

Finite element analysis of strains in a *Blaberus* cockroach leg during climbing

Sathya. Kaliyamoorthy¹, Sasha N. Zill², Roger D.Quinn¹, Roy E. Ritzmann¹ and Jongung Choi¹

¹Case Western Reserve University
Cleveland OH 44106

²Marshall University
Huntington WV 25755

Abstract

The legs of animals and walking vehicles are subject to substantial changes in loading in climbing over obstacles. Sense organs (campaniform sensilla) on cockroach legs detect these loads through strains in the exoskeleton. Signals that might be sent by the sense organs during climbing were predicted by applying forces to a finite element model of the leg in directions determined from kinematic studies. The model included an accurate, three-dimensional reconstruction of the leg segment (trochanter) that contains an array of these sensors. Calculated strains generated at different phases of climbing suggest that one group of sensors in the front leg, that shows little activity in walking, is strongly activated in climbing. This group could provide signals to aid in adapting walking patterns to the changing forces encountered in climbing.

INTRODUCTION

The performance of insect inspired robots over irregular terrain is still not appreciable from a biological standpoint. Insects on the other hand demonstrate an amazing capacity for agile locomotion (including climbing) even over demanding terrain. They achieve this with the aid of a tremendous amount of sensory feedback information that sense organs (Delcomyn et al., 1996) convey about each leg and its interaction with the environment. Understanding how insects achieve such versatility in locomotion and control using sensory feedback is extremely important for a robot engineer who is inspired by these insects.

Feedback from force sensors can enhance the capabilities of walking machines. This type of feedback is also a central element in the control of walking in animals. In insects, campaniform sensilla (CS) are a type of sense organ, characterized as mechanoreceptors, which act like strain gauges and encode compressive stresses in the exoskeleton (Zill, et al., 1996). The sensory feedback from these “biological strain gauges” provides signals about forces that occur in posture and walking. There are a number of groups of campaniform sensilla on the legs and these groups encode the direction of forces as an array (Zill, 1999; Ridgel, et al., 2000). Ramasubramanian (1999) has modeled the strains that occur in the leg during walking via Finite Element Analysis (FEA). They generated data about the patterns of compressive strains that could produce activation of specific groups of receptors. In the present study, those findings were extended and the strains that occur in the leg (trochanter) during climbing were characterized by FEA. From these data, the patterns of sensory discharges that occur in the campaniform sensilla of the front leg during each stage of climbing were examined. These results suggest that unique patterns of sensory discharge occur during obstacle climbing that include the activation of groups of receptors that do not fire during walking on level substrates.

COCKROACH CLIMBING

Recent studies (Watson et al., 1998) have shown that the pattern of movements and muscle activities that occur during climbing by cockroaches do not represent the assumption of novel strategies. Instead, these animals can ascend barriers by simply and subtly adjusting the output of the walking motor pattern generator. Alterations in leg joint angles (at the trochanter-femur and body-coxa joints) act to re-direct the vectors of force producing muscles in the limbs. The specific sensory cues that are utilized in this process have not been determined.

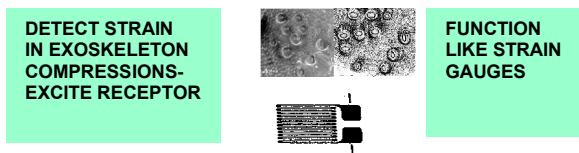


Fig 1. Campaniform Sensilla

Watson et al. characterized the specific kinematic and motor activities that occur in the cockroach *Blaberus discoidalis* at different stages in surmounting plastic blocks of varied heights. In climbing over barriers of moderate height, these stages are 1) the initial rearing phase in which the angle of the body is raised so that the front of the animal is above the level of the obstacle; 2) the climbing phase in which the center of mass is raised to the height of the barrier; and 3) a leveling phase that occurs when all legs are on the upper surface of the block. In the rearing phase, the middle pair of legs can provide lift to tilt the body due to changes in the angles of leg joints and orientation of the middle legs. The hind legs then can act to push the animal up and over the barrier in the climbing phase.

The front legs are not essential to climbing. However, they are often the first appendages to contact the barrier and could provide sensory cues in climbing. The front legs of insects are typically the most agile and are richly endowed with sense organs (Laurent and Richard, 1986 a,b). In walking, the front legs act to maintain a stable basis of support by acting to ‘brake’ or decelerate the center of mass (Full et al, 1991). They are also the most complex in their proximal musculature and movements, having seven degrees of freedom. In many behaviors such as grasping, exploration or grooming, the front legs fulfill the functions of arms of vertebrates. In climbing, the front (prothoracic) legs are the first to encounter the obstacle. They could readily provide information about the height and surface characteristics of the new substrate. Furthermore, these sensory data, although not essential, could be used to adjust the motor outputs of the force producing legs. Therefore, modeling and analyzing the strains in the front legs during climbing may be enlightening.

THE FINITE ELEMENT MODEL AND ANALYSIS METHODOLOGY

The prothoracic leg has sense organs (campaniform sensilla groups 1, 2, 3 and 4) that are serially homologous with those present on the middle and hind legs. Up to 72% of the receptors are present in the trochanter, a knee-like segment between the coxa and the femur of the leg (Fig. 2).

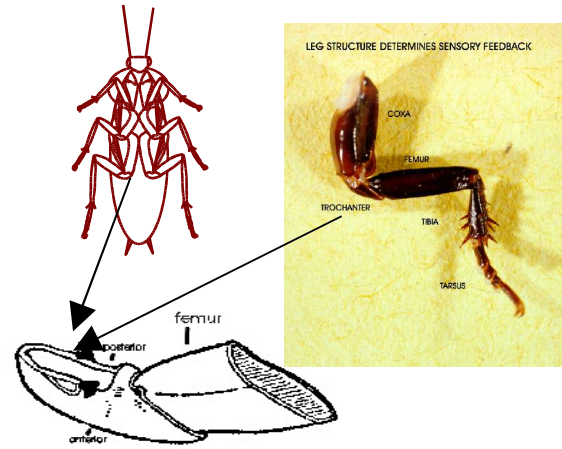


Fig 2. Trochanter of the *Blaberus* Cockroach

The trochanter measures approximately 2.1mm along its length. The exoskeleton of this segment of the leg was accurately reconstructed in three dimensions from confocal microscopic images (Zill et al., 2000). An FE mesh was developed from this reconstruction (Flannigan, 1998). The locations of different groups of campaniform sensilla and the orientations of their cuticular caps (with respect to a fixed reference frame) are shown in Fig 3. Specific nodes were selected on the FE model to represent the CS locations.

The values for the material properties of the cuticle, which comprise the exoskeleton, were derived from measurements made by Hepburn and Joffe (1976).

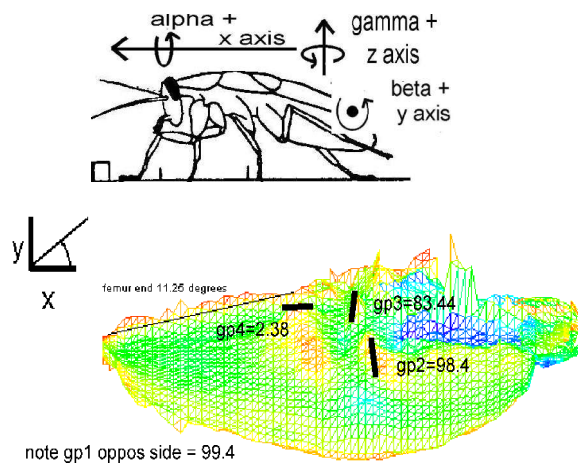


Fig 3. The FE model and CS locations

The FE model was constrained with certain boundary conditions. The movement of the trochanter was restricted to rotation about the z-axis at the coxal condyles (connections to coxa) and the coxa end of the trochanter was modeled as being restricted by a pin and hence has a degree of freedom for rotation about the z-axis. The leg could be described as being in a passively loaded state. The forces applied to the FE models of the legs were obtained from dynamic simulations of cockroach climbing rectangular barriers (Choi, 2000). In order to transform those ground reaction forces expressed in the inertial frame to the local trochanteral axes for applying FEA, a force transformation scheme as shown below was employed.

Transformation of forces:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} CFemur-Z \\ Rotation \end{bmatrix} \begin{bmatrix} BCoxa-X \\ Rotation \end{bmatrix} \begin{bmatrix} Bcoxa-Y \\ Rotation \end{bmatrix} \begin{bmatrix} Bcoxa-Z \\ Rotation \end{bmatrix} \begin{bmatrix} Bodyaxes \\ Tr.Matrix \end{bmatrix} \begin{bmatrix} F_{nx} \\ F_{ny} \\ F_{nz} \end{bmatrix}$$

where (x,y,z) denote the local trochanteral axes and (nx,ny,nz) denote inertial frame of reference. The inertial forces are transformed by a series of rotation matrices representing the inertial-body rotation, body-coxa z rotation, body-coxa y rotation, body-coxa x, and coxa-femur z rotation. The transformed forces are applied at the end of the tibia which is modeled along with the trochanter at the appropriate rotation angle (FT angle: Table 1,2, 3 and 4).

For analyzing walking, the body axes of the cockroach were assumed to be parallel to the inertial axes (Ramasubramanian, 1999). However in climbing, the body axes do not remain parallel hence the force transformation includes the inertial to body axes transformation matrix. The forces are extracted from the dynamic simulation at a representative snapshot at each of the phases, namely rearing, climbing, and leveling (Fig 4, 5 ,6 and 7). For each of the nodes specified for each CS group, the short axis strain and Von Mises strain distribution were obtained. The receptors are maximally excited by strains in the short axis orientation. These values were averaged to a mean value for each CS group as tabulated.

FEA RESULTS AND DISCUSSION

Snapshot – REARING

t=0.728	Angle (deg)	Force	Model (mN)	Inertial (mN)	Mean Strain (10 ⁻⁶)
Coxa X	57.50628	F _x	2.0386	0.765719	Gp 1 -2.30445
Coxa Y	16.88115	F _y	0.4154	-0.13318	Gp 2 -173.75
Coxa Z	-67.3332	F _z	-0.056	1.930668	Gp 3 23.4325
CTr	79.38342				Gp 4 -13.8042
FT	-53.7904				

Table 1. Mean strain in CS groups –Rearing

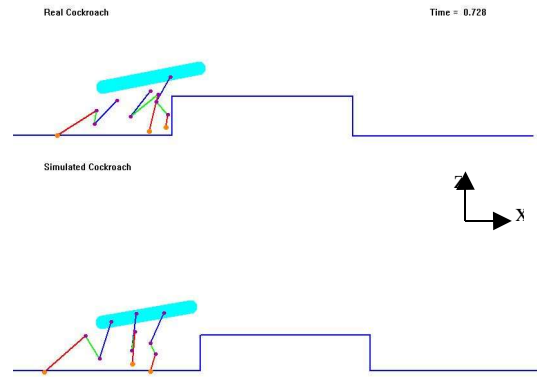


Fig 4. Rearing Snapshot

Snapshot – CLIMBING-I

t=1.176	Angle (deg)	Force	Model (mN)	Inertial (mN)	Mean Strain (10 ⁻⁶)
Coxa X	46.1322	F _x	8.861	-3.28218	Gp 1 -71.80
Coxa Y	28.5573	F _y	1.729	-8.56256	Gp 2 1210.00
Coxa Z	-45.7579	F _z	16.052	15.9716	Gp 3 106.00
CTr	91.4440				Gp 4 -420.00
FT	79.8439				

Table 2. Mean strain in CS groups –Climbing I

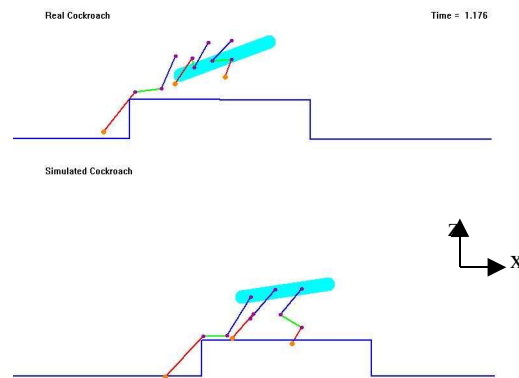


Fig 5. Climbing-I snap shot

Snap shot – CLIMBING-II

t=1.240	Angle (deg)	Force	Model (mN)	Inertial (mN)	Mean Strain (10 ⁻⁶)
Coxa X	65.58558	F _x	7.42066	1.840754	Gp 1 -6.52
Coxa Y	-2.70456	F _y	-0.3751	2.866038	Gp 2 -876.00
Coxa Z	-31.515	F _z	-1.2167	6.714533	Gp 3 106.00
CTr	83.87001				Gp 4 -36.10
FT	-71.0234				

Table 3. Mean strain in CS groups –Climbing II

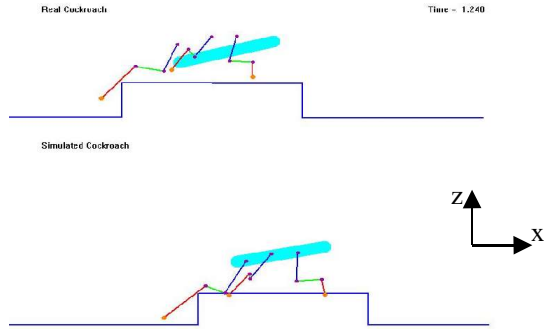


Fig 6. Climbing-II Snap shot

Snapshot - LEVELING

T=1.32	Angle (deg)	Force	Model (mN)	Inertial (mN)	Mean Strain (10 ⁻⁶)
Coxa X	48.05751	F _x	3.7866	0.886497	Gp 1 -14.90
Coxa Y	14.54732	F _y	-1.7316	-2.1684	Gp 2 -39.00
Coxa Z	-55.3403	F _z	3.0833	4.6213	Gp 3 55.10
CTr	96.5505				Gp 4 -107.00
FT	-70.479				

Table 4. Mean strain in CS groups-Leveling

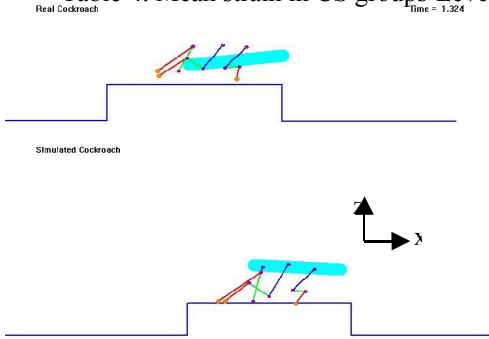


Fig 7. Leveling Snap Shot

The forces applied to the model of the leg, that emulated passive ground reaction forces during climbing, produced both compressive and tensile strains at the locations of specific groups of campaniform sensilla. However the sensilla are sensitive only for compressive strains. It is interesting to investigate the results from both an engineering dynamics and biological point of view.

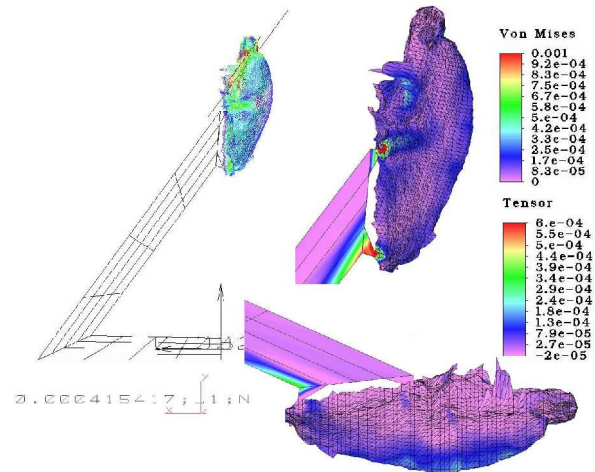


Fig 8. Rearing Snapshot- CS Group2 Short axis and Von Mises Strain values

In the present FEA study of climbing we found that the nodes showing the highest levels of compressive strain that could produce sensory discharges during the Rearing (Fig 8) and Climbing phases were in Group 2. This group is located on the anterior side of the trochanter and the cuticular caps are oriented largely perpendicular to the long axis of the trochanter and femur. Group 2 showed both the highest individual values of strains at the node locations and the largest mean value of strain when the samples at different locations were averaged. However in the Climbing-I phase, we find that the values at most of the Group 2 nodes were positive, indicative of tensions instead of compressions at those locations. This is in contrast to all other snapshots while rearing and climbing.

Nevertheless, this kind of response is not completely unexpected. In the previous walking experiments excitation of group 2 did not occur at any stage during the simulation of walking on level terrain (Table 5, Ramasubramanian 1999).

	Angle (deg)	Forces	Model (mN)	Inertial (mN)	Mean Strain
Early stance					
	Coxa X	42.975	F _x 0.2384	0	Gp 1 -8.28487
	Coxa Y	6.303	F _y -0.1361	0	Gp 2 22.2825
	Coxa Z	-48.705	F _z 0.2909	0.4	Gp 3 3.939275
	CTr	128.925			Gp 4 5.867337
	FT	-48.705			
Mid stance					
	Coxa X	34.953	F _x 8.3059	-5	Gp 1 -218.487
	Coxa Y	18.909	F _y 5.4604	-6	Gp 2 587.225
	Coxa Z	-68.187	F _z 8.2635	10.3	Gp 3 277.956
	CTr	139.239			Gp 4 -312.06
	FT	-89.961			

Table 5. Results from Walking

What is common between the Climbing-I snapshot and horizontal walking? Both Climbing-I snapshot and walking have negative F_x . So, activation of Group 2 is in direct relationship with F_x as shown in Fig 9.

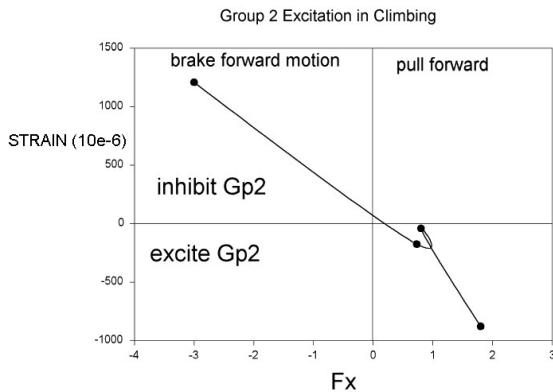


Fig 9. F_x Vs Group2 mean strain value

Positive F_x propels the animal forward while negative F_x decelerates the animal. In normal walking, the front legs “brake” whereas the hind legs propel the animal (Full et al., 1991). However, in climbing, as seen from this study, the front legs are used to propel the animal most of the time. In the Climbing-I snapshot the front legs are “braking” most probably to stabilize the animal. This possibility is evident from the dynamic simulation data (Choi, 2000), wherein the F_x of the hind legs is large during the Climbing-I snapshot and the front legs have a negative F_x to “brake” the animal for control and stability. During the Climbing-II snapshot, however the F_x of the hind legs are zero as they lose contact with ground, in which case the front legs pull the animal over the obstacle (F_x are positive). F_z is high during the Climbing I and Climbing II snapshots, indicating the exertion of more vertical force to climb the obstacle. F_y is generally directed in toward the animal as it is in horizontal walking (Full et al., 1991) for lateral stability. F_y and F_z do not show any direct relationship with the responses.

Activation of Group 2 sensilla (compression) is specific to climbing and, therefore, a consequence of the stresses that occur during the Rearing and Climbing II phases. In contrast, the strains that

occur during Leveling are somewhat similar to those obtained during the mid stance phase of walking, with Group 4 being activated predominantly. Group 2 is also firing during this phase. However, an insight into the responses of the Group 2 sensilla also comes from experiments done in the ‘pegleg’ preparation. In these experiments, forces are applied in the frame of reference of the trochanter. In the pegleg FEA studies, Group 2 showed the largest response to forces that flexed the trochanter anteriorly (Anterior Flexion) and was also activated by forces in the plane of movement of the coxo-trochanteral joint. Similar results were obtained in an FEA model of the pegleg experiments on the hind leg of *Periplaneta*, in which Group 2 was excited by forced flexion (Flannigan 1998).

In comparison with biological experiments – The specific responses of Group 2 sensilla have not been characterized in the cockroach, although Zill et al. (1996) showed that vigorous responses could be obtained in pegleg preparations of the hind leg of *Periplaneta* to anterior bending of the femur. In contrast, the responses and reflex effects of the anterior trochanteral group (aCSv, Schmitz, 1993) have been extensively studied in stick insects. Group aCSv is homologous in location and cap orientation with Group 2 in cockroaches. In the stick insect studies, the proximal part of the coxa was immobilized against the body wall and forces were applied to the distal femur. Hoffman and Bässler (1982) first showed that discharges from the trochanteral sensilla could be elicited in these preparations. Schmitz (1993) confirmed and extended those findings, and found that the anterior and posterior groups of sensilla responded differentially to forces along the body axis, as has been shown in the present study for Groups 1 and 2.

The responses of the other groups of campaniform sensilla are within the ranges found during walking. Thus, the pattern of cuticular strains and sensory activation seen in the present study are consistent with the idea that the campaniform sensilla of the leg encode forces as an array. The motor pattern used during climbing generates sensory feedback with some components that are similar to those seen in walking and others that are unique to the forces occurring during climbing.

CONCLUSION

In the present study the patterns of strain in a front leg of a simulated cockroach were calculated and analyzed while it climbed a rectangular barrier. The forces predicted from dynamic simulations of the animal were transformed to the axes of a FE model of the leg. FEA was used to find the strain patterns in the nodes at the locations of campaniform sensilla at different stages of climbing. The major finding of the present study is that CS Group 2 showed activation patterns while climbing. This group did not show activation during a simulation of walking. The difference was attributed partly due to the different inertial force directions involved during walking and climbing. Excitation of Group 2 was associated with use of the front leg to pull the animal forward, while the receptors were inhibited when the leg was used to brake forward motion, as occurs in walking. The potential correspondence of kinematic parameters and receptor response have yet to be investigated. Another group (Group 4) showed similar responses during climbing (leveling phase) and walking. Biological experiments performed to date are consistent with these results.

REFERENCES

1. Choi, J., (2000), "Dynamic simulation of cockroach climbing", M.S. Thesis, Case Western Reserve University.
2. Delcomyn, F., Nelson, M.E., and Cocatre-Zilgien, J.H., (1996), "Sense Organs of insect legs and selection of sensors for agile walking robots", *The Int. J. of Robotics Research*, Vol.15, No.2, 113-127.
3. Flannigan, W.C., (1998), "Finite Element modeling of arthropod exoskeleton", M.S. Thesis, Case Western Reserve University.
4. Full, R.J., Blickhan, R., and Ting, L.H., (1991), "Leg design in hexapedal runners", *J. Exp. Biol.* 158, 369-390.
5. Hepburn, HR and Joffe, I (1976), "On the material properties of insect exoskeleton". In *The Insect Integument*. Elsevier, Amsterdam. p. 207-235.
6. Hofmann T, Bässler U (1982), "Anatomy and physiology of trochanteral campaniform sensilla in the stick insect, *Cuniculina impigra*". *Physiological Entomology* 7: 413-426
7. Jensen, M., and Fogh, T.W., (1962), "Biology and Physics of locust flight v. strength and elasticity of locust cuticle", *Phil. Trans. Roy Soc. (London) B* 245:137-169.
8. Laurent G, Richard D (1986), "The organization and role during locomotion of the proximal musculature of the cricket foreleg. I. Anatomy and innervation.", *J Exp Biol* 123 255-283
9. Laurent G, Richard D (1986), "The organization and role during locomotion of the proximal musculature of the cricket foreleg. I. Electromyographic activity during stepping patterns.", *J Exp Biol* 123 285-306
10. Ramasubramanian, S., (1999), "Modeling of strains and activation of campaniform sensilla in cockroach leg trochanter", M.S. Thesis, Case Western Reserve University.
11. Ridgel, AL, Frazier, SF, DiCaprio, RA and Zill, SN. (2000), "Encoding forces in posture and locomotion: static and dynamic responses of cockroach tibial campaniform sensilla". *J. Comp. Physiol. A* 186:359-374.
12. Schmitz J (1993), "Load-compensating reactions in the proximal leg joints of stick insects during standing and walking.", *J Exp Biol* 183: 15-33
13. Watson, J.T., A.J. Pollack, S.N. Zill, R.E. Ritzmann, (1998), "Kinematics and leg muscle activity in cockroaches climbing over obstacles". *The Fifth International Congress of Neuroethology*, August 23-28, 1998.
14. Zill, S. N., DiCaprio, R. A. and Frazier, S. F. (1996), "Leg design and response specificity of cuticular strain detectors", *Neurosci. Abstracts* 22, Part 2, p. 1077.
15. Zill, S.N., Frazier, S.F., Neff, D., Quimby, L., Carney, M., DiCaprio, R. A., Thuma, J., and Norton, M. (2000), "Three dimensional graphic reconstruction of the insect through confocal imaging of endogenous fluorescence", *Microscopy research and Technique*, 48.
16. Zill, SN, Ridgel, AL, DiCaprio, RA and Frazier, SF (1999), "Load signaling by cockroach trochanteral campaniform sensilla". *Brain Res.* 822:271-275
17. Zill, S. N. and Seyfarth, E.A. (1996), "Exoskeletal sensors for walking". *Scientific American* 275:70-74.