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as of 05-Aug-2019

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Final Report for Period Beginning 01-May-2016 and Ending 01-Nov-2018
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Report Term: 0-Other
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 3

Major Goals: This project aims to discover the underlying mechanisms for generating fast, high power movements in soft and flexible animals. Unlike fast moving articulated animals (e.g., mantis shrimp's punches, trap-jaw ants) soft animals do not have stiff materials that can be pre-loaded for mechanical energy storage. Hydrostatic animals and plants can produce fast movements by releasing energy from pressurized compartments (squid jet propulsion and bladderwort prey capture) but this does not seem to be the strategy employed by most flexible (e.g., fish) or soft terrestrial invertebrates (e.g., caterpillars). One possibility is that animals instead exploit structural instabilities to achieve rapid motion. This implies that tissues and body structures are arranged to buckle in response to a controlled perturbation, for example triggering the body wall to collapse by activating a local muscle.
The studies use fish c-start behavior, caterpillar strike responses, and synthetic soft devices to examine how structural instabilities can extend the range of dynamic performance by compliant systems. There are two underlying hypotheses regarding such soft systems, that: (1) they exploit mechanical buckling instabilities at many scales, and (2) they control power delivery by changing the local mechanical properties of the body.

Accomplishments: The research objectives described above were originally planned for a 4-5-year period. The options were not renewed after the completion of the first year, so activities continued on a smaller scope on a no cost extension through November 1 2018. The following report reflects this reduced research plan.

A Fish C start behavior: closed-loop fish experiments and locomotor mechanics modeling
We completed the construction of a flow facility that was to be used for c-start behavioral analysis. In addition, we completed development and testing of a closed-loop system that updates the motion of a moving object based on the location of a swimming fish, in real-time; the next step was to integrate this closed-loop setup with the flow facility, had funding permitted (Fig. 1). Also, using the limited funds available we completed a modeling study on muscle mechanics ribbon-fin locomotor mechanics that was to serve as a branching off point for examining buckling mechanics. In addition, we completed a study on modeling muscle mechanics that was published this year. There is an additional paper in preparation for submission this calendar. Lastly, portions of this work have been presented at several venues.

B Manduca strike behavior: characterization and control
Using high speed videography (Fig. 2) we have shown that caterpillar strike trajectory is targeted and that this is achieved by corrective movements after the strike is initiated (Fig 3). This is an important finding since it implies the behavior is not simply a "ballistic" release of stored energy. However, it is possible that the behavior involves a transition from an uncontrolled buckling event at the start of the movement to a targeted strike approximately 50 ms later.

When a stimulus was repeated at the same site every 10 minutes, the latency to strike decreased from approximately 200 ms to around 50 ms two hours later (Fig. 4). The latency decreased linearly with successive stimuli and the effects were seen with stimuli to both segments A4 and A6 separately.
Using a split-stimulus protocol we have determined that that there are two components of this sensitization: one is a local effect, presumably occurring in the sensory neurons or their immediate connections and the other is a generalized increase in sensitivity that spreads to distant body segments (Fig. 5)
Preliminary results suggest that centrally mediated sensitization involves the activation of muscarinic acetylcholine receptors (Fig. 6). This work has been prepared for publication.
EMG recordings from the major ipsilaterial intersegmental muscles suggest that there is sequential activation occurring from anterior to posterior segments. It is not yet clear whether contralateral muscles are progressively inhibited in a similar manner. It is also unknown how the targeting at the endo of the strike is controlled.

Interestingly, insects with a single ganglion surgically removed from the A1 segment can be stimulated to strike. Compared to the sham-treated animals, these insects have a quicker strike response. There is increased preference to strike posteriorly.

Recordings using bipolar electrodes from DILs have shown a temporal difference between segments A3 and A5 upon stimulation at A6. Muscle activity also shows differences during the end of strike when the head reaches the target. We are currently, working on multi-electrode arrays to acquire muscle activity data from multiple muscle fibers (DIMs, DILs, and DIOs).

C Emulating fast, buckling movements in a soft synthetic system
- A simple mechanical model of bending based on a column of rotational joints of varying stiffness can recapitulate much of the strike movement. Similar bending profiles can be generated by limiting the angle of bend at each joint or by varying the stiffness (Fig 7). This latter version of the model lends itself to a straightforward hypothesis that Manduca could control strike trajectory by varying the stiffness at the segment boundaries through muscular activation. We are currently testing this hypothesis using multi-electrode EMG recordings.
- Simplified physical models of the strike movements are being used to test hypotheses on the mechanisms of fast movements
- Notching of pre-strained tubes produces predictable bending movements due to stress concentrations (Fig. 7)
- These stress concentrations can be designed into pressurized soft structures resembling a caterpillar, buckling is controlled by controlling local pressure changes (Fig. 8)

Training Opportunities: •Ritwika Mukherjee (Ph.D. program) was supported on this grant during this period and is preparing her PhD thesis on the subject of movement control in Manduca.

Results Dissemination: PUBLICATIONS SUPPORTED IN PART BY THIS GRANT:
E. D. Tytell, J. A. Carr, N. Danos, C. Wagenbach, C. M. Sullivan, T. Kiemel, N. J. Cowan, and M. M. Ankarali, “Body stiffness and damping depend sensitively on the timing of muscle activation in lampreys,” Integr Comp Biol, 2018.
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B. A. Trimmer. “Softworms: a non-pneumatic platform for highly deformable robot control”. Southwest Robotics Symposium. Arizona State University January 2019. Invited talk.
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Honors and Awards: •Barry Trimmer was appointed the “Benjamen Meaker Visiting Professorship” at the Institute for Advanced Studies and Bristol Robotics laboratory, Bristol University UK). Awarded July 2017. Active October 15-December 15 2017.
- Barry Trimmer was the Distinguished Visiting Fellow, Scottish Informatics and Computer Science Alliance (SICSA), October 2018.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Barry A Trimmer
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:

International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Ritwika Mukherjee
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Noah Cowan
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Erin Sutton
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Ismail Uyanik
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Guy Levy
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Vishesh Vikas
Person Months Worked: 3.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Sachin Vallamkonda
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Project Summary - W911NF-16-1-0095
(Reporting Period: 01 May 2016 - 1 November 2018)

Dynamic Tuning of Instabilities for High Power Movements in Deformable Structures

PI Barry Trimmer
Biology Department
Tufts University, Medford, MA 02155

Objective

This project aims to discover the underlying mechanisms for generating fast, high power movements in soft and flexible animals. Unlike fast moving articulated animals (e.g., mantis shrimp’s punches, trap-jaw ants) soft animals do not have stiff materials that can be pre-loaded for mechanical energy storage. Hydrostatic animals and plants can produce fast movements by releasing energy from pressurized compartments (squid jet propulsion and bladderwort prey capture) but this does not seem to be the strategy employed by most flexible (e.g., fish) or soft terrestrial invertebrates (e.g., caterpillars). One possibility is that animals instead exploit structural instabilities to achieve rapid motion. This implies that tissues and body structures are arranged to buckle in response to a controlled perturbation, for example triggering the body wall to collapse by activating a local muscle.

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Approach

The approach involves a multidisciplinary team examining the strike behavior of the caterpillar, the escape reflex of fishes, and rapid movements in synthetic soft systems that emulate them. The complete project involved the following activities.

A Fish C start behavior

- Building a test facility for producing reliable ballistic movements in electric fish
- Developing and testing a feedback loop around a freely swimming animal

B *Manduca* strike behavior

- High speed and high resolution kinematics of the strike behavior
- High speed and high resolution analysis of body shape
- Measurement of dynamic forces using an IMU
- Record the activity and muscles during a strike using EMG electrodes
- Model the movements using a) Geometric analysis
  b) Material-based models

C Emulating fast, buckling movements in a soft synthetic system

- Demonstrate fast buckling systems using both structural models and pressurized material systems

Relevance to Army

The results will generate new models of fast motion generation and control which can be applied to the design of adaptive machines. Specifically, we expect three technological breakthroughs: (i) nanofiber-elastomer composites that mimic the mechanical properties of natural tissue (e.g., skeletal and smooth muscle), (ii) digital fabrication hardware and software tools for growing synthetic muscle with integrated sensing and power, (iii) software tools for controlling the reversible actuation of high power soft actuators. We expect these technologies to be applied to any device that interacts with living systems and operates in natural and man-made environments including factories, warehouses, hospitals, vehicles and human emergency situations.

Accomplishments for Reporting Period

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Collaborations and Technology Transfer

- None.

Resulting Journal Publications During Reporting Period

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Graduate Students Involved During Reporting Period

- Ritwika Mukherjee (Ph.D. program) was supported on this grant during this period and is preparing her PhD thesis about movement control in Manduca).

Awards, Honors and Appointments

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- Barry Trimmer was the Distinguished Visiting Fellow, Scottish Informatics and Computer Science Alliance (SICSA), October 2018.

Figures and Images related to this funding

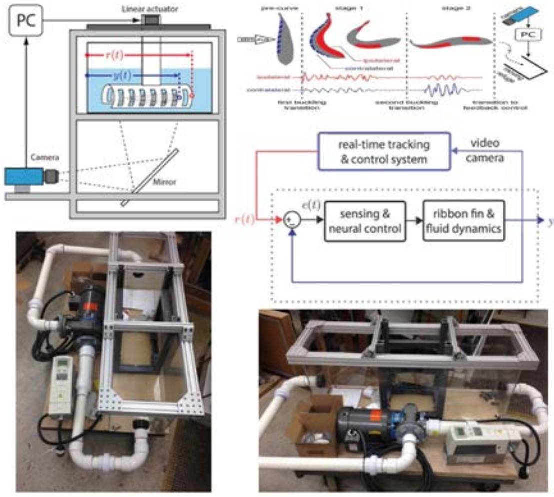


Figure 1. Feedback control system to study the transition from ballistic to feedback control. The newly designed tank system is shown in the two lower panels

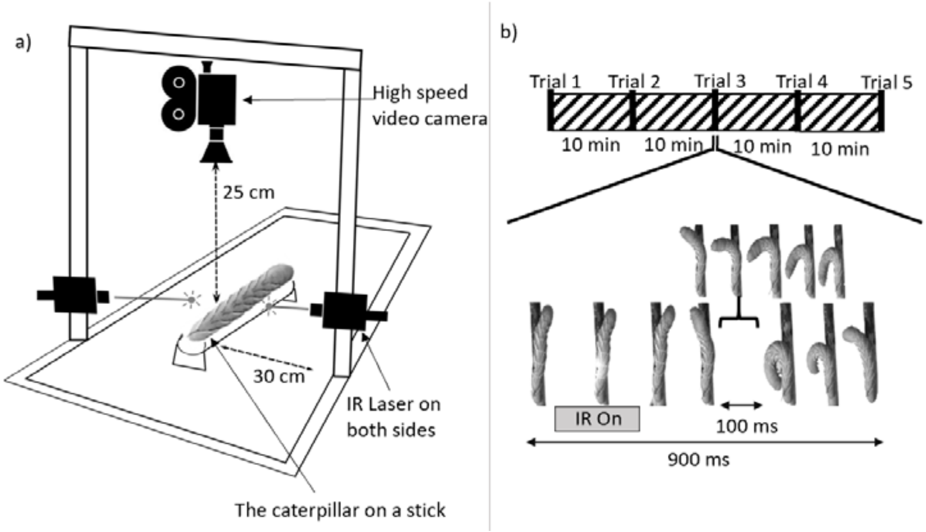


Figure 2. Design of the experimental setup and the experimental protocol. a) The two IR lasers were 30 cm on either side of the caterpillar. A high-speed video camera was situated 25 cm above the caterpillar; b) Recording of a strike in response to a stimulus lasted at most 1000 ms and stimuli were spaced 10 min apart. Most insects received fewer than 13 successive stimuli.

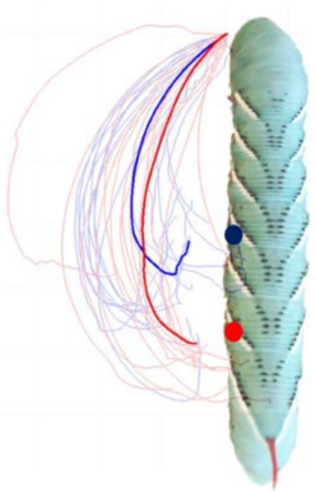


Figure 3. High speed kinematics of the strike targeted to anterior (blue) and posterior (red) segments showing multiple examples of the paths and the average paths followed by the head. Note that the trajectories are similar but that anterior targets include a late-occurring “correction

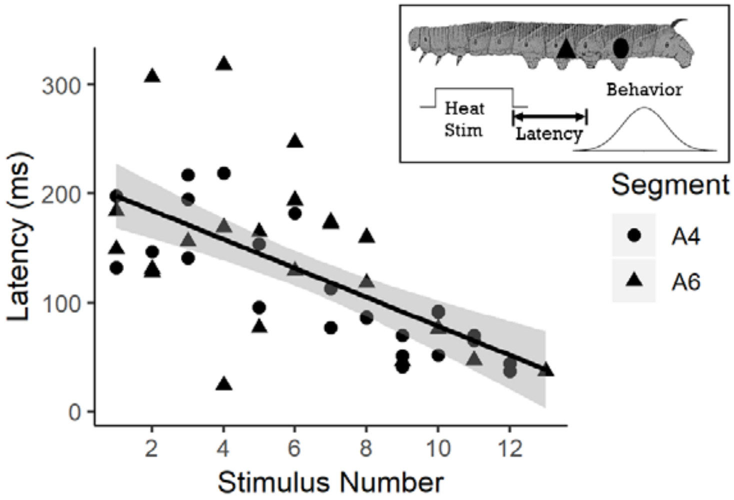
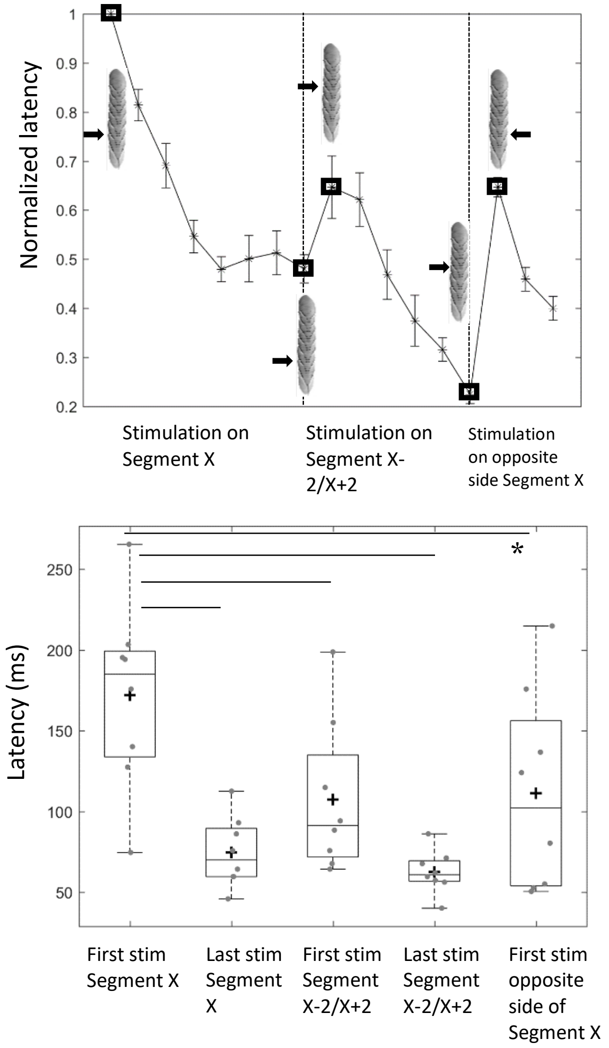


Figure 4. The latency to strike decreases linearly with repeated noxious stimuli. The different symbols indicate the different sites of stimulation at abdominal segments A4 and A6. Linear mixed models were run on the data and the model with the lowest Akaike criterion was a linear model with a linear relationship of Stimulus number and Latency (ANOVA: $\chi 2 = 5.19$, df = 1, p = 1.861e-08) with the segments being a random effect. The linear fit shown here includes data from both segments with y = -13.29*x +211.32 and the grey area shows the standard error. The inset indicates the location of the stimuli with different symbols representing the two sites on the insect. Latency was defined as the duration from the end of heat stimulus to beginning to behavior.



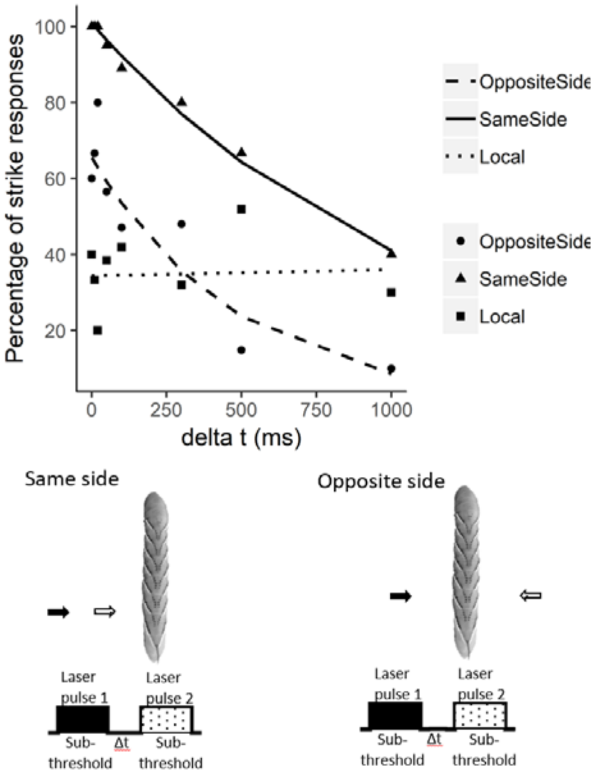


Figure 5A. Sensitization measured as a decreased latency to strike is generalized to other locations. Stimuli (200 ms) were delivered at 10 min intervals and the latency to strike recorded in 8 individual animals. A) The graph is divided into 3 columns highlighting the 3 different stimulation sites. Data were normalized by expressing the latency as a fraction of the latency in response to the first stimulus. During the first 8 stimuli to a single segment (Segment X; where X is abdominal segment A4 or A6) the latency decreased to approximately half the initial response (first column). In response to a subsequent stimulation applied two segments away (Segment X-2; A4 when X is A6 or Segment X+2; A6 when X is A4), the latency increased but did not fully recover to the original latency suggesting that sensitization is generalized to other parts of the body. The latency Finally, stimulating a new site (opposite side of Segment X) caused latency values to recover but not to the original values (mean difference between first stim on Segment X and first stim on opposite side of Segment X = 60.78 ms; Tukey's multiple comparisons test: $p = 0.0527$; $n = 8$; * $p < 0.055$, ** $p < 0.005$). On each box, the central line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points. The mean values are denoted by the '+' signs

Figure 5B. Sensitization can be resolved into local and generalized components. The degree of sensitization can be estimated with a split-pulse stimulus that measures the likelihood of a strike response at different interstimulus intervals. Stronger sensitization is produced when both decreased further upon repeated stimulation on this new segment to approximately one fifth of its original duration, indicating an additive effect of stimulation at the two successive sites (second column). Finally, stimulating a new site (opposite side of Segment X) only restored the latency to 50% of the original value and this could be reduced further by repeated stimuli (third column). B) The results for all 8 animals combined are summarized in a box plot comparing the latency values (s) of the response to the first and last stimulus at each of the 3 sites (highlighted with a box in A). There is a statistically significant difference between the original response and the first stimulus at every new site (mean difference between last stim on Segment X and first stim of Segment X-2/X+2 = -32.76 ms; Tukey's multiple comparisons test: *p* = 0.243; n = 8). The latency decreased further upon repeated stimulation on this new segment (mean difference between first stim on Segment X-2/X+2 and last stim of Segment X-2/X+2 = 44.83 ms; Tukey's multiple comparisons test: *p* = 0.211; n = 8).

pulses are applied to the same location (same side) compared with pulses delivered to two separate locations (opposite side). As the inter-pulse interval is increased, the amount of sensitization decreases for both types of stimulation. The decay in the likelihood of a strike response was best fitted by a logarithmic linear curve for both same, and opposite side, protocols (see text for detailsThe response to stimuli delivered on opposite sides is a measure of generalized sensitization and the response to same side stimuli is the combination of generalized and local sensitization. Subtraction of the two curves represents the local component alone which appears to be relatively constant (accounting for approximately 34.3 % (x intercept) of the increase in sensitization) and is unaffected by the interstimulus intervals used in this protocol

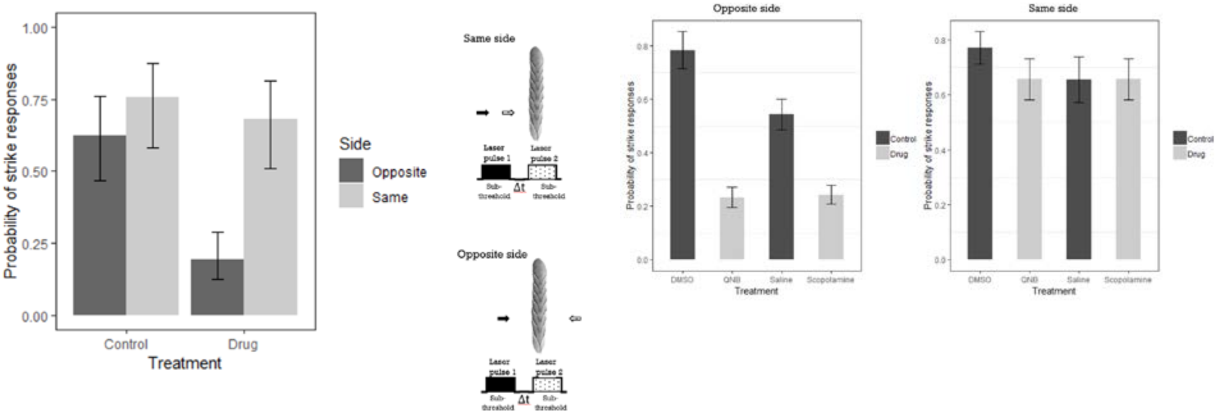


Figure 6. Muscarinic antagonists inhibit generalized, but not local, sensitization of nociceptive responses. The effect of injecting muscarinic antagonists on sensitization was tested using the split stimulus protocol. Two subthreshold stimuli were applied to the same side, or the opposite side, at short inter-pulse intervals following injections of control saline or muscarinic antagonists. A) A histogram showing that the probability of a strike response is significantly lowered for opposite side stimulation in the Multiple comparisons least square means test: p = 0.90) indicating that they block only generalized and not local sensitization produced at a local site (Probability of strike response$_{\text{DMSO}}$ = 0.771 [0.713, 0.830] vs. Probability of strike response$_{\text{QNB}}$ = 0.657 [0.582, 0.732]; Probability of strike response$_{\text{Saline}}$ = 0.655 [0.573, 0.737] vs. Probability of strike response$_{\text{Scop}}$ = 0.657 [0.582, 0.732]).

B) Detailed histogram of the effects of the two drugs and their controls on the probability of strike responses. The drugs used were the muscarinic presence of muscarinic antagonists (Drug) compared to controls (Probability of strike response$_{\text{Control+Oppside}}$ = 0.625 (including SE = [0.467, 0.76]) & Probability of strike response$_{\text{Drug+Oppside}}$ = 0.193 [0.124, 0.287]; Multiple comparisons least square means test: $p < 0.001$). The drugs do not affect the probability of strike responses for same side stimulation (Probability of strike response$_{\text{Control+Sameside}}$ = 0.756 [0.581, 0.874] & Probability of strike response$_{\text{Drug+sameside}}$ = 0.68 [0.508, 0.814]; antagonists, scopolamine and QNB, and their respective controls were saline and DMSO. The drugs affected probability of strike response significantly in case of opposite side stimulation (Probability of strike response$_{\text{DMSO}}$ = 0.782 [0.713, 0.852] vs. Probability of strike response$_{\text{QNB}}$ = 0.232 [0.194, 0.270]; Probability of strike response$_{\text{Saline}}$ = 0.543 [0.485, 0.601] vs. Probability of strike response$_{\text{Scop}}$ = 0.243 [0.208, 0.278]). Neither scopolamine nor QNB had a significant effect on sensitization

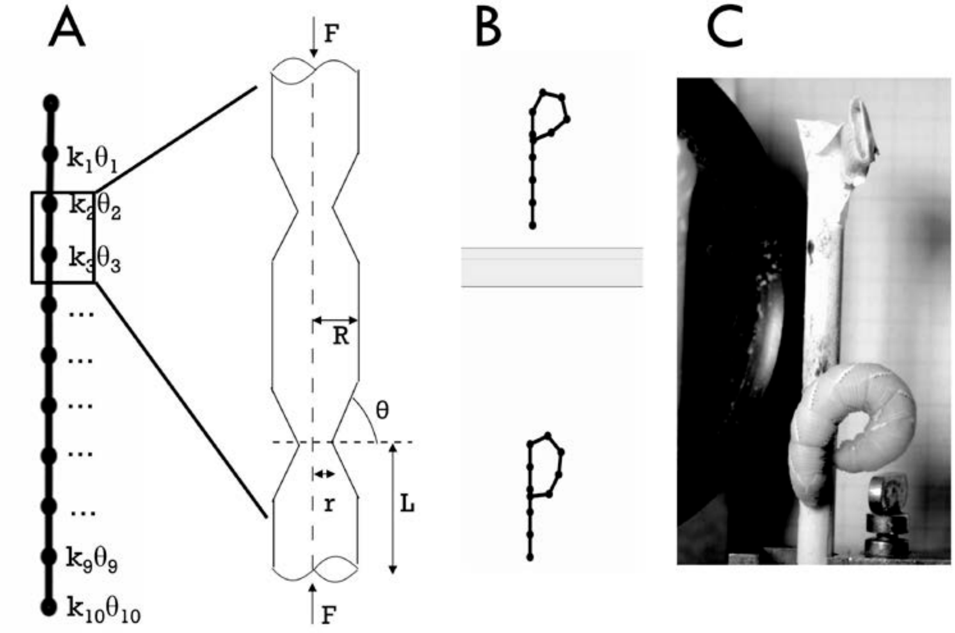


Figure 7. A 2D model of localized, elasticity-based, bending. **A** Bending is modeled as a spring rotation at the stress concentration. Load=FL/E(πr 2), where F=force applied, L=unsupported length, E=modulus of elasticity, πr 2 =cross-section area. **B** show two configurations achieved by changing only the stiffness values while keeping the geometric angle fixed. The columns bend differently because of the different stiffness values of the stress concentrations. The stress concentrations with the lowest stress concentrations bend the most followed by an ascending order of bending. **C**, The final configuration of Manduca striking at a posterior target closely resembles this bending model

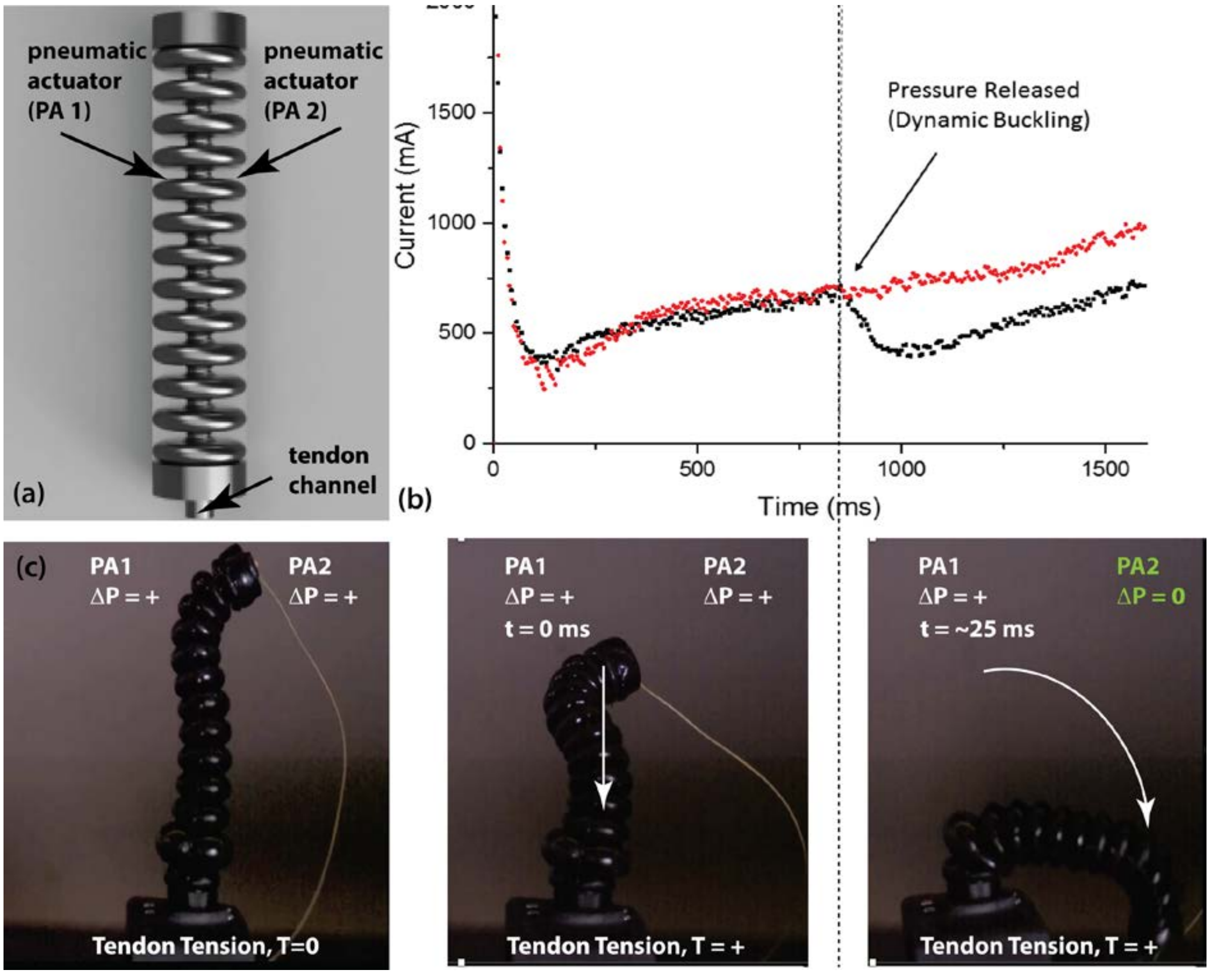


Figure 8. Pre-strained elastomeric cylinders can be predictably deformed by changing the internal pressure. (a) Schematic diagram of hybrid fluid-tendon driven actuator. Two fluidically actuated chambers are cylindrically arranged around a central tendon wire. (b) The motor that winds the tedon's current vs. time in a dynamically tuned rapid actuation using a buckling instability. (c) High speed video of the hybrid actuator. (Left) Both fluid actuators are pressurized, increasing the effective moment of inertia, *I*, of the cylinder. (Middle) The tendon wire is activated, loading the beam in compression. (Right) PA 2 is depressurized, altering the beam's *I*, and triggering the buckling instability in the direction of PA 2. The variable *I* cylinder (black) was printed using a Carbon M1 printer out of elastomeric polyurethane