A 3D Dual-SLIP Model of Human Walking Over a Range of Speeds

Yiping Liu*, Jim Schmiedeler**, Patrick Wensing***, and David Orin*
* The Ohio State University, Columbus, OH, USA, *liu.805@osu.edu, orin.1@osu.edu*
** University of Notre Dame, Notre Dame, IN, USA, *schmiedeler.4@nd.edu*
*** Massachusetts Institute of Technology, Cambridge, MA, USA, *pwensing@mit.edu*

1 Introduction

The planar Dual Spring-Loaded Inverted Pendulum (Dual-SLIP) or bipedal spring-mass model is a walking template that reproduces key human walking characteristics, such as the vertical center of mass (CoM) oscillation, double-peak ground reaction force (GRF) pattern, and finite-time double support period [1]. Consisting of a point mass and two massless spring legs, periodic, self-stable walking gaits were found for this conservative model through an exhaustive scanning of the parameter space (leg stiffness, system energy, and touchdown leg angle) with simulation over many steps. The speed range spanned roughly $0.8-1.5\frac{m}{s}$ for an 80 kg mass and free leg length of 1 m (Froude number range ∼0.25-0.5).

A recent extension of the Dual-SLIP model to 3D walking [2] (see Fig. 1) empirically found no left-right symmetric periodic gaits to be self-stable, echoing the same result found previously for running gaits with the 3D SLIP model [3]. Therefore, 3D Dual-SLIP walking gaits were generated to satisfy a 2-step periodicity constraint without relying on the self-stability of the model. The larger number of parameters in the 3D model makes an exhaustive search less feasible, motivating a nonlinear optimization approach that includes 1-step simulations within objective and constraint evaluation routines [4]. Because of the large number of local minima, the nonlinear optimization results are sensitive to the provided seeds. Optimizing over just a half step and enforcing symmetry better confined solutions to those exhibiting the human-like double-peak GRF pattern. As in the planar case, periodic solutions were confined to a relatively small speed range, about $0.7-1.3\frac{m}{s}$ (Froude number range ∼0.22-0.42).

This work shows how introducing ground impact behavior at touchdown, toe-off behavior at lift-off, and leg spring force modulation during stance increases the range of speeds over which 2-step periodic walking gaits can be found for the 3D Dual-SLIP model. A similar approach has previously been applied to the active SLIP model of planar running [5].

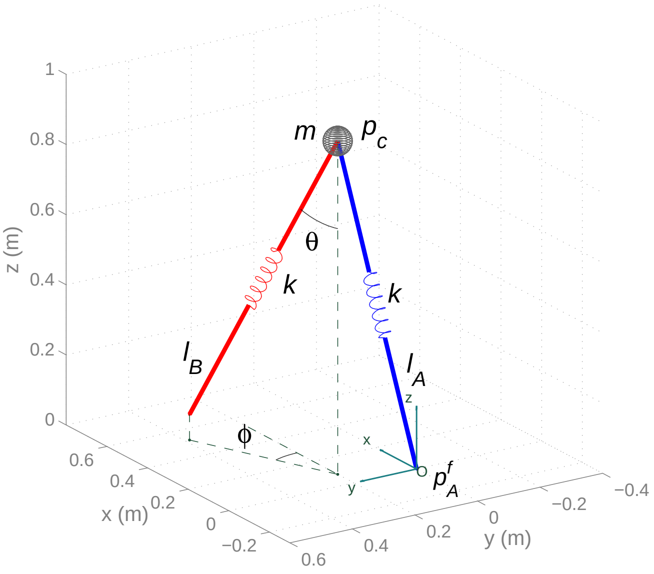


Figure 1: 3D Dual-SLIP model.

2 3D Dual-SLIP Model Details

In the conventional 3D Dual-SLIP model, the free length of the leg springs is constant. By allowing leg touchdown and liftoff to occur at leg lengths less than the free length and allowing that free leg length to vary between gait events, the model exhibits ground impact and toe-off characteristics. This actuation scheme is depicted in Fig. 2. The cycle begins at the midstance (MS) of single support of the trailing leg A (SS_A), defined as the instant of zero vertical CoM velocity. The free length $\ell_A(t)$ of leg A, initially ℓ_{MS}, increases linearly with a slope of $\beta_{A,ss}$ until touchdown (TD) of the leading leg B. Leg B touches down with a length L_{TD} that is less than its free length ℓ_{TD} at that instant. Thus, energy is already stored in the leg spring and the GRF is non-zero immediately after touchdown, similar to the effect of ground impact if the leg had mass. During double support (DS), both free lengths $\ell_A(t)$ and $\ell_B(t)$ remain constant as the leading leg B absorbs energy in weight acceptance [6] and the trailing leg A releases energy in preparation for liftoff. At liftoff (LO), the length L_{LO} of leg A is less than its free length ℓ_{LO} at that instant, so the GRF immediately before liftoff is non-zero, similar to the effect of toe-off. Finally, $\ell_B(t)$ decreases during its single support (SS_B) up to the midstance of leg B, returning to ℓ_{MS} to ensure periodicity. In this way, not only are the GRFs more realistically nonzero at touchdown and liftoff, but the force profile of the linear leg spring is modulated during stance in a manner consistent with human behavior. Still, the "actuation" of the leg spring simply alters when in the gait the energy is stored and released compared to a passive spring.

Gaits are generated via a nonlinear optimization to identify the parameters $\{L_{TD}, L_{LO}, \ell_{TD}, \beta_{A,ss}, \beta_{B,ss}, \theta, \phi\}$ that produce

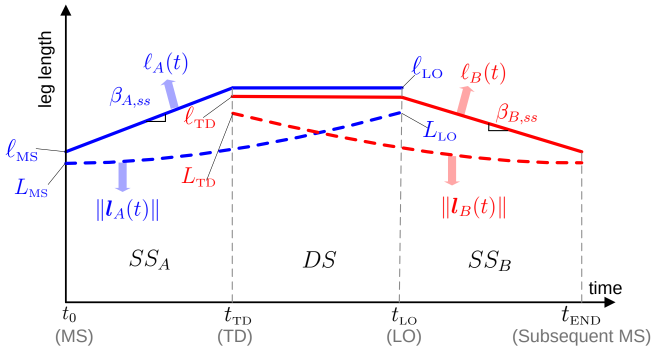


Figure 2: Illustration of the actuation variables for the leading leg B (red) and trailing leg A (blue). Solid lines are the free leg lengths, and dashed lines are the actual leg lengths.

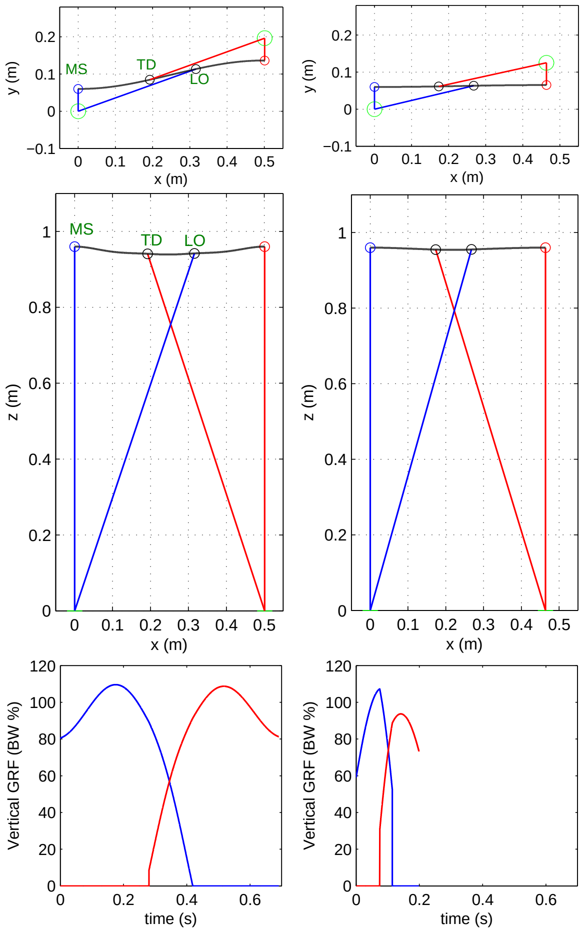
a 2-step periodic walking gait at a specified speed and leg spring stiffness (20 $\frac{kN}{m}$ herein). Per Fig. 1, θ and ϕ are the angles that the swing leg makes with the vertical and the direction of forward progression, respectively, at touchdown. ℓ_{LO} is omitted from the list because it can be computed from the other parameters. Constraints require the leg length to always be less than the rest length and the vertical GRF at midstance to be at least 60% of the body weight. Cost functions are applied to minimize the GRFs at touchdown and liftoff and to achieve double support ratios consistent with human walking (≈ 0.2). A multiple-shooting strategy is used to solve the optimization problem by dividing it into three phases, one for double support and one for single support of each leg.

3 Results

By controlling the flow of energy in the model, the range of speeds over which the 3D Dual-SLIP model can walk is substantially increased. Periodic gaits from 0.6 to 2.3 $\frac{m}{s}$ (Froude number range ~0.19-0.73) were found with the methods described herein. This extends the 3D Dual-SLIP model to gaits up to and beyond the typical walk-to-run transition speed. Figure 3 shows both the transverse and sagittal plane motions of the model and the GRFs as a percentage of body weight (BW) at the two extreme speeds. Both the vertical and lateral excursions of the CoM are smaller in fast speed walking, as the CoM progresses almost in a straight line. The GRFs exhibit the double-peak pattern across speeds, but asymmetry in that pattern is greater in fast speed walking.

4 Conclusion

Modulating the free length of the leg springs in the 3D Dual-SLIP model of human walking introduces ground impact and toe-off-like characteristics and achieves human-like GRFs without energy dissipation in the model. As a result, 2-step periodic walking gaits can be found over a full range of realistic human walking speeds. This suggests that the energy flow management associated with weight acceptance and toe-off may be critical to high-speed walking even in the absence of energy dissipation.



(a) 0.6 m/s

(b) 2.3 m/s

Figure 3: Transverse plane motion, sagittal plane motion, and GRF patterns for one step at two extreme walking speeds.

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