A muscle-reflex model that encodes principles of legged mechanics, produces human walking dynamics and muscle activities

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Outline

1. Motivation
2. Introduction
3. Objective
4. Methodology
   - New model of human lower limb
   - General equation of muscle stimuli
   - Muscle stimuli during the stance phase
   - Muscle stimuli during the swing phase
5. Results
   - Walking Gait
   - Steady-State Patterns of Joint Angles and Torques
   - Predicted Motor Output
   - Adaptation to Slopes
6. Conclusion

Motivation

The bipedal spring-mass model could describes the legged locomotion dynamics[1]

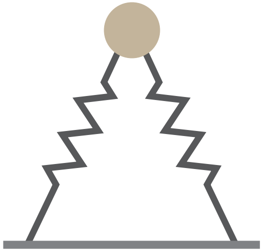

Figure: Spring-loaded inverted pendulum (SLIP)

- SLIP model describes the dynamics during walking and running[1]
- SLIP model is based on self-stability and compliant leg behavior principles[2]
- SLIP model does not present a clear relation with human motor control[2]
- Spinal reflexes can relate sensory information of leg with muscle activation[2]

[1] H. Geyer (2006).

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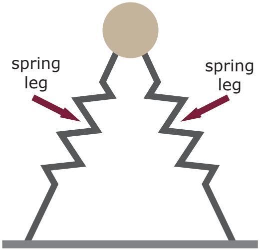

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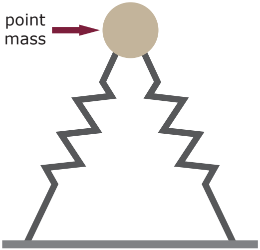

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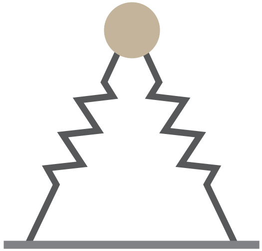

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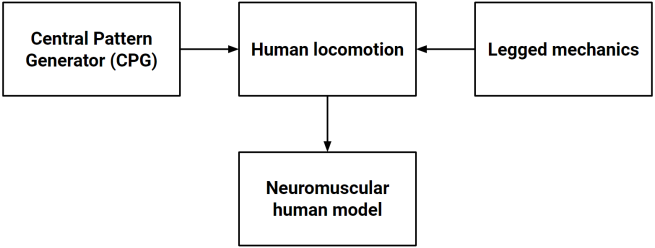
Introduction



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Objective

To develop a neuromuscular human model that encodes the principles of legged locomotion with muscular reflexes

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New model of human lower limb

- Replacing the spring leg with a segmented leg

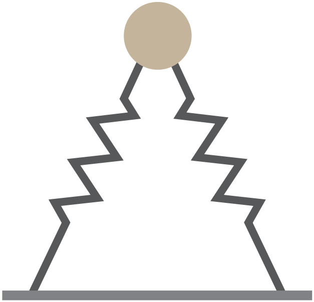


Figure: Spring-loaded inverted pendulum (SLIP)

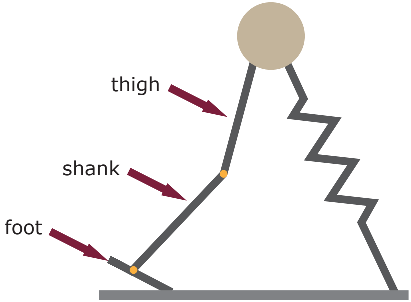
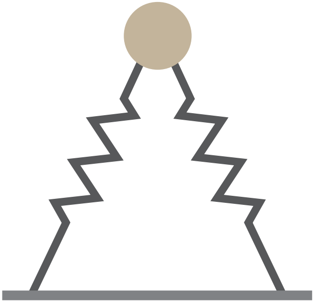


Figure: New model with three segment leg

New model of human lower limb

- Replacing the point of mass with a trunk



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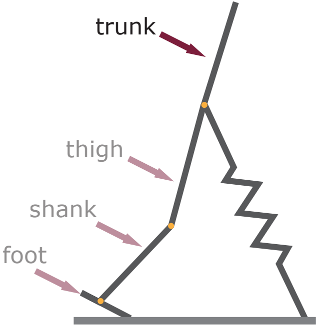


Figure: New model with three segment leg and a trunk

New model of human lower limb

- Vastus group muscle (VAS) generates knee extension motion
- Soleus muscle (SOL) generates ankle plantarflexion motion

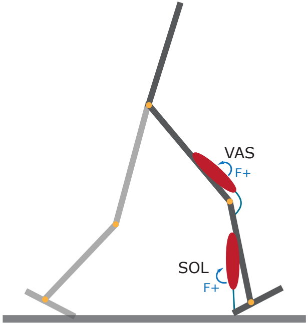
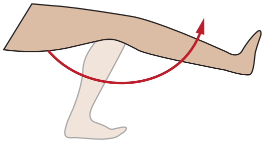
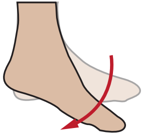


Figure: New bipedal locomotion model with muscles



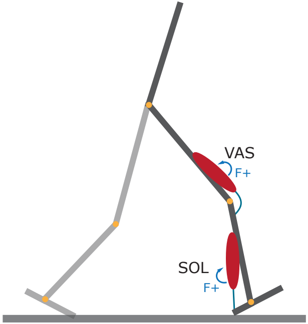
(a) Knee extension



(b) Ankle dorsiflexion

New model of human lower limb

- Vastus group muscle (VAS) generates knee extension motion
- Soleus muscle (SOL) generates ankle plantarflexion motion



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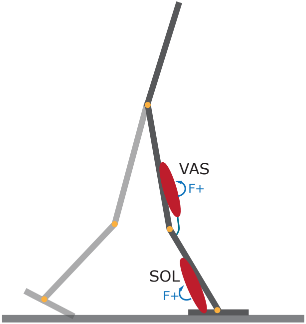

Figure: overextension case

New model of human lower limb

- Gastrocnemius muscle (GAS) generates knee flexion and ankle plantarflexion motion
- Tibialis anterior muscle (TA) generates ankle dorsiflexion motion

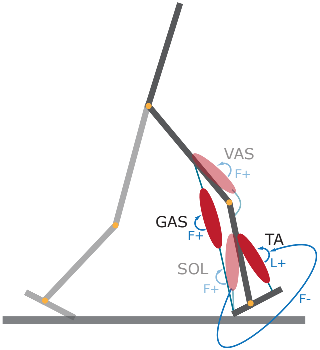

Figure: New bipedal locomotion model with muscles

- GAS prevents knee overextension
- GAS contributes to generate compliant behavior
- TA prevents ankle overextension

New model of human lower limb

- Gluteus muscle group (GLU) generates negative orientation
- Hip flexor muscle group (HFL) generate positive orientation

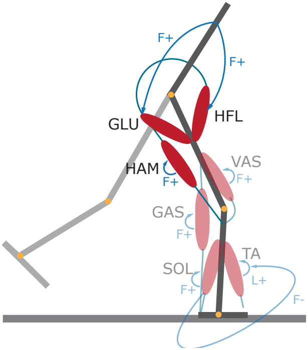

Figure: New bipedal locomotion model with muscles

- GLU and HFL maintain the balance of the trunk
- Hamstring muscle group (HAM) prevents knee hyperextension

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General equation of muscle stimuli

- Spinal reflexes activate muscles during locomotion

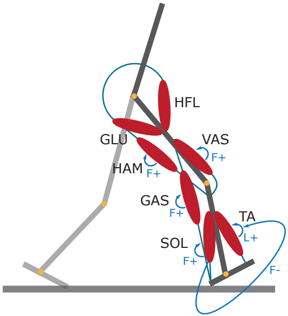

Figure: New bipedal locomotion model with muscles

The stimulation of a muscle is given by

$$S_m(t) = S_{0,m} + G_m F_m \delta t_m,$$
$$\delta t_m = (t - \Delta t_m),$$

where,

- S_m: stimulation
- S_0: prestimulation
- F_m: force
- G_m: gain
- Δt_m: muscle time delay
- ΔL_m: muscle stretch

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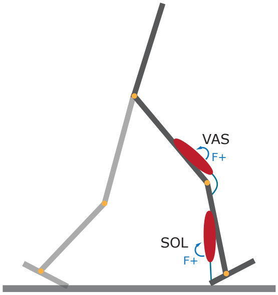
Stance phase: initial contact

The stimulation of **VAS** is given by

$$S_{VAS}(t) = S_{0,VAS} + G_{VAS} F_{VAS}(t - \Delta t_{VAS})$$

The stimulation of **SOL** is given by

$$S_{SOL}(t) = S_{0,SOL} + G_{SOL} F_{SOL}(t - \Delta t_{SOL})$$



- Vastus group muscle (VAS) generates knee extension motion
- Soleus muscle (SOL) generates ankle plantarflexion motion

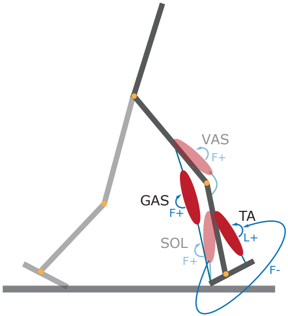
Stance phase: initial contact

The stimulation of **GAS** is given by

$$S_{GAS}(t) = S_{0,GAS} + G_{GAS} F_{GAS}(t - \Delta t_{GAS})$$

The stimulation of **TA** is given by

$$S_{TA}(t) = S_{0,TA} + G_{TA}(\Delta L_{TA})(t - \Delta t_{TA}) - G_{SOL,TA} F_{SOL}(t - \Delta t_{SOL})$$



- GAS prevents knee overextension
- GAS contributes to generate compliant behavior
- TA prevents ankle overextension

Stance phase: loading response

The stimulation of **GLU** and **HFL** is given by

$$S_{GLU}(t) \sim k_p(\theta - \theta_{ref})_{GLU} + k_d\dot{\theta}_{GLU},$$
$$S_{HFL}(t) \sim k_p(\theta - \theta_{ref})_{HFL} + k_d\dot{\theta}_{HFL}$$

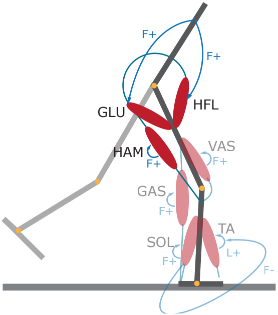


Figure: New bipedal locomotion model with muscles

The stimulation of **HAM** is given by

$$S_{HAM} \sim S_{GLU}$$

- GLU generates negative orientation
- HAM prevents knee hyperextension
- HFL generate positive orientation

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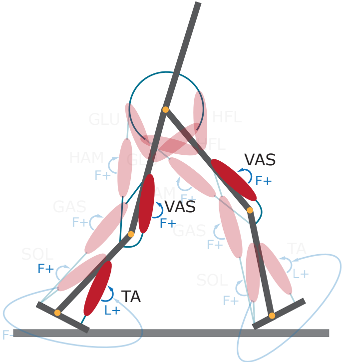
Swing phase: pre-swing

The new stimulation of **VAS** is given by

$$S_{VAS}(t) = S_{0,VAS} + G_{VAS} F_{VAS}(t - \Delta t_{VAS}) - k_{bw} |F_{\mathrm{leg}}^{\mathrm{ctr}}|$$



where,

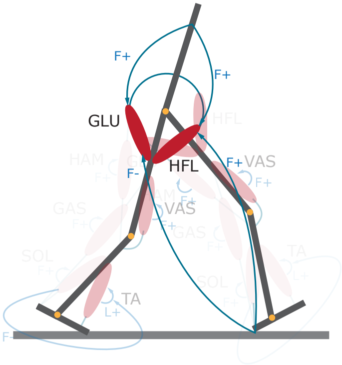
- k_{bw}: gain proportional to body weight
- $F_{\mathrm{leg}}^{\mathrm{ctr}}$: force applied on contralateral leg

The VAS of swing leg should be inhibit to allow compliance behavior

Swing phase: pre-swing

The new stimulation of **HFL** and **GLU** is given by

$$S_{HFL}(t) = k_p(\theta - \theta_{ref})_{HFL} + k_d\dot{\theta}_{HFL} + \Delta S,$$
$$S_{GLU}(t) = k_p(\theta - \theta_{ref})_{GLU} + k_d\dot{\theta}_{GLU} - \Delta S$$



where,

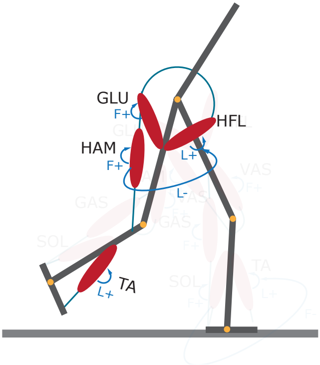
- ΔS: constant parameter

The model initiate swing incresing HFL and decresing GLU stimulation

Swing phase: initial swing

The new stimulation of **HFL**, **GLU** and **HAM** is given by

$$
\begin{aligned}
S_{HFL}(t) &= k_p(\theta - \theta_{ref})_{HFL} + G_{HFL}\Delta L_{HFL} - G_{HAM,HFL}\Delta L_{HAM}(t - \Delta t_{HAM}),\\
S_{GLU}(t) &= S_{0,GLU} + G_{GLU}F_{GLU}(t - \Delta t_{GLU}),\\
S_{HAM}(t) &= S_{0,HAM} + G_{HAM}F_{HAM}(t - \Delta t_{HAM})
\end{aligned}
$$



The new formulation improve gait stability by enforcing swing-leg retraction

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Walking Gait

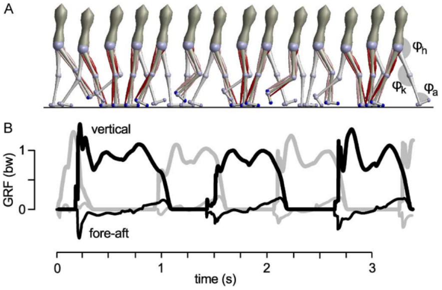

Figure: Walking self-organized from dynamic interplay with ground

- The modeled muscle reflexes include signal transport delays of up to 20 ms
- The vertical GRF of the legs in stance shows the M-shape pattern characteristic for walking gaits

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Steady-State Patterns of Joint Angles and Torques

Maximum cross-correlation coefficients R quantify the agreement between model and human trajectories. $R = 1$ indicates perfect agreement and $R = 0$ indicates no agreement.

Quantity/Articulation	R
Angle/Hip	0.98
Angle/Knee	0.97
Angle/Ankle	0.96
Torque/Hip	0.45
Torque/Knee	0.65
Torque/Ankle	0.99

Figure: Maximum cross-correlation coefficients R for each quantity

- The performance of the model, in general, is very close to the human movement
- The major difference occurs in the knee and hip torques in stance

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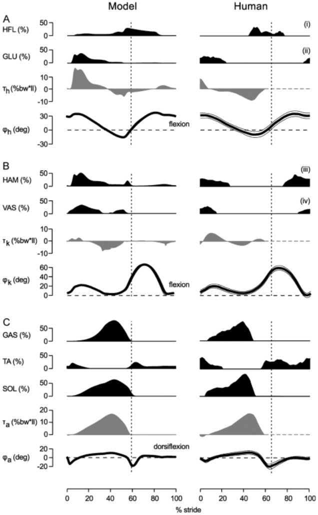
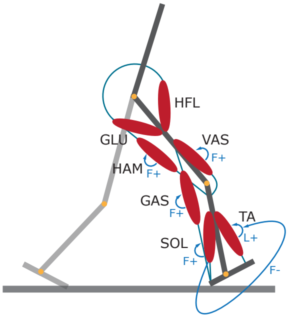


Figure: Maximum cross-correlation coefficients R for each quantity

- The reflex model produce both walking dynamics and kinematic as predicts known activation patterns
- The model can also be evaluated with maximum cross-correlation coefficients R

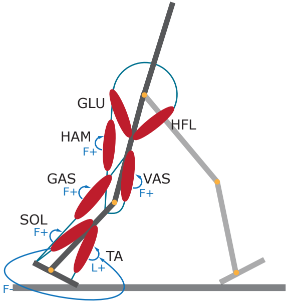
Predicted Motor Output



Muscle	R
SOL	0.97
GAS	0.99
GLU	0.93
HAM	0.90
VAS	0.87
TA	0.87
HFL	0.84

Figure: Maximum cross-correlation coefficients R for each muscle (stance)

Predicted Motor Output



Muscle	R
HAM	0.95
HFL	0.87
TA	0.87
GLU	0.51
VAS	0.51

Figure: Maximum cross-correlation coefficients R for each muscle (swing)

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Adaptation to Slopes

The model can adapt to slopes ($< \pm 4\%$) without parameter interventions.

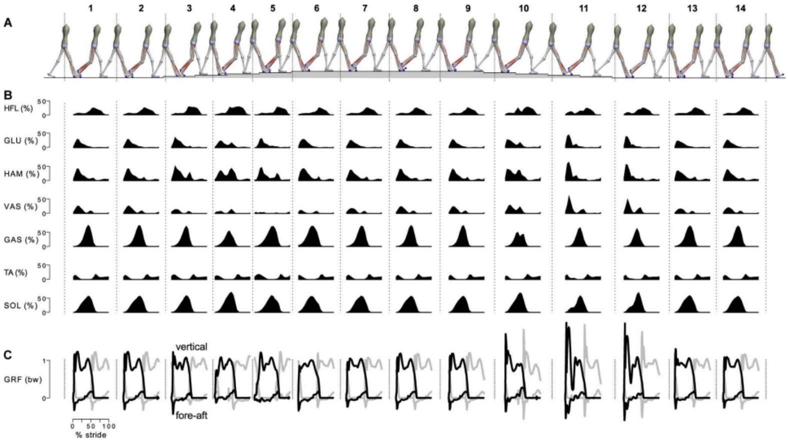

Figure: Slope adaptation

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Conclusion

- Mechanics and motor control cannot be viewed separately in human locomotion
- The principles of legged mechanics were fundamental to simplify the dynamics of walking
- After tuning the resulting muscle reflexes that, by combining these principles, human walking dynamics and leg kinematics emerge and the model tolerates ground disturbances and adapts to slopes without parameter interventions
- The model predicts some individual muscle activation patterns observed in walking experiments
- The interplay between mechanics and motor control is not only important, but could for some muscles dominate human motor output in locomotion