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

Motivation

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

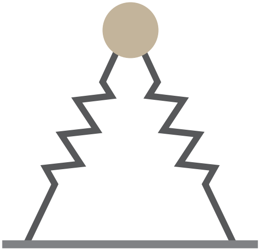

Figure: Spring-loaded inverted pendulum (SLIP)

- 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]

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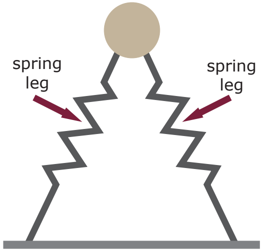

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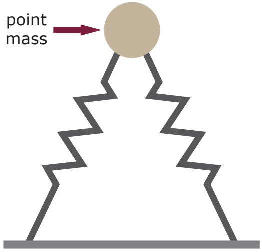

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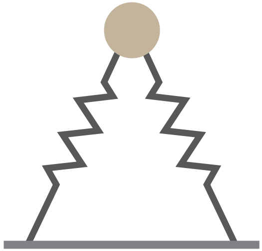

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Objective

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

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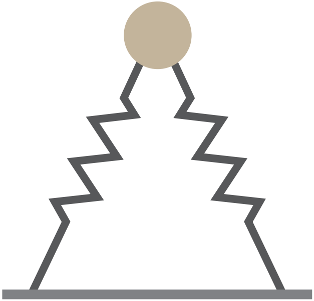
- Replacing the spring leg with a segmented leg



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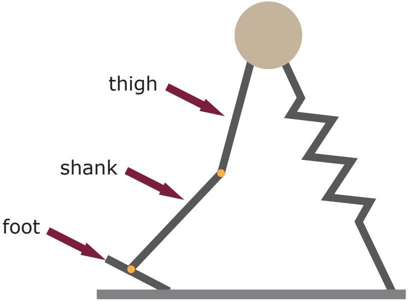


Figure: New model with three segment leg

New model of human lower limb

- Replacing the point of mass with a trunk

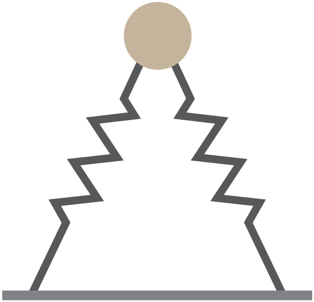


Figure: Spring-loaded inverted pendulum (SLIP)

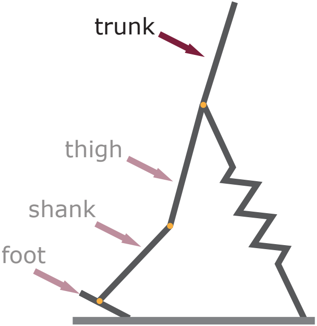


Figure: New model with three segment leg and a trunk

New model of human lower limb

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

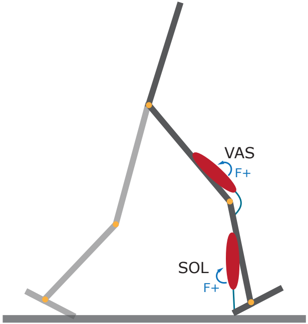
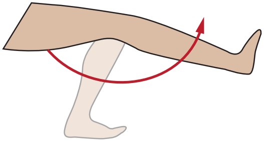
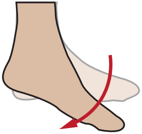


Figure: New bipedal locomotion model with muscles



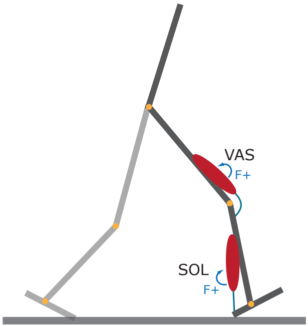
(a) Knee extension



(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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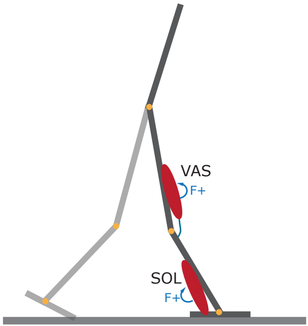

Figure: overextension case

New model of human lower limb

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

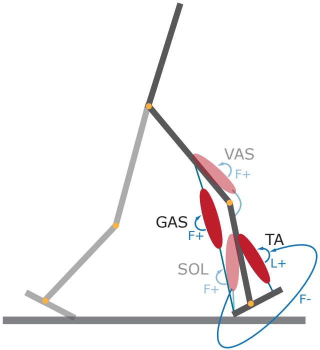

Figure: New bipedal locomotion model with muscles

- 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

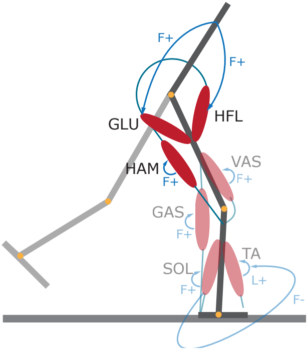

Figure: New bipedal locomotion model with muscles

- 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

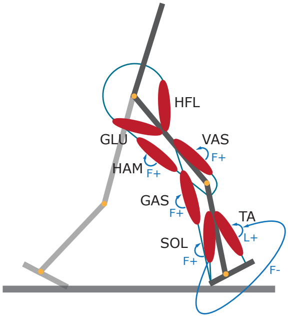

Figure: New bipedal locomotion model with muscles

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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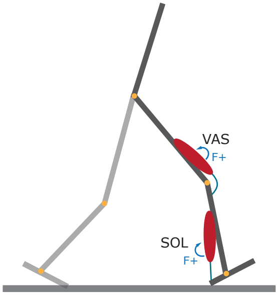
Stance phase: initial contact

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

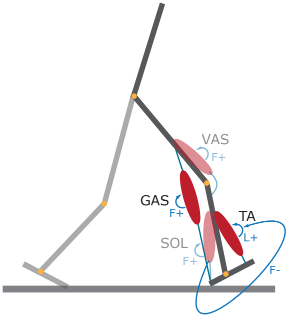
Stance phase: initial contact

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

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

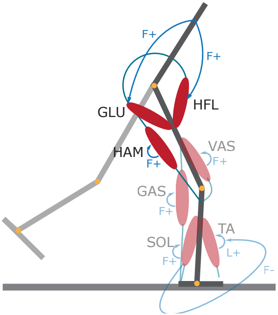


Figure: New bipedal locomotion model with muscles

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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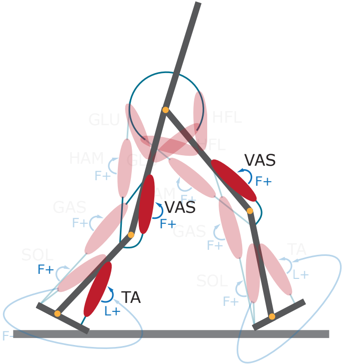
Swing phase: pre-swing

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

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



where,

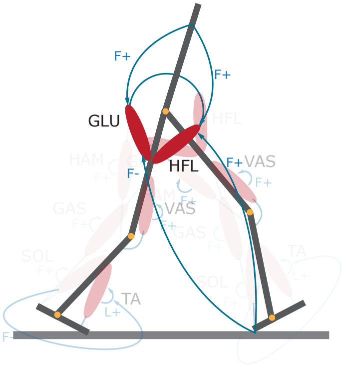
- k_{bw}: gain proportional to body weight
- $F_{\text{leg}}^{\text{ctr}}$: force applied on contralateral leg

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,

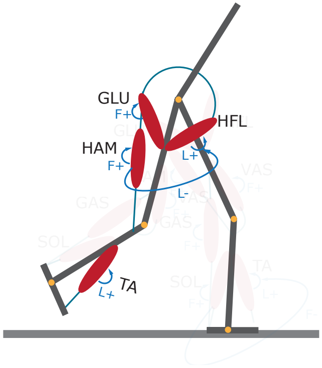
- ΔS: constant parameter

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

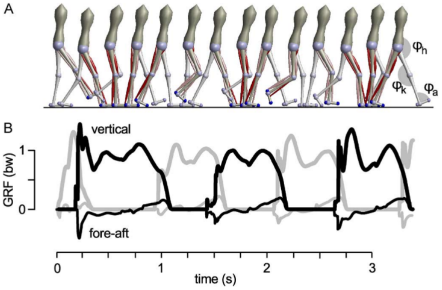

Figure: Walking self-organized from dynamic interplay with ground

- 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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Predicted Motor Output

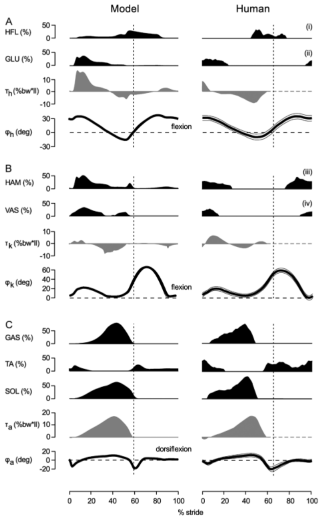

Figure: Maximum cross-correlation coefficients R for each quantity

- 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

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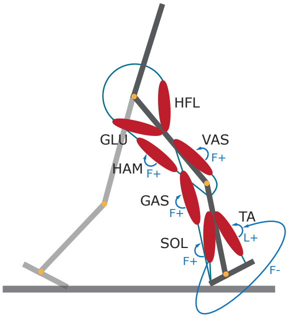
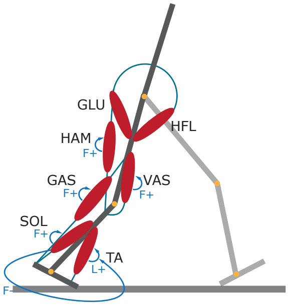


Muscle	R
SOL	0.97
GAS	0.99
GLU	0.93
HAM	0.90
VAS	0.87
TA	0.87
HFL	0.84

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.

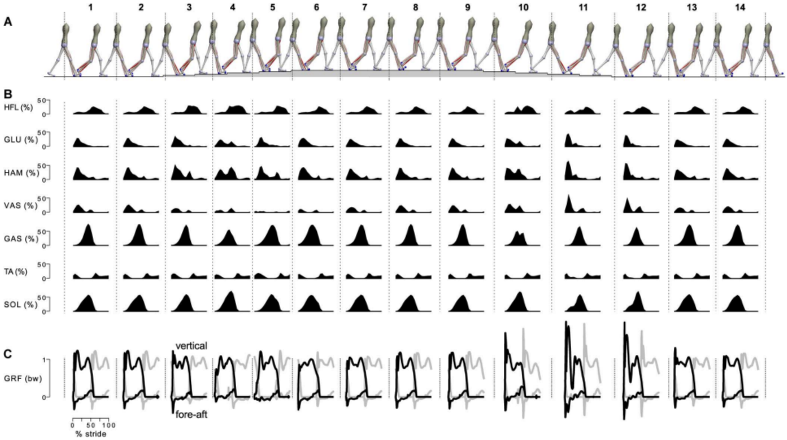

Figure: Slope adaptation

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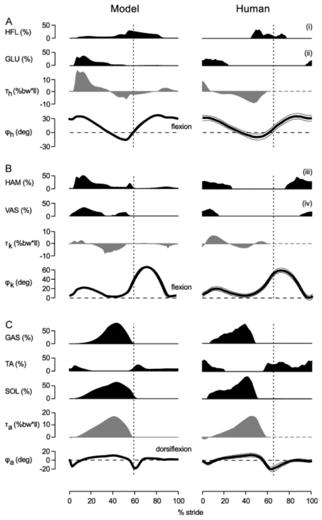

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