Robust Walking using Piecewise Linear Spring
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**Motivation**

Legged system can benefit from compliance for stability, speed, adaptability and robustness. Recently, we have studied the effects of compliant spine in quadruped robots. We have observed that having nonlinearity in the spine compliance can set a better trade-off between speed and energy efficiency. Similar to the spine in quadruped robots, compliance at the hip joint of bipedal robot can also improve the walking performance such as compliance. Here, we test the efficacy of piecewise linear hip compliance for robust bipedal walking.

**Piecewise Linear Spring**

![Graph showing piecewise linear spring model](image)

For nonlinear spring, we focus on piecewise linear spring since:
- Minimum parameters to optimize
- Easy to analyze
- Easy to realize

**Simple Model for Locomotion**

In our previous work, we focused on a skid propelled model of a running baby. High compliant spines are used in baby locomotion. Each foot impacts in each other by a spring. The spring makes the flexible spine while foot and torso parts are articulated in a fixed and joint part of a quadruped.

**Most important result**

We have observed that having nonlinearity in the spine compliance can set a better trade-off between speed and energy efficiency.

**Quadruped with Nonlinear Flexible Spine**

Energy consumption and speed of a quadruped robot with linear and piecewise linear flexible spines are compared using a more realistic model developed in Matlab. This quadruped is a simple mechanical model and a simple model presented earlier. Each foot impacts in each other by a spring. The spring makes the flexible spine while foot and torso parts are articulated in a fixed and joint part of a quadruped.

These simply arranged rotational springs on the spine result in quadruped spring passive spine.

Hip and shoulder joints are controlled on simulated trajectories.

**Results**

Energy consumption and speed of a quadruped robot with linear and piecewise linear flexible spines are compared using a more realistic model developed in Matlab. This quadruped is a simple mechanical model and a simple model presented earlier. Each foot impacts in each other by a spring. The spring makes the flexible spine while foot and torso parts are articulated in a fixed and joint part of a quadruped.

**Passive Walker with Nonlinear Flexible Hip**

A simple mechanism at hip joint which results in a piecewise linear spring.

**Performance measure**

- Stable: robot walks with a stable and regular gait
- Stopped: robot stops after a few steps of walking
- Unstable: robot falls down after a few steps of walking

**Results**

As the table shows, the robot with no spring cannot walk stably while having spring at the hip joint enhances the robot stability. The nonlinear spring is superior in terms of stability — i.e. lowest (highest) percentage in Unstable (stable) category — as well as its walking distance.

**Conclusion**

- Compliance can improve locomotion performance.
- Higher degrees of freedom in nonlinear compliance can improve locomotion performance further.
- Piecewise linear spring is a good candidate for nonlinearity since it is easy to realize.
- Nonlinear hip compliance can improve walking robustness.

**Future Work**

- Study the robotic dynamics of nonlinear spring.
- Adaptive methods to exploit such robust dynamics.
- Finding the optimal nonlinear compliance for specific tasks.

**References**


**Figures**

- Fig. 18: The toddler robot with rotational springs at its hip joint.
- Fig. 19: The toddler robot with rotational springs at its hip joint.
- Table 1: Comparison of stability between different spring settings.