Minimizing Angular Momentum Yields More Robust Walking Trajectories in Five-Link Biped

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RESEARCH HIGHLIGHT

- Our findings support the idea that human walking tends to have low angular momentum because it allows human gait to be more robust to disturbances.

INTRODUCTION

Trajectory Tracking

- The manner in which walking trajectories are obtained is critical, since a controller may not yield a stable walking gait if the trajectories which it tracks are not robust to disturbances.

Human Walking

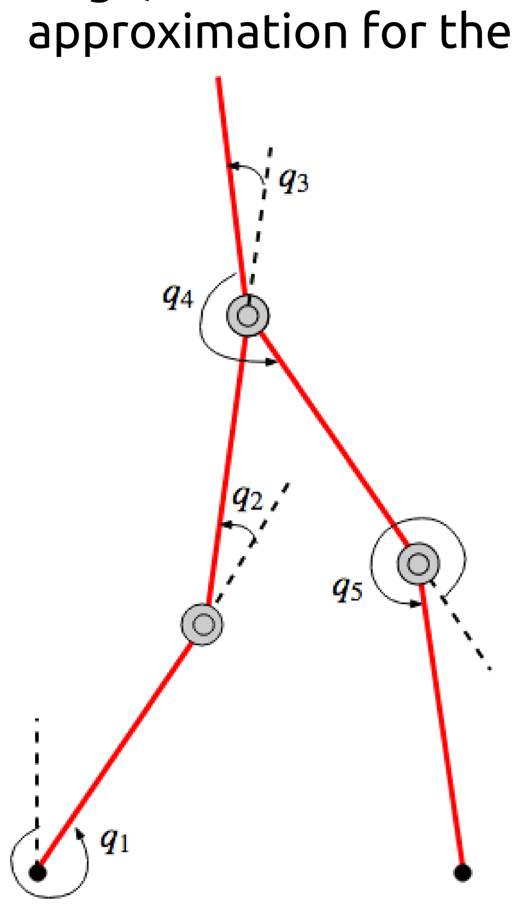
- Prior research has shown that angular momentum H about the whole body center of mass (COM) is highly regulated during human walking [1].

Robustness of Trajectories

- The objective of this study is to examine the robustness to a disturbance of joint trajectories generated with different cost functions.
- Terms which facilitate the minimization of H are added to the cost function, and the performance of base-line trajectories is compared to the performance of trajectories which also minimize H.
- We would expect trajectories yielded by the cost function including H to be more robust.

FIVE-LINK BIPED MODEL

- The simulated walking robot is the five-link biped shown in Figure 1(a). It has dimensions, masses, and inertias similar to that of a human for the shank and thigh, and uses the head-arms-torso (HAT) approximation for the upper body [2].



$$\min \sum \tau^2 + \alpha H_{spin}^2 + \beta H_{orb}^2$$

s.t.

Dynamics = 0
ImpactDynamics = 0
JointRange ≥ 0
TorqueLimit ≥ 0
StepLength ≥ 0
ImpactVelocity = 0

Figure 1: (a) Five link biped **(b)** Optimization formulation. Note that all inequality constraints are expressed with "≥ 0"

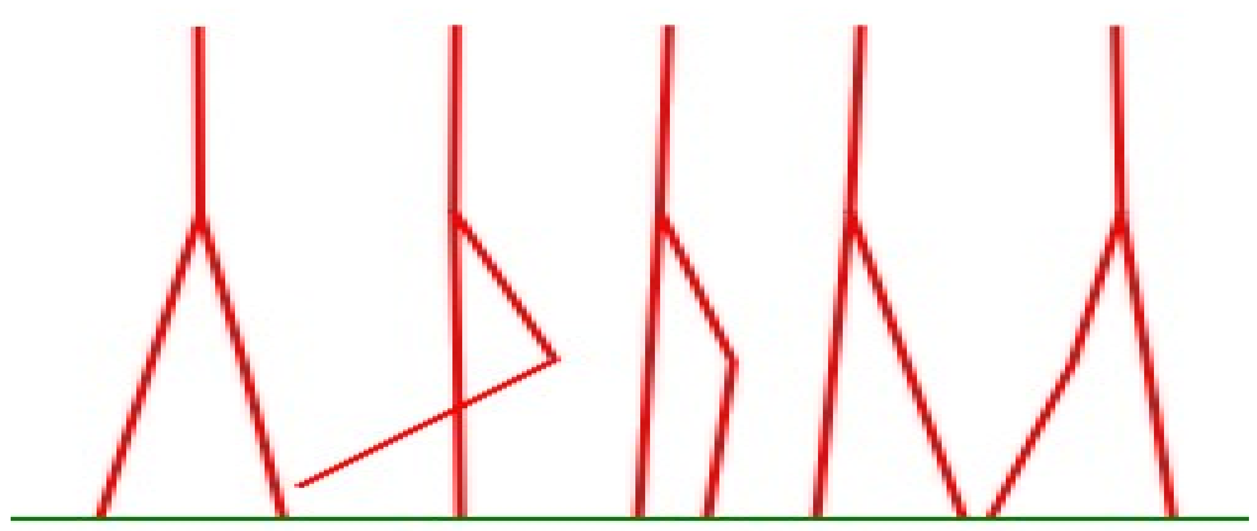
METHODS

Trajectory Generation

- The joint trajectories are generated via trajectory optimization using direct collocation, in which the desired optimal trajectories are discretized and used as the decision variables in the optimization [3].
- The accelerations, post-impact velocities, and impact forces are included with the decision variables in addition to those shown in [3].
- The optimization is done in Julia (v1.3) using JuMP as an interface and IPOPT as the solver.
- The Hermite-Simpson method is used for the direct collocation [3].
- The base-line cost function is the sum of the squared joint torques τ^2. This cost function is augmented with the spin angular momentum squared H_{spin}^2 (i.e., α = 1, β = 0), orbital angular momentum squared H_{orb}^2 (i.e., α = 0, β = 1), or both H_{orb}^2 and H_{spin}^2 (i.e., α = 1, β = 1).
- H_{orb} is the angular momentum of a segment COM (point mass) in the reference frame of the whole-body COM.
- H_{spin} is the angular momentum of a segment about its own COM (in its own reference frame).
- The optimization includes many constraints such as those for respecting the dynamics, a minimum step length of 0.2 m, periodicity constraints so that the step behavior is repeatable, limits on the joint angles, and impact at the heel strike.
- The details of these constraints can be found in [4].

Forward Simulation

- A forward simulation is conducted in which a horizontal impulsive force is applied at 1.0 sec at the hip joint for a duration of approximately 0.4 sec, against the direction of the step.
- The biped is tasked with walking 10 steps without falling over.
- A PD controller is used for all simulations to track the trajectories, and center of mass forward progression is used as the phase variable (i.e., time parameterized by state variables).



RESULTS

- The maximum force the biped withstands without falling over for a given cost function's set of optimal trajectories is reported in Table 1.
- To rule out the potential effects of step lengths on the maximum force, trajectories were generated for different fixed step lengths as well.

Table 1: Maximum force (N) of perturbation without falling for sets of trajectories with different cost functions and step lengths.

Step Length [m]	τ^2	$\tau^2+H_{spin}^2$	$\tau^2+H_{orb}^2$	$\tau^2+H_{spin}^2+H_{orb}^2$
0.200	222	657	536	536
0.241	221	586	563	551
0.272	unstable	477	570	547

- Adding angular momentum into the cost function improved the maximum force tolerated in all cases.
- For H_{spin}^2, the maximum force decreased for increasing step length. The opposite trend is seen for H_{orb}^2.
- Surprisingly, the maximum force for the cost function with both terms was lower for the shorter two step lengths.

CONCLUSIONS

- It may be advantageous to include one type of angular momentum over the other depending on the desired step length.
- The inclusion of angular momentum terms in the cost function increased the robustness of the biped to a disturbance without altering the controller.
- These results support the idea that human walking tends to have low angular momentum because it allows human gait to be more robust to disturbances.

FUTURE WORKS

- This experiment could be expanded to include more types of perturbations and step lengths.
- The conclusions of this experiment should be verified with other controllers and maybe even other methods of trajectory generation.

References

[1] Popovic et al., ICRA, pp2405-2411, 2004.
[2] Winter, Wiley, 4th ed., 2009.
[3] Kelly, SIAM Review, 59(4), pp849-904, 2017.
[4] Chao et al., IROS, pp1435-1440, 2019.