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Author(s)	Mo, An; Izzi, Fabio; Gönen, Emre Cemal et al.
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Slack tendon enables tunable damping for legged locomotion

An Mo[1,*], Fabio Izzi[1,2], Emre Cemal Gönen[1], Daniel Haeufle[2,3], Alexander Badri-Spröwitz[1,4]
[1]Max Planck Institute for Intelligent Systems, Stuttgart, Germany
[2]University of Tübingen, Tübingen, Germany
[3]University of Stuttgart, Stuttgart, Germany
[4]KU Leuven, Leuven, Belgium
* *mo@is.mpg.de*

1 Introduction

Animals have a remarkable running agility in diverse conditions. It has been hypothesized that the hierarchies of control strategies contribute to the locomotion robustness; including high-level neural networks and low-level intrinsic mechanics [1] (Fig. 1). Especially in fast running, the reflex-based control models struggle during perturbation, due to large sensorimotor delays [2]. Instead, the immediate physical response of the musculoskeletal system can compensate disturbance faster than the neural networks.

Similarly, bioinspired legged robots exploit passive compliance. Stiffness has been studied extensively in legged locomotion, from spring-loaded inverted pendulum (SLIP) models [3] to springy robot leg implementations [4]. In comparison, damping is often overlooked, despite its benefit of reducing control effort, stabilizing movements and reject unexpected perturbations [5].

Legged robots commonly implement "virtual damping": actively produced negative work by actuators. However, it requires precise sensors, high-frequency control, and powerful actuators to produce peak damping force and absorb negative power. Alternatively, a physical damper embedded in a leg design acts instantly, produces adaptive forces, and requires no sensors or control feedback.

Up to now, few implementation of physical dampers in legged robots exists. It remains unclear how physical damping can benefit legged locomotion. A tunable damping is even more challenging due to the coupling of force generation and effective damper stroke [5].

In this work [6], we aim to develop tunable physical damping strategy for legged robots and investigate its benefits to legged locomotion. Our solution is inspired by the tendon slack observed in biology [7]. We evaluate our proposed slack damper mechanism on a robotic leg during vertical and forward hopping. Our results demonstrate effective tunable damping leading to a trade-off between locomotion robustness and energetic economy. This trade-off is resolved by the perturbation-triggered capacity of the design.

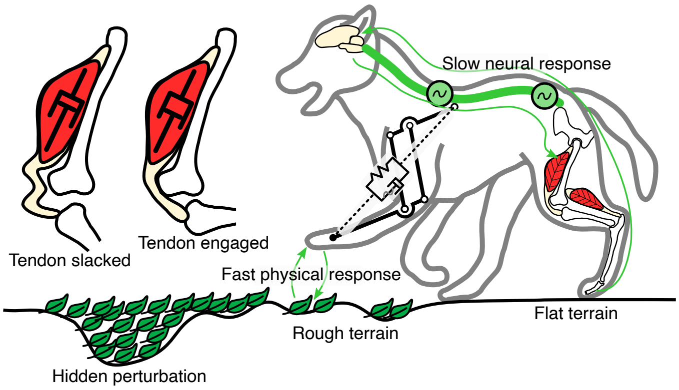

Figure 1: Fast running over diverse terrain is challenging due to the slow neural control loop. The intrinsic mechanics of the musculoskeletal system can provide fast physical response to compensate unexpected perturbations. The tendon slack observed in biology inspires our tunable damping strategy for robust and effficient locomotion.

2 Bio-inspired design

We built a robot leg setup to examine our tunable damping strategy. Inspired from the leg anatomy of mammalian quadruped, we designed a 3-segment robot leg (Fig. 2). The hip and knee joints were actuated by geared brushless motors. In parallel to the belt transmission, the knee joint was coupled to a spring and a hydraulic damper via tendon connection.

In our previous 2-segment leg design [5], we expected to regulate the damper energy dissipation by adjusting the damping rate. Counter-intuitively, tuning the damping rate only made marginal changes in damper dissipated energy. The dissipated energy is an integral of damper force and effective stroke. While a higher damping rate will increase the damper force, the effective stroke will be reduced by stronger deceleration.

Instead of tuning the damping rate, we propose damping control by adjusting the damper's tendon slack [6]. Tendon slack has been observed in biology, with tendon strained up to 2% before transferring considerable forces, representing the stretching-out of the "crimp-pattern" [7]. Motivated by this observation, we introduce slack in the tendon connect-

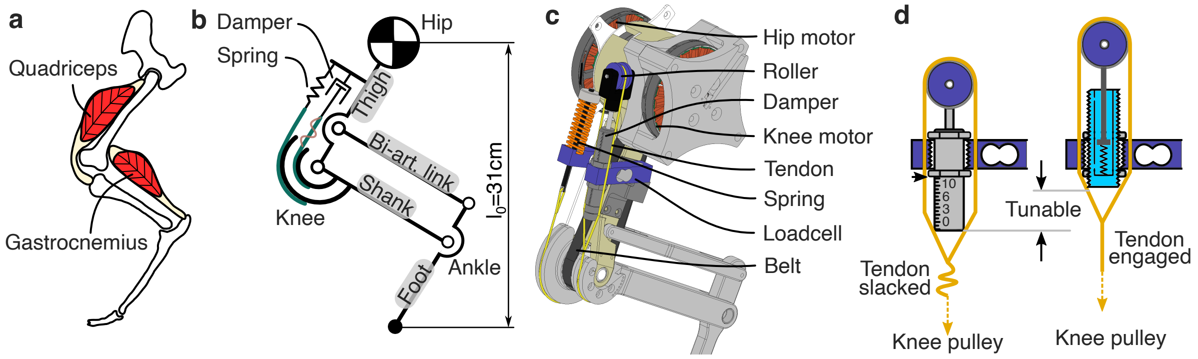

Figure 2: (a) Leg anatomy of mammalian quadruped. (b) Schematics of our pantograph leg design. (c) Rendering of the embodiment design. (d) Working principle of the slack damper mechanism.

ing the damper to the knee pulley (Fig. 2d). In this design, the damper body and the load-cell are threaded connected. Tuning the damper body allows adjusting the damper position, therefore the tendon slack, in resolution of 1 mm per turn. This tendon slack delays the damper's engagement, reducing both damper force and effective stroke, and hence enabling previously unachievable tuning.

3 Hopping experiment

To evaluate our slack damper mechanism and investigate the benefit of physical damping, we tested our bio-inspired leg with four tendon slack settings in three perturbed hopping experiments:

1) Vertical hopping + step-down perturbation
2) Forward hopping + continuous perturbation
3) Forward hopping + ramp-up-step-down perturbation

(Video: `https://youtu.be/Sa-q-5NucGY`)

To focus on the physical response of the mechanics, we implemented an open-loop hopping controller that cannot detect ground perturbations.

Our results confirmed the damping tunability enabled by the slack damper design. The tendon slack controlled the onset timing, stroke engagement and energy dissipation of the attached damper. For all three types of perturbation, we found improved robustness with higher damping, i.e. less damper slack. However, this improved robustness is associated with higher energy cost, as the actuators needed more power to compensate the energy dissipation through damping during steady state locomotion. Therefore, our findings suggest a trade-off between locomotion robustness and energetic economy when damping control is employed.

Further, our slack damper mechanism is capable of a perturbation-triggered damping strategy, which could potentially eliminate such trade-off. The tendon slack can be set to barely engage during steady-state locomotion, hence minimizing unwanted damping dissipation. When a hidden perturbation, such as a ground drop, increases the impact velocity of a foot, the leg will flex more and engage the damper as needed. This way the damping force is triggered during the perturbed step to compensate for the excessive energy.

4 Conclusion

We proposed a bio-inspired tunable damping strategy based on tendon slack. We tested this slack damper mechanism on a robot leg during perturbed hopping. Our embedded physical damping improves hopping robustness, but at the cost of larger energy consumption. The perturbation-triggered capacity of our design auto-engages the damper only during perturbation, making the trade-off between locomotion robustness and energy consumption more favorable. Our work could motivate the development of future robots exploiting morphological intelligence to facilitate the controller design by taking advantage of damping. For future research direction, we are interested in exploring how close-loop control can benefit and exploit tunable damping.

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