The Effect of Variable Jumping Frequency on Cost of Transport

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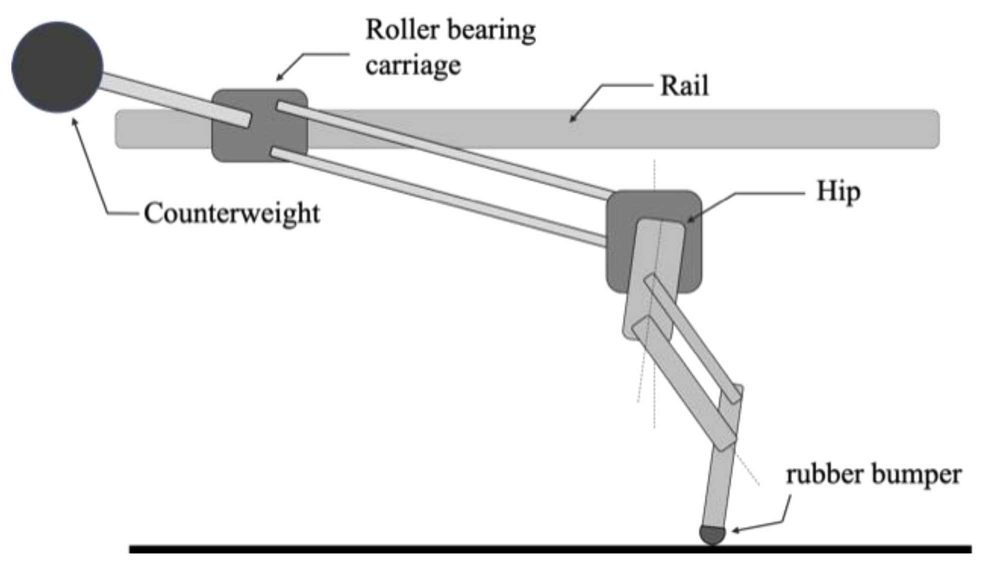
Introduction

- For legged locomotion, moving at constant velocity can be achieved with two types of strides or jumps
    - Case 1: Frequent, short distance
    - Case 2: Infrequent, long distance
- Examples: Kangaroos, human walking vs. running
- Which type of motion is more energy efficient?

Objective Question: *How does cost of transport (CoT) differ between longer jumps and shorter jumps?*



Control Strategy

Time-based, phase-dependent control

1. Torque control for $0 < t < t_{stance}$
2. Impedance Control in Task Space for $t_{stance} < t \leq t_{jump}$
3. Reset time to 0 when $t > t_{jump}$

** Does not require contact detection

Data Analysis

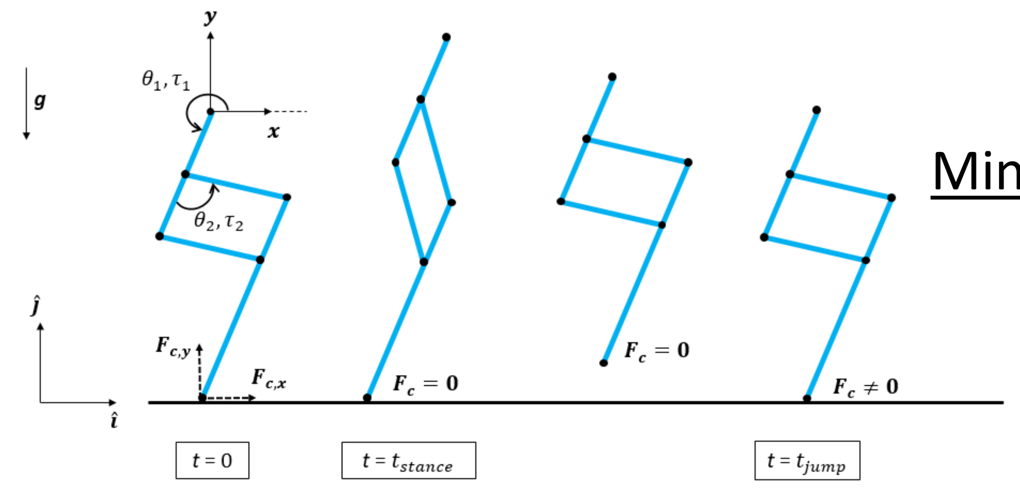
For a *single jump*:

$$E_{total} = \int R\,(I_1^2 + I_2^2)dt + \int \tau_1 d\theta_1 + \tau_2 d\theta_2$$

Joule Heating — Work done by system

$$P_{avg} = \frac{E_{total}}{t_{jump}} \qquad CoT = \frac{P_{avg}}{MgV}$$

Simulation Methods



Minimize: $\int(\tau_1^2 + \tau_2^2)dt$

Degrees of freedom:	$x,\ y,\ \theta_1,\ \theta_2$
Control inputs:	$\tau_1,\ \tau_2$
Other generalized forces:	$F_{x,c},\ F_{y,c}$

Constraints:

No hyperextension: $0 \leq \theta_2 \leq \pi$

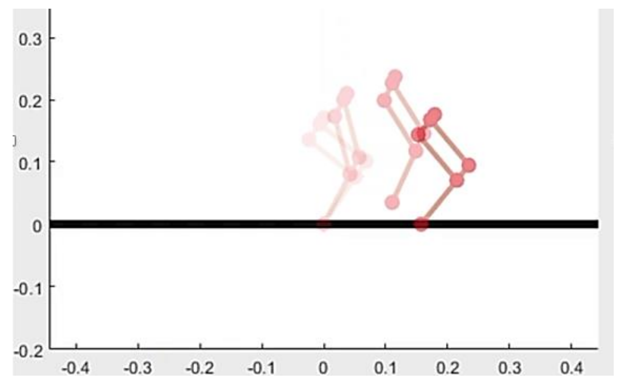
No slip: $|F_{c,x}| \leq \mu |F_{c,y}|$

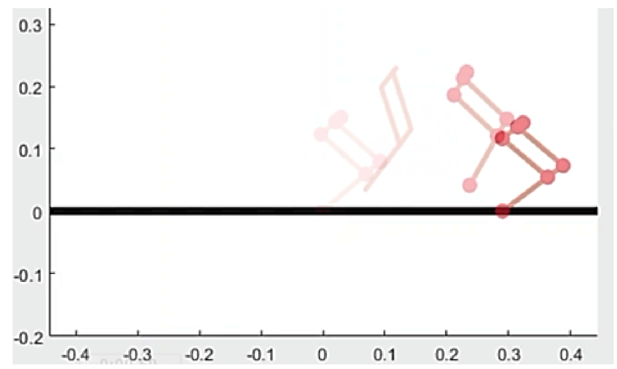
Constant speed: $\frac{x_{end}}{t_{jump}} = V_{desired}$

Jump is **cyclical**

Simulation Results

Case	Time between jumps (sec)	Cost of Transport
1	0.38	28.3
2	0.62	28.9





Cost of transport is *similar* between high frequency and low frequency

Experimental Methods

Gantry	Robot leg	Bumper	Counterweight	Treadmill
Control direction of robot	**2 DoF with motors**	**Increase contact friction**	**Reduce weight of robot**	**Provide constant velocity**

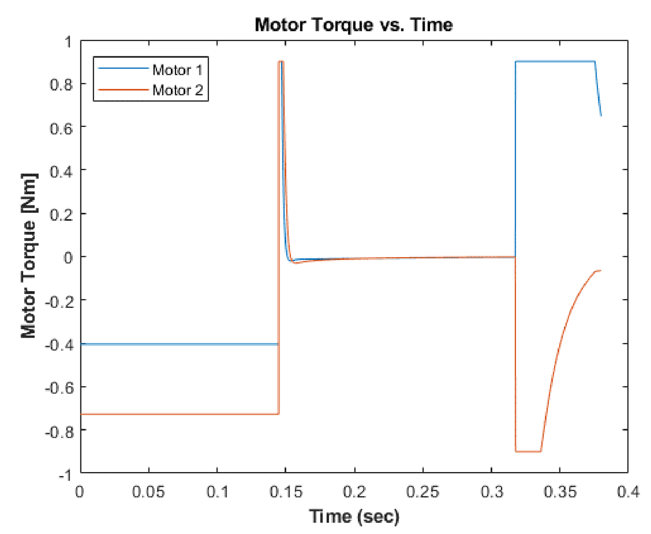
Experimental Results

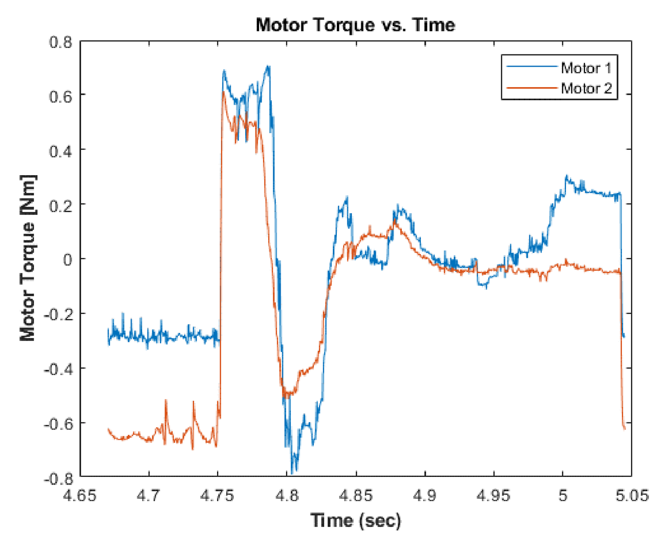
Case	Time between jumps (sec)	Cost of Transport
1	0.38	23.2 ± 1.5
2	0.63	40.8 ± 1.2

Cost of transport is lower for high frequency jumping

Discussion

- Control scheme behaves as predicted by simulation
- CoT values are similar between simulation and hardware
- Knee motor consistently saturated to allow robot to jump
- Foot slipping was occasionally observed (could solve with improved contact friction)
- Some out-of-plane motion was observed; should stiffen hardware for future tests





Conclusion

- From simulation, we predicted that the CoT would be similar between high and low frequency jumping
- From experiments, CoT was significantly lower for high frequency jumping

References

[1] S Seok, Sangbae Kim, Design Principles for Energy-Efficient Legged Locomotion and Implementation on the MIT Cheetah Robot, Transactions on Mechatronics