Turning Behavior of Running Systems induced by Leg Placement

Aditya Sripada (asripada@cmu.edu) and Hartmut Geyer (hgeyer@cmu.edu)
The Robotics Institute, Carnegie Mellon University

I. Introduction

Compared to legged robots, animals and humans can perform much faster and larger turns, even when they run at high speeds. Such rapid turns require the body of a runner to reorient dynamically and in synchrony with its redirection during stance. While it is clear that foot placement affects both direction and orientation [1, 2] the functional relationship between the three is not well understood. Some analytical models of turning dynamics have been proposed. Specifically, Jindrich and Qiao [2] derived an analytical expression that relates leg placement in the transversal plane to the ratio of body reorientation and redirection given the running velocity and stance time. For comparably small turns in human running, the expression holds well. However, it was derived for preset, sinusoidal patterns in the fore-aft and medio-lateral leg forces, and it is unclear if this assumption generalizes well to larger, more dynamic turns. To gain a better understanding of the turning behavior induced by leg placement, we explore a dynamic running model.

II. Approach

We build on the established spring-mass model for running, replacing its point mass by a rigid body with off-center hip joint (Fig. 1-a). To focus on reorientation, we assume the body's moments of inertia are human-like about the yaw axis and quasi-infinite about the roll and pitch axes. Furthermore, we assume the model has human-like body mass, leg length and stiffness, and runs at 5ms^{-1}. We then compute and analyze the model's apex return map similar to [3]. Specifically, the state vector $\boldsymbol{s}_i = (y, d\theta, \psi, \dot{\psi})_i$ of the model at apex i is defined by the apex height y_i, body redirection $d\theta_i$, body reorientation ψ_i (relative to the new direction), and spin velocity $\dot{\psi}_i$. The turning behavior of the model is captured by the single step return map $\boldsymbol{s}_{i+1} = R(\boldsymbol{s}_i, \alpha, \beta)$, where α and β are the leg angles of attack and splay at touch-down.

III. Results and Discussion

We first search for leg placements that synchronize redirection and reorientation ($\psi = 0$, $\dot{\psi} = 0$) (Fig. 1-b). We find the model produces such turns for a range of initial apex heights and resulting new directions ($d\theta$), although inner leg turns (negative sign of $d\theta$) are limited to less than 5° in redirection. We then compare the ratio of reorientation to redirection predicted in [2] and observed for the model (Fig. 1-c). Given the stance times and running speed of the model, the predicted and observed ratios have similar magnitude ranges and share

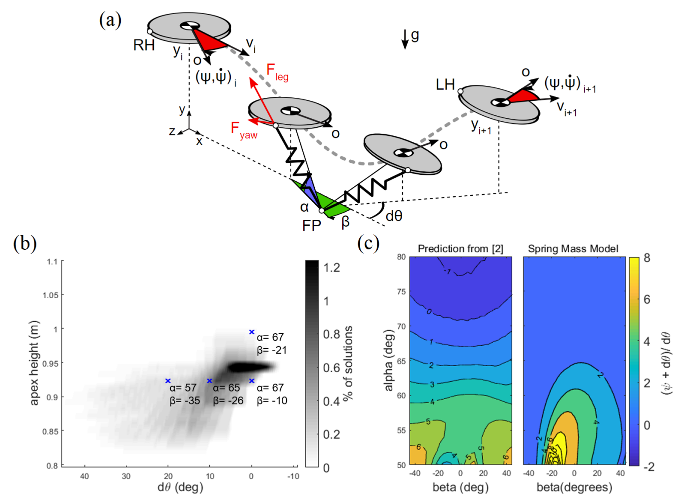

Fig. 1. Turning behavior induced by leg placement. **(a)** 3-D spring mass model with center body and offset hip. **(b)** Percent of leg placements that synchronize redirection ($d\theta$) and reorientation ($\psi = 0 \pm 5°$, $\dot{\psi} = 0 \pm 10° s^{-1}$). **(c)** Ratio of reorientation to redirection for different leg placements predicted by [2] (*left*) and observed in model (*right*) for initial height $y_0 = 0.95m$.

the general trend of increasing toward shallow angles of attack ($\alpha \rightarrow 50°$), but their functional shapes clearly differ.

Our results suggest two things. First, leg placement can induce synchronous turns for even large redirections (Fig. 1-b) without the need for active hip or foot torques about the yaw axis. Taking advantage of this 'passive' behavior may help legged robots to achieve more dynamic turns. Second, the difference in the predicted and observed relationships between leg placement, redirection and reorientation (Fig. 1-c) indicates that constant leg force patterns do not well represent the details of turning dynamics, and better analytical models are needed to pinpoint the parametric dependencies.

We currently explore how these results generalize to a more realistic model with actual pitch and roll controls. Ultimately, we seek to identify a quasi-passive control policy for stable rapid turns on rough terrain using leg placement.

References

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