Muscle-tendon mechanics resolve the trade-off between energy-efficient and robust locomotion?

Matthew Araz[1,2], Tobias Siebert[3], Alexander Badri-Spröwitz[4], Syn Schmitt[2], Daniel Haeufle[1]
[1]Hertie Institute for Clinical Brain Research, University of Tuebingen, Tuebingen, Germany
[2]Institute for Modelling and Simulation of Biomechanical Systems, University of Stuttgart, Stuttgart, Germany
[3]Motion and Exercise Science, University of Stuttgart, Stuttgart, Germany
[4]Department of Mechanical Engineering, KU Leuven, Leuven, Belgium
Email: matthew.araz@uni-tuebingen.de

Summary

During bouncing gaits like running and hopping, terrestrial animals use their limbs in an energetically economical way by cycling most of the energy through elastic tissues like tendons to minimize muscle work. Simultaneously, they maintain stability on unpredictable terrains despite significant neural delays. While nature achieves robust and energy-efficient locomotion, robotics often views efficiency and robustness as trade-offs. This study shows that muscle-tendon mechanics can enable both energy-efficient and robust locomotion against step perturbations. Incorporating muscle-tendon-like viscoelastic materials into legged robots could offer a viable solution to this perceived trade-off.

Introduction

Terrestrial animals achieve energy-efficient and robust locomotion on rough terrains. In the presence of neural delays, they rely on open-loop muscle stimulation [1]. Yet, the robotics community often sees a trade-off between energy efficiency and robustness. Studies suggest that muscle intrinsic properties which generate zero-delay force responses, known as preflexes, may contribute to robustness [2]. Here, we explore the trade-off between energy-efficiency and robustness on the muscle level in locomotion.

Methods

We analyzed a two-segment leg model (Figure 1B) with a Hill-type muscle model (Figure 1C) under steady and unsteady hopping [2]. Here, we compared two control signals (Figure 1A), (a) an open-loop rising ramp signal (Preflex-Rising, PR) [2], (b) an optimal stimulation signals minimizing muscle fiber length changes during stance (Quasi-Isometric, QI). Both generate periodic hopping with the same hopping height. The model was tested against step-down perturbations, with metabolic cost measured as suggested in [3] and muscle viscous contributions quantified as suggested in [2].

Results and Discussion

The QI stimulation strategy reduced dissipative muscle work by approximately 50% during steady-state locomotion compared to the PR strategy. Surprisingly, this energy efficient strategy does not come with the cost of robustness. Instead, QI provides slightly improved robustness in terms of faster recovery from perturbations. With QI, the metabolic costs are even reduced directly in the perturbation response. These findings suggest that muscle-tendon mechanics may enable to achieve both energy-efficient and robust locomotion without relying solely on task-level stability.

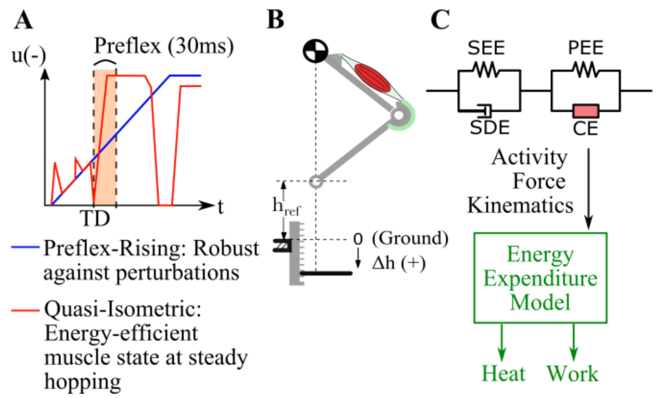

Figure 1: (A) Tested muscle stimulation strategies Preflex-Rising (PR) and Quasi-Isometric (QI), TD is the touchdown (B) Single leg hopping model (C) Hill-type muscle model with energy expenditure model.

Conclusions

Animals have evolved to interact with their environment in highly energy-efficient, robust, and agile ways. Our results suggest that muscle-tendon viscoelasticity plays a crucial role in enabling these locomotion characteristics. Incorporating muscle-tendon like viscoelastic materials into robots could offer a promising solution to achieve energy efficient and robust locomotion in legged robotics.

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References

[1] Daley M. and Biewner A. (2006), *PNAS* , 103: 15681-15686
[2] Izzi F. et al. (2023) *Sci Rep*; 13: 45-59.
[3] Lichtwark G. and Wilson A. (2007). *J. Biomech.*, **40**: 1768-1775.