

Caterpillar locomotion: A new model for soft-bodied climbing and burrowing robots

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Abstract – Caterpillars are some of the most successful scansorial and burrowing animals and yet they lack a hard skeleton. Their hydrostatic body and prolegs provide astonishing fault-tolerant manoeuvrability and powerful, stable, passive attachment. This paper describes some of the biomechanics of caterpillar locomotion and gripping. It then describes our recent work to build a multifunctional robotic climbing machine based on the biomechanics and neural control system (neuromechanics) of the caterpillar, *Manduca sexta*. The new robot (“Softbot”) is continuously deformable and capable of collapsing and crumpling into a small volume. Eventually it will be able to climb textured surfaces and irregular objects, crawl along ropes and wires, or burrow into winding, confined spaces. These robots will be simple, cheap (disposable), and scaleable. They will have numerous applications including search and rescue in emergency situations and mine reconnaissance in complex environments such as rubble-fields.

Index Terms – Soft robots, caterpillar, SMA, elastomer.

I. INTRODUCTION

Current highly flexible (hyper-redundant) biologically inspired machines are mostly built from concatenated rigid modules with multi-axis joints between them. Well known examples include the “snake-like” robots of Hirose [1], Burdick and Chirikjian [2], Borenstein [3] Choset [4] and Miller [5]. Similar modular designs have been used as re-conformable machines [6], and form the basis for many undulating or swimming robots [7, 8].

However, most flexible animals are soft bodied with no rigid skeleton at all. Instead they use highly compliant materials and vary their stiffness using

hydraulics, muscle tension and tissue compaction. Of these soft-bodied animals, caterpillars are the most successful climbing herbivores on the planet. Their multi-legged crawling is distinct from the bouncing gaits of articulated animals [9, 10] and from the peristaltic movements of worms or mollusks [11]. Caterpillars use passive grip to secure themselves to complex branched substrates [12] and have a multidimensional workspace, able to bend, twist and crumple in ways that are not possible with a rigid skeleton. They use dynamic hydrostatics to vary body tension and can cantilever over gaps that are 90% the length of the body.

There have been very few attempts to build truly soft-bodied robots with the intrinsic capacity to deform, twist and crawl. Several ingenious flexible designs have been developed based on peristalsis [13-15], conformable wheels [16], or continuously bending elements (“continuum robots”)[17, 18]. Each of these has its own advantages but most only function in a specific environment and none of them can climb or completely collapse for access to restricted spaces.

The present work describes some of the mechanisms of caterpillar locomotion and recent developments in the development of a robotic climbing machine based on the biomechanics and neural control system (neuromechanics) of the caterpillar, *Manduca sexta*.

A. *Manduca* as a model system for distributed control of movements

Manduca is an excellent model system for studying the neuromechanics of soft-bodied movements. First, the caterpillar has a multidimensional workspace; it can bend, twist and crumple in ways that are not possible with a rigid skeleton. Second, these movements are achieved through the coordination of concatenated segments each containing ~ 70 distinct muscles. Third, despite the complexity of movements and large number of muscles, each muscle is innervated by a single (or occasionally two) motoneuron(s) and there are no inhibitory motor units. Therefore, most of *Manduca*'s movements are controlled by a few hundred motoneurons whose activity can be monitored using electrodes implanted in the muscles of freely moving animals. One of the ultimate goals of our studies is to understand how complex flexible movements are controlled by a relatively simple nervous system. The overall hypothesis is that much of the computation is “off-loaded” to the biomechanics. This hypothesis implies that a large component of movement coordination and response to external forces is built into the nonlinear mechanics of the body wall, muscles and hydraulics (see also [10, 19]). In addition, *Manduca*'s locomotion contrasts markedly with most model systems. Caterpillars are extraordinarily successful climbers and can maneuver in complex three-dimensional environments, burrow (in preparation for pupation), and hold onto the substrate using a very effective passive grasping system [12]. Understanding how these different movements are generated and

controlled in a caterpillar will help to explain how animals (and robots based on them) incorporate elasticity and resilience into their motor control systems.

II. CATERPILLAR MOVEMENTS

A. Locomotion

A three-dimensional kinematic study of straight line crawling shows that caterpillars do not move by worm-like peristalsis. Waves of movement pass from the terminal segment (TS, Fig. 1) towards the head. Furthermore, there is a distinct transition in the kinematics between posterior segments and those in the mid body. The TS and adjacent abdominal segment (A7) are lifted and pulled forward into stance phase; the segments then pivot around the terminal proleg (TP) attachment point in a motion that resembles an inverted pendulum. Vertical displacements precede changes in horizontal velocity by 30° (one step $=360^\circ$). In the mid body segments the horizontal velocity and height are essentially in phase (lead or lag $<10^\circ$) and each body segment is at its maximum length during the stance phase. As the wave moves forward, segments compress in the first part of the swing phase and re-extend before entering stance again. Velocity and length measurements show that this cyclic compression is not true harmonic motion (phase lag 90°) but is damped (mean phase lag of $73^\circ \pm 3.17$, $n=23$ segments, 7 animals) consistent with storage and release of viscoelastic energy. [11].

The dorsal and ventral parts of each segment change length in phase with one another, implying that lifting and bending across the length of the caterpillar occurs by folding of the intersegmental membranes. Unexpectedly, the length and radius of each body segment co-vary, that is, each segment was narrowest when it was shortest. Hence, unlike the leech [20, 21], segment volume in *Manduca* is not necessarily conserved during a crawl, so tissue, fluid, or air can be transported from one part of the body to another and back again.

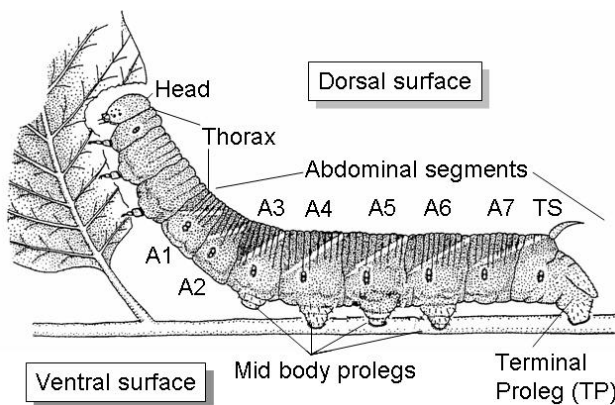


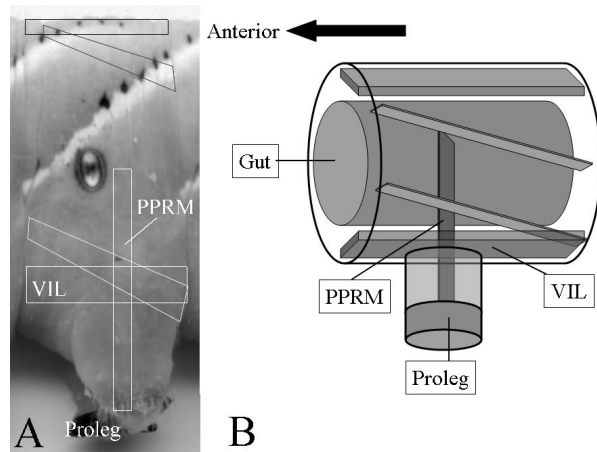
Fig. 1 External anatomy of the caterpillar, *Manduca sexta*.

The essential kinematics of crawling are not different on curved or flat surfaces although there are slight changes in the

relative timing and duration of movements in some parts of the body. These subtle changes occur in de-brained larvae, suggesting that they are mediated by local biomechanical or proprioceptive events.

B. Proleg adduction

A study of the 3-D kinematics and neural control of proleg adduction shows that extension and adduction are not separate processes [12]. Extension occurs primarily by unfolding the membrane between the proleg segments. Adduction results from an asymmetric unfolding of the membrane along the lateral to medial axis to rotate the proleg medially. This motion is not replicated by inflating isolated prolegs and it appears to depend on upon the normal passive stresses provided by muscles. Contrary to expectation, hemolymph pressure pulses are not necessary to extend the proleg; instead, pressure at the base of the proleg decreases before adduction and increases before retraction. Hence the prolegs are forced out through their own elasticity and by baseline pressure. The pressure changes are caused by muscles that stiffen and relax the body wall during cycles of retraction and adduction. Extracellular nerve and muscle recordings in reduced preparations show that stimulation of sensory hairs on one proleg strongly and bilaterally excites motoneurons controlling the ventral internal lateral muscles (VIL) of all the proleg bearing segments (Fig. 2). However, ablation, nerve section and electromyographic experiments demonstrate that VIL is not essential for adduction in restrained larva but that it is coactive with the retractors and may be responsible for stiffening the body wall during proleg movements. Relaxation of the principle planta retractor muscle (PPRM) is essential for normal adduction. These findings demonstrate how caterpillars control gripping. The results have wider implications because



they illustrate the importance of structural mechanics in shaping movements and highlight the non contractile role of muscles in soft body control.

Fig. 2 (A) A side view of one proleg-bearing body segment with the approximate location of the muscles VIL and PPRM. (B) A diagram of the three-dimensional position of the major muscles involved

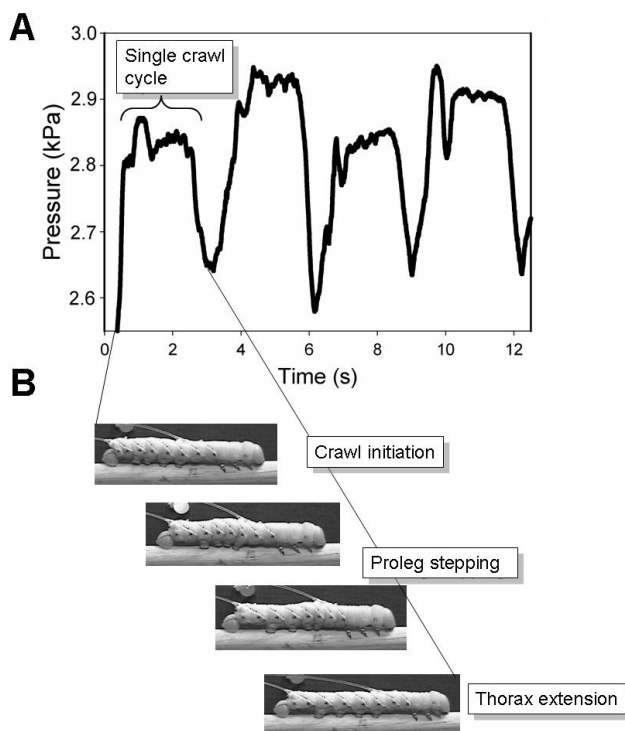
in proleg movement.

C. Body wall stiffness and hydrostatic pressure

Materials testing of the body wall using a custom made ergometer show that *Manduca* cuticle does not behave as a simple rubber but is instead highly viscoelastic. To test for anisotropy, a comparison was made between stretches in the radial and longitudinal directions. The cuticle exhibited a typical J-shaped stress-strain curve in both directions, with a Young's modulus value (in the linear part of the stress-strain curve) of $0.823 \pm .179 \text{ N/mm}^2$ when

loaded in the radial direction and $0.879 \pm .286 \text{ N/mm}^2$ when loaded in the longitudinal direction (no significant difference, $p = 0.63$, $n=18$, two-tailed t-test). There was also no significant difference ($p = 0.18$, $n=9$) found between ultimate stress of the cuticle between longitudinal samples ($0.191 \pm .029 \text{ N/mm}^2$) and radial samples ($0.166 \pm .047 \text{ N/mm}^2$). These values of Young's modulus shows that the body wall is stiffer than soft cuticle in the abdomen of a gravid locust but more flexible than the shell membrane of an egg [22].

Fig. 3 Internal pressure increases during stepping and decreases during anterior extension.



Manduca has an open circulatory system with no septa or valves to prevent hemolymph flow [23] and its body wall is not rigid. During a crawl the internal pressure (measured inside the terminal segment) rises during the abdominal stepping phase and falls as the head and thorax extend (Fig. 3). However, simultaneous measurements of internal pressure at different locations in *Manduca* suggest that the hemocoel is not isobarometric. This implies that fluid flow is

restricted along the body and that local pressure changes could drive discrete movements. Barriers to fluid flow might result from changes in tissue geometry or from activity in body wall muscles.

III. ROBOT DESIGN CONCEPT (“SOFTBOT”)

The robot under development is a contoured cylinder constructed from highly elastic silicone rubber (Fig. 4). It moves using shape memory alloy (SMA) springs as actuators, bonded directly to the inside of the body wall. Instead of circular and longitudinal “muscles” used in most worm-like designs, Softbot has discrete groups of actuators modeled on those of the caterpillar. Future prototypes will have a set of passive grip/active release opposable legs capable of gripping flat surfaces, irregular objects and wires or ropes. The body contains an inner compartment (the “gut”) that will be used to hold components of the control system and additional payload. The space

between the “gut” and body wall is pressurized to transmit forces and regulate stiffness. Release of pressure will also allow the robot to collapse and compress into a freeform volume limited only by the payload size. This new robot will be highly scalable and could be miniaturized very easily (the caterpillar itself grows in mass 10,000 fold without changing its musculature or central control system). Softbot is expected to be fault tolerant [24], capable of extreme mobility (including shape changing) and exceedingly simple to build.

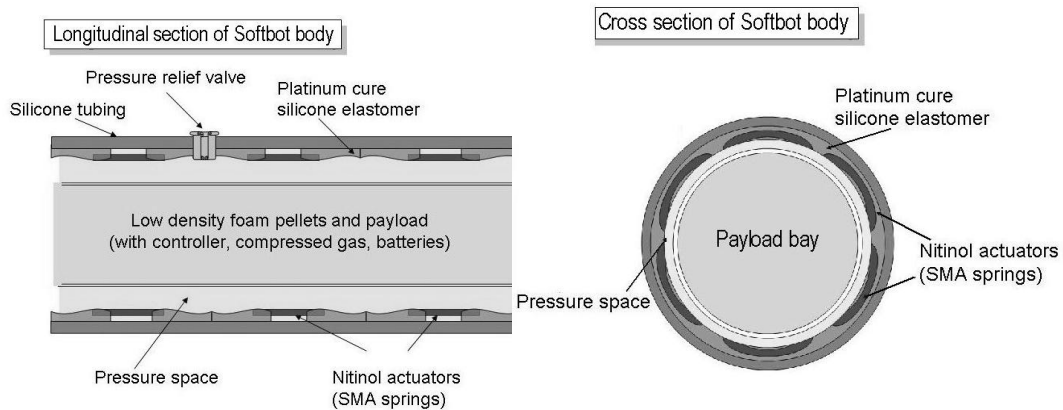


Fig. 4 Overall layout of Softbot in longitudinal, and cross, sections.

A. Actuators

SMA springs from a single wire can be wound to provide different strains and forces [25-27]. The prototype uses 150 μ m nitinol which normally has a working strain of 3% and a recovery force of 3N. When wound as a micro-spring 1 mm in diameter, the actuator works over 100% strain and develops 0.3N of repeatable working force (Fig. 5). These SMA springs are bonded to the body wall whose elasticity serves as a bias (recoil) spring.

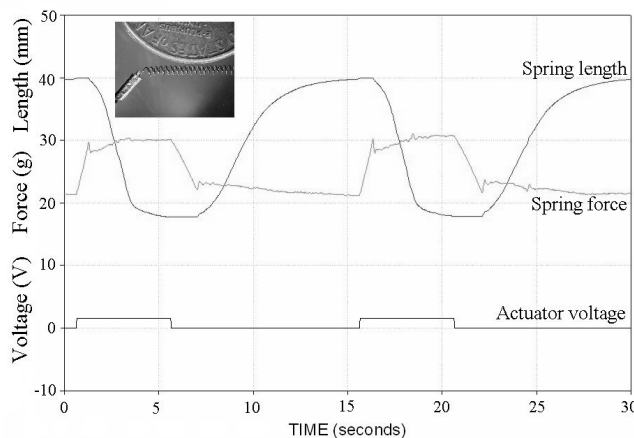


Fig. 5 Dynamic responses of a 1mm SMA spring (inset) carrying a 30g load activated for 5s periods every 15s.

B. Body wall

The main body of Softbot is cast from a soft silicone elastomer (Fig. 6. Dragonskin™, Smooth-On Inc., Easton, PA). Alternative approaches include

the use of woven textile materials. The silicone body wall is thickened and contoured in segments to resemble the caterpillar and to promote useful deformations. This shape will eventually be optimized using structurally based constitutive models of the caterpillar and robot.

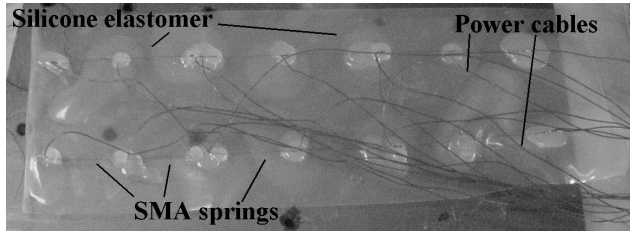


Fig. 6 SMA springs embedded in the silicone test material before it is rolled into the cylinder shaped body wall.

C. Grippers

The tenacious attachment of caterpillars to their food source is achieved using a passive gripping system (the prolegs/crochets) that resembles Velcro™. A major advantage of the caterpillar system over commercial hook and loop fastenings is that grip can be released instantly without the large shear forces required to undo Velcro™.

To test our designs of these attachment hooks we have built a test apparatus (Fig. 7) consisting of a simple pair of opposable pads held in the gripping position by tension in a mounting arm, laser-cut from 1/8 in. cast Delrin. These pads can be surfaced with fine-grit or hooks and are disengaged by the contraction of a SMA spring that causes them to pivot away from the midline. To test climbing ability, two of these grippers are linked by another nitinol spring set in parallel with a 1.5 in. stainless-steel compression spring. For climbing motion, the controller activates spring C to release the bottom gripper. Spring B is then activated, pulling the bottom gripper up. Springs B and C are turned off, and spring A is activated to push the top gripper up along the dowel.

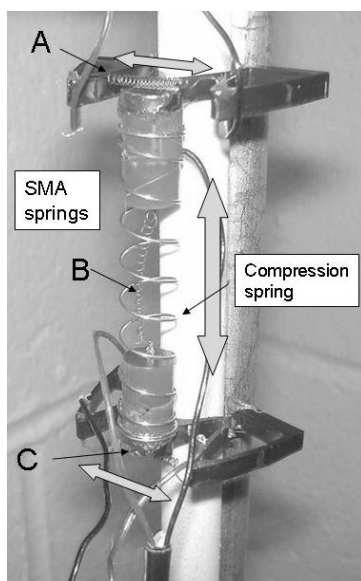


Fig. 7 A testing system for the passive gripping mechanism.

This design is being used to test the optimum geometry of the claw itself. The crochet-like gripper will be integrated into the robot design by mounting it on a silicone rubber.

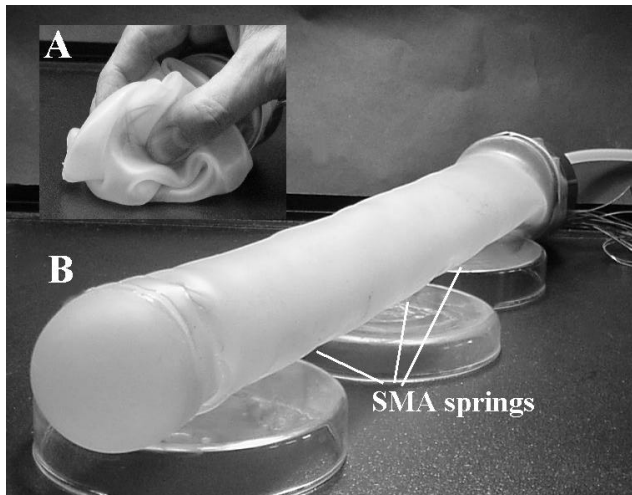
D. Controller hardware

The actuators are controlled using a pulsed current source. By varying the frequency, duty cycle and duration of the pulse bursts the actuator can contract at different rates and to

different peak force. This closely resembles the activation of muscle by a motoneuron. Currently the robot is tethered to the offboard power and controller driven by Labview. The eventual goal is to make Softbot autonomous using VLSI circuits and flexible PCBs housed inside the “gut”.

E. Softbot assembly

The current prototype is 40 cm long and 5 cm in diameter and contains only 12 actuators arranged in two serial rows on opposite sides of the body wall (Fig. 6 and Fig. 8). Each actuator is capable of generating substantial strain to bend and fold the local body wall. By activating pairs of SMA springs in turn waves of contraction pass along the body in a simulated crawling motion. Tension in the body wall itself is sufficient to restore springs to their pre-activated length although adjacent springs can be activated to speed this process [25]. This first functioning prototype demonstrates that SMA springs and silicone elastomer can be bonded firmly to produce muscle-like



movements. A second generation prototype is currently under construction using SMA springs oriented to mimic the main locomotory muscles of the *Manduca* caterpillar. This will be assembled with the artificial prolegs to produce the first soft-bodied climbing robot.

Fig. 8 The first prototype of Softbot. (A) Shows the robot collapsed and folded. (B) The robot is inflated and the positions of three actuator SMA springs are indicated.

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