Abstract

Bipedal locomotion remains a fascinating field due to its vast potential for enhancement. Template models like compass-gait biped and spring-loaded inverted pendulum (SLIP) have been proposed to capture characteristics of biped walking and running effectively. However, when we compare reported biped template models with human gaits, the scope of improvement becomes apparent. Shortcomings include over-estimation of the center of mass (CoM) trajectory, unexplored jogging gaits, and the inability to produce different gaits at the same locomotion speed. These limitations highlight the need for further refinement and enhancement of current models to simulate and analyze diverse bipedal locomotion patterns accurately.

This study aims to enhance the existing SLIP-compliant-leg models for producing human-like gaits. This was achieved through the introduction of an additional model parameter, initial leg compression. This was motivated by the adaptation of effective touchdown leg length observed in human gait. The dynamic equations for the template model were derived using the Euler-Lagrange method, and natural initial conditions for achieving stable periodic gaits were identified through a numerical optimization process. Different gaits were obtained by varying model parameters, such as initial leg compression, spring stiffness, and touchdown angle, with gait speed as the resultant parameter.

We began by examining a passive dynamic biped with two flexible links, distinguishing it from the rigid-compass gait biped. We investigated the existence of a stable walking gait in a flexible passive dynamic biped for movement along an inclined plane and on flat ground. Our model progresses towards ground-level walking, jogging, and running with several modifications, employing a 2D SLIP model without a swing leg and with an instantaneous double support phase (DSP). We further incorporated a DSP by combining single support, double support, and flight phases along with relevant transition events to obtain more human-like gaits.

The model thus obtained could predict the CoM trajectories in humans across walking, jogging, and running at different speeds. These gaits are differentiated by vertical ground re-

action force (vGRF) patterns. This approach provides additional control over peak vGRF and CoM oscillation amplitude and thus can capture the overlap (in terms of achievable locomotion speed) seen in similar human gaits. It was not possible with existing models. Additionally, the impact of leg stiffness and the variation in touchdown length on gait parameters was studied to identify improvements over existing SLIP models. The robustness of gaits predicted by models with instantaneous DSP, as well as a finite DSP, was analyzed for traversing uneven terrain, incorporating a series of bumps and dips. The model demonstrated the ability to traverse surfaces with height differences of approximately 5% of its leg length per step.

Overall, we present a unified approach to produce gaits from slow walking through jogging to running without significant changes in the model. The SLIP template proves effective at capturing CoM dynamics in legged locomotion. While most studies with SLIP have focused on running gaits, our work elaborates on modeling complete walking cycles, including double support phases. Using the same biped model, we combined single support, double support, and flight dynamics to predict CoM trajectories for all three gaits at different speeds. The model predictions align closely with experimental data across all gaits. The observed variations in model parameters, such as stiffness, initial leg compression, and touchdown angle modulation, reveal underlying similarities with adaptations exhibited by humans. Thus, this work enhances the capability of minimal SLIP models to recreate CoM movement and GRF patterns found in human gaits. These findings can lead towards a better understanding of human gait biomechanics, with potential applications in bipedal robotic locomotion.