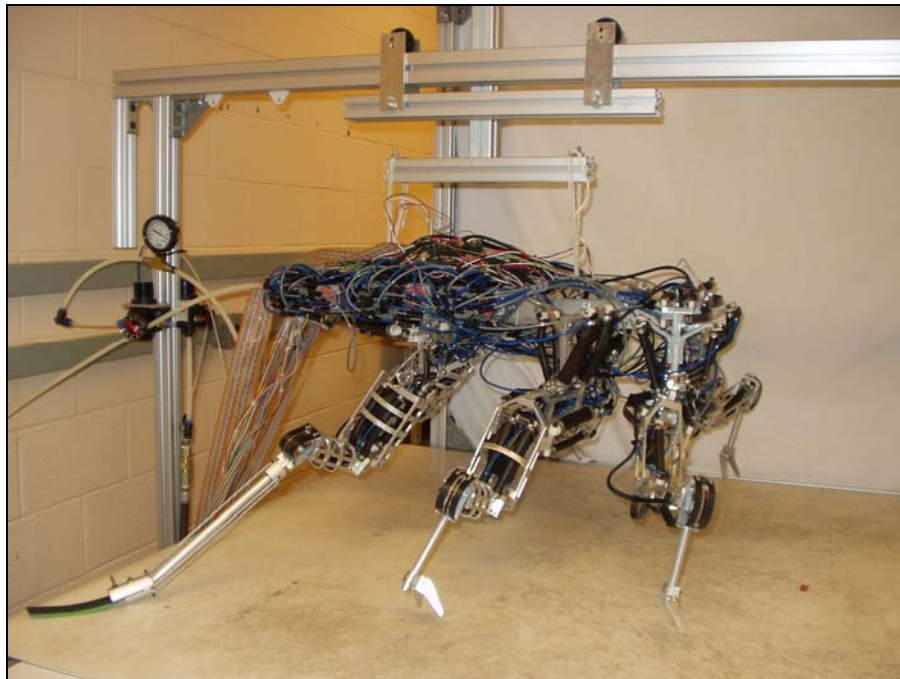


Creating Cockroach-Based Pads for Robot V



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Abstract

Robot V, a large, pneumatically-actuated, cockroach-based robot constructed in Dr. Roger Quinn's laboratory, slips when it attempts to walk. A lack of friction and feet that were not designed after those of a cockroach are believed to be the causes. A group of undergraduate biologists and engineers have worked over the course of the semester on this issue and have developed, based on the biology of the cockroach *Blaberus giganteus*, a passive foot/ankle design with frictional pads that should help the robot. In this paper, I discuss the biological basis for and the development of the frictional pads. Recommendations for future alterations and adjustments of the design are also covered.

Introduction

The construction of biologically-inspired robots can have a positive effect on the field of biology as well as that of engineering. While engineers benefit from imitating nature's designs, which evolution has already shown to be advantageous, biologists can learn about a creature's biology through the robot in ways they could not with the animal alone. A robot can attempt to walk without a foot, but, if one cuts the foot of an animal off, chances are they will refuse walk. Similarly, when a robot design does not work, the engineers can go back to the animal to examine how it differs from the design.

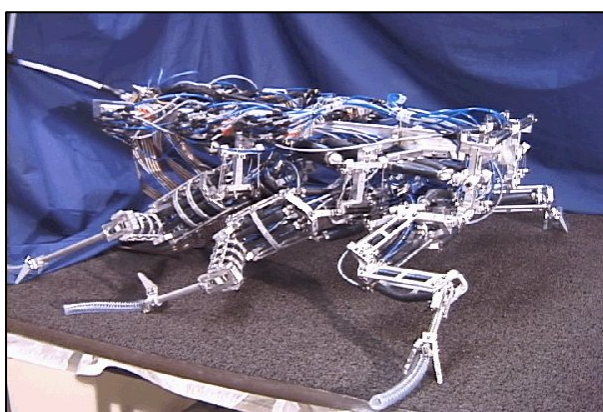


Figure 1. Robot V standing. Note the Tygon® tubing and aluminum spines on the ends of the tibia.

Robot V, shown at the left, is a pneumatically actuated, cockroach-based robot built in Dr. Roger Quinn's laboratory based on research on cockroaches from Dr. Roy Ritzmann's lab. When originally built, Robot V was designed to imitate the leg movements of a cockroach—namely *Blaberus discoidalis*—and little attention was given to the feet of the robot. Claw-like aluminum spines were placed on the end of the robot's tibiae along with Tygon®

tubing. It quickly became apparent that such measures were inadequate; when walking, Robot V's front and middle legs tend to slip out from under it. The rear legs, rather than openly slipping, tend to catch on a single spine and move back and forth around that point without actually lifting the foot and taking a step. Sometimes the rear foot is dragged slightly forward.

A clear concern with Robot V, therefore, is that of friction. Cockroaches generate frictional and adhesive forces capable of holding them upside-down on ceilings by shearing outward with their sprawled legs (Gorb 2005). Similarly, Robot V needs suitable friction to walk with a sprawled, cockroach-like posture.

Otherwise, the torque and moment about the robot's leg will be great enough to cause slipping—as it does now—or worse, overwhelm the joints and actuators at the top of the robot's legs and break the control mechanisms—similar to breaking a cockroach's leg off at the body/coxa joint.

A group of undergraduate biologists and engineers chose to address Robot V's problems by researching, designing, and fabricating feet for Robot V. Two designs, one passively and one actively controlled, were developed. My role within this project was to engineer pads, based on the biology of the feet of cockroaches, for the two designs. Due to time constraints, however, I focused my efforts on developing frictional pads for the passive foot design alone.

The Biological Basis of Friction

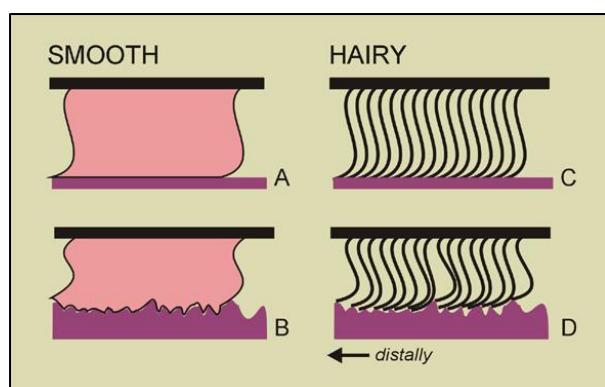


Figure 2. Diagrams of smooth and hairy systems interacting with smooth surfaces (A and C) and rough surfaces (B and D). Image courtesy of Dr. Stanislav Gorb.

Insects have two primary methods of attachment: smooth and hairy systems (Beutel and Gorb 2000).

Although the systems look quite different, their function is the same: both systems create friction by maximizing the surface contact area between the insect and the substrate upon which it is walking. In the case of the hairy system, this is done with

hundreds of thousands of microscopic hairs, frequently on the legs and feet of insects, that deform to closely match the inconsistencies of a surface on

the microscopic scale. The smooth system, on the other hand, generally consists of a smooth, flexible pad that molds itself on a similar scale to the surface upon which it rests. The cockroach—both *Blaberus discoidalis* and *Blaberus giganteus*, which was the species studied by the biologists during the development of our designs for Robot V—uses a smooth system with four pads on each foot.

The pads consist of smooth, soft cuticle that deforms on contact with a substrate. The cockroach can control, to an extent, its frictional contact with a surface by controlling the pressure it places on the pads. A greater pressure flattens the pads further, creates a larger surface contact area, and, therefore, generates more friction. Cockroach pads also secrete tiny amounts of adhesive that further assist the animal in remaining in contact with a substrate.

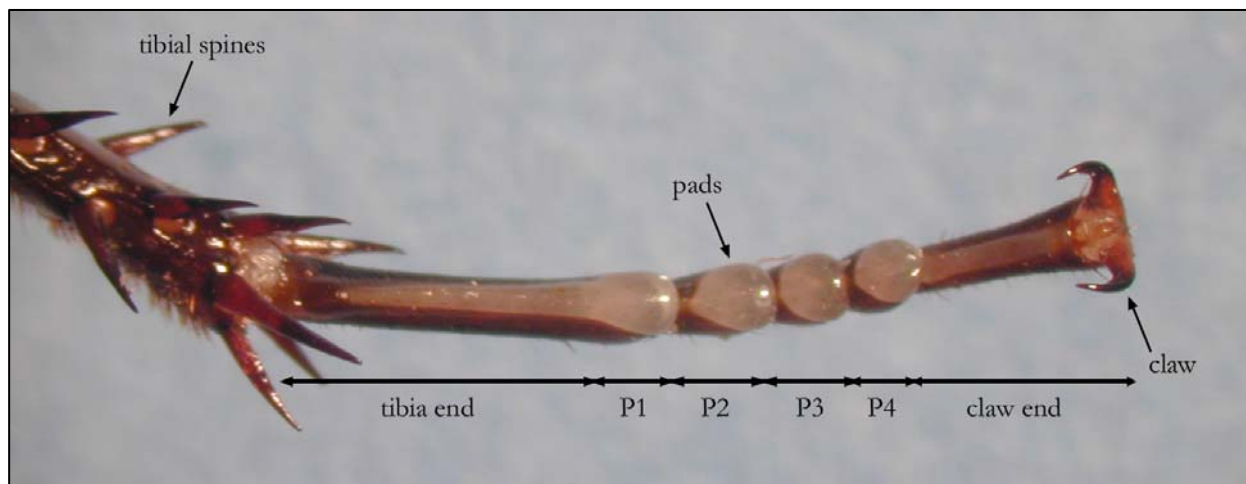


Figure 3. A cockroach foot with appropriate segments and features labeled.

Although the cockroach foot has two other features, tibial spines and its claws, that help it maintain contact with substrates, the pads are the animal's primary source of friction and adhesion on most surfaces (Funt 2005, unpublished) and were, therefore, the primary focus of efforts to improve Robot V's foot/substrate interaction. Another reason for focusing on the pads is that they appear to be passively controlled, whereas the cockroach's claws are actively controlled by a tendon that runs down the leg and into the foot (Howard 2005, unpublished).

The Design

Criteria and Considerations

When moving from a biological system to an engineered one, certain alterations and considerations must be made. The engineered system cannot be as complicated as the biological one: firstly, because the complexity of the biological system is not entirely known or understood, and, secondly, because modeling the full complexity of the biological system—even if we understood it—would require more actuation and active control than is currently feasible. The engineering must, therefore, be a simplification of the biological system without being an *oversimplification*.

This principle drove us to consider—rather than an active design in which many compliant segments rotate—a passive system in which rotation was kept to a ball joint that served as an ankle, so that the purpose of the section of the foot that contacted the ground was to maintain full contact with the ground but release quickly for the transition into stride. This is unlike the cockroach, which will actually pivot about one or more of its pads while in stance (Tan 2005, unpublished). With this passive ankle/foot design, it makes sense to have a single continuous pad rather than the discrete pads the segments of the cockroach’s foot have.

Similarly, since the cockroach shows signs of breaking its adhesive contact with a substrate by rotating its foot, it was both sensible and practical, with a non-pivoting foot design, to avoid adhesive materials and focus instead on materials with a high coefficient of friction. This choice also freed me from having to consider possible methods of self-cleaning for the robot because the strength of an adhesive depends very much on the cleanliness of the adhesive surface, and anyone who has watched insects for long knows that they spend much of their time cleaning themselves.

Other design considerations included resistance to wear, manufacturability, and cost.

Final Design

In the final passive foot/ankle design, the foot, by which I mean the section of the design intended to contact the ground, is made of curved spring steel, which fits into an aluminum collar that holds the ball joint ankle and connection to the tibia. (For

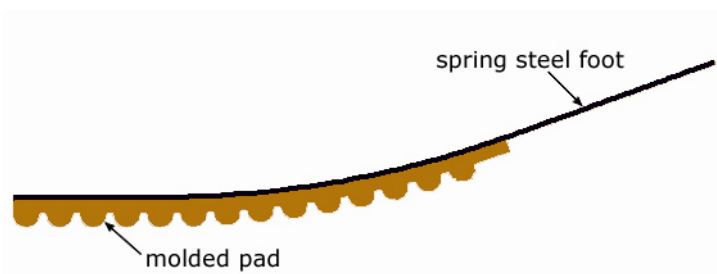


Figure 4. Diagram of final design for rear foot.

details on this design, please see Taylor 2005, also unpublished.) To this spring steel a continuous pad of a high coefficient of friction material was added. When the molds were originally designed, this material was intended to be Flexane 80™, but, after a visit from Dr. Stanislav Gorb, we switched to polyvinylsiloxane (PVS) for reasons that will be discussed shortly.

Treads a quarter inch in diameter were added to the pad to imitate the behavior of the semi-spherical pads of the cockroach. The idea was that the treads will flatten out some under the force of the robot, and that this will increase the surface contact area—and thus the friction—between the robot's foot and the substrate upon which it is walking. The more pressure the robot applies to its foot, the greater the friction between it and the substrate. I would have preferred that these treads be smaller in diameter than a quarter of an inch, but I was limited both by the viscosity of liquid Flexane 80™ and by the physical limitations of cutting through 1.25 inches of low density polyethylene (LDPE) with a small diameter endmill.

Manufacturing Process

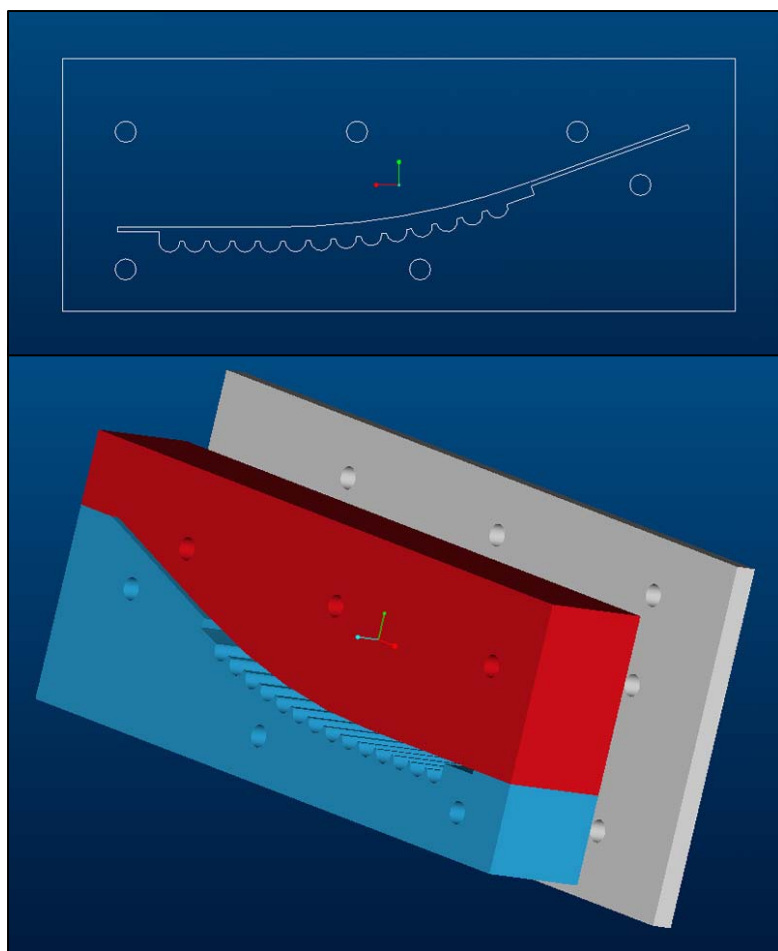


Figure 5. Model and assembly of mold for frictional pads.

The mold for the pads was cut from 1.25 inch thick low-density polyethylene (LDPE). Figure 5 shows a top view of the mold; it would extend 1.25 inches into the page. The mold consists of three parts: two sections of LDPE that define the shape of the pads (shown in red and blue) and a backing made of aluminum (shown in gray), into which the two LDPE sections can be screwed, thus securing them in place for the duration of the time needed for the molded material to cure. The LDPE segments were cut using a Mastercam program in a computerized milling machine, and the aluminum backing was drilled and tapped by hand.

As mentioned before, the mold was designed with the intention of using Flexane 80™ as the molded material; however, a visit from Dr. Stanislav Gorb prompted a switch to polyvinylsiloxane (PVS). Both

materials have a high coefficient of friction, though PVS's is higher (Daltorio and Charnas 2005, unpublished). Flexane 80™ is already in use in Dr. Quinn's lab on some of the other biorobots. Its production is rather complicated, as it consists of three parts—a resin, a curing agent, and a softening agent—that must be combined properly by weight. When in liquid form, it is still highly viscous and does not flow well into pieces of a mold that are smaller than 100/1000ths of an inch. Once the material cures, it is quite hard and does not deform much on contact.

Polyvinylsiloxane (PVS), on the other hand, is a fast-curing material used to make impressions in dental work. Its real advantage over Flexane 80™ is its ability to mirror whatever surface against which it is molded, right down to its nanostructure (Gorb 2005). Since the molds had already been cut, nanostructure was not as important in this case, but the higher coefficient of friction and the fast curing time prompted me to try PVS as a pad material for Robot V.

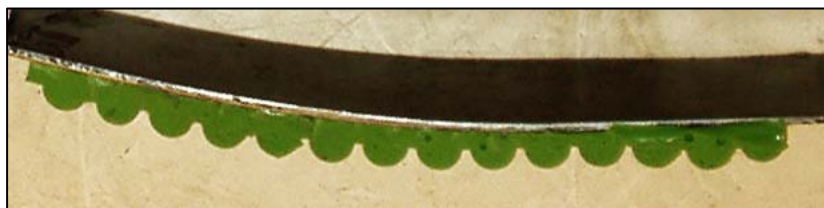


Figure 6. Polyvinylsiloxane (PVS) frictional pads attached to spring steel.

PVS comes in two tubes, which are mixed in equal parts. Once the material was mixed, I quickly applied it to the mold and pressed the spring steel foot on top. Early

tests showed that PVS would not mold directly to the spring steel, so, once the PVS had hardened, I peeled the spring steel off and removed the pad from the mold. After trimming the pad with a knife, I glued it to the bottom of the freshly sanded spring steel foot using Permabond™ super glue, which I chose for its high strength against shear forces. After curing for about a half hour, the pad was fully attached to the foot.

Disadvantages of the Design

Although the design uses a soft, flexible, high coefficient of friction material, there are several disadvantages to this design. Firstly, PVS is an expensive material. Tests have not been entirely conclusive, but other materials may perform as well or better as robot pad materials than PVS does and will do so at a better price. Another unresolved issue is the question of PVS's durability. How well will the material hold up to repeated exposure to the forces of Robot V walking?

Finally, although this design takes some elements of the cockroach's pads into account, it does not imitate either a smooth or hairy design as well as it could. This shape-based aspect of the design will be discussed further later.

Testing

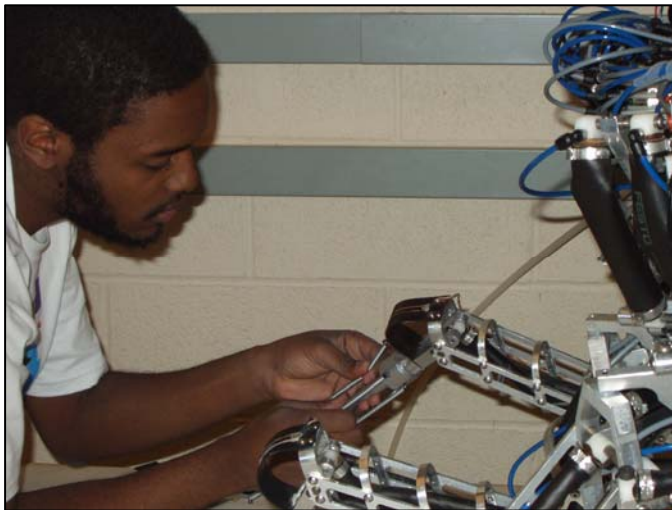


Figure 7. Brian Taylor adjusts the biasing of the springs between tests.

Tests intended to quantify and compare the differences between the old foot design for Robot V and the newer passive foot design were conducted in late April. Unfortunately, circumstances were such that no comparisons could be made. The raw data, along with comments about each run, are noted below in Table 1. Only the forward distances that the robot moved, as measured from the front of its frame, were tallied. The robot moved a varying distance to the side as well.

Date of Test	Foot Used	Run Number	Walking File Used	Forward Distance	Comments
04/18/2005	Old	1	12	11 inches	We were later told that file #12 was faulty and should not be used.
		2		9.25 inches	
		3		12.75 inches	
		4	10	1.25 inches	Sensor plugged in incorrectly.
		5		N/A	
		6		N/A	
4/29/2005	New	7	13	1.25 inches	Valve was leaking, foot was incorrectly biased, and <i>pad did not touch the substrate during the run.</i>
		8		4.33 inches	

After two runs with the new feet, it was clear that adjustments needed to be made to the passive foot design before the pads would even impact the ground as originally intended. Another issue was the comparative length differences of the front and middle legs to the newer back legs. Although the longer rear legs raise the robot enough that its coxa/femur joint does not

impact the ground as before when the robot walked, the front and middle legs are too short with respect to the newer rear legs for the robot to walk as intended.

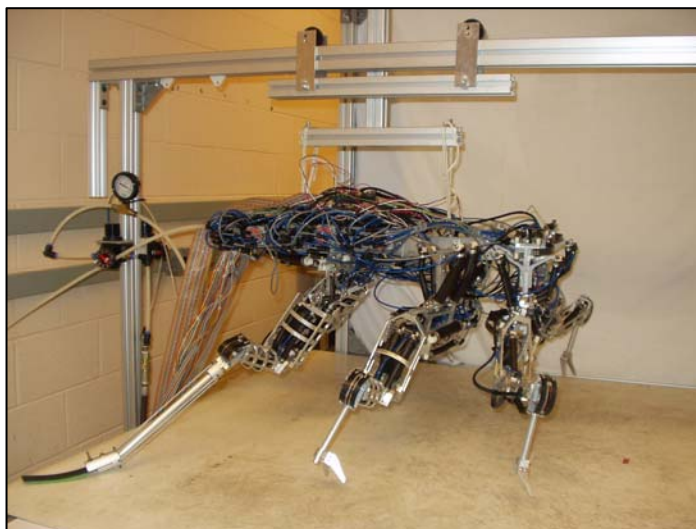


Figure 8. Robot V with new passive rear foot. Despite the incongruent sizes, the robot looks more like a cockroach with the longer rear foot.

Suggested Future Work

Although formal testing gave no quantifiable results of improvement over the former design, I have ideas and suggestions for further improvement of the pad design. Before these can be developed and tested, of course, alterations must be made to the passive foot/ankle design as a whole to ensure that the pads contact the substrate, and longer front and middle legs should be made to help correct the kinematics. At that point, the current design can be tested, and we will be able to determine how effective it is for Robot V.

Imitation of Hairy Insect Pad Systems

In the “Disadvantages of the Design” section, I discussed the lack of imitation of the biological basis for friction in the current design. I have also mentioned PVS’s remarkable ability to mirror the surfaces against which it cures. With alterations to the current manufacturing technique, a structured version of the current pad design could be made. Rather than cutting through a depth of 1.25 inches of LDPE, we could design a mold that is cut 1.25 inches wide and to a much smaller depth. This would allow us to use endmills with a smaller diameter as there would be less chance of them breaking. Having made large treads, even smaller

cutting implements could be used to create micro-tread features, thereby imitating the hairy insect pad in its hierarchy of surface-matching features (Gorb 2005).



Figure 9. Concept drawing of "hairy" anisotropic rear foot.

To take the treading idea even further, we could create anisotropic treads that will complement the robot's kinematics. As I noted earlier, the robot does not so much lift its rear leg as drag it forward when it walks. By creating an anisotropic surface that allowed dragging in one direction while hindering it in the opposite direction, the robot's forward motion could be increased. Interestingly enough, this idea is something akin to taking the cockroach's tibial spines and applying them to the bottom of the robot's foot instead.

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Although this idea addresses the lack of imitation of biological systems in the current design, it would entail the use of PVS, which, as noted earlier, is expensive and may not hold up well to heavy use, particularly with respect to the finer structures that would be needed for the hairy insect pad concept.

Use of Sorbothane™

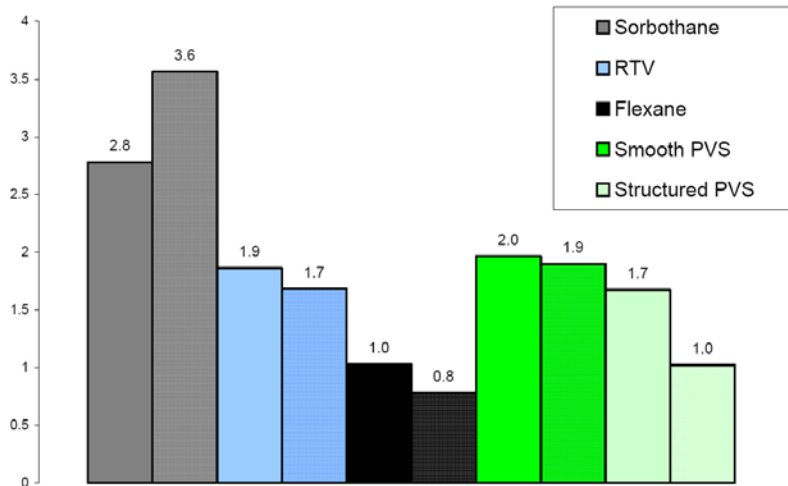


Figure 10. Coefficient of friction data collected by Daltorio and Charnas. The solid bars denote coefficient on smooth surfaces while the dotted are coefficients on rough surfaces. Image courtesy of Kathryn Daltorio.

Another group of undergraduates working in Dr. Quinn's lab this semester have discovered and tested a material called Sorbothane™, which has a coefficient of friction even greater than that of PVS (Daltorio and Charnas 2005, unpublished). The Sorbothane™ sample Daltorio and Charnas purchased was smooth and deforms well in the normal direction but not much in the lateral

direction. It comes with an adhesive backing on it, making it simple to apply to the curved spring steel feet.

The high coefficient of friction, smoothness, and deformability of Sorbothane™ make it an excellent candidate, in my opinion, for a material that imitates the smooth insect pad systems. Once the passive foot/ankle design has been adjusted to enforce pad/substrate contact, I recommend testing spring steel feet with samples of flat Sorbothane™ attached.

Conclusions

By studying and imitating the design and function of cockroach pads, I developed pads from a high coefficient of friction material that, despite a lack of quantifiable evidence, show improvement over the original Robot V feet. Once adjustments and improvements to the overall passive foot/ankle design have been made, it will be clearer what effect the pads have on Robot V's ability to walk. In the meantime, longer feet and corresponding pads need to be made for Robot V's front and middle legs. Although the mold for the middle foot was never manufactured, a Mastercam file for the mold has been made, so creating the pads for the middle feet, given additional PVS, would not require much time and effort.

After testing of the current design is completed, I recommend comparing the current design's performance to that of flat Sorbothane™. I also recommend investigating different shapes for pads made from PVS, namely those that better imitate the anisotropic hairy insect systems discussed by Dr. Gorb. By creating frictional pads that are better able to mirror the surfaces on which they rest, we will enhance Robot V's ability to walk without slipping.

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