Variable-Leg-Spring Hopping with Velocity-Dependent Stiffness

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MOTIVATION

Even though biological legs operate amazingly spring-like, they clearly deviate from a perfect spring. For instance, experimental data of human hopping and running suggest an increase in leg length and a decrease in leg stiffness between touchdown and takeoff. Here, this variability of human gait is considered as a fundamental system property and introduced via non-constant leg parameters to a 1-DOF spring-mass model. This approach may help overcome the need for precise parameter tuning and complex control schemes in artificial legged locomotory systems.

STATE OF THE ART

The spring-loaded inverted pendulum (SLIP) model is a well-established description of bouncy gaits. While in the original SLIP model [1] leg parameters are fixed, more recent studies include variations of rest length, e.g. [2], or stiffness, e.g. [3]. However, simultaneous variations of rest length and stiffness have been investigated for the first time in [4]. In this previous study, rest length and stiffness were changed linearly with time throughout the ground contact. Within this variable-leg-spring (VLS) approach, stable periodic hopping requires increasing leg length and decreasing stiffness (if damping is neglected). Furthermore, the stable hopping patterns are more human-like with respect to center-of-mass trajectories and ground-reaction forces. Recent developments in the field of robotics reflect the VLS concept, e.g. the hopping robot Chobino1D [5]. This 1-DOF hopper features a knee joint that is actuated by an improved MACCEPA, with joint stiffness increasing with knee deflection.

OWN APPROACH

In this study, we consider a modified implementation of the VLS scheme (4). As before, rest length continues to change linear-in-time,

$$l_0(t) = l_{\mathrm{TD}} + \dot{l}_0(t - t_{\mathrm{TD}}),$$

where TD denotes touchdown. Motivated by a recent study emphasizing the importance of the force-velocity relationship of muscles for stable hopping [6], stiffness is here considered to be velocity-dependent,

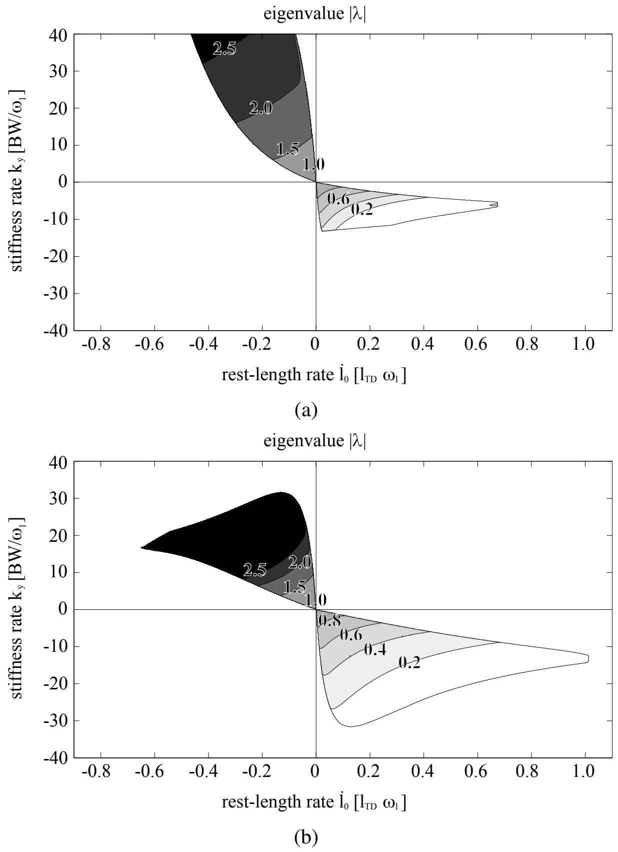
$$k(\dot{y}) = k_{\mathrm{TD}} + k_{\dot{y}}(\dot{y} - \dot{y}_{\mathrm{TD}}).$$

Rest length and stiffness are kept constant during flight phases and reset at each apex to l_{TD} or k_{TD}, respectively. $\dot{y}_{\mathrm{TD}}$ is calculated via the conservation of energy during flight phase, $\dot{y}_{\mathrm{TD}} = \sqrt{2g(y_0 - l_{\mathrm{TD}})}$, with initial apex height y_0.

Furthermore, to incorporate the concept of swing leg control [7] and to analyze whether it is beneficial for stable hopping, a second model is investigated. The simplest way to introduce this kind of control to our model is to allow stiffness to change continuously throughout the whole hopping cycle,

$$k(\dot{y}) = k_{\mathrm{Apex}} + k_{\dot{y}}\dot{y},$$

rather than keeping it constant during flight phases and



(a)

(b)

Fig. 1. Region of periodic hopping solutions for velocity-dependent stiffness (a) without and (b) with swing leg control. Stiffness at touchdown, k_{TD}, and stiffness at apex, k_{apex}, respectively are set to $k = 25\,\mathrm{BW}\,l_{\mathrm{TD}}^{-1}$. Solutions are mapped with respect to stiffness rate $k_{\dot{y}}$ and rest-length rate $\dot{l}_0$. Increments of $0.1\,\mathrm{BW}\,\omega_l^{-1}$ for $k_{\dot{y}}$ and $0.002\,l_{\mathrm{TD}}\,\omega_l$ for $\dot{l}_0$ were used, with $\omega_l = \sqrt{g/l_{\mathrm{TD}}}$. Eigenvalue λ for periodic hopping is shown. Stable solutions require $|\lambda| < 1$.

resetting at the instant of apex. This model has the advantage that for appropriate parameter setups, $k_{\dot{y}} < 0$, stiffness at touchdown increases with hopping height. Thus, for these parameter choices corresponding to increasing rest length and decreasing stiffness during stance, the spring is able to better support the point mass.

DISCUSSION OUTLINE

Clearly separated regions of stable and unstable hopping solutions are inherited from the model with time-dependent stiffness. Similarly, negative $k_{\dot{y}}$, i.e. net stiffness decreases, are needed for stable hopping (Fig. 1).

However, by introducing a velocity-dependent stiffness stability is increased considerably. Stable hopping requires eigenvalues $|\lambda| < 1$; the smaller $|\lambda|$ the more stable the system. Instead of eigenvalues $\lambda \gtrsim 0.7$ for a time-dependent stiffness (without damping) now eigenvalues $\lambda \approx 0$ can be realized and therefore, perturbations can be compensated much faster.

Hopping heights and maximum ground-reaction forces are restricted to a physiologically more reasonable range, e.g. hopping height $y_{0,\max} \approx 3\,l_{\mathrm{TD}}$ for $k(\dot{y})$ in comparison to $y_{0,\max} > 10\,l_{\mathrm{TD}}$ for $k(t)$. The values of stiffness and rest length at takeoff remain of comparable size.

For the VLS-hopper with swing-leg control the region of stable hopping increases. This is due to higher touchdown stiffnesses as a result of swing-leg control.

A difference of the models presented here compared to the time-dependent model is that they require continuous feedback control. Thus, the control effort is higher. However, as the velocity changes roughly linearly between minimum and maximum velocity (and vice versa), one might envision a triggered piecewise-linear control scheme, where stiffness increases with a fixed rate during flight and for ground-reaction forces smaller one time body weight (corresponding to the extremal velocities) and decreases otherwise.

Another alternative would be to use actuators with built-in muscle-like properties mimicking the force-velocity relationship of Hill-type muscle models [6]. With such an actuator design, control effort could be highly facilitated.

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