Anchoring the SLIP template: The effect of leg mass on running stability

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Abstract: Spring-like leg behavior was found in the global dynamics of human and animal running in sagittal plane. The corresponding template model, the conservative spring-loaded inverted pendulum (SLIP), shows stability for a large range of speeds and is, therefore, a promising concept for the design of legged robots. However, an anchoring of this template is needed in order to provide functions of biological structures (e.g., mass distribution, leg design) and engineers' details for construction. We extend the SLIP template model towards two new models that we call M-SLIP and BM-SLIP by adding considerable leg masses to investigate the influence of leg rotation on running stability. Our study clearly reveals that the spring-loaded inverted pendulum can be anchored in a leg mass model. This supports model- and simulation-driven engineering towards robotic behavior inspired from biological systems.

Keywords: anchor; template; legged locomotion; stability; leg swing control; leg swing dynamics

1. INTRODUCTION

The biomechanical description of human and animal locomotion relies on so called *template models* [1]. A template model is the simplest model and has the least number of parameters, which is able to describe the basic behavior of the considered gait. The most common template model for human locomotion is the spring-loaded inverted pendulum (SLIP, [2]). By abstracting the leg to a massless linear spring with stiffness k and the body to a point mass m, the SLIP resembles the global dynamics of running in sagittal plane [2]. Furthermore, gait patterns from the SLIP model show self-stability if the leg stiffness k and the angle of attack α (landing angle of spring) is adjusted properly [3]. That means, that despite its great simplicity, the SLIP model can recover from small perturbations (e.g. drop height or initial velocity) without any control, neither feed-forward nor feedback. Therefore, the SLIP model is a promising underlying concept for the design of legged robots that combine both, energy-efficiency and dynamic stability.

However, the transfer of the SLIP to a technical device needs an anchoring in more elaborate structures. Due to its template character, the SLIP is missing important structures from a higher level of detail like, for instance, trunk, segmented leg, foot, friction, slipping or leg inertia. Following the concept of *templates and anchors* [1], a piecewise adding of details to the SLIP model can reveal the mechanisms or the functions of biological structures, and thus, guide engineers towards nature-driven robotics.

In the present paper, we extend the SLIP model by adding leg mass (M-SLIP and BM-SLIP model, see Fig. 1). About one third of the human mass is covered by both legs [4, 5] with a leg CoM located at 40% of leg length with respect to the hip joint. This gives rise to high rotational inertia and a significant influence on the overall dynamics can be expected. Effects emerging from adding leg mass include swing leg dynamics and impact forces. Further, the leg behavior in a SLIP model is represented by one spring. Since running has clear single contact and flight phases, this procedure is appropriate. However, in humans, running is characterized by an alternating stance and flight phase of legs. These coupled legs interact in each phase. For SLIP running, it was shown that running stability is largely influenced by the swing leg dynamics [6]. The effect of swing leg dynamics on mass-attached legs is yet unclear.

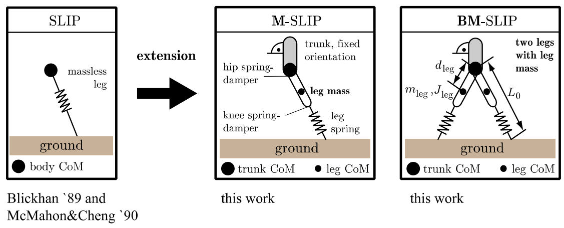

Fig. 1 We extend the SLIP model (a template model for describing human and animal running) by adding leg mass (m_{leg}) and leg moment of inertia (J_{leg}) at a particular distance from the trunk CoM (d_{leg}). We include a hip spring-damper (parallel combination of a linear spring and viscous damper) to control the leg during swing phase to a certain position. We distinguish a monopedal version (M-SLIP) and a bipedal version (BM-SLIP) to describe single-legged running (like kangaroos) and bipedal running (like humans). The knee spring-damper accounts for the alignment of rigid leg and massless spring, thus modeling a telescopic mass-attached leg. For the sake of simplicity and to disregard the problem of trunk stabilization, we fix trunk orientation.

In a first approach, we aim at investigating the influence of leg mass on gait stability and test the hypothesis that SLIP solutions can be inherited to the M-SLIP model. If so, the curse of dimensionality [7] could be broken because model designers can follow the low-dimensional SLIP path of stability within the higher-dimensional M-SLIP model when searching for stable gait patterns. Here, we vary two parameters (leg stiffness k and angle of attack α) and keep the initial velocity fixed to search for stable running patterns. The corresponding domain of stable running patterns, i.e. the combination of leg stiffness k and angle of attack α, is known from SLIP simulations as J-shaped area [3]. Here, we investigate how this domain is transformed in the M-SLIP model. In a second approach, we extend the M-SLIP model by adding a second leg (BM-SLIP) to investigate the influence of swing leg inertia on gait stability.

2. RESULTS AND DISCUSSION

We use the steps-to-fall map to determine stable running patterns. Thereby, we record the number of steps until the model falls over. We limit the maximum number of steps to 50. If the model achieves this number, we classify the solution as stable. We vary leg stiffness k and angle of attack α on an equidistant grid (64 x 64) and record corresponding domains of stable running patterns for the SLIP, the M-SLIP and the BM-SLIP model (see Fig. 2).

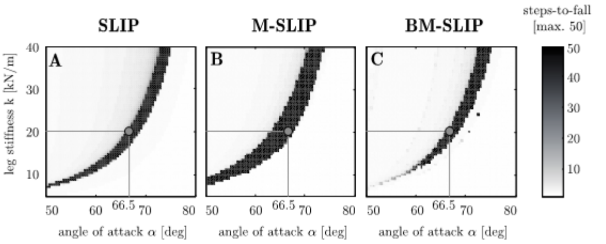

Fig. 2 Steps-to-fall maps by varying leg stiffness k and angle of attack α. The domain of stable SLIP running patterns is inherited to the M-SLIP and BM-SLIP model. The stable domain enlarges in single-legged running (M-SLIP), and slightly shrinks in bipedal running (BM-SLIP). Physiological leg data from humans are applied. Hip stiffness (1.5 kNm/rad) and knee stiffness (50 kNm/rad) are chosen to guarantee appropriate landing condition.

Steps-to-fall maps of the SLIP (running with massless legs), M-SLIP (single-legged running or forward hopping respectively) and BM-SLIP (bipedal running) show the characteristic J-shape. The domain of stability enlarges in single-legged running: For any angle of attack α, the range of leg stiffness k that yields to stable running is increased. In bipedal running, the stability domain is thinned out slightly: Stable running patterns of flat angles of attack (α = 50 deg – 60 deg) disappear, while those of steeper angles of attack (α = 65 deg – 75 deg) are kept completely.

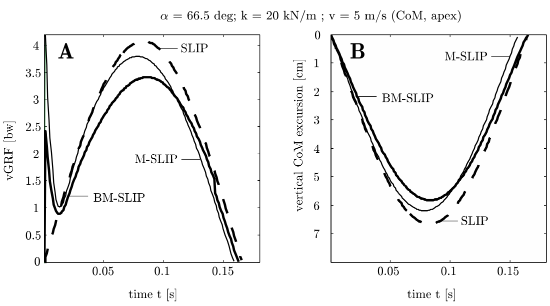

Fig. 3 ***A.*** Vertical ground reaction force (vGRF) in bodyweights (bw) of all three investigated models: SLIP (dashed line), M-SLIP (single-legged running, medium line) and BM-SLIP model (bipedal running, bold line). Leg rotation causes a strong impact peak at the instant of touch-down (t = 0) which smoothly decays within the first 20 ms. ***B.*** Vertical excursion of the body CoM during stance phase of all three investigated models (SLIP – dashed line; M-SLIP – solid line; BM-SLIP – bold line). The body CoM excursion is calculated with respect to the touch-down height (0 cm). The maximum body CoM excursion decreases in leg mass models (M-SLIP and BM-SLIP).

We select one pair of leg stiffness k and angle of attack α (demarked in Fig. 2: k = 20 kN/m, α = 66.5°) to record vertical ground reaction force (vGRF) and CoM excursion of all three models (see Fig. 3). While the vGRF of the massless SLIP does show a smooth single hump, the vGRF of M-SLIP and BM-SLIP show a large impact peak at the instant of touch-down (t = 0 s), which smoothly decreases within 20 ms. Shortly after the impact peak (t > 20 ms), the M-SLIP model follows the vGRF shape of the SLIP but then increases bending before achieving peak vGRF of the SLIP. The vGRF of the BM-SLIP is even lower than in the M-SLIP model. Comparing peak values of vGRF, the SLIP model takes the highest value ($\sim 4\ bw$), followed by M-SLIP ($\sim 3.75\ bw$) and BM-SLIP model ($\sim 3.5\ bw$).

3. CONCLUSION

In this work, we extended the SLIP model by adding leg masses, which yield to the M-SLIP (modeling single-legged running) and BM-SLIP (modeling bipedal running). Both models were able to inherit self-stability by coordinating additional degrees of freedom to SLIP behavior (e.g., hip control) and adjusting additional parameters to biological data (e.g., human mass distribution). Furthermore, both models allow a more realistic transfer to control and design of real legged robots and, as a novel feature, leg swing dynamics can now be predicted. We are presenting simulation results comparing the three models.

4. ACKNOWLEDGMENT

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