Simplification of the Hill Muscle Model Computation for Real-Time Walking Controllers with Large Time Steps

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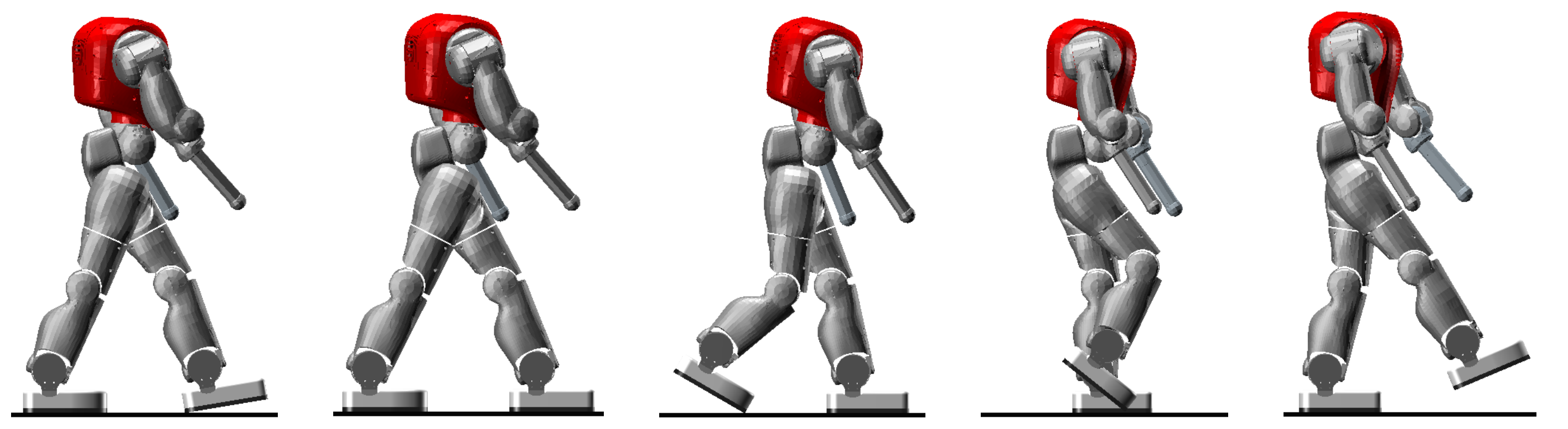
Motivation & Proposed solution

Bio-inspired controllers are emerging as a promising way to implement dynamic walking. In this study, we implemented the one proposed by Geyer & Herr (2010), relying on reflex-controlled virtual **Hill muscles**. In this model, muscles' state is determined by the length ($\mathbf{l_{ce}}$) of their active, contractile element. However, its update rate is governed by a stiff and strongly non-linear state equation, thus requiring a **small integration time step**.



The contributions of this study are:

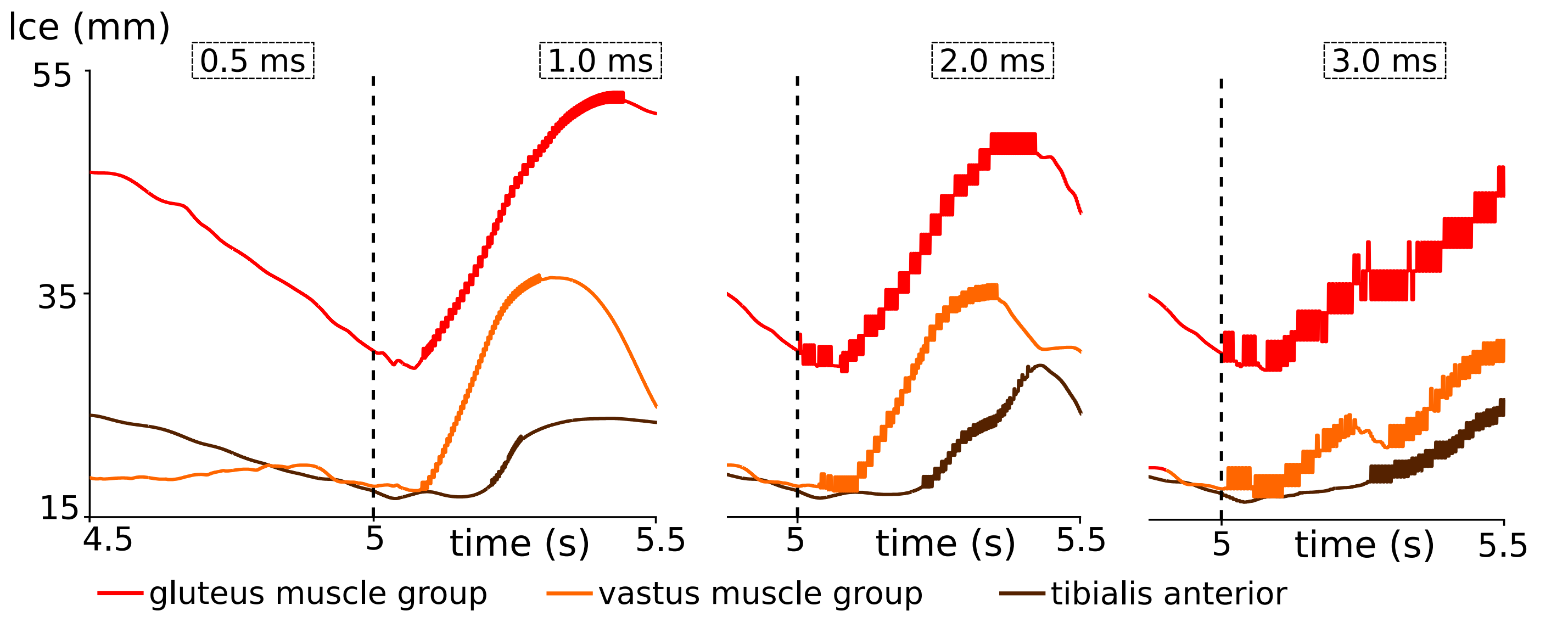
- the presentation of 3 methods to get the **steady-state** value of $\mathbf{l_{ce}}$
- the study of their accuracy and computational cost
- the illustration that the $\mathbf{l_{ce}}$ dynamics can be neglected for **fast muscles**
- a method to mix the steady-state approximation with the full muscle dynamic model for **slow muscles**

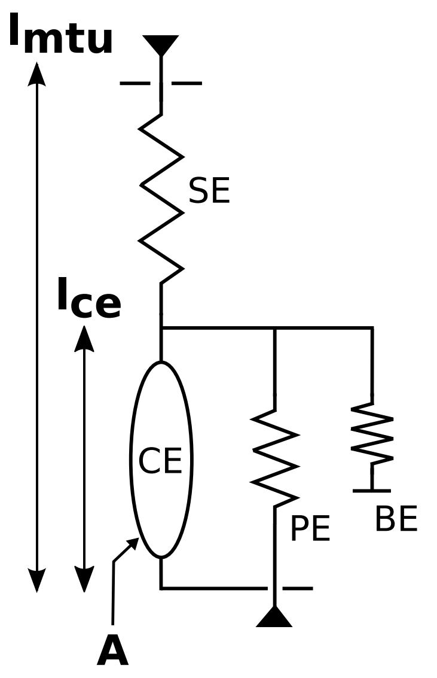
Time step numerical issue

The length $\mathbf{l_{ce}}$ is updated with a time integration of its derivative $\dot{\mathbf{l}}_{\mathbf{ce}} = \mathbf{f}(\mathbf{l_{ce}}, \mathbf{l_{mtu}}, \mathbf{A})$.

- $\mathbf{l_{mtu}}$: total muscle-tendon unit length
- **A**: activation provided by the motor neuron

Due to the stiffness and non-linearity of $\mathbf{f}(\cdot)$, exceeding a **critical time step** value generates **numerical oscillations**.



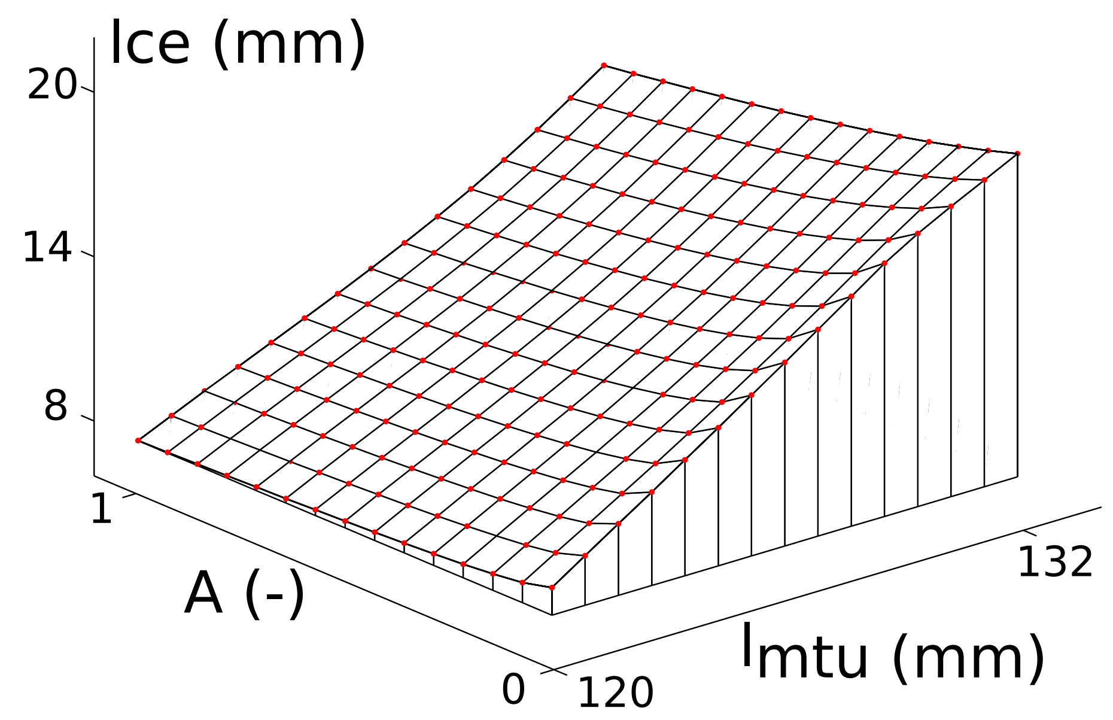


Control rules are **impacted by $\mathbf{l_{ce}}$** in the feedback loop, causing the walker to fall.

Steady-state computation - Three methods to get $\mathbf{l_{ce}}$ without integration

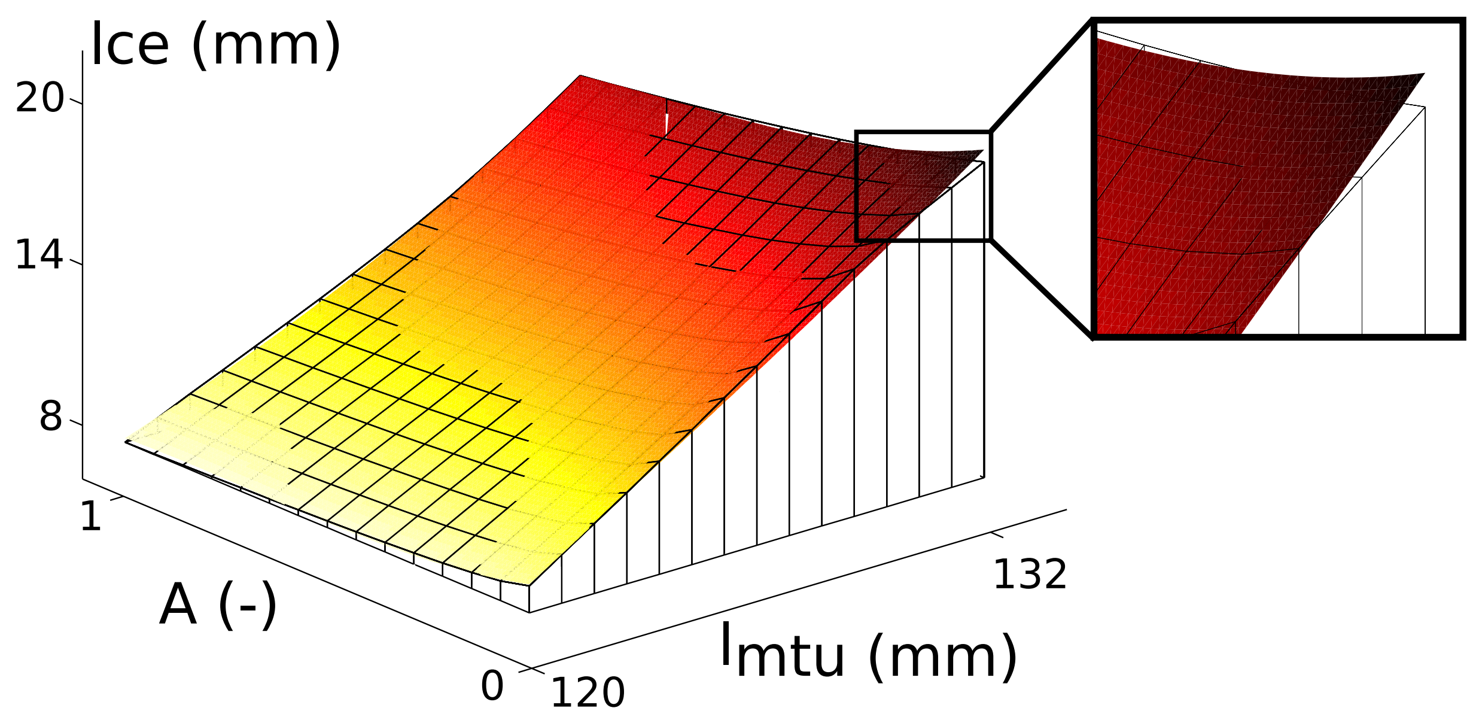
Neglecting the muscle dynamics: $\mathbf{l_{ce}}$ is always at steady-state, i.e. $\dot{\mathbf{l}}_{\mathbf{ce}} = 0$. Then, the problem is to solve $\mathbf{f}(\mathbf{l_{ce}}, \mathbf{l_{mtu}}, \mathbf{A}) = 0$, i.e. to find $\mathbf{l_{ce}} = \mathbf{g}(\mathbf{l_{mtu}}, \mathbf{A})$.

Look Up Table (LUT) interpolation



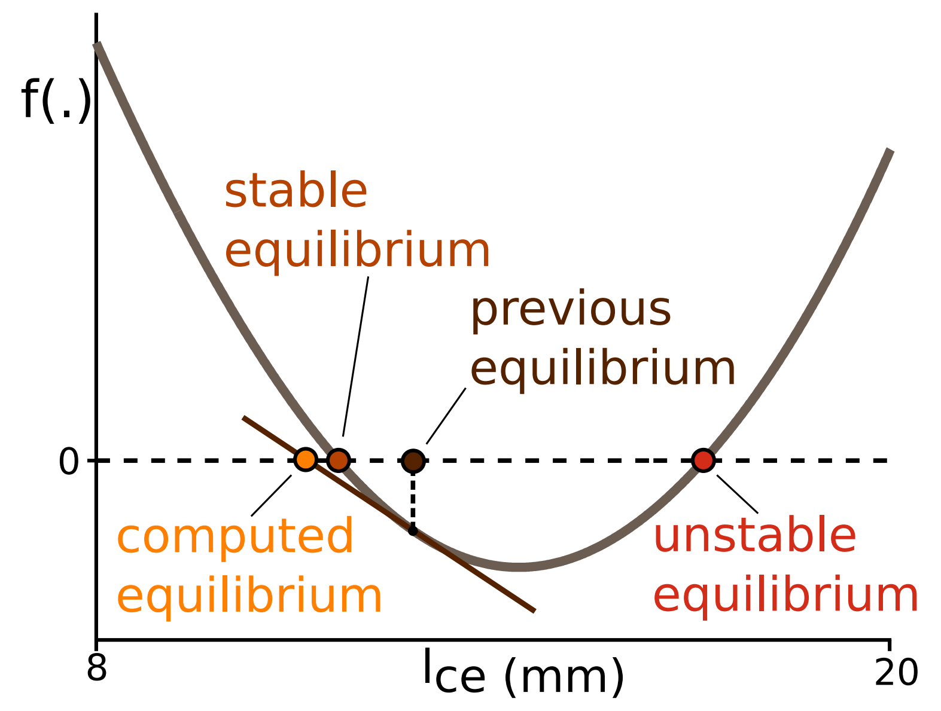
- generated off-line
- cost depends on the mesh refinement
- accuracy depends on the mesh refinement

Third-order polynomial (TOP) approximation



- generated off-line
- computationally efficient
- accuracy depends on the LUT to fit

Newton-Raphson scheme (NRS)

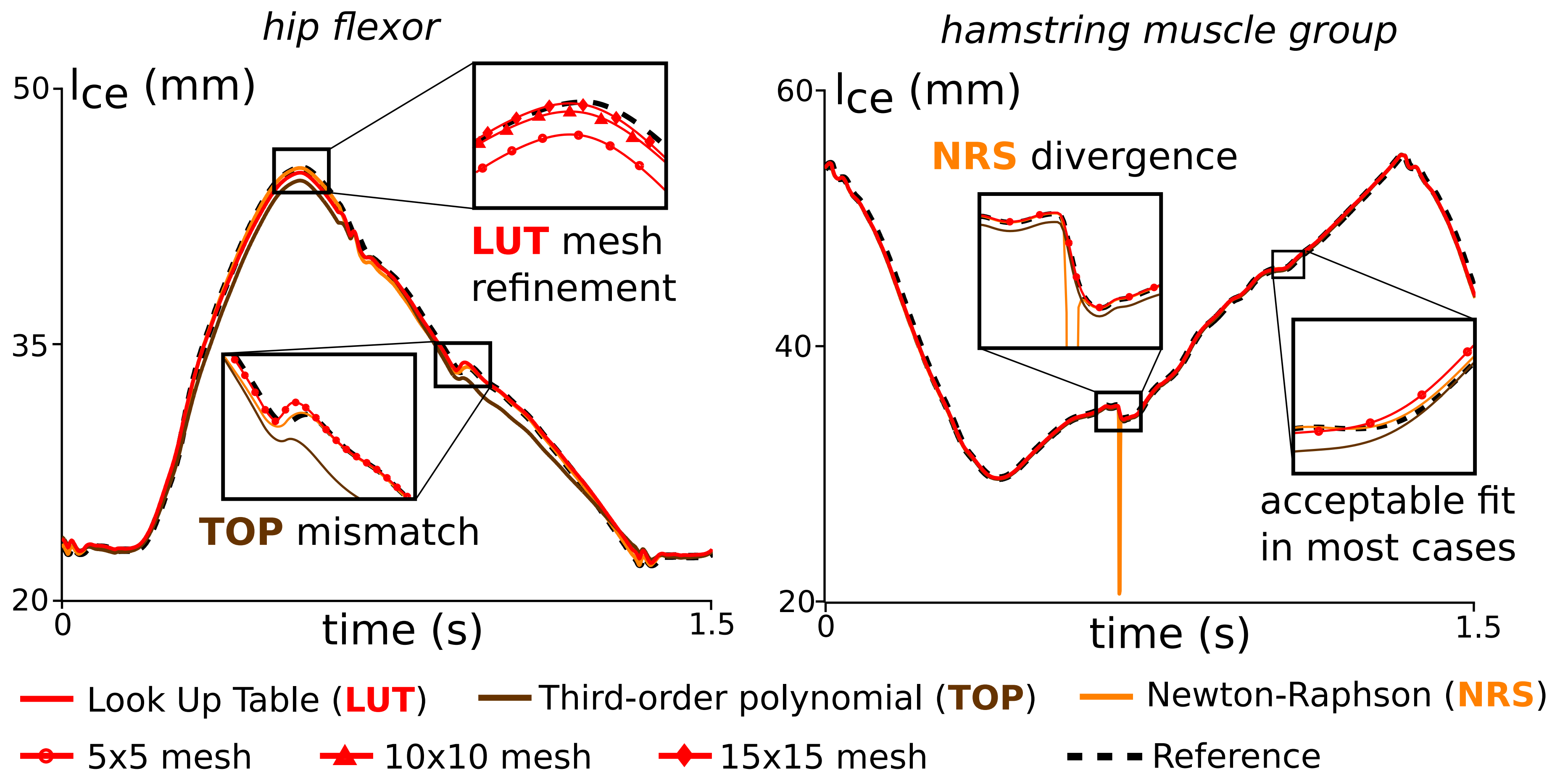


- no pre-process computation
- convergence to a stable equilibrium not guaranteed
- more than one iteration might be needed

Results

We compare the three steady-state $\mathbf{l_{ce}}$ profiles with a reference based on the muscle dynamics.

- **LUT**: refining the mesh increases the accuracy.
- **TOP**: accuracy deteriorated for some muscles at some phases of the gait.
- **NRS**: excellent fit with only one iteration, except when the gradient of $\mathbf{f}(\cdot)$ is close to 0.



The **LUT** approximation **never diverges** and is **accurate**, provided a good mesh refinement.

We replaced the full dynamics model by these steady-state approximations.

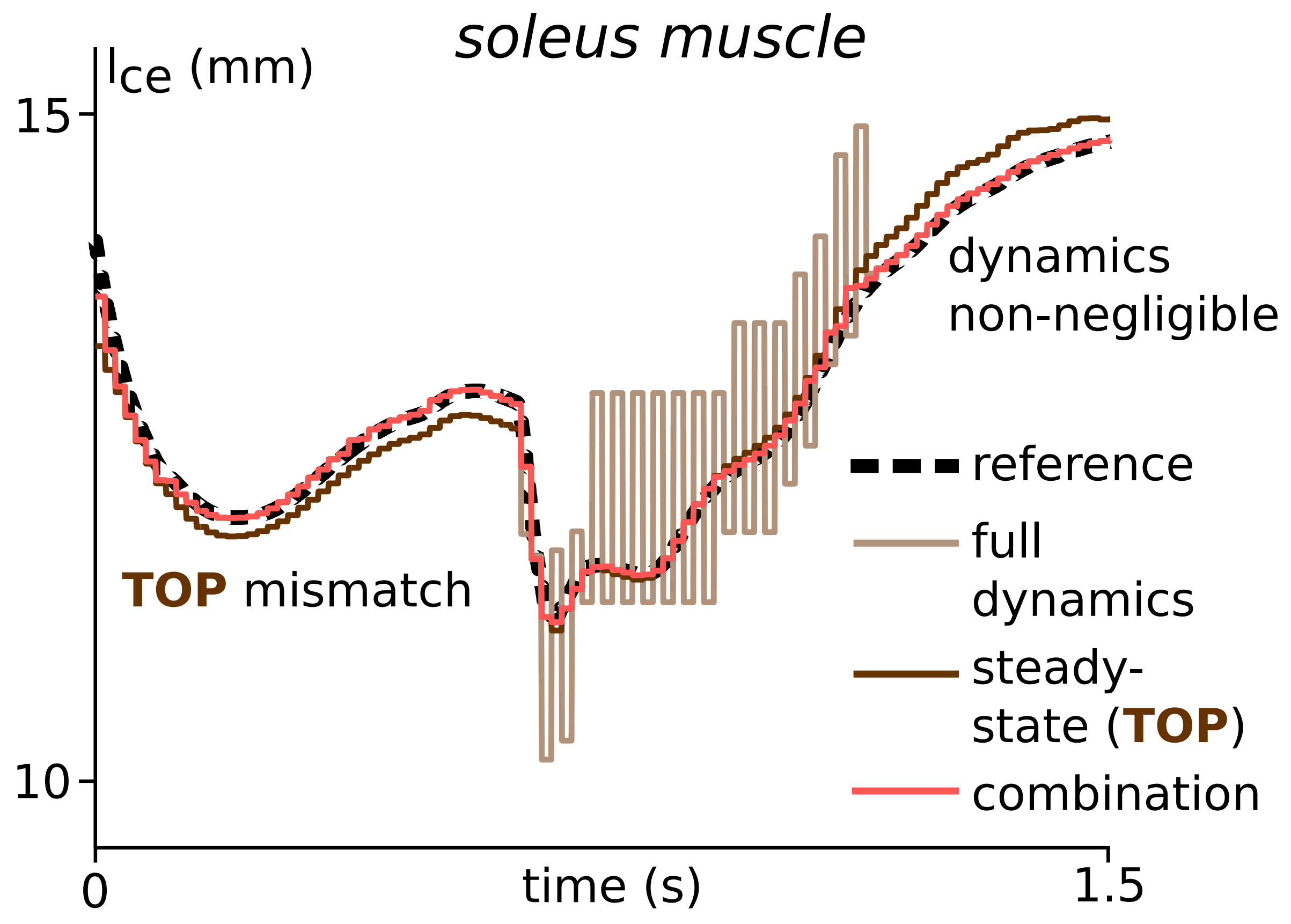
- Any of the these approximations preserved the dynamic walking gait.
- However, the pattern was more jerky than with the original model.
- Re-optimizing the controller led to retrieve natural and smooth gaits.

Controllers were able to cope with **3 ms time steps**, instead of **0.5 ms before**.

Slow dynamics muscles case

At some phases of the gait, the *soleus muscle* **dynamics cannot be neglected**, i.e. all steady-state approximations diverge from the actual $\mathbf{l_{ce}}$ value.

- Reference computed with a 0.5 ms time step, the others with a 10 ms one.
- Neither using the full dynamics model nor a steady-state approximation provided a correct fit.
- Combining these two signals led to a correct fit. Combination is done by saturating the $\mathbf{l_{ce}}$ determined by the full dynamics to the steady-state value.



This **signal combination** highly improves the accuracy for **slow dynamics** muscles computed with **large time steps**.

Acknowledgment & Reference

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H. Geyer and H. Herr. A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 18(3):263 - 273, 2010.