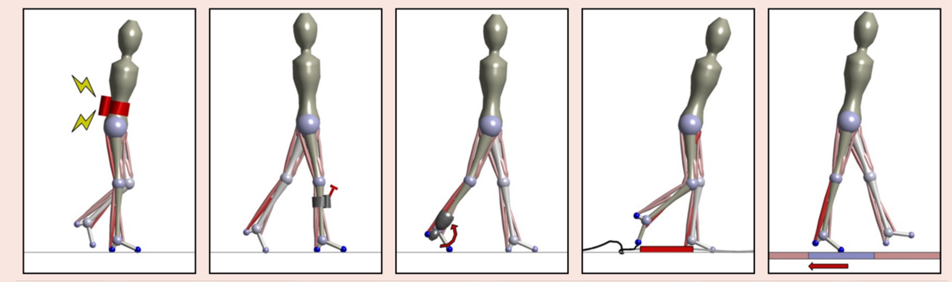
Neuromuscular simulation study

# Disturbance reactions suggest human walking is generated by spinal reflexes[1]

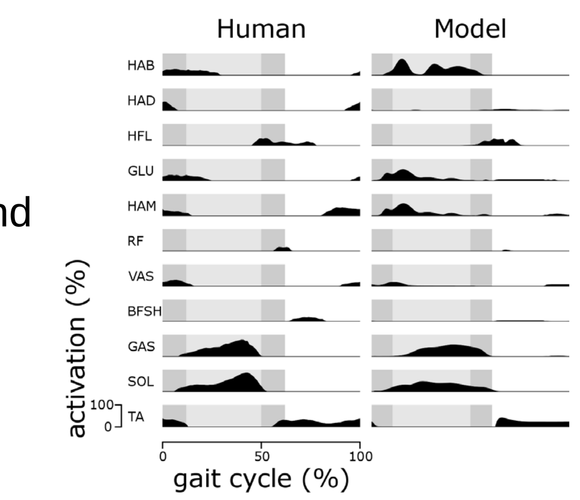
**Seungmoon Song and Hartmut Geyer**



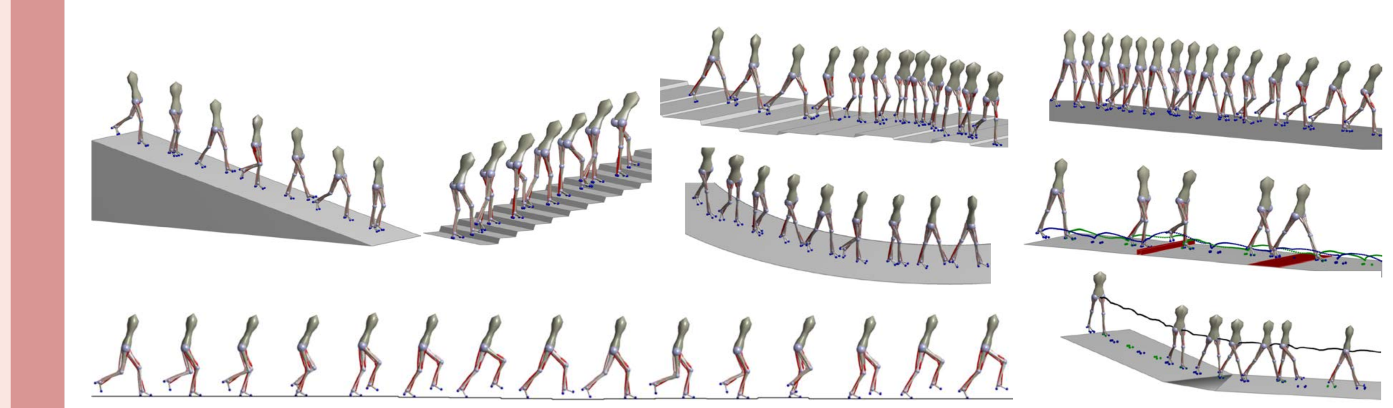
- The spinal control structure of human locomotion, such as the relative contributions of central pattern generators (CPGs) and reflexes, is a long standing topic in neuroscience, which has fundamental implications in gait rehabilitation.
- Neuromuscular models, which embody different control hypotheses, have demonstrated human-like normal walking, calling for a comparison of individual models to human data beyond steady gait.
- Here we test the plausibility of a neuromuscular model[2] with no CPGs by comparing its reactions against a range of unexpected disturbances with those observed in humans.
- Remarkably similar muscle activation responses reinforce the plausibility of the models reflex circuits, and the mismatches on the response amplitudes against particular disturbances suggest that human control involves more reflex pathways, such as location-specific cutaneous reflexes.
- Such observation emphasizes the relative contributions of spinal reflexes over CPGs in human locomotion.

## Our reflex-based neuromuscular model of human locomotion †[2]

- The control model consists of 10 spinal (mostly proprioceptive) reflex modules that realize limb functions essential to legged locomotion.
- When the control is optimized for energy efficiency, the model generates kinematics, dynamics, and muscle activations similar to those observed during normal human walking.




- The control can generate diverse human locomotion behaviors.



## Introduction

### State of the problem

- A substantial portion of human locomotion control is conducted in the spinal cord.
- Although this spinal control is composed of CPGs and spinal reflexes, their relative contributions are unknown.
- Experimental techniques do not provide full access to the spinal control circuits, making it impossible to directly probe the entire control in complex animals.
- Simulation studies remain inconclusive, since various neuromuscular control models with different combinations of CPGs and reflexes demonstrate more or less human-like locomotion in simulation studies.
- A more in-depth comparison to experimental results , such as reactions to unexpected disturbances, is required to verify individual control models.

### Our approach

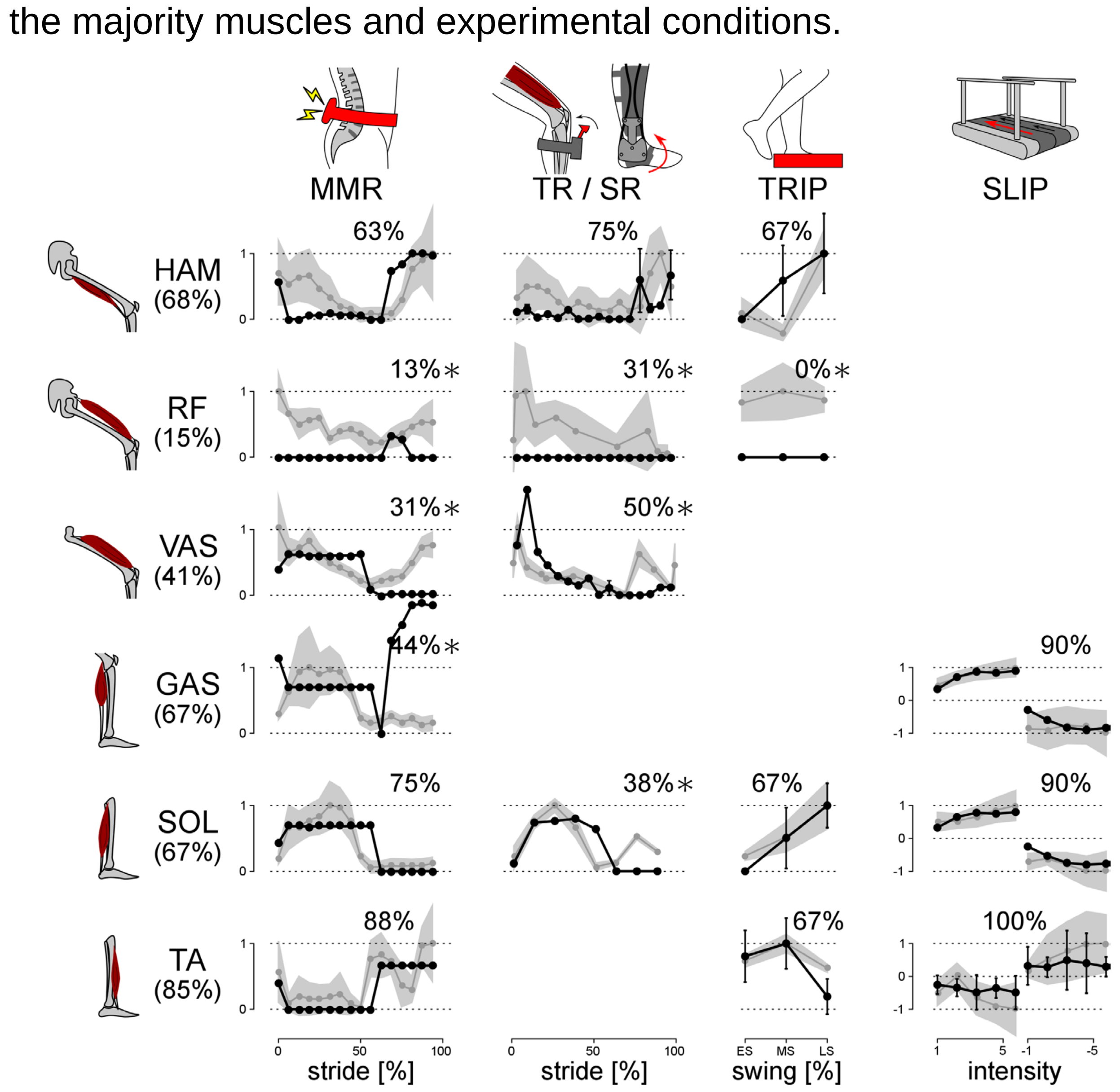
- We further investigate a previously proposed neuromuscular control model† which is selected based on two reasons:
  - The model is CPG-free and consists of mostly spinal reflexes
  - The model generates diverse and human-like locomotion behaviors
- The model is compared with human reactions against five representative unexpected disturbances from the literature: electrical stimulation of the lumbar spinal cord (MMR), mechanical tap of tendons (TR), mechanical joint actuations (SR), tripping (TRIP), and slipping (SLIP).

MMR: multisegmental monosynaptic response (human data from Courtine et al., 2007)
TR: tendon tap reflex (human data from Dietz et al., 1990 and Faist et al., 1999)
SR: stretch reflex (human data from Sinkjaer et al., 1996)
TRIP: tripping (human data from Schillings et al., 1999)
SLIP: slipping (human data from Sloot et al., 2015)

## Results

### Response trends

The model and humans react to disturbances with a similar trend for the majority muscles and experimental conditions.




### Response amplitudes

The model's responses are much smaller than humans against TRIP and SLIP:

- MMR and TR: not applicable
- SR: 90% (of human response amplitudes)
- TRIP: 20%
- SLIP: 4%

## Interpretations

### Response trends

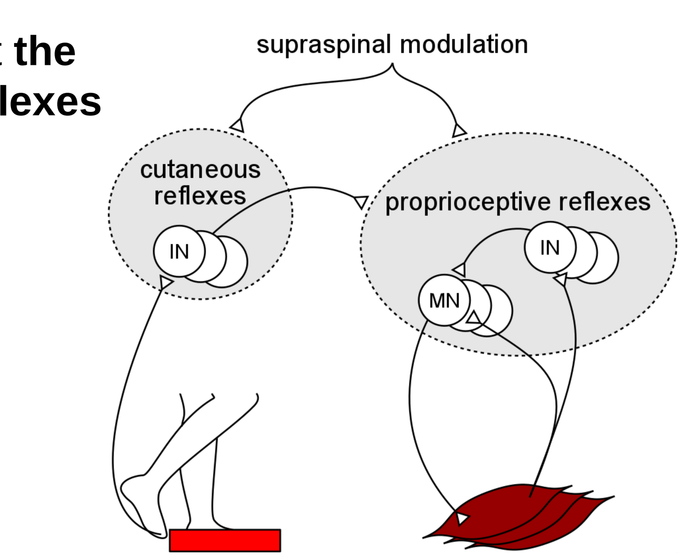
- Similarities in most of the muscles support that the reflex pathways of those muscles are active during human walking
- Most of the dissimilarities in some muscles (marked as *) still can be explained within the current control structure.

→ The results support that **the reflex pathways of the model is active in humans during walking**.

### Response amplitudes

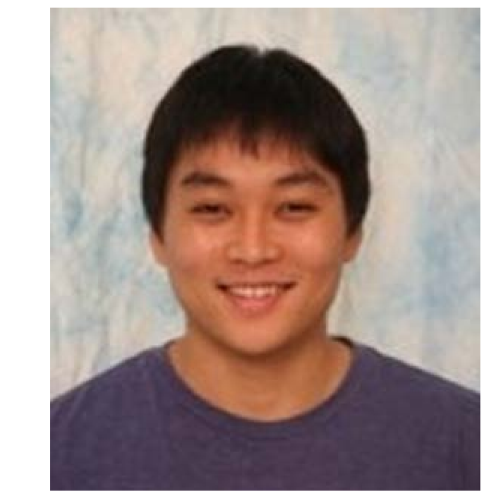
- The proprioceptive sensory data (muscle states) are disturbed much more in SR than in TRIP and SLIP experiments.
- The model, therefore, shows much smaller responses in TRIP and SLIP than in SR experiments.
- On the other hand, humans show large responses in all experiments.

→ A plausible explanation is that **the activities of proprioceptive reflexes are amplified by exteroceptive feedback in TRIP and SLIP experiments.**




### Conclusion

**Both the normal locomotion and the disturbance reactions of humans can be explained by an exclusively spinal reflex-based control structure**, which leaves the contribution of CPGs obscure.



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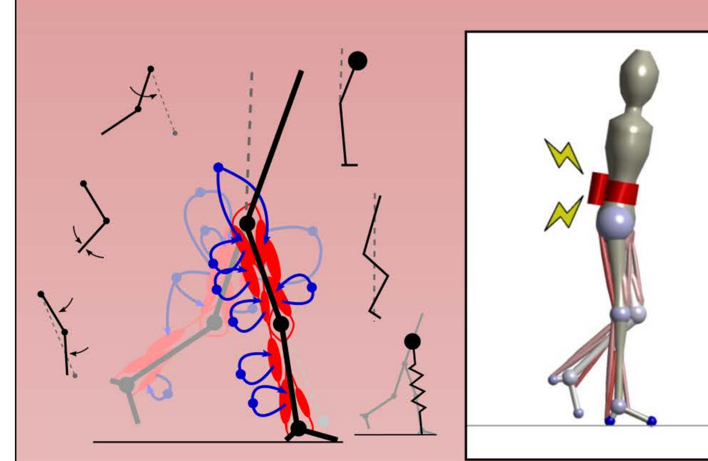
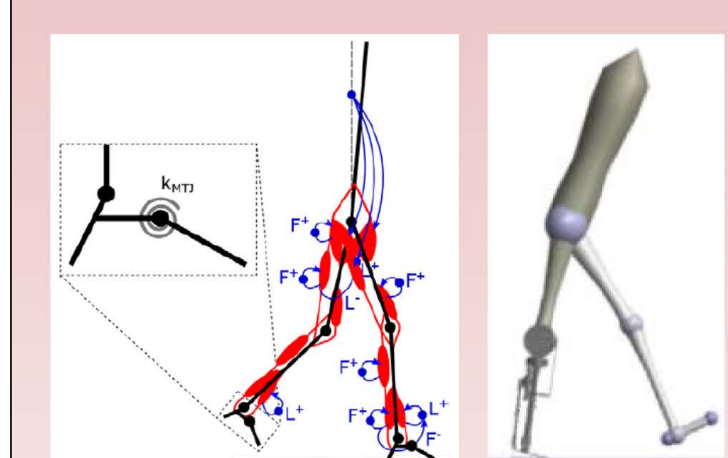
## Neuromuscular simulations

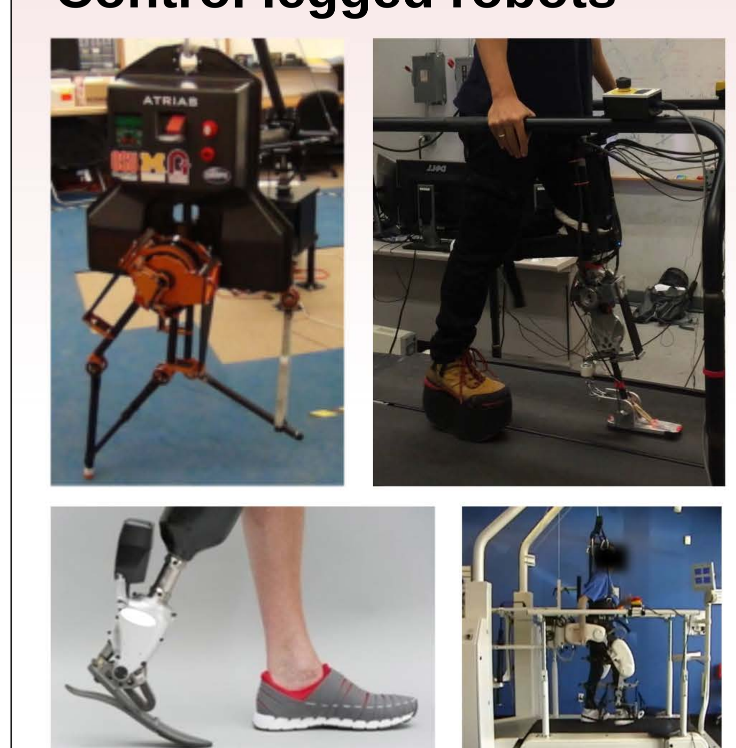
### Model and validate human control of locomotion[1,2]



### Develop high-fidelity simulation test-beds [3,4,5]



### Control legged robots[4,6,7]



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[2] S Song and H Geyer. A neural circuitry that emphasizes spinal feedback generates diverse behaviours of human locomotion. *The Journal of Physiology*, 2015.
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