BIOMECHANICS OF GOAT AND DOG LOCOMOTION: BIOINSPIRATION FOR BIGDOG

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INTRODUCTION

To ensure stability, animals must control the pitch, roll and yaw moments exerted about their body center of mass (CoM). Terrestrial animals exert time-varying forces on the ground that result in a net resultant ground reaction force (GRF) that acts from a center of pressure (CoP) under the animal. Moments about the animal's CoM depend on the location of the CoP and orientation of the GRF relative to the animal's CoM. With the goal of informing the design of BigDog™, a large quadrupedal robot constructed by Boston Dynamics to move quickly over uneven and variable grade terrain, we sought to examine how the CoP and net GRF of dogs and goats track their whole-body CoM during trotting and galloping gaits. These data were used to assess the magnitude of CoM pitch, roll and yaw through time. We hypothesized that pitch moments would be greatest during galloping due to asymmetrical fore versus hind limb ground contact and that roll moments would be greatest during trotting due to misalignment of CoM position relative to net GRF and CoP produced by the in-phase contralateral fore-hind support of this gait. We also examined how goats produce forces with their forelimbs versus their hindlimbs when climbing a 65 degree instrumented wall.

METHODS

Four dogs (BM=41 kg) and four goats (BM=32 kg) were trotted and galloped over a series of force platforms (2 AMTI and 2 Kistler) that enabled ground reaction forces to be collected from all four limbs over full strides for both gaits. Trunk kinematics were recorded from infrared markers (Qualysis, Inc. 240 Hz) along with digital video (30 Hz) gathered in lateral view. CoM position was determined from integration of GRF_{x,y,z} and initial conditions for velocity and body position. Speed was determined from motion capture of the animal's horizontal movement. Measurements of CoP and net GRF exerted through time were then used to calculate the temporal patterns of pitch, roll, and yaw moments about the animal's CoM. Limb GRFs were also obtained for four goats during running jumps and climbing against a 65° wall (2.5m height) instrumented with two AMTI force plates mounted on cinder blocks. Infrared motion capture (Qualysis, 240 Hz) was used to carry out joint kinematics and inverse dynamics of joint moments.

RESULTS AND DISCUSSION

Consistent with our hypothesis, pitch moments were largest during level galloping compared with trotting for both dogs and goats (Fig. 1). Though smaller in magnitude, pitch moments about the CoM were larger than either roll or yaw moments at a trot as well. Given the animals' straight movement, it is not surprising that yaw moments

![Fig. 1: Peak CoM moments (mean+SD) developed during trotting versus galloping in goats and dogs. Moments are normalized to BM^{5/3} due to size differences between the two species.](image-url)
were small for both gaits. The peak magnitudes of pitch and roll moments were minimized by the animals maintaining a remarkably close alignment of the net whole-body GRF to the position of their CoM, despite the time-varying location of individual limb contact and GRFs. Pitch moments in dogs were significantly greater than in goats at a gallop. This likely reflects the greater vertebral body-axis flexibility of dogs compared with goats, as well as the fact that the dogs galloped at a faster speed than goats (6.6 vs 4.3 m/s).

During wall ascent, the fore and hind limbs both produced positive work to elevate the animal's CoM to gain PE during the initial running jump. However, during the subsequent climbing stride on the wall, the forelimbs produced little force to avoid unwanted pitch away from the wall. Instead, the hind limbs produced all of the propulsive force and work for continued ascent. The forelimbs instead provided a 'follow-the-leader' target for the hind limbs' position of ground contact.

The close alignment of net GRF and tracking of CoP with respect to CoM position that we observed during steady level terrestrial gaits for dogs and goats is not surprising given the importance of avoiding large CoM pitch and roll moments that would otherwise cost additional metabolic and mechanical energy to control and likely lead to decreased locomotor stability. This is exemplified by the much-improved performance of BigDog compared with a previously developed quadrupedal robot that produced forces using in-line limb actuation and prismatic springs [1], inspired by the spring-loaded inverted pendulum mechanics that has been successfully used to model a variety of legged running animals [2, 3], but which suffered large CoM pitching moments.

By adopting a more compliant limb design [4], together with mass-spring mechanical energy savings [2,3], animals are able to reduce their energy expenditure and smooth the motion of their trunk relative to their limbs by minimizing CoM moments during running gaits. This reduces the mechanical and metabolic energy requirements for locomotion, as well as improving the stability of the animal's movement. These features are incorporated in the design of BigDog, which has significantly improved its performance compared with an earlier first-generation quadrupedal robot [1].

CONCLUSIONS

Despite the time-varying pattern of fore and hind limb contact and individual limb ground reaction forces, the phasing of limb support in quadrupeds during trotting and galloping gaits results in remarkably close tracking of the animal's net center of pressure and whole-body ground reaction force relative to its body CoM, which keeps CoM moments and trunk inertial rotations low. These features of quadrupedal limb design and time-varying ground force distribution have been successfully implemented in BigDog, enabling it to achieve exceptional speed and stability for its size when moving over rugged terrain. The varying use of fore versus hind limbs during steep ascent is also critical for maintaining CoM pitch control, while at the same time achieving the propulsive work needed for ascent.

REFERENCES


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