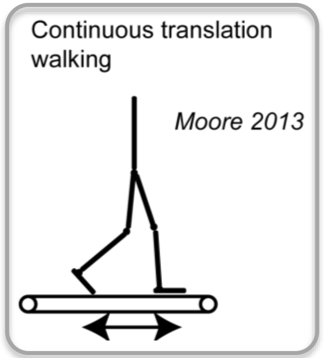

$$T_{ankle}(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta \dot{COM}(t-\tau)$$

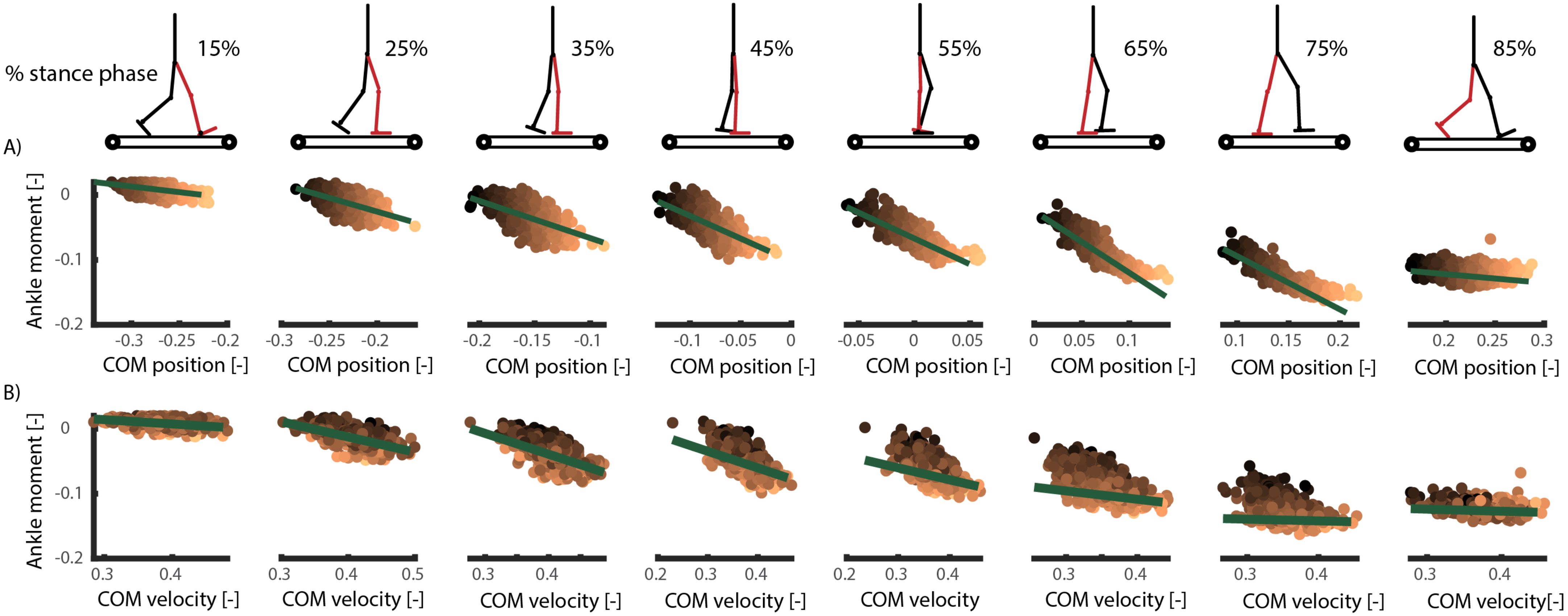
# Modulation of COM feedback gains during the gait cycle



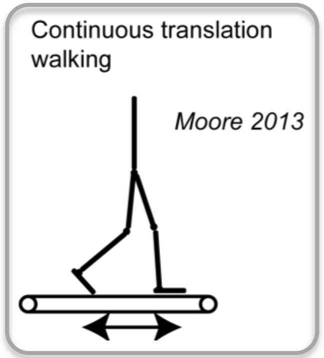

$$T_{ankle}(t) = K_p \cdot \Delta COM(t-\tau) + K_v \cdot \Delta \dot{COM}(t-\tau)$$

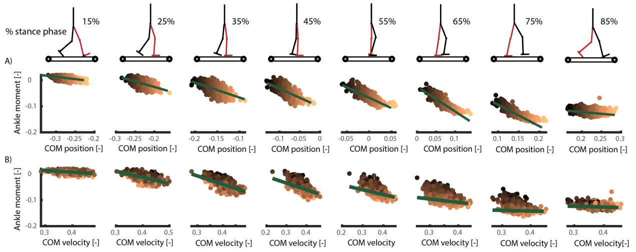
# Modulation of COM feedback gains during the stance phase

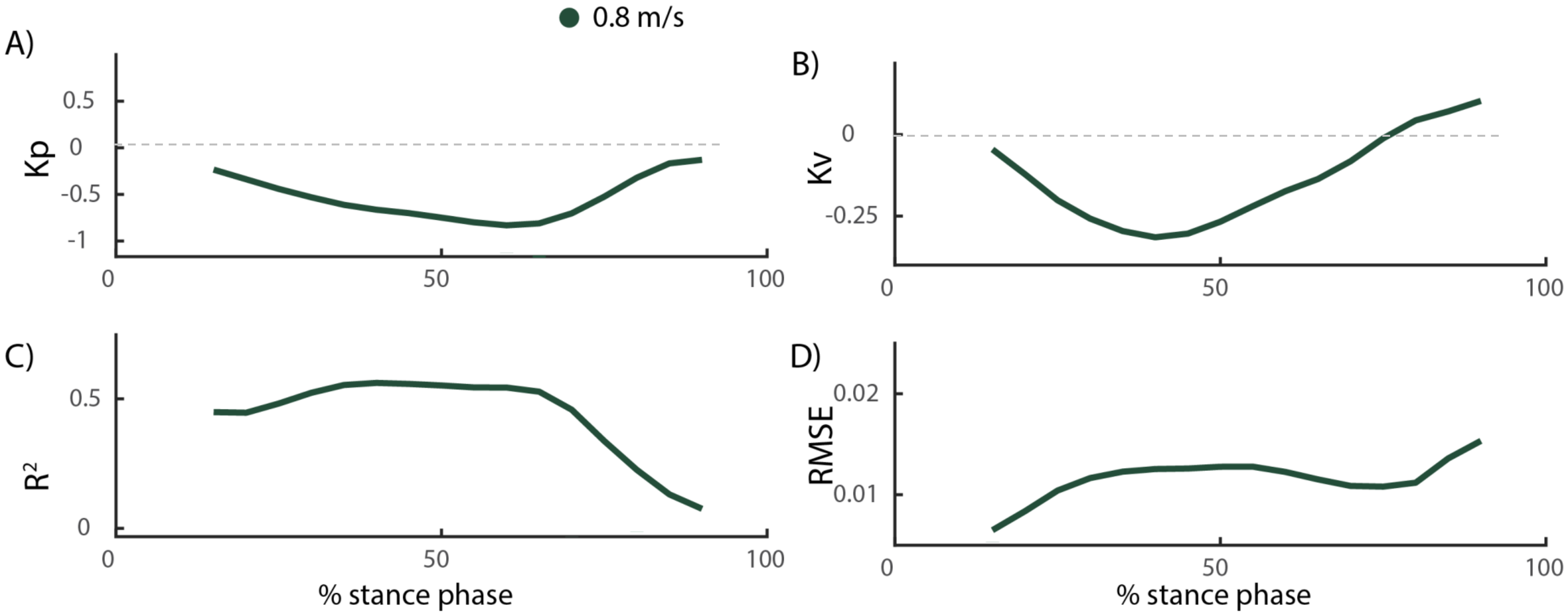


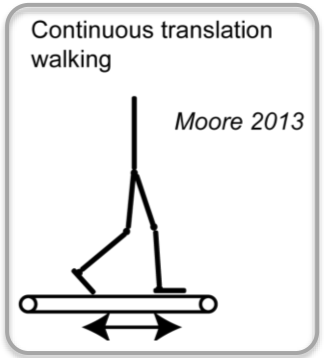
# Modulation of COM feedback gains during the stance phase

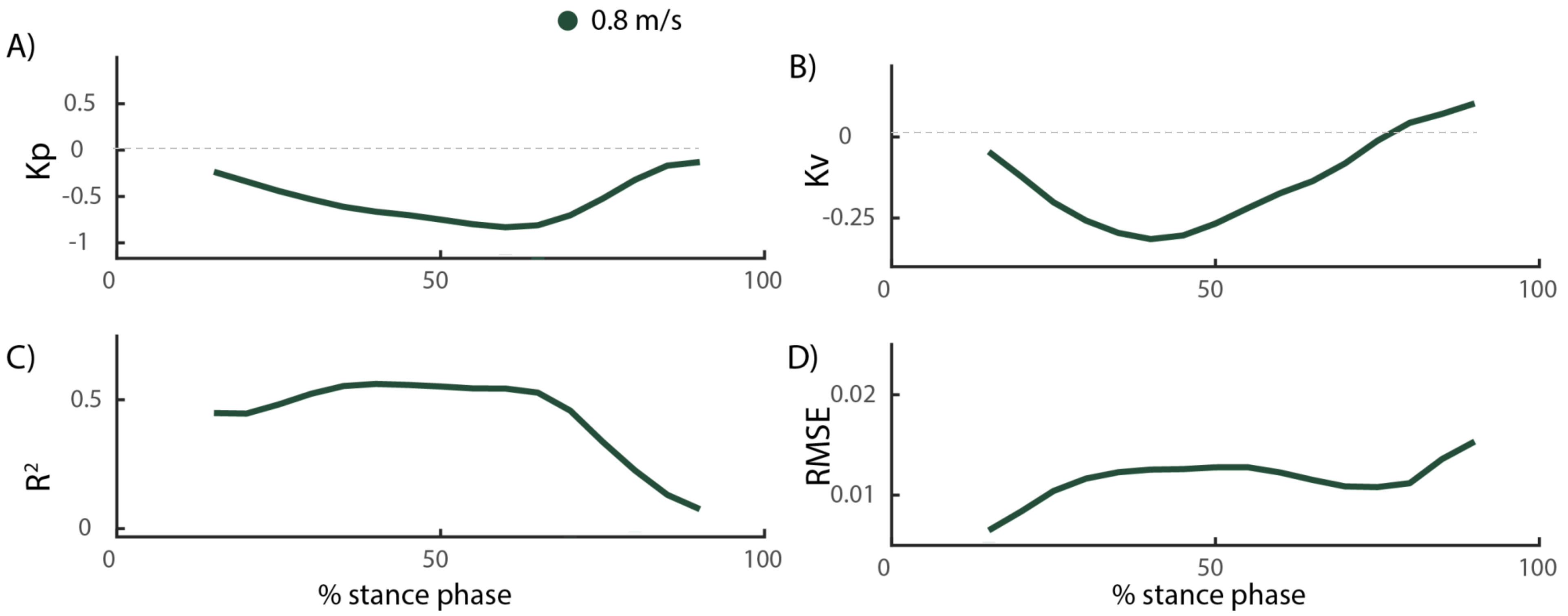


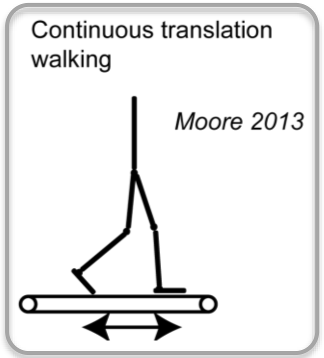



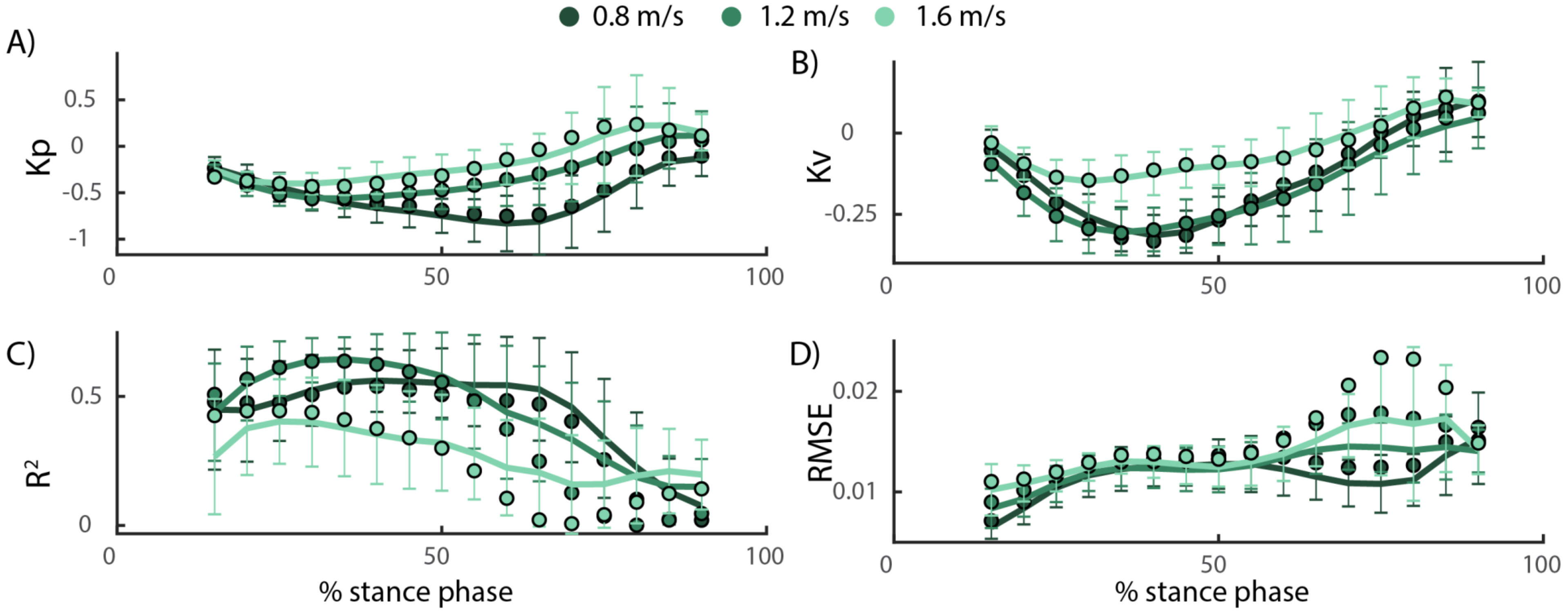
# Modulation of COM feedback gains during the stance phase



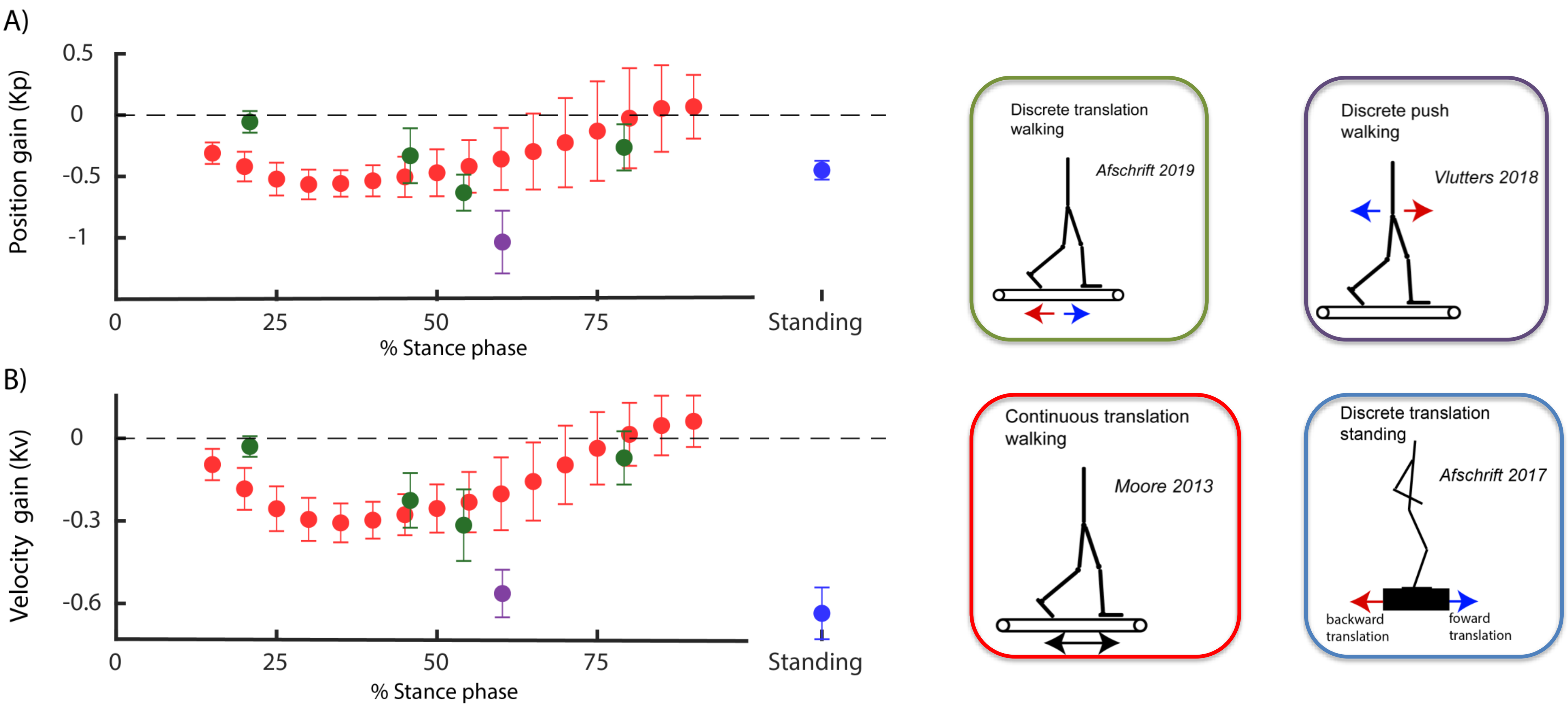



# Modulation of COM feedback with gait speed



# COM feedback explains changes in ankle moment across perturbation protocols



# In summary

- Delayed COM feedback can explain changes in ankle moment after various perturbations in standing and walking
- Feedback gains are modulated during gait cycle and with gait speed
- Future directions
  - Feedback control in individuals at risk of falling ?
  - COM feedback for biomimetic control of wearable robotic devices (e.g. ankle exoskeleton) ?