Viscous Damping in Legged Locomotion

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Damping likely plays an essential role in legged animal locomotion, but remains an insufficiently understood mechanism. Intrinsic damping muscle forces can potentially add to the joint torque output during unexpected impacts, stabilise movements, convert the system's energy, and reject unexpected perturbations [1, 2].

Recent legged robots exploit **virtual damping** as part of a virtual compliance controller [3]: actively produced and sensor-controlled negative actuator work. Virtual damping requires high-frequency force control loops, and precise timing to identify loading conditions during touch-down and take-off events. Virtual damping systems must feature high-power actuators mechanically and electrically capable of producing negative power, and absorbing negative power peaks. **Mechanical damper** leg configurations can act instantaneously and without the need for sensing and control feedback, similar to springs [4] (Fig. 1A). Dampers can also share impact loads with leg designs featuring parallel actuator and spring configurations [5]. However, only a few implementations of mechanical damped-systems exist in robotic legged locomotion [6]. The requirements for mechanical dampers are not yet defined, and it remains unknown how the expected benefits from mechanical damping transfer into practice. Real-world effects such as unsprung mass impact dynamics and nonlinear effects of segmented leg designs shape the stance-phase locomotion dynamics and might interfere with mechanical damper implementations.

We want to understand how physical damping can be exploited for locomotion tasks [7]. We study the effect of mechanical damping on the total energy of the leg-system and quantify the dissipated energy within one drop cycle—from touch-down to lift-off—for different drop heights and at different damping rates. The simplified drop experiment captures the core aspects of the more complex legged locomotion task: negotiating ground contact, including uncertainties. With a wide parameter space to explore, we combine insights both from numerical simulations and hardware experiments.

In a numerical simulation, we implemented a 2-segment leg model with a passive spring-damper element at the knee-joint (Fig. 1A). We characterised this system under different drop conditions: drop height, damping rate, and damping strategy. The simulation results indicate that an adjustable and viscous damper is desired to reject perturbations of the system's total energy due to variations in the drop height.

We examined how our predictions from the numerical simulation relate to hardware experiments (Fig. 1C). We separated the measured dissipated energy into its components by experimental design. The recorded work loops (Fig. 1B) allowed us to characterise the dissipation from the early impact (unsprung-mass effects), viscous damping, Coulomb damping, and damping adjustments *individually, and qualitatively*. We also observed that the damping characteristics of mechanical dampers are complex and mostly dependent on the impact's loading conditions, and mechanical configuration. Hence we emphasise the importance of characterising mechanical dampers during real legged impacts to evaluate their effectiveness for compliant legged locomotion.

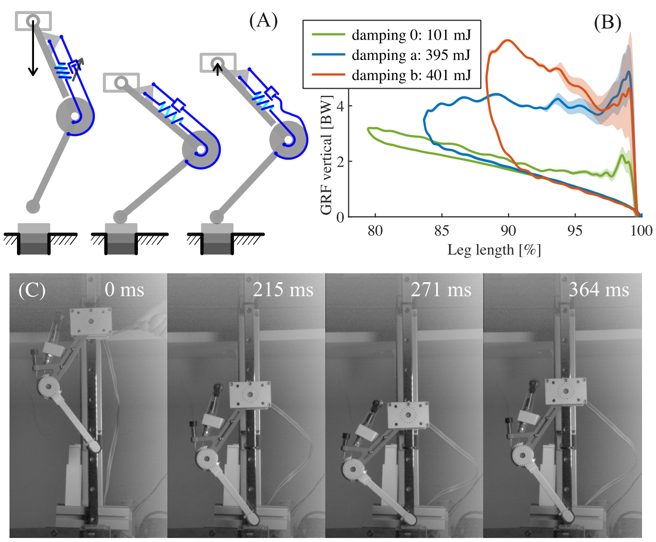

Fig. 1: (A) 2-segment leg model with parallel spring-damper element mounted at the knee joint. (B) Example of work loop for different damping settings – data from hardware experiments. (C) High-speed snapshots of the hardware set-up, dropped onto force sensor.

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