Canid, Pronking XRL Preliminary Comparison Dataset

Jeffrey M. Duperret[a], Jason L. Pusey[b], G. Clark Haynes[c], Daniel E. Koditschek[a]

[a] University of Pennsylvania, Philadelphia, PA
[b] Army Research Laboratory, Aberdeen, MD
[c] National Robotic Engineering Center, Carnegie Mellon University, Pittsburgh, PA

1. INTRODUCTION

This technical report documents the comparison of Canid's initial bounding behavior to open-loop pronking on the XRL robot as a supplement to[2,3] . The robots, shown in Figure 1 have nearly identical structure actuators, power-budgets, and electronics. The main differences are that XRL is a hexapod while Canid replaces the middle 2 leg motors with a parallel elastic actuated spine mechanism and uses four bar mechanisms on its front and rear legs. Further details about each robot are given in[3,4] .

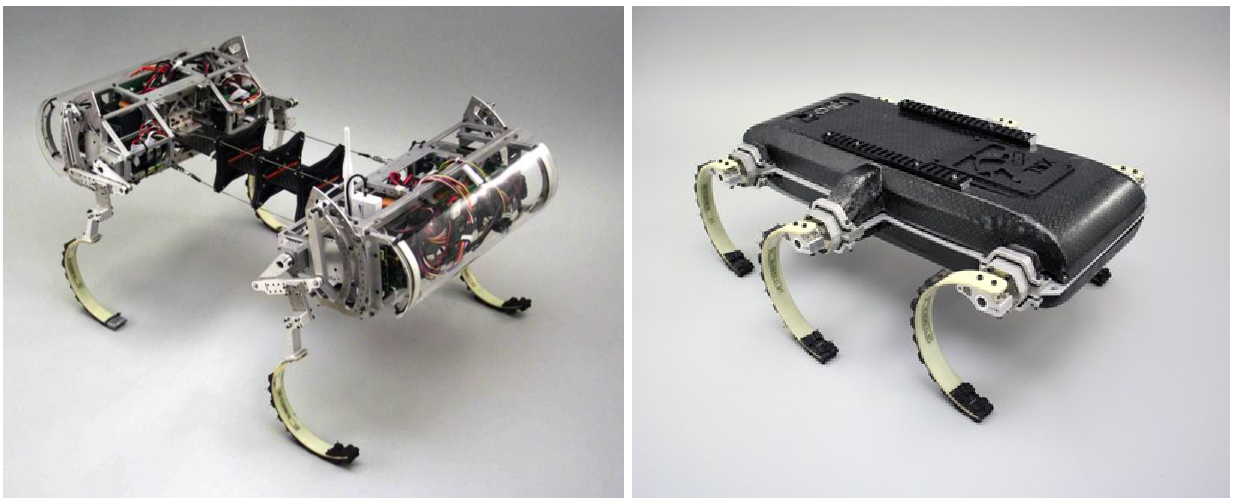

Figure 1. Canid (left) and XRL (right) both have nearly identical electronics, actuators, and power budgets.

Both robots were run 3 times under a Vicon motion capture system to gather position and velocity information, which was used in conjunction with motor position data to derive the body energy [*] of each robot presented in Section 2. This data is analyzed in depth in[2,3] .

2. CANID BOUDING/XRL PRONKING ENERGETIC COMPARISON

2.1 Canid Bounding Data

Figure 2 shows the body energy of Canid during all of its runs, previously presented in.[3] Canid's average body energy during the runs was 59J.

[*]We define body energy as the sum of the robot's kinetic energy, gravitational potential energy, and stored spring potential energy (in this case, in the elastic legs and spine mechanism).

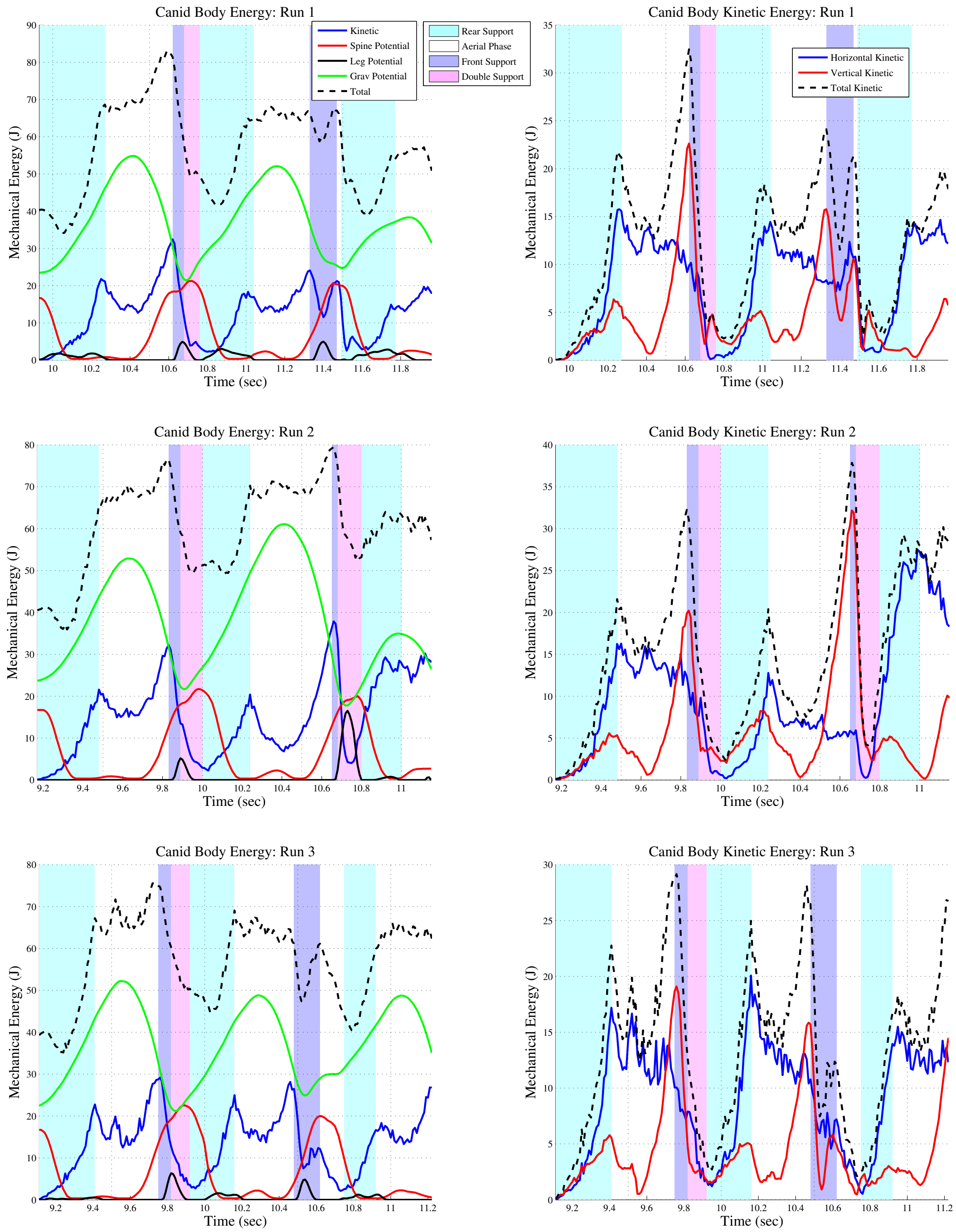

Figure 2. Body energy of XRL during runs shows Canid's average body energy was 59J.

2.2 XRL Pronking Data

Figure 3 shows the body energy of pronking XRL during all of its runs.

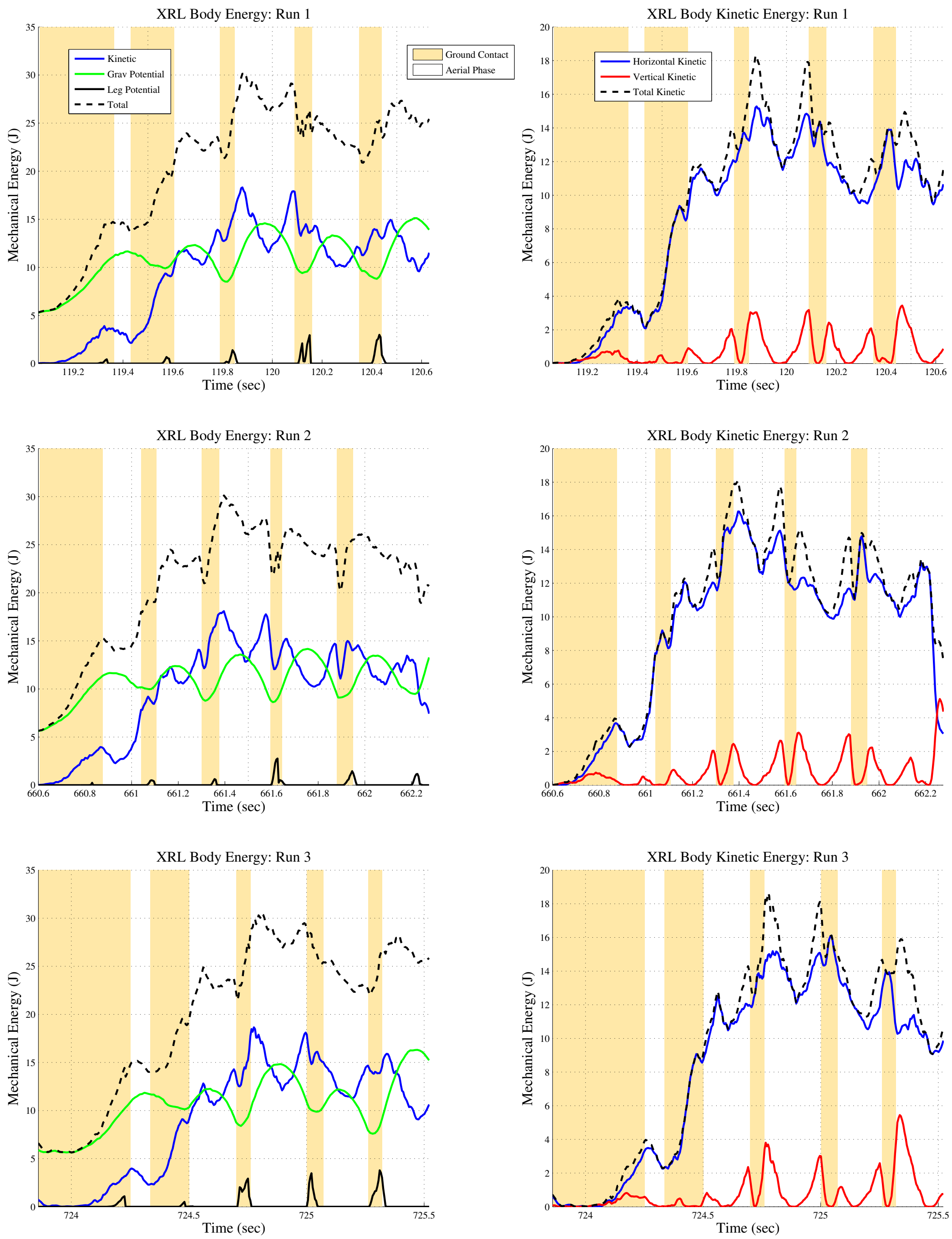

Figure 3. Body energy of XRL during runs shows XRL's average body energy was 26J.

2.3 Motor Current

Figure 4 shows that XRL's leg actuators are never limited by their maximum allowed currents while pronking and only Canid's rear legs are briefly limited. Canid's spine motors however operates at their current limits for a large fraction of Canid's runtime.

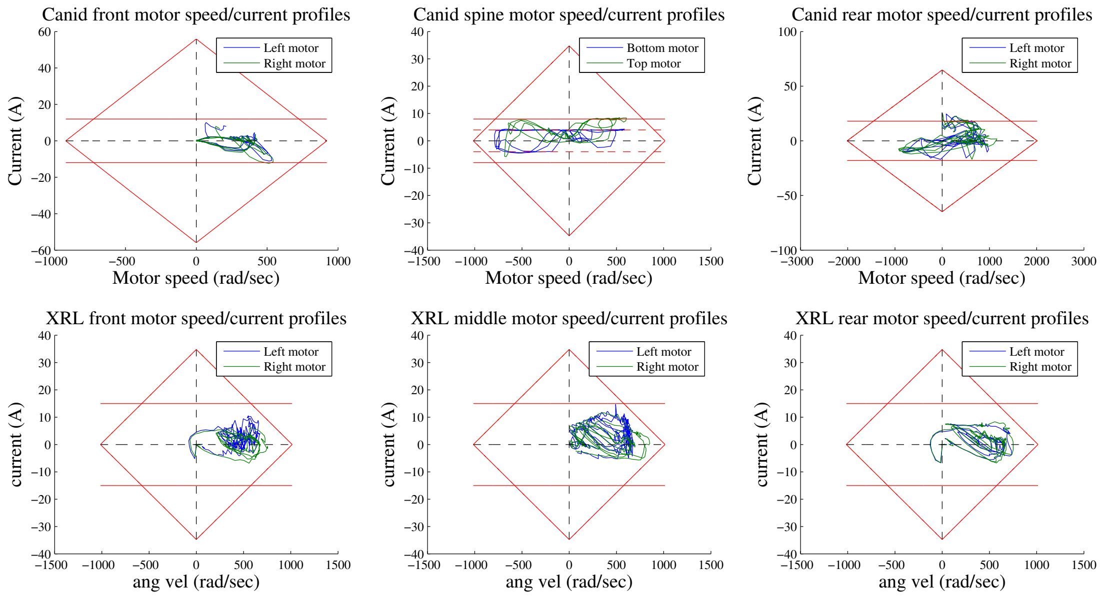

Figure 4. Motor currents of Canid and XRL. The red lines denote current limits, thus none of XRL's leg actuators are limited by their maximum currents while running, and only Canid's rear legs are briefly current limited.

3. ANALYSIS OF PRELIMINARY CANID BOUNDING

In this section we document important features of Canid's preliminary bounding behavior, namely the release of energy in the spine mechanism, the contribution of this energy to Canid's body energy, rear leg toe-stubbing, and roll perturbations.

3.1 Spine Energy Release

The power profiles of Figure 5 show that the spine mechanism releases energy at a peak of over 215W during each leap through parallel elastic actuation. The release of potential energy in the elastic compliance peaks at over 155W while the motors output power peaks at over 90W when taking gearbox inefficiencies into account. The plot illustrates that both these sources of work have very different power profiles. The spine releases energy at a high power but for a short duration, while the spine actuators work at a lower power but for longer duration.

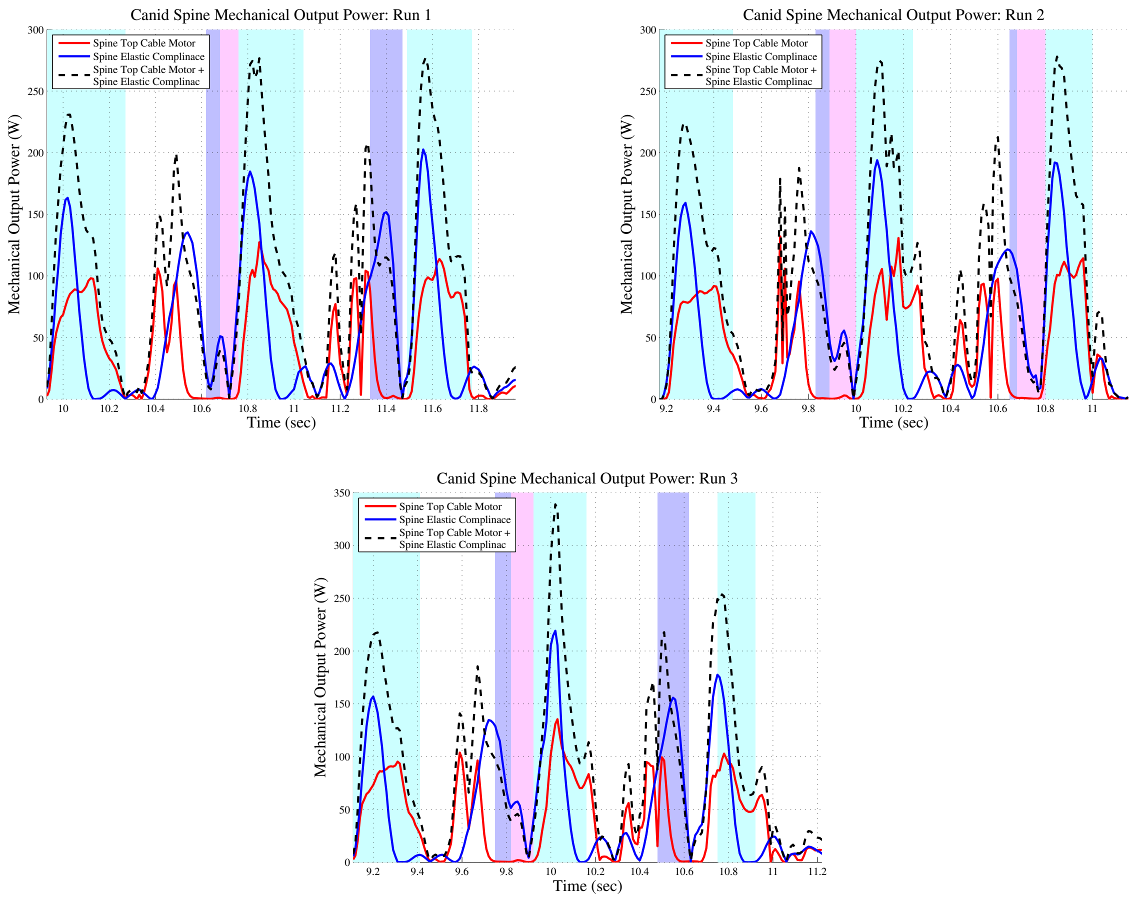

Figure 5. The combination of the spine elastic energy release and actuation of the top cable spine motor responsible for flinging the front mass on liftoff lead to a combined spine mechanical output power of over 240W. The plot also illustrates the differences in power profiles between the release of the spine spring potential energy and the spine actuation. The spine motor power values are shown after taking the gearbox inefficiency into account.

3.2 Contribution Of Spine

Figure 6 demonstrates that the spine's mechanical energy output described in Section 3.1 is indeed directly contributing to Canid's body energy for the first 2 leaps — open-loop disturbances make the spine's energetic contribution on the 3rd leap less numerically obvious. During the first 2 rear stances, Canid gains more body energy than is dissipated by the rear legs when discounting the spine spring potential energy. Since the front legs are recirculating, the spine is the only mechanism capable of inputting energy into the system and thus must be responsible for the remainder.

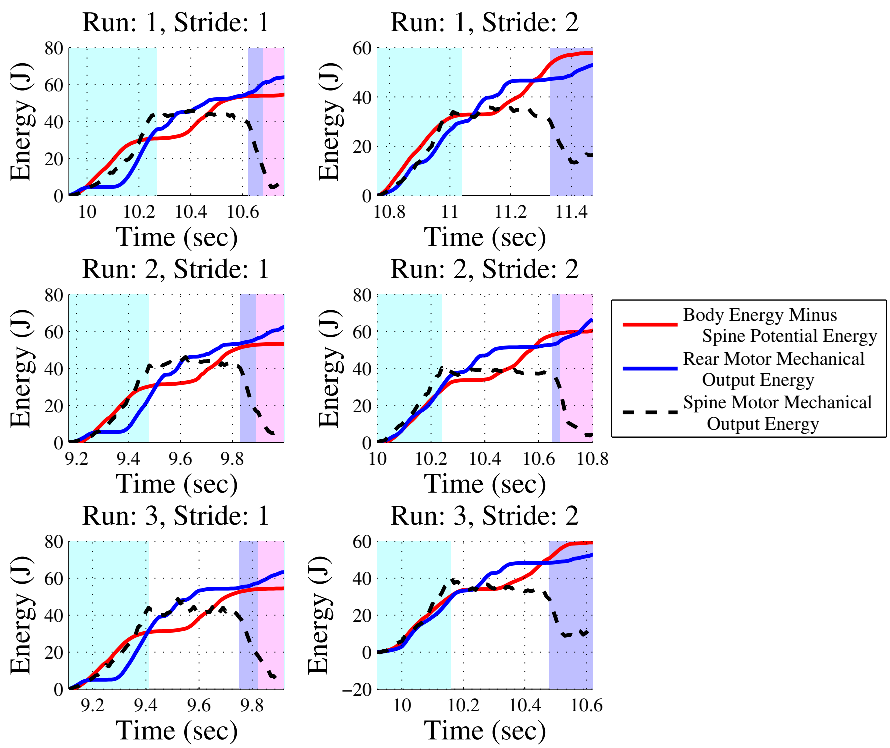

Figure 6. Canid's body energy not including the spine potential energy increases more than mechanical output energy from the rear motor on the first 2 leaps of every run. The rear leg motors output an average 33J during rear support, which is less than the average 40J of body energy gained not including the spine spring potential energy during rear stance. Thus on average 7J of body energy are unaccounted for by the rear legs alone, and could only have come from the spine mechanism (since the front legs are recirculating in air). The energy contributed by the spine is likely much more since this assumes perfect rear leg efficiency.

3.3 Toe Stubbing

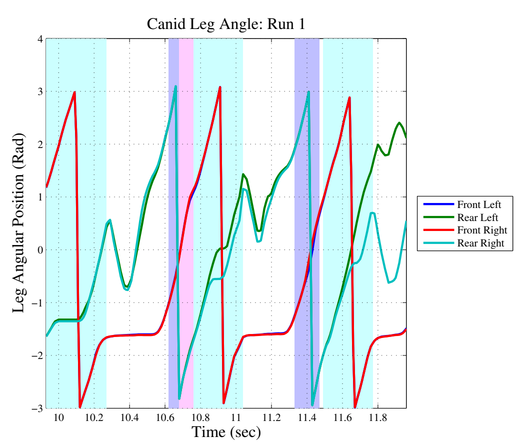

Figure 7. Canid leg angles for a typical run. The negative slope of the rear leg angles during rear stance phase are the result of toe stubbing. Due to open-loop disturbances, on the third depicted leap only the right rear leg stubs its toe. Toe stubbing in the rear legs was intentionally implemented to regulate Canid's pitch during flight.

A notable feature of Canid's bound is the rear-leg toe stubbing that occurs during liftoff in rear-stance. As the rear legs lift off, the toes catch the ground, giving Canid a pitching moment and causing the legs to momentarily change direction in aerial phase as shown by the negative slope of the leg angles in Figure 7. Toe stubbing was intentionally implemented to pitch Canid forward during flight so that the robot lands at the proper angle on its front legs. This strategy surprisingly doesn't seem to come at a prohibitively high cost to the kinetic energy of the robot.

3.4 Roll Perturbations

Statistics of Canid's roll angle during the course of a stance given in Figure 7 show that both the front and rear masses have a large roll angle before their respective legs touch down. We hypothesize that this roll angle is a main culprit for the sudden decrease in Canid's forward kinetic energy upon rear-leg touchdown. While there is also a large roll angle present in the front mass during front leg touchdown, the front leg motors are not applying a large torque during front-support as shown in[3] and thus the front leg compliance is able to achieve better ground contact than if a large torque was being applied. On the other hand, when the rear legs touch down they apply a large torque which causes them to bounce off the ground out of phase with each other before eventually achieving lasting leg-ground contact. These initial ground impacts appear to slow Canid's forward speed down significantly.

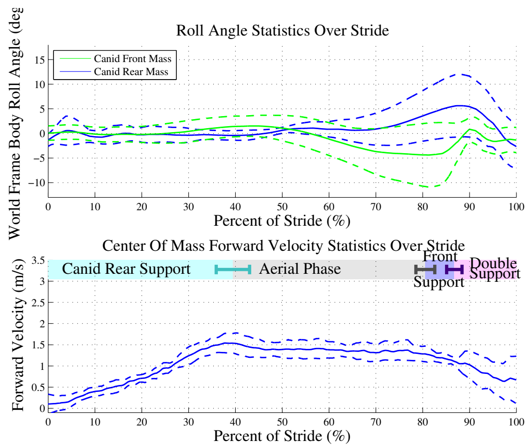

Figure 8. Canid roll angle statistics over the course of a stride. The uncontrolled roll angle in the rear mass is suspected to be the main reason Canid's forward velocity decreases upon rear leg touchdown. The error bars and dotted lines represent 1 standard deviation from the mean.

Acknowledgements

The authors thank Ryan Knopf for contributing to the design and construction of Canid, Aaron Johnson for contributing to the XRL pronking behavior development, and Martin Buehler for discussions about RHex pronking.

This work is supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-0822 and by the Army Research Laboratory under Cooperative Agreement Number W911NF-10-2-0016.

REFERENCES

1. J. M. Duperret, J. L. Pusey, G. C. Haynes, and D. E. Koditschek, "Canid, pronking xrl preliminary comparison dataset," tech. rep., University of Pennsylvania, 2013.
2. J. M. Duperret, J. L. Pusey, G. C. Haynes, and D. E. Koditschek, "Energetic benefits of elastic spine actuation for a quadrupedal robot," in *Proceedings of the IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, October 2013. Submitted.

3. J. L. Pusey, J. M. Duperret, G. C. Haynes, and D. E. Koditschek, "Leaping experiments with a power-autonomous, compliant-spined quadruped," in *Unmanned Systems Technology XV*, SPIE, 2013. To Appear.
4. G. C. Haynes, J. Pusey, R. Knopf, A. M. Johnson, and D. E. Koditschek, "Laboratory on legs: an architecture for adjustable morphology with legged robots," in *Unmanned Systems Technology XIV*, R. E. Karlsen, D. W. Gage, C. M. Shoemaker, and G. R. Gerhart, eds., **8387**(1), p. 83870W, SPIE, 2012.