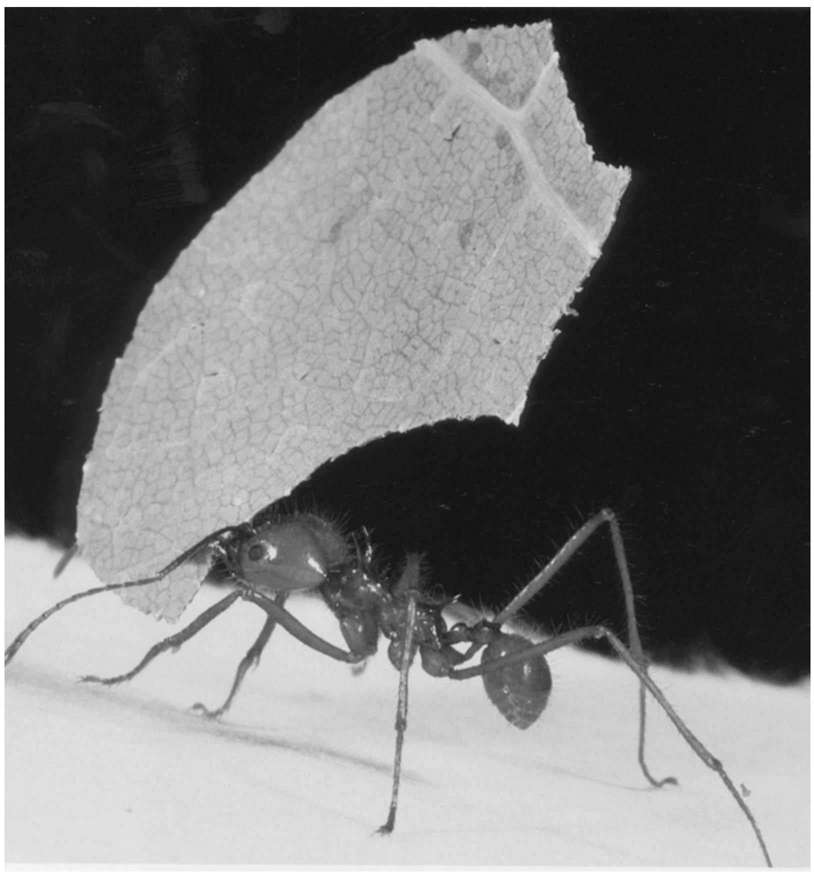
The Effect of Load Carrying on the Speed of Locomotion in Arthropods and a Biomimetic Arthropod Robot



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Abstract

The effect of load carrying in insects has been compared to the effect of load on the speed of a biomimetic arthropod robot, "Sprawlita." Mass, location of mass, and leg angles of the robot were varied and resultant speed measured as the dependent variable. Plots of speed versus mass for various mass locations and speed versus mass for various leg angles were produced. The findings of a literature review of load carrying in insects are compared to those from the experimental findings and the results discussed. It was found that the robot performed best with back leg angles at 115 degrees (25 degrees counterclockwise from the vertical) for almost every mass configuration. It was also found that adding mass at the center of mass of the robot affected the speed of the robot the least, as compared to 2.5 inches in front and in back of the COM. In the unladen state, the robot performed best (speed) for an alternating tripod frequency of 8 Hz for all tested leg configurations.

Cover: A worker ant of *Atta cephalotes* carries a cut piece of leaf back to the nest [Hoelldobler and Wilson, 1990]

Background

Researching load carrying and its relation to speed in insects has proven to be a somewhat fruitless endeavor. Not many insects carry significant loads in their daily activities, and they are rather difficult to convince to carry them at the investigator's command. Ants are one exception to this rule (not the rule that they will carry loads on command). In an enormous book by Hoelldobler and Wilson, called "The Ants," [1990] the authors present a number of examples of ants carrying objects, mostly other ants. Examples of this from the text are shown in figures 1 through 4. This phenomenon is typically that of "major" worker ants carrying "minor" worker ants to another location where their service is required. However, in some species of "slave-maker" ants, the raiding colony of ants will carry away the slaves taken in the raid. Most of the "slaves" are ants of a different species, however, certain species of ants will enslave those of their own kind. [Hoelldobler and Wilson, 1990]

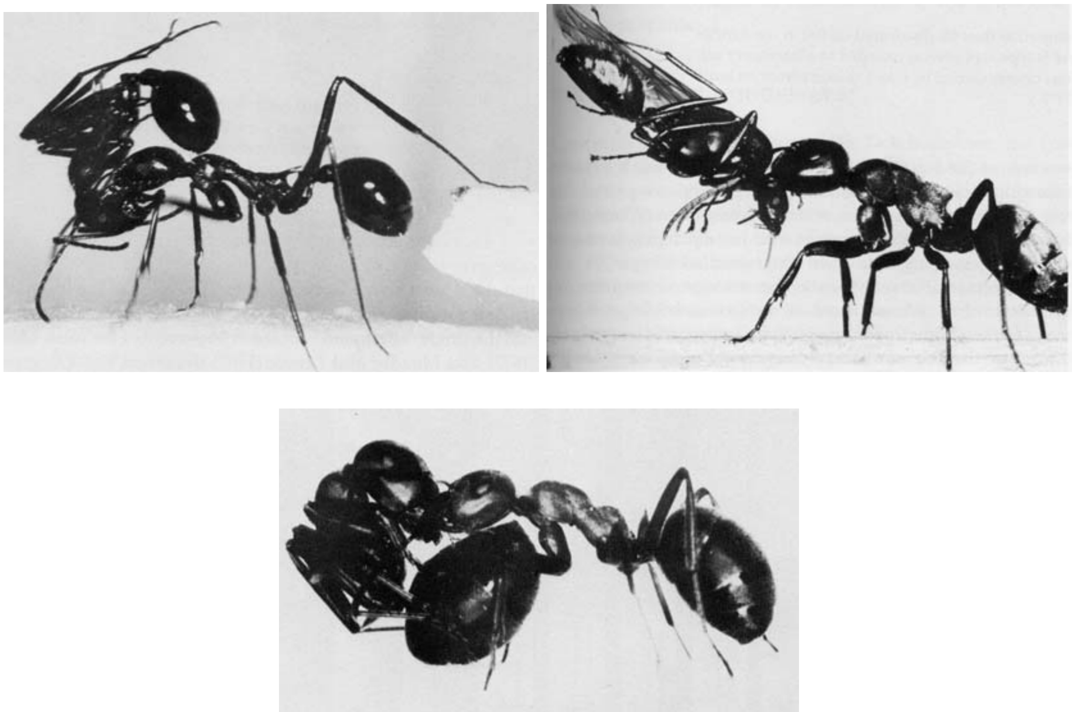

Figure 1: Transport postures assumed by three different species of ants: *Aphaenogaster cockerelli* (top left), *Camponotus sericues* (top right), and *Formica sanguinea* (bottom). [Hoelldobler and Wilson, 1990]

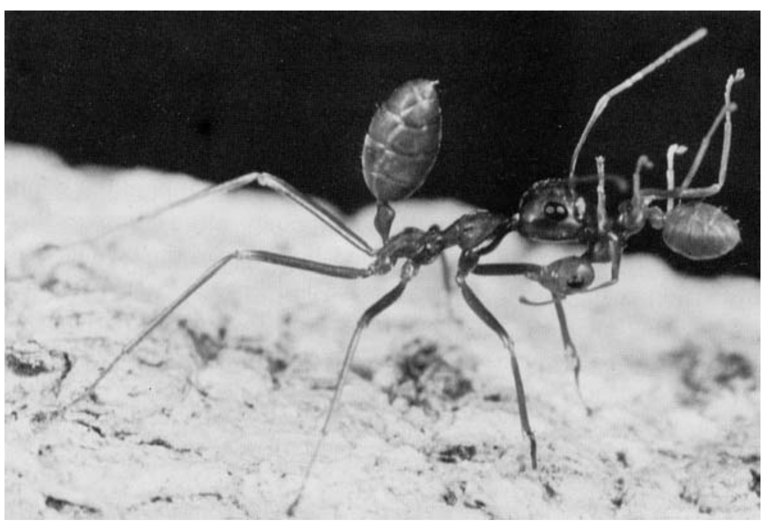

Figure 2: A major worker ant of *Oecophylla longinoda* carries a minor worker ant in the mandibles. The minor workers rarely leave the leaf-nests and are transported to the places where their work is required. [Hoelldobler and Wilson, 1990]

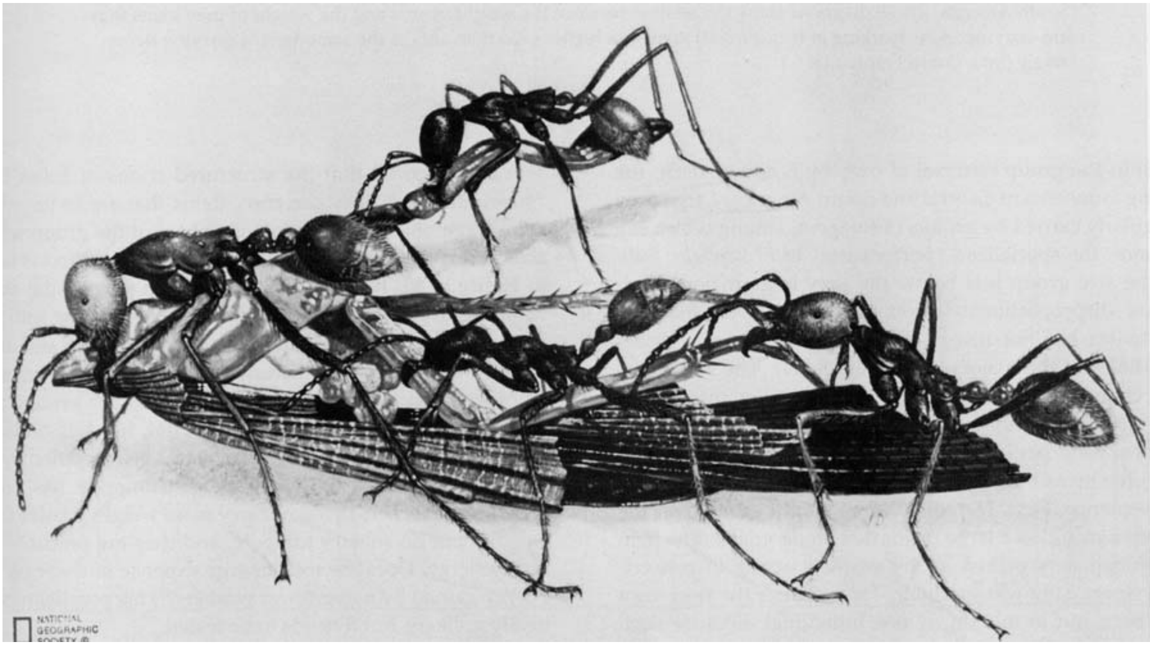

Figure 3: A team of army ants transporting prey (part of a cockroach) back to the nest
[Hoelldobler and Wilson, 1990]

Figure 4: A pupa from a rival colony is stolen during a raid and carried back to the nest where it will be a slave when fully developed. [Hoelldobler and Wilson, 1990]

Interestingly, the slave-maker ants have specialized mandibles to aid in their raids, and an example of these can be seen in figure 5.

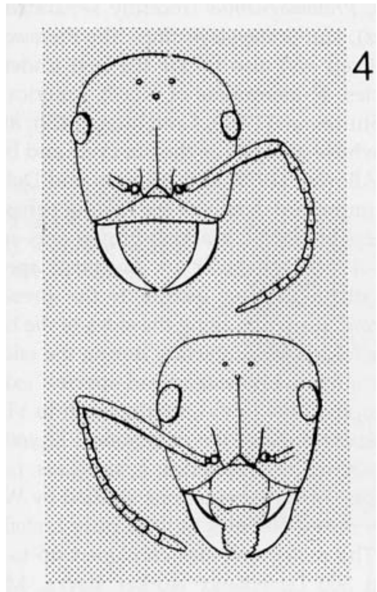

Figure 5: Mandible variations in ants. The top shows normal, sickle-shaped mandibles, and the bottom those of a slave-maker ant species that have developed to form blades with teeth.
[Hoelldobler and Wilson, 1990]

The fact that ants can carry another ant of the same size with ease is amazing in and of itself (especially in postures such as that in figure 1 top right – think of the torque created!). However, ants have been known to carry 50 times their own body weight in their mandibles! [Waldbauer, 1998] The following literature review presents the published research that was found concerning load carrying in insects, and mostly deals with ants.

Rodger Kram [Kram, 1996] performed an interesting study in which he velcroed a flexible lead strip with weights on the ends to a rhinocerous beetle (*Xylorctes thestalus*) and measured energetics of walking on a treadmill with the added mass (figure 6). He found that the beetles could walk while carrying loads of up to 100 times their body weight (2.38 grams mean body mass, N=4). However, the beetles could only sustain steady motion of 1 cm/sec (the speed of the treadmill) while carrying 30 times their body mass. Interestingly, Kram found that the metabolic cost of moving external loads is more than five times cheaper than that of moving body mass (on a gram to gram basis). It should be noted that the beetles do not have a mechanism to naturally carry large external loads such as those presented in the study.

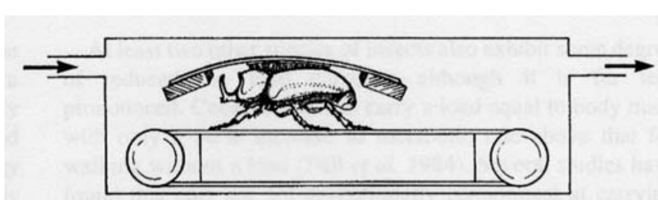

Figure 6: A rhinocerous beetle on a treadmill with weights glued to its back.

In a series of papers based on his PhD dissertation, Christoph Zollikofer [Zollikofer, 1994a-c] investigates the influences of speed, path curvature, body shape, and load carrying on the stepping patterns of 12 different species of ants. In the first paper (speed and curvature, 1994a), the author finds that the positions of the feet remain constant with speed, but are altered during turning (unsurprisingly). Stride length, however is increased with increasing speed. He also found that, when turning, the stride length on the outside of the curve remains the same for all curvatures (constant speeds), but that of the inside of the curve is shortened with increasing curvature. The results applied to all 12 ant species.

Unfortunately, the author does not report on the specific values of frequency of the alternating tripod gait with speed. However, he does present a plot of stride length vs. speed for a specific species (figure 7). From this plot, frequency can be calculated (speed/stride length). Rough calculations indicate that the frequency changes from around 6 Hz (at 50 mm/sec) to about 16 Hz (at 200 mm/sec).

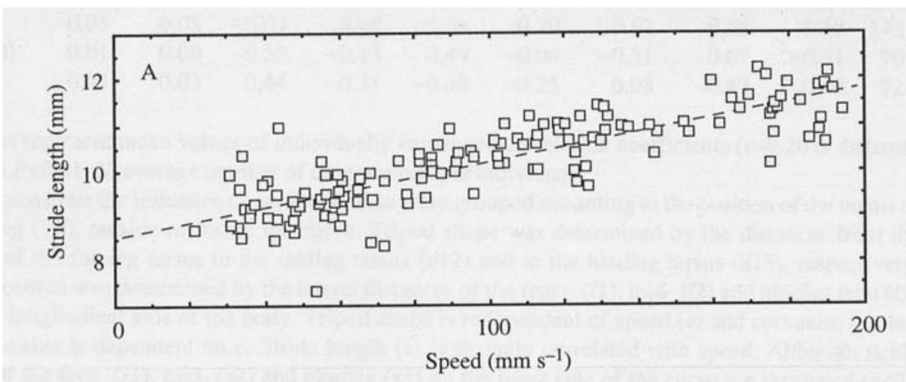

Figure 7: Stride length vs. speed for ants of *Cataglyphis albicans*. [Zollikofer, 1994a]

In the second paper (body morphology, 1994b), Zollikofer investigates the effect of body mass and leg length on the observed stepping pattern. He found that relative leg length of the ants stays almost constant (normalized by the length of the thorax), even with body mass variability of a factor of ten. It was found that tripods were of similar size for leg length in all but one of the twelve species, and normalized stride length was also fairly constant. Stride frequency, however, varied between 10 and 20 Hz (mean) for the 12 species tested. Interestingly, it was found that species species show an aerial phase between stance phases at high speed, a result the author has deemed "trotting." Some individual species displayed other interesting locomotive patterns. Females of *Lasius niger* were found to drag their hindlegs, rather than use them for propulsion. At high speeds, ants of *Cataglyphis bombycina* utilize an alternating diagonal quadrupedal pattern, with front legs rarely touching the ground. This species also shows an aerial phase between stances at highest speed, even with the quadrupedal gait.

In his third paper (load, 1994c), the author presents the results of a study in which ants were given food items of known mass in order to observe the locomotion patterns while carrying loads. The results show that stride length and stride frequency are not altered for any speed during load carrying as compared to the normal, unladen state. However, the geometry of the tripod is changed. In the loaded case, the hind leg and mid leg are placed further away from the body laterally, whereas the front leg is placed closer to the body but further out (figure 8). In general, this configuration shifts the tripod base forward to offset the forward shift in center of mass. The author found that this distortion in tripod geometry is proportional to the shift in center of mass due to the load.

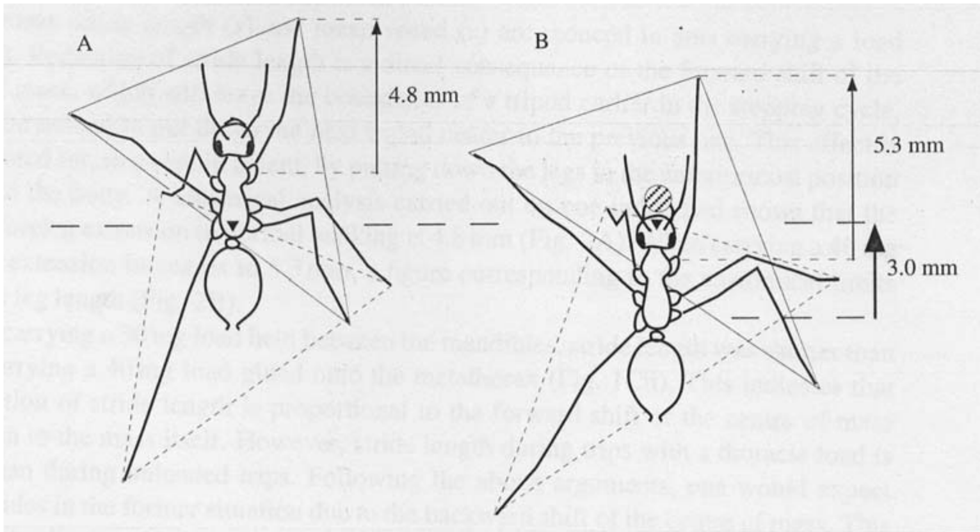

Figure 8: Foot placements of an ant without (A) and with (B) a load carried in its mandibles. Note the larger step length in B and the wider stance. [Zollikofer, 1994c]

A number of papers were found that discuss the energetics of load carrying and/or locomotion in ants. Although the results pertaining to energetics are not necessarily pertinent to this review, the data on load carriage and running speeds is useful. The results of these papers are shown in table 1. Interestingly, no significant change in speed was found in the Ponerine and Honeypot ants during load carriage of around half of their body weight. However, the Desert Harvester ant, carrying a load one and a half times its body weight, ran significantly slower. Note that, despite large variability in body sizes (from 5 to 26 mg), the running speeds across species does not vary much (between 1.9 and 4.0 cm/sec). It should also be noted that the Honeypot ants [Duncan and Lighton, 1994] carried loads internally, by consuming honey water. All other species carried an external load in their mandibles.

Other interesting results were reported by the invesitgators in these papers that should be noted. Duncan and Lighton [1994] commented that their observations that the ants ran faster with the load is consistent with the findings of other investigators, but none found statistically significant differences in the value. However, the fact that the animals run at similar speeds laden and unladen is curious (see also the results of the Ponerine ants). The authors do not mention whether this result could be attributed to the fact that the foraging ants are no longer "foraging" once they have acquired a food item, and can simply run directly back to the nest.

In his paper, Duncan [1999] reports on the method of running and acquiring of prey. He reports that the ants typically run for a short period, then stop and move the head from side to side, and then continue running. And once a termite food source was located, the ants would immobilize it by stinging, and then sling the termite under its body (carried in the mandibles), carrying it without dragging.

An amazing result from Lighton et al. [1993] was the effect of the running on the ants. For trials of 75 minute runs, the ants lost between 10 and 15 percent of their body mass! Sounds like a diet plan worthy of a late-night infomercial – "Lose 15 to 20 pounds in just one 75 minute period - naturally!"

Other interesting results were identified in the literature review that did not pertain directly to insects. Heglund and Taylor [1988] found that speed scales approximately with 0.2 power of body mass and frequency scales with -0.15 power of body mass over a large variety of quadrupeds, ranging from mice to horses. Wickler et al. [2001] found that the preferred speed of horses what that which minimized the metabolic cost of locomotion. The same result was found when external loads of 19% of body mass were added – the preferred speed was shifted to minimize metabolic cost. Hoyt et al. [2000] found that smaller species of horses use a relative step length that is longer than that used in larger animals. They also found that time of contact increased while the horse was carrying a load, whereas the step length stayed constant.

Robot Load Carrying Experiment

A biomimetic cockroach robot, "Sprawlita," was used in the load carrying experiments (figure 9). The robot was mounted with three long posts (actually, straightened heavy-duty paper clips) around which brass weights could be placed to add weight at the three positions. Five mass values were used – 0g (unladen), 50g, 100g, 150g, and 200g. Each of these mass values was tested at the three different mass positions – center of mass of the unladen robot, 2.5" in front of the center of mass, and 2.5" in back of the center of mass. Finally the above configurations were each tested on four different leg configurations. Only the back leg angles were varied. This choice was based on the fact that, at the default configuration, the front legs did not touch the ground, and the middle legs serve mainly to lift the robot off the ground, providing little forward thrust. The configurations tested were 135° (default), 125°, 115°, and 105°, all measured counterclockwise from the horizontal platform (at 3 o'clock). All of the above factors resulted in 60 different configurations. Five trials were run for each of the configurations.

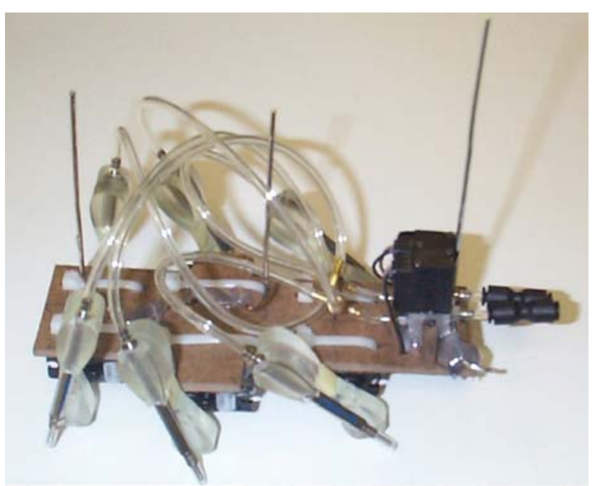

Figure 9: The cockroach biomimetic robot with attached posts around which the added weights were placed.

Species	Reference	Body mass (mg)	Load (x body mass)	Total mass (mg)	Speed (cm/sec)
Desert Harvester ant (*Pogonomyrmex rugosus*)	Lighton et al., 1993	12.96	unladen	12.96	3.39
		12.96	1.51	32.53	2.04
Ponerine ant (*Pachycondyla berthoudi*)	Duncan, 1999	26.00	unladen	26.00	2.60
		25.48	0.43	36.44	2.42
Honeypot ant (*Myrmecocystus mendax*)	Duncan Lighton, 1994	6.04	unladen	6.04	4.00
		6.19	0.62	10.03	4.20
Honeypot ant (*Myrmecocystus mexicanus*)	Duncan Lighton, 1994	13.78	unladen	13.78	2.90
(Formica fusca)	Jensen Jensen, 1980	4.72	unladen	4.72	2.73
(Formica rufa)	Jensen Jensen, 1980	9.00	unladen	9.00	1.88
(Camponotus herculeanus)	Jensen Jensen, 1980	26.25	unladen	26.25	3.03

Table 1: Summary of the results of the speed data of ants taken from a number of ant energetics paper

Experimental Apparatus and Procedure

The robot used was designed to have the same fundamental mechanical design as a cockroach. The legs are positioned such that the middle legs stick out laterally from the body further than the front and back, similar to the cockroach configuration. The legs are set to default at angles that are similar to the ground contact angles of the cockroach, and can be adjusted by the servo motors that they are mounted on. The legs provided thrust via pneumatic cylinders that are actuated in an alternating tripod (left front and back and right middle alternate with right front and back and left middle). Each tripod is controlled by a valve mounted on the back of the robot, which activates all three legs at the same time. There is a passive rubber 'spring' that connects the housing of the pneumatic cylinder to the servo motor. The spring provides damping to the system to aid in disturbance rejection. In real cockroaches, the joints contain resilin, a rubber-like natural polymer that researchers believe is fundamental in the ensuring the stability of the animal. The robot was found to have a mass of 220 grams, unladen.

The air supply into the pneumatic valves was set at 80 psi, a little less that the supply's 100 psi capability. The pneumatic valves were powered by a 5V square wave at 8 Hz. The square wave was generated by a Tektronix CFG250 function generator and was powered by a Tektronix PS282 DC power supply (figure 10). The servo motors were powered by a separate Tektronix PS282 DC supply, set at 12V.

Figure 10: Power sources supplying the pneumatic valves (5V) and the leg servos (12V). The function generator on top provides the alternating square wave fed to the valves, which engage the alternating tripod

The robot ran on the table top track shown in figure 11 below. The robot is shown postioned at the starting line and ran 0.5 meters until it hit the wall at the end. Guard rails were added at the sides to prevent the robot from falling off the table during the many wild runs at sub-optimal configurations. For each run the robot was started from this line and timed using a stopwatch until it hit the wall at the end. If the robot hit the side rail and was not significantly impeded, the run was recorded.

Figure 11: The racetrack. Sprawlita is positioned at the 0.5 meter mark and will run until she hits the wall at the end. Guard rails were placed on both sides to help prevent injury in the event of a wild run.

The figure below shows the four different back leg configurations tested. Note that the angle of contact for the pneumatic cylinder did not necessarily match the angle set by the servo motor, especially at the lower angle configurations. This is primarily due to the interference between the tubing supplying air to the different pistons. As mass was added, the leg springs deformed even more as a result of the increased torque.

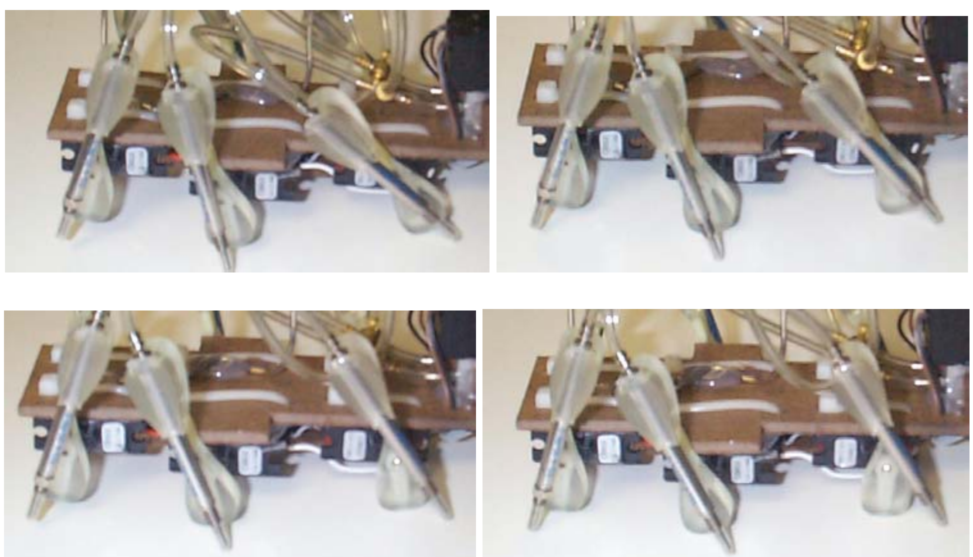

Figure 12: Closeup of the legs for the four back leg configurations: 135 degrees (top left), 125 degrees (top right), 115 degrees (bottom left), and 105 degrees (bottom right).

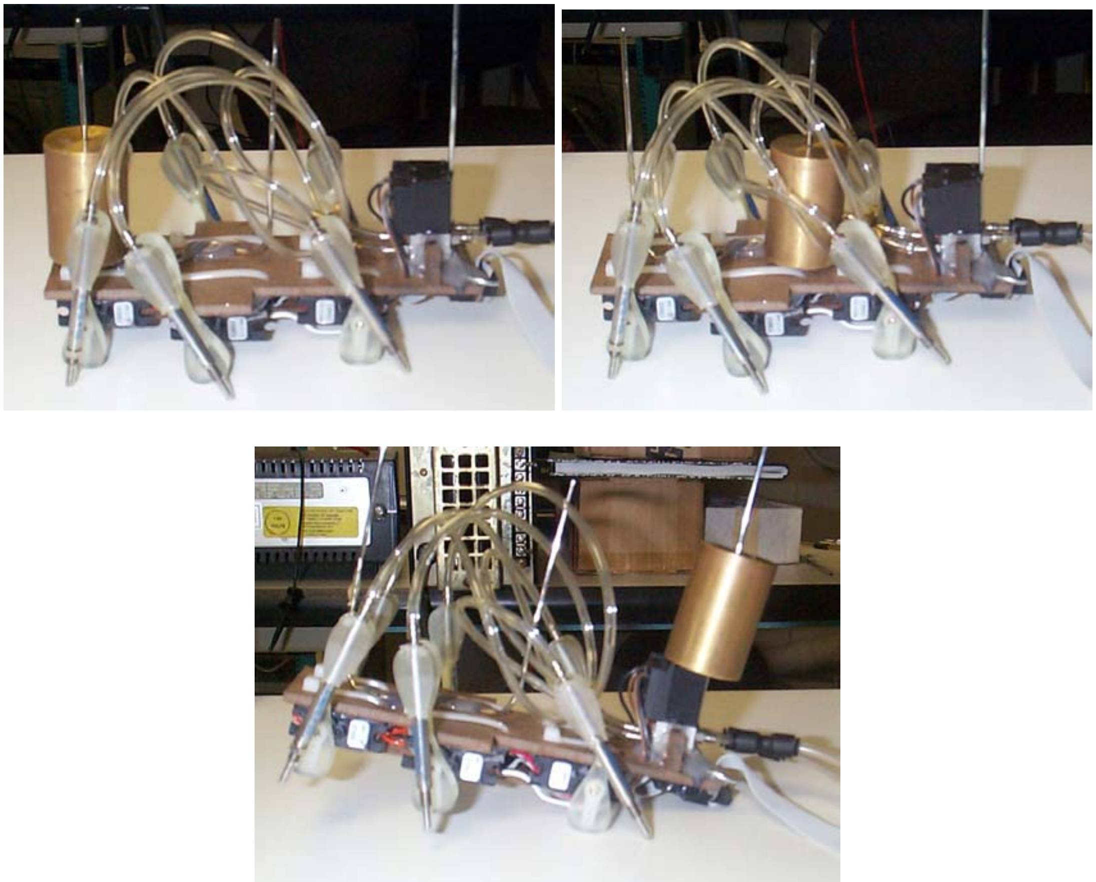

Figure 13: Sprawlita loaded with a 200g mass in the three positions

Figure 13 above shows the three different mass positons tested in the experiment. Note the discrepancy between the actual contact angle of the back leg and that which was set by the servo (which can be seen by looking at the part of the leg seen below the cylinder, which is controlled by the motor).

<u>Analysis</u>

For the robot trials, a number of sources of error have been identified. As was already mentioned, the leg angles that were set by the servo motors did not necessarily correspond to the actual contact angle, nor was the 'discrepancy' linear. At high values, the actual and desired leg angles were much closer than those for the low values of leg angle. Also, the discrepancy increased with added mass, and so the group of trials for, say 115 degrees, included a range of actual contact angles, different for each mass. Also, the viscosity in the rubber spring added another dimension of error. The shape of the spring conformed over time to the different mass values such that the angle of contact for the first trial was not necessarily the contact angle for the fifth.

Another source of error is the variability between runs of the 'same' configuration. For many of the sub-optimal configurations, it was very difficult to get the robot to run straight for the desired distance. Because of this, many of the trials in which the robot hit the sides of the track were included in the data analyzed. Hitting the sides resulted in some interesting dynamics. For most cases, it simply slowed the robot down until it hit the end wall. However, in configurations where large masses were added at the back of the robot, hitting the rails often allowed the front legs to touch the rail, propelling the robot upwards and back towards the center of the track.

A number of systematic errors were also recognized. These included human error in the timing of the run, variability in positioning of the robot at the starting line, and runs that were not straight (but did not hit the sides).

Results

Before the actual trials were run, a quick experiment was conducted to determine the frequency at which the alternating tripods should be actuated. For each of the four leg configurations, the robot was run at an appropriate range of frequencies to give significant variability in the results (for three trials each). Figure 14 shows the results of this experiment. Conveniently, it was found that the robot ran the fastest (which was considered 'best' performance in this study) for frequencies of around 8 Hz, for all tested configurations. These trials were conducted with no added mass. Based on these results, the robot was run at an alternating tripod frequency of 8 Hz for all mass, mass position, and leg angle trials.

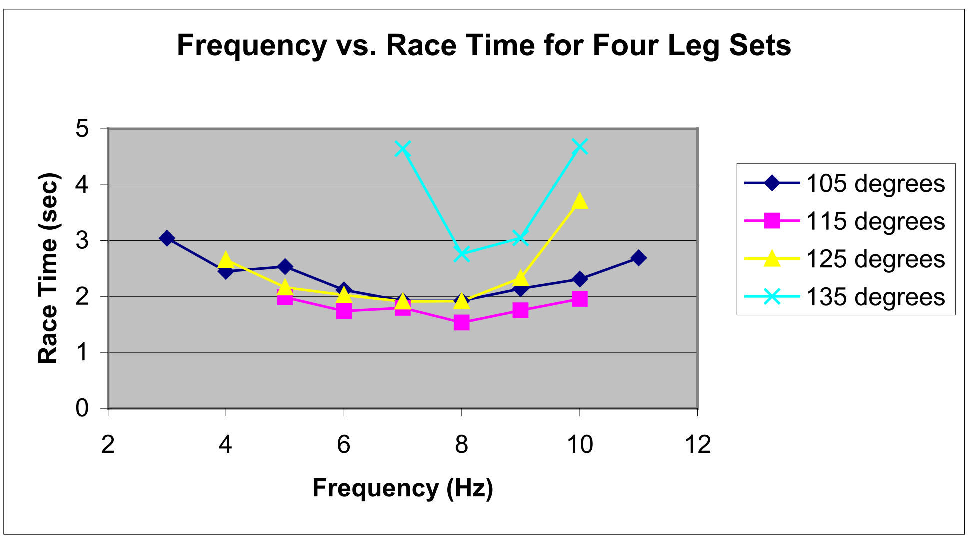

Figure 14: Frequency vs. race time for the four leg sets. The trials included no added mass.

In the following two pages, the results of the 60 different configurations are presented in plots of velocity vs. added mass. Figure 15 shows a plot for each of the four different leg angle conditions, with a line on each plot corresponding to each of the three different mass positions. It can be seen from these plots that the velocity of the robot was highest for configurations in which the mass was placed at the center of mass, rather than at the front or back. An exception to this is in the 125 degree configuration, in which the resultant velocity was highest when the mass was placed at the back (except for the 200g case).

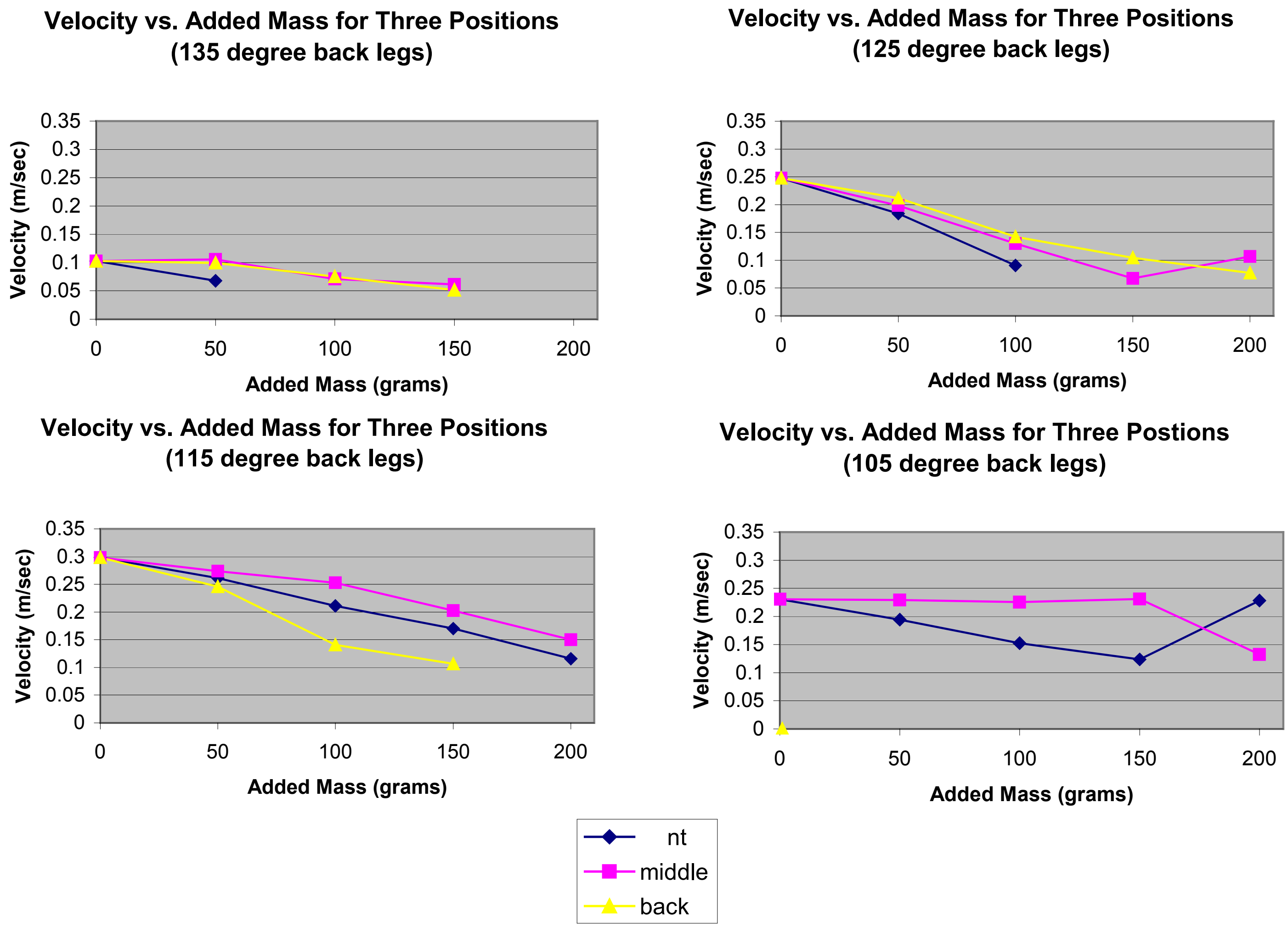

Figure 15: Plots of Velocity vs. Added mass for the four different leg configurations. The three lines correspond to the three different mass positions.

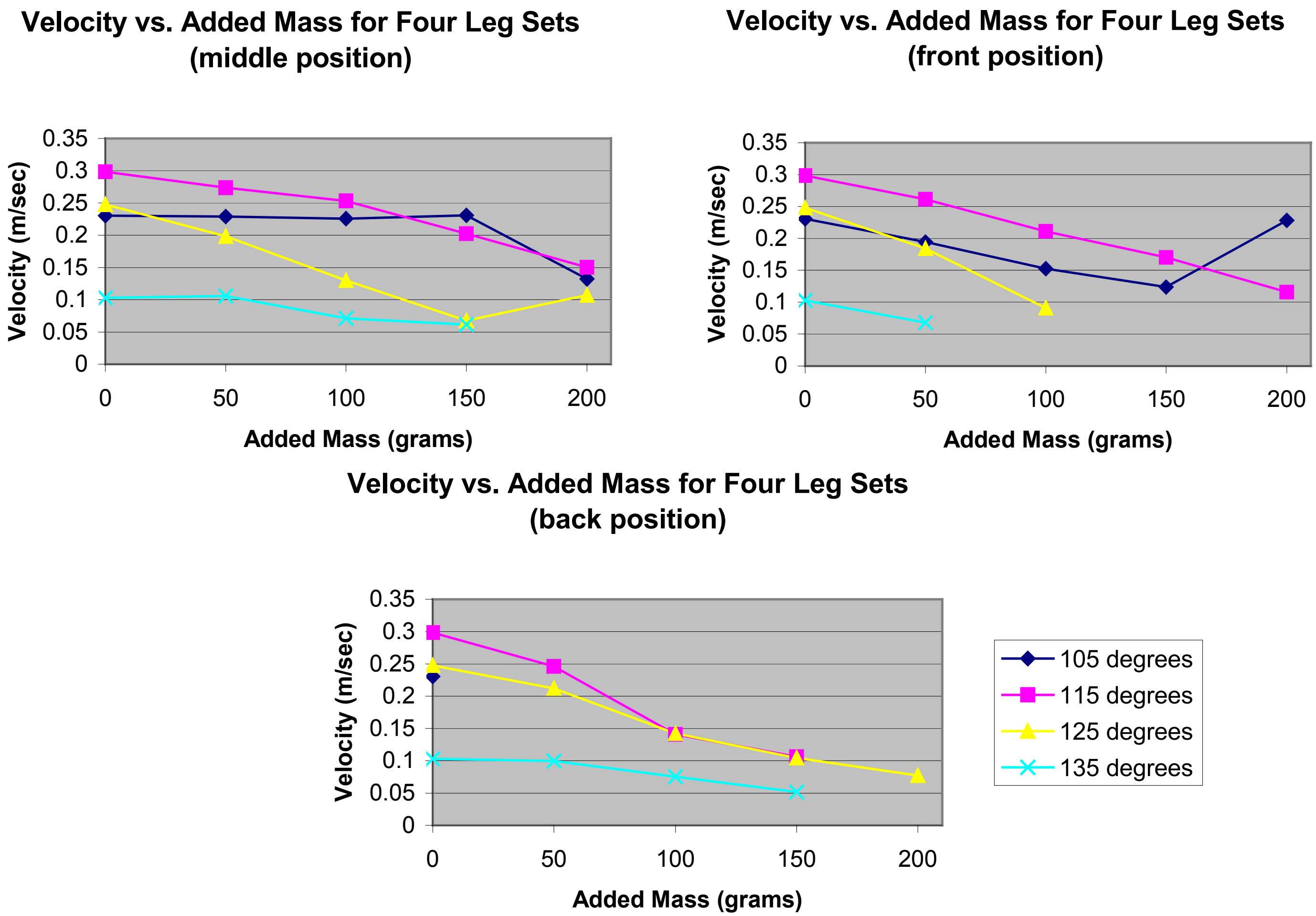

Figure 16: Velocity vs. added mass for each of the three mass positions. The four lines represent the four leg angle sets.

Figure 16 shows three plots corresponding to each of the three different mass positions, with a line for each of the four different leg angle sets. From these plots it can be seen that the robot performed best for configurations in which the back legs were set at 115 degrees (with a few exceptions). Note that many of the lines in both figures terminate before the 200g configuration (and the 105 degree back-loaded configuration is non-existent). For these cases, the robot was not able to move well enough to finish the 0.5 meter race.

The two plots below (figures 17 and 18) show the average standard deviation for the different configurations, demonstrating the variability of the data within configurations. From figure 17, it can be seen that the 115 degree leg angle set gave the most consistent results between trials (although 105 degrees is also very good for this measure). Figure 18 shows that front-loaded configurations gave the most consistent results between trials. This plot is a bit deceiving, however, because it can only demonstrate standard deviation based on the number of configurations that actually resulted in forward motion of the robot, which was significantly less for the front and back configurations (11 and 10 respectively) than for the middle configurations (15). Thus, the standard deviation values show that the front and middle configurations give relatively consistent results.

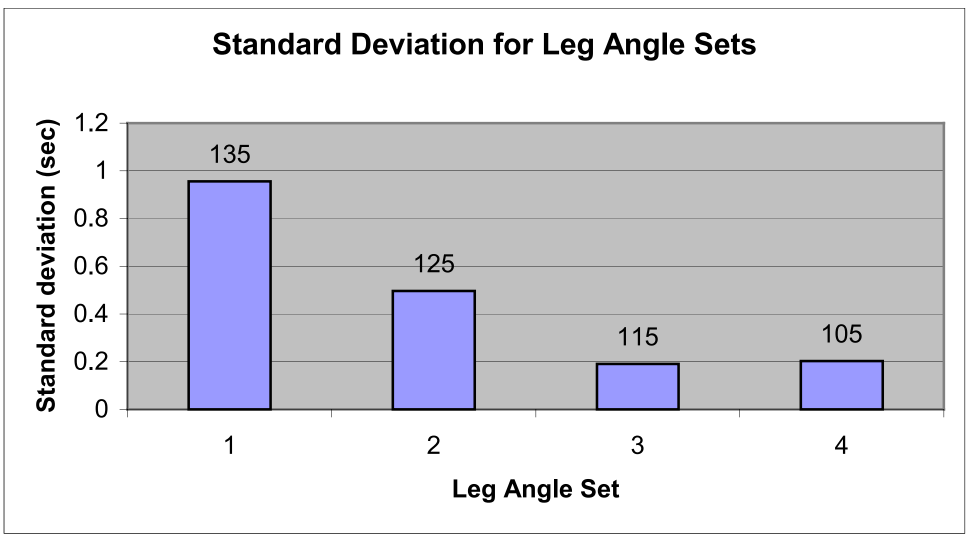

Figure 17: Standard deviations for the four leg angle sets

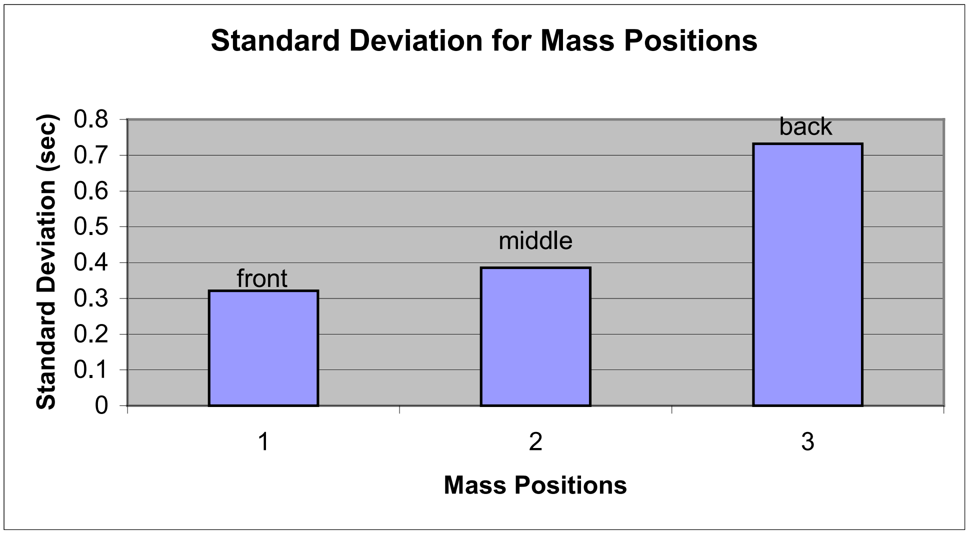

Figure 18: Standard deviations for the three mass positions

Discussion

Based on all of the results presented above, it can be seen that the robot runs best with the back legs set at 115 degrees. It also can handle external loads with the least amount of disruption (for velocity and consistency between trials) when they are placed closer to the center of mass, rather than at the front or back.

A number of other interesting observations made during the trials should be pointed out. As was mentioned above, the front legs of the robot rarely touched the ground, except in the front-loading cases and for the higher masses. (Looking at some of the papers on the CDR Stanford site, I think that our version of Sprawlita is a bit longer than the Shape Deposition Manufactured version, and probably a bit lighter, which could explain this result.) The robot was very difficult to control at some of the sub-optimal configurations, particularly those with steep leg angles and/or back loading. Oftentimes in the trials for these configurations, the robot would turn abruptly right or left, or simply sit on its butt and not go anywhere. For one configuration (200 grams front-loaded at 135 degree leg configuration) the robot consistently walked backwards, and did so at a fairly high rate.

Not many comparisons can be made between the findings of the literature review and the experimental results. There are a number of reasons for this, and most involve the fact that insects change their gait when loaded, and the robot did not. It was shown in the experimental results that the robot performed best when the external load was applied nearer to the center of mass. This is not a surprising result, but could be used to explain the reason for the way the ants in figures 1 (top left and bottom) and 2 through 4 carried the other workers, slung under or over their bodies. But even their method of carrying is not consistent across ant species (see figure 1 top right). The results of the literature review can help to guide future studies, however.

Zollikofer [1994] found that footfall positions stay constant with speed, whereas stride length varies (therefore frequency varies). He also found that adding load changed the footfall positions, but not stride length and frequency. Based on these findings, it would be interesting to test Sprawlita for the same factors and see how changing footfall positions, frequency, and stride length affect the locomotion (all three factors were held constant in our study).

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