Comparing the Locomotion Dynamics of the Cockroach and a Shape Deposition Manufactured Biomimetic Hexapod

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Abstract: We describe the locomotion dynamics of a biomimetic robot and compare them with those of its exemplar: the cockroach. The robot is a small (0.275kg) hexapod created using a layered manufacturing technique that allows us to tailor the compliance and damping of the limbs to achieve passive stabilization similar to that observed in insects. The robot runs at over 3 body-lengths per second (55 cm/s) and easily traverses hip-height obstacles. However, high-speed video and force data reveal differences between the robot's locomotion dynamics and the inverted spring-pendulum model that characterizes most running animals, including cockroaches. Closer examination of the individual leg forces shows that these differences stem from the behavior of the middle and rear legs and points to suggestions for future designs and further experimentation.

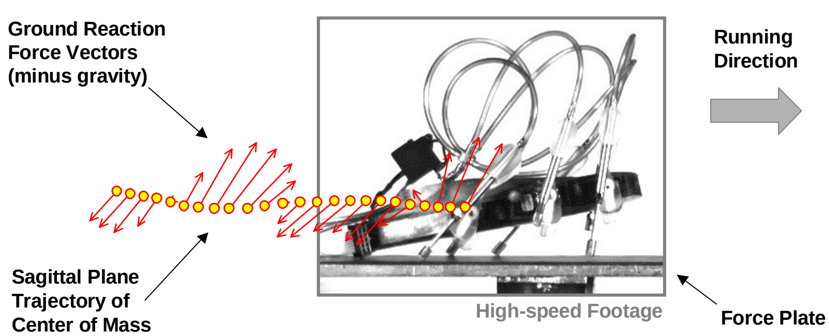

Figure 1. *Sprawlita*, a dynamically-stable running hexapod, and the force plate used for measuring ground reaction forces. Reflective markers were used for high speed video motion capture.

1. Introduction

The basic behaviors of running and walking in animals have been reproduced in legged robots [1][2]. Some have attempted to copy the morphology of biological systems in their design [3], while others implement controllers based on observed animal behavior [4]. More recent work has focused on emulating the mechanical properties of biological structures. As described in [5], a novel rapid-prototyping technique called Shape Deposition Manufacturing allows robots to be built with soft, visco-elastic materials integral to the structure that provide functional compliance and damping [6]. Using this technique, we have built a biomimetic robot named *Sprawlita* intended for fast robust locomotion through uncertain terrain.

In this paper, we describe the cockroach-inspired robot design and the resulting robot performance. We then present results using two experimental measures traditionally used in biomechanics to characterize running: pendulum-like energy recovery and ground reaction forces. Finally, we draw conclusions about the difference in locomotion styles and discuss the changes in design and future experiments that these findings suggest.

2. Biomimetic Design: The Animal and the Robot

For its size, *Periplaneta americana* is among the fastest known animals with maximum speeds of over 50 body lengths per second [7]. Although it is significantly slower at 10 body lengths per second, the *Blaberus discoidalis* cockroach [8] is still far faster for its size than legged running machines built to date.

The cockroach's physical robustness is widely recognized, but its performance over extremely rough terrain is less well-known. The *Blaberus discoidalis* cockroach can easily traverse a fractal surface containing obstacles of up to three times the height of its center of mass [9], a feat only recently achieved in legged robots [10]. Of particular interest is that this fast and robust performance is thought to be achieved by a relatively simple motor control pattern. Preliminary results suggest that there are only minor changes in the cockroach's muscle activation pattern as it rapidly transitions from smooth to uneven terrain [9], suggesting heavy dependence on the ability of the mechanical system to reject disturbances [11]. In essence, fast robust locomotion appears to be the result of the dynamic interaction between sprawled posture, a timed feedforward motor controller [10][12][13], and well-tuned passive visco-elastic elements, also known as “preflexes” [14][15][16]. This is in contrast to the control schemes of many robots, which rely heavily on active feedback control rather than passive components.

We have built a biomimetic robot named *Sprawlita* which incorporates these suggested components for fast robust locomotion: passive visco-elastic mechanical properties tuned to a timed feedforward motor controller. This robot was fabricated using a rapid-prototyping technique called Shape Deposition Manufacturing (SDM) [5][17] which allows for integrated structures with soft, viscoelastic materials that provide compliance and damping. The ability of the SDM process to embed active components such as actuators inside the structure of the robot also allows us to approach the

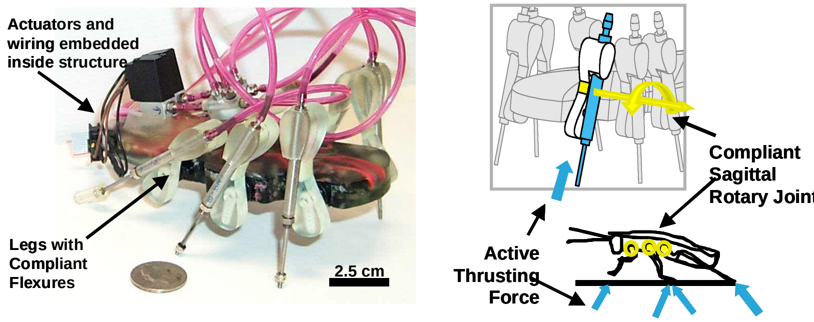

Figure 2. *Sprawlita* was designed based on functional principles from biomechanical studies of the cockroach. The prototype was fabricated using Shape Deposition Manufacturing and is capable of speeds of over 3 body-lengths per second. Studies of ground reaction forces in cockroach locomotion show that forces are directed towards the hip joints, essentially acting as thrusters.

physical robustness of the mechanisms found in nature.

Rather than directly copying the morphology of the cockroach leg, the robot was designed through “functional biomimesis,” drawing from studies of leg function, arrangement and passive properties [17]. As shown in Figure 2, the robot’s legs are arranged in a sprawled posture in the sagittal plane and consist of a simple mechanism that incorporates a pneumatic piston attached to the body through a viscoelastic hip joint. The compliant hip joint is designed to mimic the function of the trochanter-femur joint which is believed to be a mostly passive, viscoelastic element [6] rotating about an axis perpendicular to the sagittal plane. The thrusting piston is designed to mimic the function of the coxa-femur-tibia linkage.

Our robot is controlled by alternately activating each of the leg tripods in an open loop fashion at fixed time intervals. Each tripod is pressurized by separate 3-way solenoid valves. This simple, open-loop control scheme is the extreme of the minimal feedback control hypothesized for the cockroach. Therefore, the robotic system relies heavily upon the passive, self-stabilizing properties of the robotic mechanical system[1].

For the results presented here, the tripods are alternately activated over a 130 ms stride period at a 35% duty cycle, with 50% corresponding to a half-stride, or 65 ms. Despite the binary pneumatic actuation scheme, the force output at the pistons is surprisingly muscle-like in form as shown in Figure 3. The tubing lengths, valve porting, and small piston orifices conspire to transform the square wave valve input into a smooth force output.

Despite this simple mechanical arrangement and motor controller, *Sprawlita* achieves speeds of over 3 body lengths per second, or 0.55 m/s, and can overcome hip-height obstacles with little difficulty. This performance, though humble in light of the cockroach’s, begins to compare to that seen in nature.

[1] The same degrees of freedom were designed into another biomimetic robot called *Rhex* [10], although the active and passive degrees of freedom are reversed resulting in a different functional mapping.

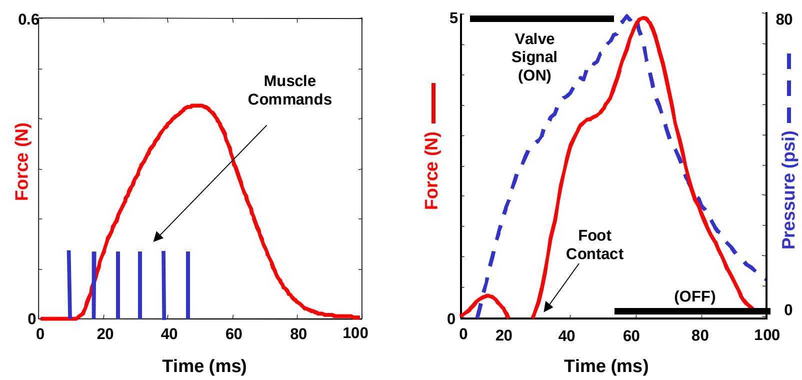

Figure 3. A comparison of isometric muscle force output [18] in response to motor commands and pneumatic piston force output in response to a solenoid valve input.

3. Basis for Comparison: Walking and Running Models of Animals

In animals there are very distinct patterns of force and motion when walking or running [19][20]. During walking, the kinetic and potential energy of the center of mass fluctuate sinusoidally and out of phase. Theoretically, the potential and kinetic energies can be exchanged via a pendulum-like energy recovery mechanism.

In contrast, running in animals is characterized by the kinetic energy and potential energy being in-phase, eliminating the possibility of pendulum-like energy exchanges. This type of motion is characterized by what is called the spring loaded inverted pendulum (SLIP) model. In addition, this model produces a characteristic set of ground reaction patterns, with the vertical force leading the horizontal force by 90 degrees [19].

As we will see, ground reaction force patterns and pendulum-like energy recovery measures help qualitatively determine how much each basic mechanism of locomotion is utilized.

4. Comparison Testing: Equipment and Methods

4.1 Cockroach Measurements

Position, velocity and ground reaction force measurements for the *Blaberus discoidalis* cockroach (mean mass 0.0026kg) were originally obtained in [8]. In summary, the cockroaches were run along a track with a force platform while a high-speed video system captured the locomotion at 60 frames/second. Velocity, position and kinetic and potential energy data were calculated by integrating the force signals. Stride beginnings and endings were determined by vertical ground reaction force patterns and verified using video information.

4.2 Robot measurements

Sprawlita (mass 0.275kg) was run along a plywood surface, with reflective markers attached to nose, back, each leg, and each foot. A high-speed video system captured the locomotion at 250 frames per second.

The force platform was a modified 6-axis force sensitive robotic wrist. An aluminum plate covered with a thin rubber layer to prevent slippage, as shown in Figure 1, was attached to the force wrist and placed flush with the plywood surface. The natural frequency of the force plate was 143Hz. Forces were filtered by an analog 4th order Butterworth filter at 100Hz, and then sampled at 1000Hz and converted to a digital signal. Forces were then digitally filtered at 50Hz by a Butterworth filter with zero phase shift. The minimum resolution of the force plate is approximately 0.1N in the vertical and fore-aft directions.

Center of mass position data were calculated by tracking the reflective markers attached to the body. The accuracy of this method is approximately 0.0001m. Velocity was calculated by taking the derivative of the position data. As with the cockroach, stride beginnings and endings were determined by vertical ground reaction force patterns, and verified using video information.

5. Biomimetic Comparison: Pendulum-like Energy Recovery

As discussed previously, a significant amount of energy may be available for recovery during walking via a pendulum-like energy recovery mechanism. In animals, this mechanism is used extensively, as energy recovery values approach 70% in walking humans [19] and 50% in crabs[20]. This measure can be calculated by:

$$\frac{(\Sigma HKE + \Sigma GPE) - \Sigma TE}{\Sigma HKE + \Sigma GPE} x 100\%$$

Here, ΣHKE is the sum of the positive changes in horizontal kinetic energy during one stride, ΣGPE is the sum of the positive changes in gravitational potential energy during one stride, and ΣTE is the sum of the positive changes in the total mechanical energy of the center of mass during one stride [19]. If there is only one peak in the given energy measure per stride, then the sum of the positive changes is simply the amplitude. In addition, vertical kinetic energy is typically excluded from these calculations as it is generally negligible in comparison to the other energies. Typical pendulum-like energy recovery is about 2% in running animals [19]. Thus, this metric is a quantitative indication of whether the observed locomotion is well represented by an inverted pendulum model, indicating walking dynamics.

5.1 Energy Recovery - *Blaberus discoidalis*

The pendulum-like energy recovery values for a cockroach during running are quite low, with a mean of 15.7%. This is a result of the kinetic energy leading the potential energy by only 7.6 degrees as shown in Figure 4 (**P**) [8]. While this is not surprising for the animal during fast locomotion, it is interesting that even at one-quarter the

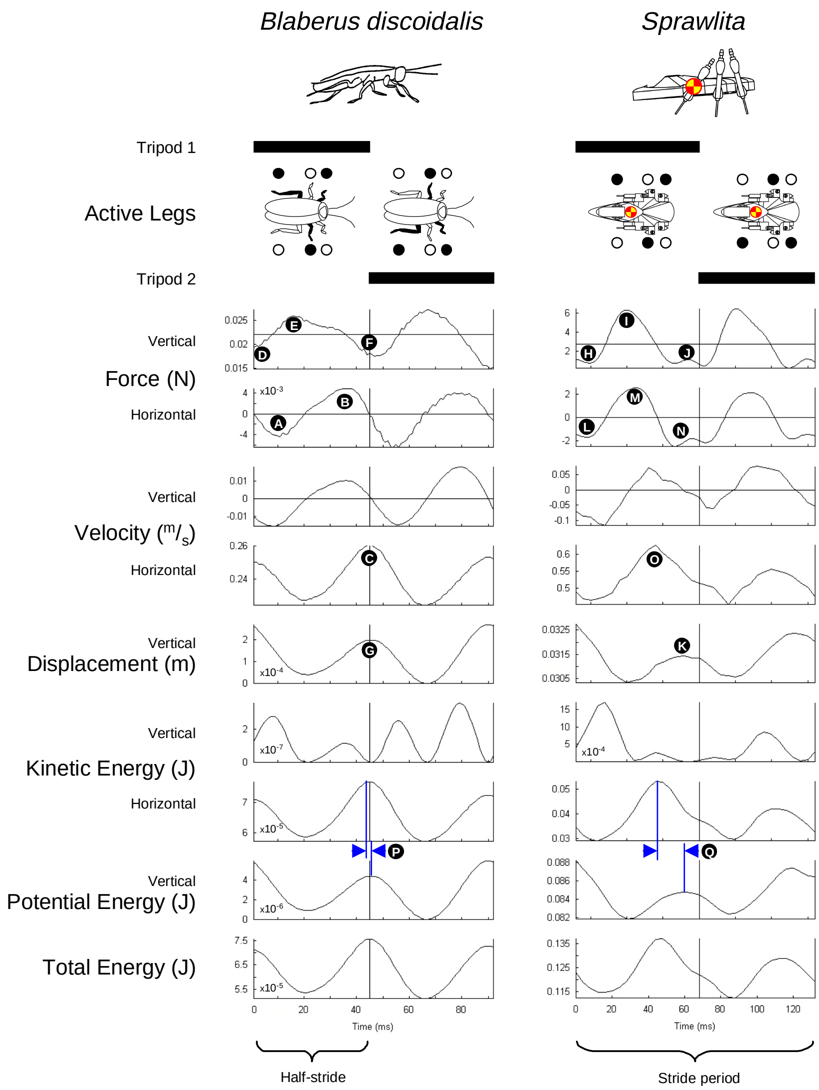

Figure 4. The results of force plate and high-speed video experiments described in Section 3 show differences in the locomotion of *Blaberus discoidalis* [8] and *Sprawlita*. The respective amounts of pendulum-like energy recovery, calculated from the center-of-mass energetics, indicate that neither hexapod is "walking." The respective ground reaction force plots show that the standard model of animal running, the spring-loaded inverted pendulum (SLIP) model, fits the cockroach well but the robot poorly. Labels (A) - (Q) correspond to features discussed in Sections 5 and 6.

maximum stride frequency (3Hz), the amount of pendulum-like energy recovery is low. At very low speeds, locomotion becomes intermittent, taking only a few quick strides at a time. Thus it seems that this animal actually *prefers* a running gait.

5.2 Energy Recovery - *Sprawlita*

The phasing as shown in Figure 4 (**Q**) between the kinetic and potential energies in our robot seem to place it closer to the inverted pendulum model observed in walking animals than to the running observed in the cockroach, as the kinetic energy leads the potential energy by 60 degrees. However, when the actual pendulum-like energy recovery is calculated, the value for *Sprawlita* is surprisingly low at 10.2%. This low value is due to the non-sinusoidal shapes of the energetics and the almost one order of magnitude difference between the magnitudes. Thus, while the robot, like the cockroach, does not exhibit the pendulum-like energy recovery associated with walking, it is dynamically dissimilar to the cockroach. The dynamic dissimilarity is underscored by examination of the ground reaction forces.

6. Biomimetic Comparison: Ground Reaction Forces

6.1 Ground Reaction Forces - *Blaberus discoidalis*

The ground reaction forces produced by *Blaberus discoidalis* are what one would expect for a running animal with bouncing dynamics. During the first part of a half-stride, the fore-aft horizontal force applies a braking force, slowing the body down as shown in (**A**) of Figure 4. As the half-stride progresses, the fore-aft force changes direction and an accelerating force is produced (**B**), causing the body to increase speed, with maximum horizontal velocity attained at the end of half-stride (**C**). In short, there is a clear *brake-propel* pattern over the course of each half-stride.

As shown in Figure 4, the vertical force pattern is just as distinctive. The vertical force is a minimum at the beginning of a half-stride (**D**) and increases to a maximum that occurs during in the middle of the half-stride (**E**). The vertical force then returns to the minimum by the end of the half-stride (**F**), resulting in a maximum vertical displacement as the cockroach switches from one tripod of legs to another (**G**). In short, the vertical force oscillates about the weight of the body in a *minimum-maximum-minimum* pattern over the course of the half-stride.

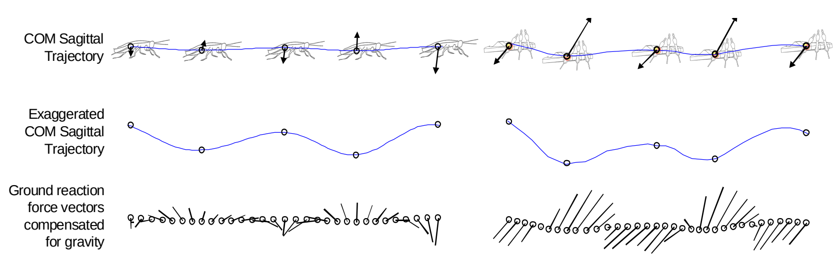

Figure 5. Ground reaction force vectors superimposed onto position data for an entire stride period. The vertical axis of the middle plot is exaggerated for detail. The ground reaction force vectors shown have been compensated for gravity by subtracting the weight of the robot from the vertical force measurement.

The aggregate of these fore-aft and vertical force patterns as shown in Figure 5 verify that the overall body motion is well characterized by the spring-loaded inverted pendulum model and is dynamically similar to other animals during running [8][21].

6.2 Ground Reaction Forces - *Sprawlita*

As shown in Figure 4, the vertical force patterns generated by the robot are quite similar to the cockroach. At the beginning of the half-stride, the vertical force is a minimum (**H**), very close to zero. Midway through the half-stride, the vertical force peaks (**I**) and then decreases back towards the minimum by the end of the half-stride (**J**), resulting in a maximum displacement near the tripod switch (**K**). As with the cockroach, there is a clear minimum-maximum-minimum pattern over the half-stride.

The fore-aft horizontal forces, on the other hand, are not as similar. As in the cockroach, the fore-aft forces begin the half-stride at a minimum (**L**), decelerating the body, and increase to a maximum (**M**), accelerating the body. Considering only this portion of the half-stride, there is a *brake-propel* cycle in both the animal and the robot. However, the latter part of the half-stride shows a pattern of light vertical forces (**J**) and decelerating fore-aft forces (**N**), resulting in an early horizontal velocity peak (**O**). This difference in the horizontal forces explains the large phase difference between the kinetic and potential energies as discussed earlier and is the key dynamic dissimilarity between the robot and the cockroach.

Examination of the video data reveals that the robot assumes a “pseudo-flight” phase during this part of the half-stride. Unlike a true flight phase, the middle and rear feet never leave the ground. Instead, they drag along in light contact, which accounts for the differing force patterns. The phenomenon is a result of the thrusting pistons reaching the end of their stroke before the stride is complete. At the same time, the torsional elements in the hips apply torques to the legs which keep the feet in contact

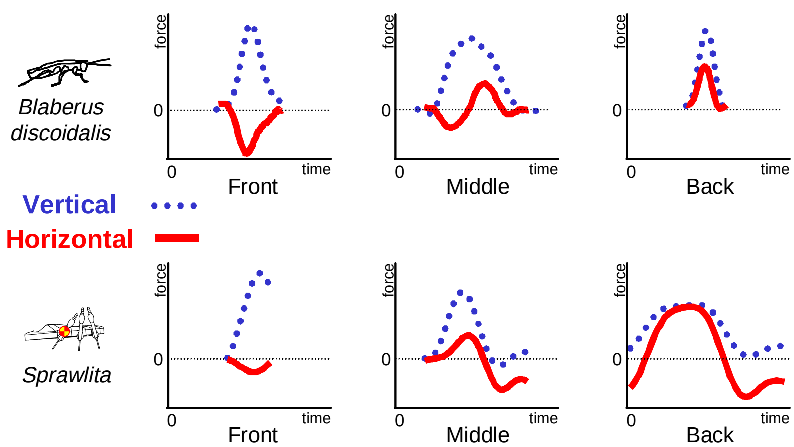

Figure 6. Plots of the individual leg ground reaction forces for *Blaberus discoidalis* [22] and *Sprawlita*. As indicated, dragging occurs in the middle and rear legs of *Sprawlita* during locomotion. This and the relative lack of deceleration provided by the front legs account for differences in locomotion dynamics.

with the ground.

While roughly similar in form, the comparison in Figure 5 shows that *Sprawlita* is not well characterized by the SLIP model.

7. Biomimetic Comparison: Individual Leg Ground Reaction Forces

7.1 Individual Leg Ground Reaction Forces - *Blaberus discoidalis*

There are many ways in which the SLIP model ground reaction force patterns can be produced by a system with multiple legs. In contrast to the Raibert approach of running with symmetry [1], the cockroach legs carry out very different functions in producing the SLIP-like behavior. While the vertical force patterns for individual limbs are similar, forces in the fore-aft direction are quite different. In general, the front legs decelerate, the rear legs accelerate, and the middle legs do both, as shown in Figure 6.

7.2 Individual Leg Ground Reaction Forces - *Sprawlita*

When we examine the plots in Figure 6, we see that there are differences between the individual leg functions in the cockroach and the robot. While the rear legs accelerate during the first part of the half-stride, there is a significant amount negative fore-aft force during the latter part of the half-stride due to dragging. When we consider the middle leg force profile, we see that it is actually the opposite of the cockroach's. The middle legs initially provide acceleration, and then deceleration. Finally, unlike the cockroach, the front legs provide little deceleration.

8. Discussion and Conclusions

Sprawlita has demonstrated the feasibility of small, biomimetic robots that exploit passive properties in combination with an open-loop controller to achieve fast, stable locomotion over obstacles.

However, while *Sprawlita's* scurrying is insect-like, a comparison of the ground reaction forces reveals significant differences, particularly in the horizontal direction. A closer inspection of the individual leg forces shows that the front, middle and rear legs behave differently than they do for a cockroach (or other running hexapedal animals). Instead of being decelerated primarily by the front and middle legs at the end of each stride, *Sprawlita* is decelerated substantially by foot dragging in the rear legs. As a consequence, the robot does not display the typical phasing of horizontal and vertical forces associated with the SLIP model found in running animals. In essence, the rear legs are "running out of stroke length," resulting in a pseudo-flight phase with dragging feet.

These observations suggest modifications for incorporation into the next generation of biomimetic hexapods. In particular, we can increase the stroke length of the middle, and especially the rear legs by embedding custom pistons with a longer stroke length or by fabricating a compliant SDM linkage that multiplies the pistons' motion. We anticipate that if we can prevent the pseudo-flight phase and foot dragging, the front and middle legs will be able to take on the role of compliantly decelerating the robot at the end of each stride, and a more SLIP-like motion will be observed. Whether this motion will truly be faster or more robust remains to be verified, but given that it is ubiquitous in running animals it is certainly worth investigating.

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