

New challenges in biorobotics: incorporating soft tissue into control systems

Neuromechanics of caterpillar locomotion: muscles as multi-state materials, soft-bodied robots

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Abstract –The development of truly biomimetic robots requires that soft materials are incorporated into the mechanical design and also used as an integral part of the motor control system. One approach to this challenge is to identify how completely soft animals control their movements and then apply the found principles in robotic applications. Here I show an example of how a combination of animal kinematics, neural patterning, and constitutive modelling of tissues can be used to explore motor control in the caterpillar, *Manduca sexta*. Although still in its early stages, these findings are being used to design and fabricate a new type of robot that does not have a rigid skeleton and that is structured entirely from soft or compliant materials. It is hoped that this new robotic platform will promote the development of actuators, sensors and electronics that are compatible with soft materials.

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

I. INTRODUCTION

A major challenge in the field of biorobotics is to reproduce the astoundingly precise, robust and versatile motions of animals. In fact, most robots can be instantly recognized as synthetic machines because they fail to negotiate complex environments as smoothly and quickly as their biological counterparts. One factor that helps animals adapt movements so well to a changing environment is their reliance on soft and flexible materials. In contrast most robots are built from very stiff components that have more predictable mechanical performance but lack compliance and “self-correction”. The extensive use of soft materials in robot construction is limited by the difficulty of integrating non-linear materials into traditional control systems. One goal of the research described here is to begin to understand how soft tissues contribute to the control of animal movement and to use these findings to build conformable robots from soft materials.

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 locomotion in the caterpillar *Manduca sexta*, and some of the neuromechanics that appear important for its movements. In particular, the elastomeric nature of their muscles is altered by neural activation in complex but predictable ways. It is our hypothesis that, by controlling the *material state* of tissues such as muscle, soft animals can greatly simplify neural encoding of hyper-flexible movements. These findings are being applied to the design and construction of a new type of collapsible, soft-bodied robot (“Softbot”).

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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.

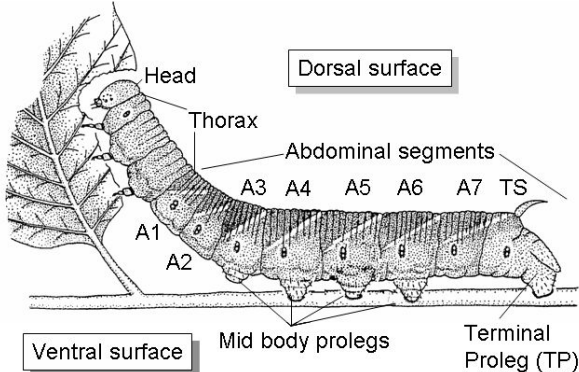


Fig. 1. External anatomy of the caterpillar, *Manduca sexta*.

Their movements are achieved through the coordination of concatenated segments (Fig. 1) each containing ≈ 70 distinct muscles. Because *Manduca* larvae metamorphose into adult moths having jointed limbs, their muscles are organized into individual, discrete units each with distinct orientations and attachments analogous to the muscular organization of vertebrates (Fig. 2A). Despite the complexity of *Manduca*'s movements and the 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. In addition, *Manduca*'s locomotion contrasts markedly with most model systems. Caterpillars are extraordinarily successful climbers and can burrow (in preparation for pupation), and hold onto the substrate using a very effective passive grasping system [12].

II. CATERPILLAR NEUROMECHANICS

A. Kinematics

A three-dimensional kinematic study of straight line crawling shows that caterpillars do not move by worm-like peristalsis [11]. Waves of movement pass from the terminal segment (TS, Fig. 1) towards the head and there is a 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°). 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 [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 [19, 20], segment volume in *Manduca* is not necessarily conserved during a crawl, so tissue, fluid, or air (in the tracheal system) can be transported from one part of the body to another and back again.

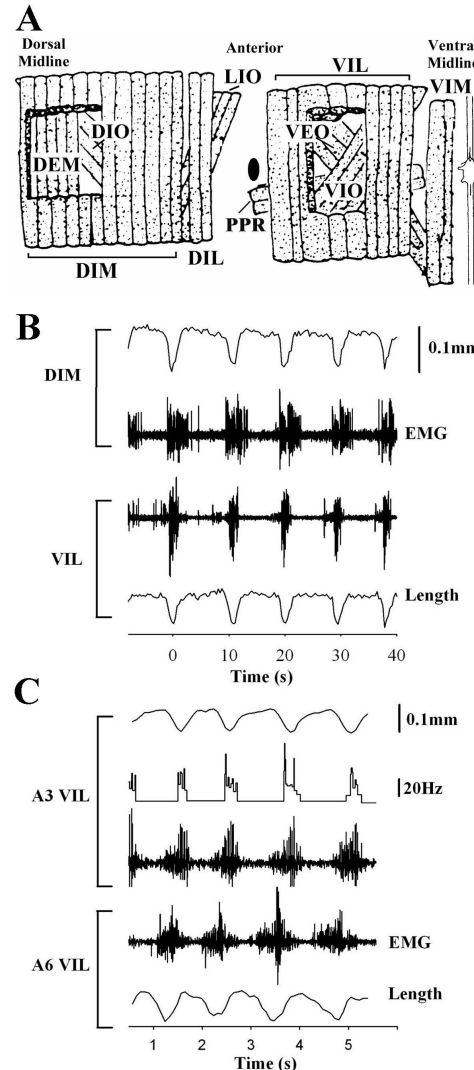


Fig. 2. A) Major muscles on one side of an abdominal segment (from [21]). Muscle abbreviations are defined in the text. B) Strain cycles of 2 muscles in segment A4 (DIM, dorsal, top; VIL, ventral, bottom), and corresponding EMGs during horizontal crawling. Dorsal and ventral muscles are phase-locked and co-active, although DIM continues to be activated during its re-extension. C) Strain cycles of VIL in 2 segments (A3, A6) and their corresponding EMGs during horizontal crawling. Also shown in A3 is the instantaneous spike frequency of the motoneuron driving VIL, derived from the EMG (see text). The EMG and VIL strain in A3 are phase-delayed relative to A6, but co-active for much of their duty cycle.

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 some of *Manduca*'s adaptability is mediated by local biomechanical or proprioceptive events.

B. Motor patterns during horizontal crawling

In contrast with the widely accepted model of caterpillar locomotion [22-25], both dorsal and ventral muscles in each body segment co-contract (**Fig. 2B**). Single muscles (e.g. VIL) in different segments are phase-delayed, but even muscles that are 4 segments apart are co-active for 70% of their duty cycle (**Fig. 2C**). Some muscles (e.g., the dorsal internal muscle, DIM) continue to be activated as they re-extend (**Fig. 2B**), suggesting that they play an important role in resisting stretch, perhaps stiffening the body wall to transmit forces. While *Manduca* crawling is distinct from simple peristalsis, it is unknown how these movements are translated into propulsive forces. In addition, using direct motoneuron stimulation in reduced preparations, we have identified characteristic features of the extracellular muscle potentials to translate the EMGs of intact animals into motoneuron spike frequencies (**Fig. 2C**). This technical breakthrough more accurately defines motor patterns and enables us to reproduce natural spike trains for stimulated muscle work loops.

C. Passive and active muscle properties

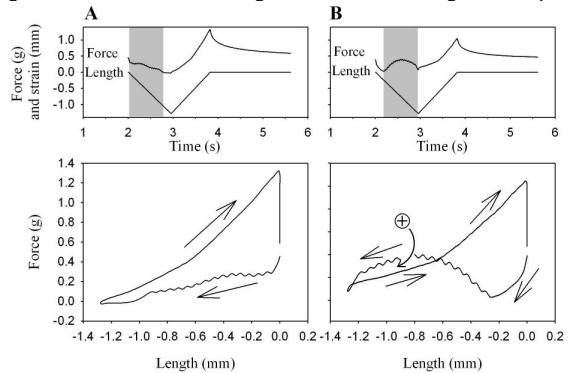
Studies on the characteristics of VIL show that it has a large tetanus-to-twitch force ratio (8.5; see also [26]), a peak isotonic contraction velocity (and amplitude) at 10% of the peak active tension, and a very slow contraction (peak tension in 1s) [27]. In contrast to most arthropod striated muscles, VIL has an enormous working strain range (50-100%), suggesting that it is a supercontracting muscle. During sinusoidal strain cycling, VIL dissipates work (clockwise work loops) in both passive (unstimulated), and tetanic states, with higher stiffness and more work dissipation during stimulation. This property is similar to that of locust flight muscle [28], except that VIL operates at 10 times the strain and 30 times more slowly. Furthermore, when VIL is cycled at increasing speeds, the work loops change trajectory (viscoelasticity) and passive dissipation becomes a larger proportion of the total work absorbed during stimulation. These time-dependent non-linear properties will strongly impact dynamic responses during active contraction.

D. Reconstructed crawling work loops

Length changes measured in VIL during crawling (e.g., **Fig. 2C**) were used to construct simplified strain ramps that were applied to VIL. VIL was also stimulated with spike trains whose intensity, duration and timing matched those occurring during crawling (**Fig. 2C, trace 2**). These "crawling work loops" show that timing of a natural stimulus has a major impact on VIL performance. Phase

advanced (**Fig. 3A**), or phase delayed (not shown), stimuli resulted in work dissipation throughout the strain cycle.

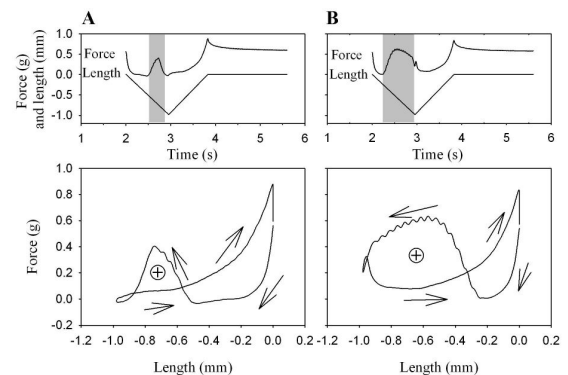
Fig. 3. Effect of stimulus timing on simulated crawling work loops for



VIL. Both traces and work loops are from a single muscle undergoing a simplified crawling strain cycle with a stimulus (20Hz) lasting 0.68s beginning at the start of shortening (**A**) or after a delay of 0.19s, which normally occurs during crawling (**B**). + indicates a region of positive work (actuation).

Stimulus timing that matched crawling produced a region of positive work output (actuation, **Fig. 3B**). Interestingly, the region of positive work was strongly dependent on the stimulus duration (**Fig. 4**), suggesting that muscle function could be controlled by small variations in motor neuron activity [27].

Fig. 4. Effect of stimulus duration on simulated crawling work loops for



VIL. Both traces and work loops are from a single muscle (from a different animal than that in Fig. 2) undergoing a simplified crawling strain cycle with a stimulus (20Hz) ending at the peak of shortening. (**A**) stimulus duration=0.28s (**B**) stimulus duration=0.68s. + indicates a region of positive work (actuation).

E. Elastomeric properties of Manduca muscle

The fundamental pseudoelastic properties of passive and tetanically stimulated muscle have been characterized using constant velocity strain changes. The dissipation of work by VIL resembles that of high carbon particle rubber [29], including its tendency to work softening (Mullins effect). These properties can be accurately modeled using constitutive elastomeric theory [30]. In addition, *Manduca* muscles are visco-elastic over a variety of strain rates including slow increases in residual stress at low strains, velocity-dependent yield after stretch, changes in work

loop trajectories at different strain cycle frequencies, and stress hysteresis at constant velocity strains [27]. These properties could be mechanisms for autonomous control of the biomechanical responses thereby lowering the demand for real-time neural control. It is also possible that neural commands exploit some of these complex material states to more effectively control hyper-redundant locomotion. These questions will be explored in simulation models (the “Virtual *Manduca*”) and in a hardware robotic environment (“Softbot”).

III. ROBOT DESIGN CONCEPT (“SOFTBOT”)

The robot under development is a contoured cylinder constructed from highly elastic silicone rubber. 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 [31], capable of extreme mobility (including shape changing) and exceedingly simple to build.

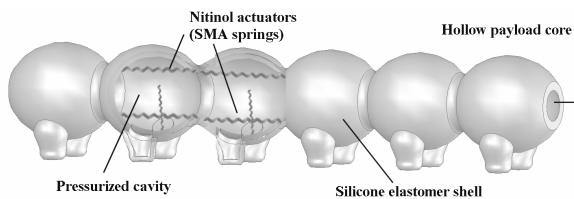


Fig. 5. Overall layout of Softbot in partial cutaway longitudinal section.

A. Actuators

SMA springs from a single wire can be wound to provide different strains and forces [32-34]. 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.

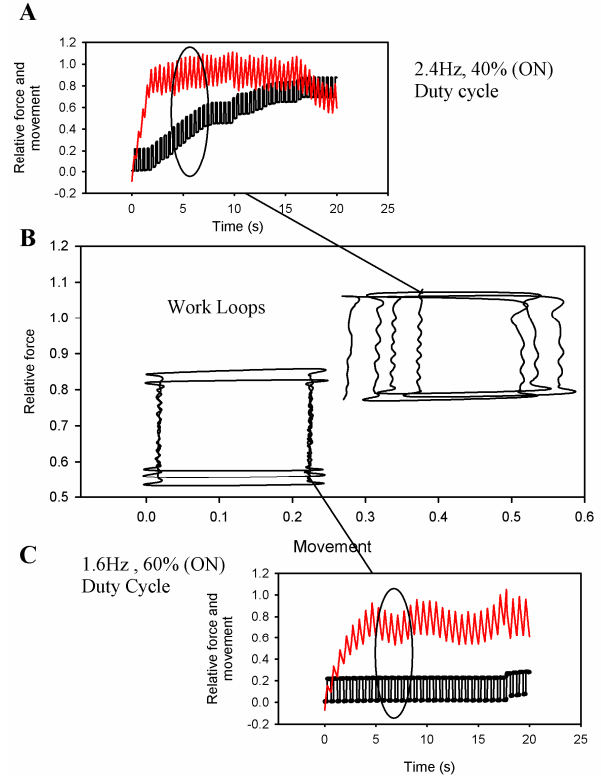


Fig. 6. SMA spring actuators can be operated in different work loop configurations using pulsed current at different frequencies and duty cycles. The performance of a 1 mm diameter spring is shown carrying a 30g load activated for 20s at either 2.4Hz, 40% duty cycle (A) or 1.6Hz, 60% duty cycle (C). Work loops plotted from the indicated response region of each trial are shown in (B).

B. Body wall

The main body of Softbot is cast from a soft silicone elastomer (Fig. 6. Dragonskin™, Smooth-On Inc., Easton, PA). As part of the design of the robot we have developed a process to quickly manufacture a large number of prototypes for testing changes in morphology and material properties. The method uses rapid prototyping tools to produce casting shells with the SMAs mounted in place. 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.

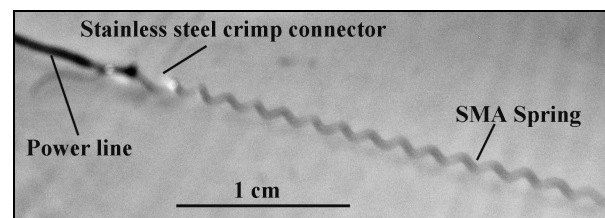


Fig. 7. SMA springs attached to the silicone test material on the inside surface of the robot.

C. Controller hardware

Each actuator is controlled using a pulsed current source driven by a master oscillator to maintain the overall cadence of a crawl. This rhythm is coupled to a second oscillator whose frequency and duty cycle can be varied to generate square wave bursts which are analogous to the trains of action potentials that cause muscle contraction. Alterations in these parameters can be used to control the overall amplitude of the force and contraction of the actuator or to move the work-loop responses into a different operating range (Fig. 6). This method of driving the actuators has been found to be more consistent than direct amplitude modulation (e.g., changing the driving current) and it has the additional advantage of a rich and complex range of responses. The coupled signal can be set globally or differently for each actuator so that the phase of the pulses relative to one-another, their polarity (inverted pulse timing analogous to an inhibitory neuron connection), frequency, and duty cycle are all variables available for movement control.

Currently the robot is tethered to the offboard power supply and the hardware is implemented at the level of discrete components driven by Labview programs. This system controls 48 SMAs but can be readily expanded to 72 simultaneous outputs. The eventual goal is to make Softbot autonomous using VLSI circuits and flexible PCBs housed inside the "gut".

D. Softbot assembly

The current prototype is 24 cm long and 4 cm in diameter and contains only 12 actuators arranged in two serial rows on opposite sides of the body wall (Fig. 5 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 [32]. 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.

IV. CONCLUDING REMARKS

The details of how soft-bodied animals position their bodies appropriately to accomplish complex movements are currently unknown. Despite their extreme flexibility (with enormous degrees of freedom), and lack of discrete joints (to define position or orientation), soft-bodied animals do not have larger or more intricate brains than their rigid skeleton counterparts. The work described here has begun to explore how such flexible movements are controlled by a relatively simple nervous system. The tobacco hornworm (*Manduca sexta*) offers several powerful advantages for

analysing interactions between neural and biomechanical elements. In addition, its muscular organization is analogous to that of animals with jointed skeletons so many of the found principles can be applied to the movements of legged vertebrates and adult arthropods, as well as for animals with hydrostatic skeletons. By integrating data and methodologies from neuroscience, materials science, and robotics we will begin to form a deeper understanding of the role of soft materials in animal locomotion and discover ways to use these materials to produce more versatile, and life-like devices.

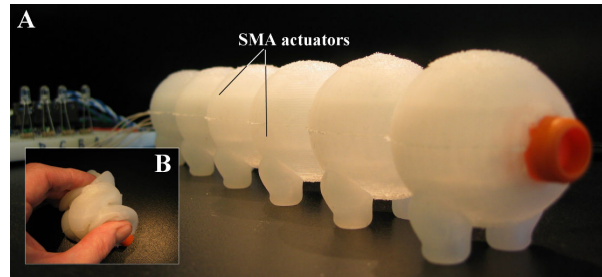


Fig. 8 The prototype Softbot. (A) The robot is inflated and the positions of two actuator SMA springs inside the body shell are indicated. (B) Shows the robot collapsed and folded.

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