Towards a biomorphic soft robot: design constraints and solutions

Barry A. Trimmer, Huai-Ti Lin, Amanda Baryshyan, Gary G. Leisk and David L. Kaplan

***Abstract*—Soft animals move by controlling body deformation instead of actuated joints and they are able to exploit changes in conformation for different forms of locomotion. The goal of this study is to identify the key constraints in a soft-bodied animal and attempt to produce locomotion in a robotic platform with the same constraints. We first designed a soft robot platform as a reduced physical model of a caterpillar. Then we fabricated a variety of devices to explore possible modes of locomotion under the constraints of such a body plan. In particular, we found six gaits and several examples in which the soft actuators and body structure determine gait generation. We intend to translate these locomotion methods and body plans directly to a biomorphic robot that is biocompatible and biodegradable. This device will be actuated by cultured insect muscles and made from soft biomaterials.**

I. INTRODUCTION

One of the continuing challenges in robotic engineering is the design of robots that can adapt to unpredictable natural terrain and complex environments. Soft robots are an attractive approach to this problem because they can adapt to the environment mechanically and thereby reduce the need for sensors and sophisticated control systems. This view is supported by studies of soft-bodied animals that can conform to varied terrain without knowing the exact geometry of the substrate [1-4].

Our studies of caterpillar locomotion [5-11] suggest that a soft crawling structure can be reduced to three key functional components: a highly deformable body, muscle-like tensile actuators and a mechanism to control grip (Fig. 1). In this study, we constructed a family of caterpillar-like robots according to the above reduced model to explore all possible modes of locomotion. Under the constraints of this simple body plan, these robots are able to move with a variety of inching and crawling gaits. A ballistic gait can be achieved via careful tuning of the body mechanics.

One of our long term goals is to produce a truly bio-synthetic soft robot that is powered by engineered muscles and moves like a caterpillar. This study of component integration and gait development in a caterpillar body plan lays down the foundation for implementing such a robot. The last section of this paper will describe a new approach to creating muscle actuators using insect cells. We show that they are remarkably robust and can survive for months in vitro at room temperature. By engineering the formation of these biocomponents we expect to develop new forms of robotic devices that will self-assemble and provide entirely new capabilities including being biocompatible and biodegradable.

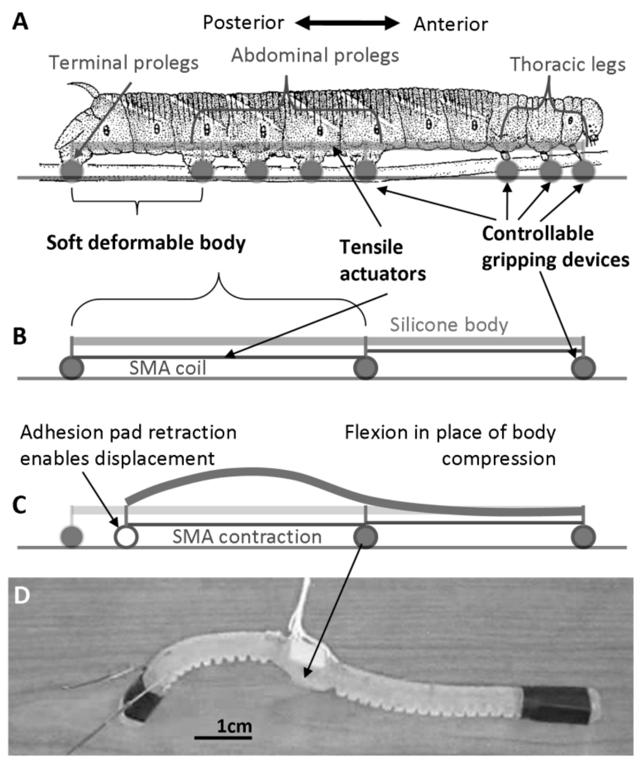

Fig. 1 Physical modeling of caterpillar locomotion. (A) Mechanically, a caterpillar (*e.g.*, *Manduca sexta*) can be reduced to three elements: soft body axial deformation, tensile actuators, and substrate attachments. **(B)** The reduced model is implemented using silicone rubber for the body and shape memory alloy (SMA) coils as the actuators. Controllable attachments are implemented as either retractable adhesion pads or unidirectional gripping flaps. **(C)** Flexion is the primary functional deformation driven by embedded SMA contractions. **(D)** Coordinating the mid body attachment enables the body deformation to propagate forward.

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B. A. Trimmer is in the Department of Biology, Tufts University, 200 Boston Avenue, Medford, MA 02155 (phone: 617-627-3924; fax: 617-627-3805; e-mail: barry.trimmer@tufts.edu).

H-T. Lin was in the Department of Biology, Tufts University, 200 Boston Avenue, Medford, MA 02155 and is now at the Howard Hughes Medical Institute, Janelia farm, 19700 Helix Drive, Ashburn, VA 20147 (e-mail: huaiti.lin@gmail.com.

A. Baryshyan and D. Kaplan are in the Department of Biomedical Engineering, Tufts University, 4 Colby Street, Medford, MA 02155 (e-mail: amanda.baryshyan@tufts.edu, and david.kaplan@tufts.edu).

G. Leisk is in the Department of Mechanical Engineering, Tufts University, 200 College Ave., Medford, MA 02155 (e-mail: gary.leisk@tufts.edu).

II. EXPERIMENTAL METHODS

A. Actuator characterization

The mechanical performance of shape memory alloy (SMA) coil actuators (wire diameter 100µm, coil outer diameter 0.4mm Toki Corp. Tokyo Japan) was characterized by uniaxial material testing in static mode to measure tension (Instron Inc., model 3366, Norwood, MA). SMA samples of 100 coils were tested against increasing series elastic cord stiffness (K_1=8.67N/m, K_2 =34.90N/m, K_3 =87.85N/m) with increased preload (Q_1=50, Q_2=100, Q_3=200 mN). We also tested the effect of increasing stimulation power (low (P_L), standard (P_O) and high (P_H)) at constant energy input using a digital power supply (Agilent E3634A, Agilent Technologies Inc., Santa Clara, CA), and a high power relay module (NI USB-9481, National Instrument, Austin, TX) to generate the digital stimulation patterns. Each test was repeated 3 times to extract the peak force and initial loading rates.

B. Measuring adhesion forces

A retractable adhesion pad was designed to provide grip at the head end of the robot. Adhesion was characterized by dragging a pad unit (weight 3.0±0.05g) across a smooth acrylic plate at a speed of 0.5mm/s (simulating static body sliding in our soft robots). The sticky pad surface could be retracted with an SMA actuator that folded the membrane crest inward. The pad was pre-stressed so that the membrane buckled out to re-expose the adhesive surface when the SMA was relaxed.

C. Body material testing

We use silicon materials to construct our soft robots. In this paper three silicone material samples are described. The first two specimens were made of VTV800 (MTT Tech Inc. Knoxville, TX), and Dragonskin 20 (Smooth-On, Easton, PA), respectively, (40mm long, 7mm wide 1.5mm thick). The third specimen was a laminated composite consisting of a Dragonskin 20 duplicate bonded to a 120% pre-strained black silicone rubber sheet (0.005" thick high-purity silicone rubber; McMaster Carr, Princeton, NJ). In this configuration, the specimen buckles in its resting state due to the residual stress in the black rubber. We focused on two uniaxial loading behaviors: stretching and buckling. Material samples were stretched or compressed using a computer-controlled lever arm ergometer (Aurora Scientific Inc., Ontario, Canada) that also measures force in the direction of loading (positive load represents tension and negative load represents compression). For stretching tests, the ergometer elongated each silicone sample by 2.5%. In buckling tests each sample was compressed longitudinally by 10%.

D. Robot control

In the robots the SMAs are controlled using bursts of current pulses. Within a range of compatible currents this allows the SMAs to be partially activated by changing the pulse frequency and duration. Open-loop control was used with either direct computer control of the pulse trains (tethered robots) or by a simple analog central pattern generator consisting of two oscillators. The master oscillator sets the gait cycle period (~2s) and drives the anterior body flexion for a fixed duration. During this time, a capacitor is slowly charged. When this capacitor reaches an adjustable threshold, the second oscillator fires and drives the posterior body contraction. Such coupling can be tuned to produce a large variation of behaviors.

III. CHARACTERIZING THE ROBOT COMPONENTS

A. Soft tensile actuators

The majority of living animals move by coupling molecular interactions between actin and myosin in muscle cells to other tissues. This type of actuator is constrained because it can only produce tension in one direction. Locomotion requires reciprocal motion and skeletal systems typically get around this problem by employing antagonistic tensile actuators. In soft-bodied animals similar antagonism can be achieved through hydrostatics; earthworms, for example, can restore body length after an axial contraction by constricting the body using circumferential muscles [12]. Caterpillars do not have circumferential muscles and must restore body length using a combination of forward force provided by the thoracic legs and passive shape restoration. Since this study aims to develop locomotor strategies for biomorphic robots powered by engineered muscles, we use soft tensile actuators in our robot to simulate the constraints.

SMA coils are very muscle-like tensile actuators. Most traditional motors driving a load use feedback control to linearize the system and control the speed of the motor. In contrast, the performance of actuators such as muscles or SMA coils is critically dependent on stimulus timing, duration and magnitude and is therefore hard to linearize. An alternative approach is to characterize the actuator behaviors and use them in the design of the robot locomotion. As an example of this approach we measured the force-length relationships of SMA coils while systematically altering coil number, pre-load, resisting stiffness and input power. For simplicity, we present data from an SMA actuator with 100 coils but results from SMAs of different sizes follow most of the same trends.

i. Resisting load stiffness

Increasing mechanical resistance consistently generates higher forces in SMA actuators (Fig. 2A). However this is often accompanied by a decrease in the achievable displacement (Fig. 2B). Increasing tensile preload usually offsets the loading curves (Fig. 2A). In general, there is a tradeoff between force and displacement and increasing the stimulation power always boost the peak force.

ii. Preload and power

Peak force production increases with more preload. The relationship is almost linear in the typical range of operation (Fig. 2C). Higher stimulating power allows SMA coils to develop larger peak forces (Fig. 2D). High power stimuli ensure that all the crystals in the SMA alloy transform into the austenite state at the same time, leading to synchronized force production, analogous to muscle fiber recruitment in animals. That is also why initial loading speed increases with resisting load, most dramatically at high power (Fig. 2D).

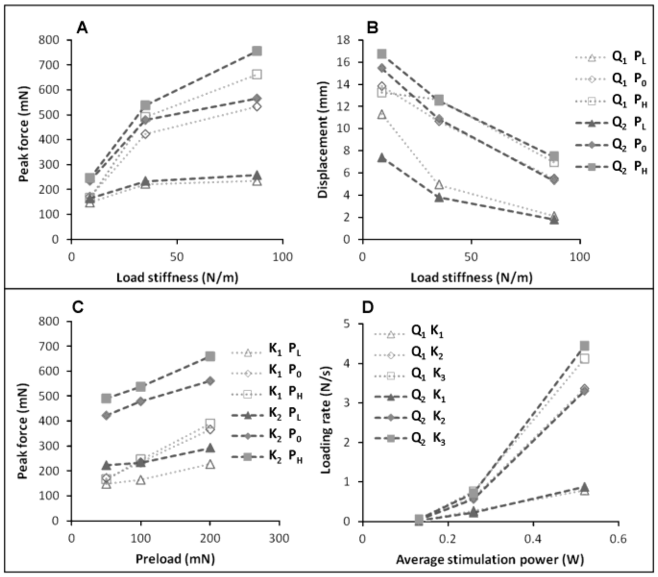

Fig. 2 Characterizing shape memory alloy actuators (A) For each preload Q_i and stimulation power P_i, increasing load stiffness induces higher peak forces. Overall, increasing preload also increases the peak forces but this effect is most notable at high stimulation power. (**B**) The increasing peak force in response to stiffer loads is accompanied by decreasing displacements although the trends are less linear with low preload Q_1 and small load stiffness. (**C**) In general, increasing preload induces higher peak force in a linear fashion. (**D**) Increasing stimulation power boosts the SMA initial loading rate. The trend is almost independent of the preload or load stiffness.

iii. Variations and efficiency

Under controlled conditions SMA actuators can produce very consistent responses (Standard deviations are plotted in Fig. 2 but virtually invisible). The variable performance of SMA actuators in practice comes from our inability to control key parameters, in particular the heating conditions. In soft robot applications it is therefore helpful to operate the SMA coils at high stimulation power with short duty cycles and to use motor units consisting of small actuators instead of one big SMA coil.

B. Discrete anchors

For most small climbing animals footholds are meant to be attachments and below the force limit they can operate in an on-off manner. We designed a simple retractable adhesion pad to provide controllable body anchors for the soft robots. The adhesion material is tacky silicone rubber made by adding "*Silicone Slacker*" (polyorganosiloxanes) to the platinum-cure silicone mixture. In general, the amount of slacker added determines how sticky the end product is [13]. However, adding too much slacker produces a silicone gel that does not resist shear force very well. A 1:1 ratio of silicone mixture to slacker works well for the adhesion pad application. Casting about a 2mm thickness of such tacky silicone rubber directly on a silicone substrate produces an effective adhesion pad. The retractable adhesion pad can introduce an immediate >100mN localized traction to a soft robot in motion and provide >400mN anchor in the static condition.

C. Nonlinearity in large deforming structure

Large deforming bodies have inherent nonlinearities in their stress-strain responses. For instance, homogenous silicone rubber may respond as a linear elastic up to very high strains in a tensile test but will then exhibit pseudo-elastic behavior in the buckling state (elastomer 1, Fig. 3A.). In the buckling configuration, the compressive force between the two ends is the greatest at the beginning and decreases as buckling progresses. This response is also seen in stiffer homogeneous materials (elastomer 2, Fig. 3A). Interestingly, an initial buckling bias preload can alter the loading profile completely. To show that this nonlinearity comes from the loading condition, we prevented one side of elastomer 2 from rotating applied both tensile and compressive tests. Tensile responses were unaffected, but by delaying buckling the linear responses extended into the initial compressive range (Fig. 3A) and once the loading exceeded ~70mN, the specimen buckled with a new characteristic work loop (w/preload curves). Indeed, the material itself is perfectly linearly elastic (as shown in tension and compression tests), but depending on the loading condition it can produce highly nonlinear responses which are tunable and repeatable.

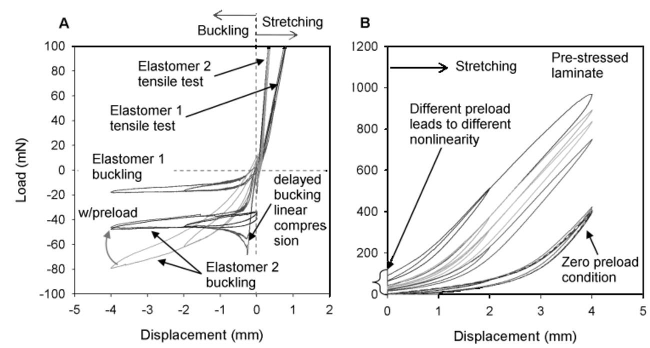

Fig. 3. Nonlinear behaviors from linear materials. (**A**) Stretching tests of two silicone elastomers with different stiffness's confirm that they respond linearly in tension. Under compression they buckle, a nonlinear loading condition which depends on the initial conditions (see text for details). (**B**) When two different linear elastic materials are combined into a laminate, residual stress can lead to pseudo-elasticity (differing displacements during loading and unloading) and work softening (changing curves with increased displacement).

Another example of nonlinearity is residual stress. Most biological tissues are developed by lamination and therefore contain residual stress. We can simulate this condition in a silicon rubber specimen by bonding one layer of rubber under stress to another unstressed layer. This produces a material with a buckled resting configuration due to the residual stress (pre-stressed laminate). In extension tests this specimen produces load-stiffening behavior, which depends closely on the amount of preload (Fig. 3B). In essence, any stretching force has to unbuckle the specimen before it can engage in the linear material stretching. The unbuckling process increases the material stiffness gradually as the structure aligns itself to the loading direction. At high load, the composite is again linear (Fig. 3B). Reducing the preload means starting the loading at a more buckled configuration, and therefore engages more load-stiffening effects. This behavior is highly repeatable and analogous to the responses of caterpillar soft cuticle [7].

IV. A FAMILY OF SOFT INCHING ROBOTS

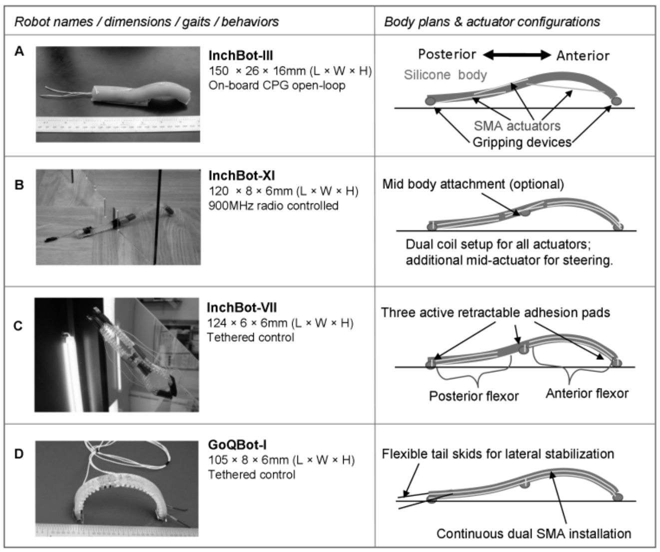

Fig. 4 Representative soft robots for the studies of caterpillar locomotion. The left panel shows four representative robots and their basic characteristics. The right panel shows the positions of the embedded SMA actuators, adhesion pads and the overall body configurations.

A. Robot body movements and basic locomotion

Based on the body plan outlined previously (Fig. 1), we designed a family of soft inching robots to explore different possibilities for soft body locomotion. Some representatives are shown in Fig. 4 with key design parameters and schematics conveying the body plan and actuator configurations. One of our earliest inching robots, InchBot-III, was cast using silicone foam. Ethyl alcohol was added in the silicone curing process as a foaming agent. Unidirectional gripping structures were implemented at the two ends of the body (active sticky pads were not used in this early model) to facilitate locomotion. The second-generation robots assumed the two-segment body plan as exemplified by InchBot-XI (Fig. 4B). Pairs of SMA actuators were installed in the robots and the body actuators were functionally divided into anterior and posterior flexors. Retractable adhesion pads were introduced with SMA controlled retraction. This robot was steerable, radio controlled, and capable of creeping under a 1cm gap. The robustness of this crawling gait was demonstrated for a flat surface climb in InchBot-VII (Fig. 4C) that was able to climb an inclination angle of 45 degrees. Improved and/or additional adhesion devices should allow even better performance in the future. In an attempt to develop faster modes of locomotion, we implemented a ballistic rolling behavior in the later inching robots, and the robots were named "GoQBot" (Fig.4D). Details of GoQBot's dynamic locomotion (> 0.5m/s) has been published separately [14]. In the rest of this section, we will discuss how different properties of the soft robot components were used in our robot design.

One key element for effective robot movement is to match the SMA actuator properties to robot body stiffness. Since it is difficult measure the in-situ stiffness of a silicon body, we tested each actuator installation and adjusted the loading conditions using the performance trends described in Fig. 2. For example, buckling is a nonlinear loading condition in which stiffness decreases with the amount of flexion. Therefore, the peak force of an SMA actuator determines whether the actuator can buckle the segment and initiate curling movements. Once the movement starts, the stiffness decreases and the SMA exerts less force accordingly. The peak force to cause curling was manipulated by changing the preload and stimulation power (Fig. 2C). For movements that require long strokes it is important to minimize the load stiffness. This can be done by installing two SMA actuators in parallel and thereby shifting the available displacement to higher values (Fig. 2B).

In the most basic locomotion gait, (Fig. 5A) InchBot III pulls its body forward by flexing the anterior segment. The posterior part of the body is lifted in the process, which reduces friction to help move forward. Once the robot starts to relax, the posterior segment settles down to the substrate and stops the body from sliding backwards. The anterior segment then can re-extend through internal restoring forces. Alternatively, the posterior segment could initiate a crawl by curling up the rear end to produce a small forward displacement (Fig. 5B). Combining these two basic movements, InchBot-XI employs a loose crawling gait (Fig. 5C) which is much faster than using either alone.

B. Gait variations and transitions

Controllable attachments increase the robustness of the loose crawling gait. With three retractable adhesion pads, InchBot-VII propagates a displacement in the anterior-grade manner up an incline of 45 degrees without any noticeable change in kinematics (Fig. 4C). As illustrated in Fig. 5D, the InchBot-VII initiates a crawl cycle by first releasing the posterior adhesion pad and then pulling the posterior segment forward. After replanting the posterior adhesion pad, the mid-adhesion pad releases followed by a forceful contraction in the anterior segment. This transfers the body contraction (buckling) forward. As soon as the mid-adhesion pad reattaches to the substrate, the anterior adhesion pad would release in order to advance. The mid-body adhesion pad isolates the anterior deformation from the posterior one. This allows the posterior segment to recover quicker and initiate another crawling cycle while the anterior segment is recovering. This simple "3-point climbing" gait represents the fundamental mechanism of crawling in caterpillars. Of course, crawling caterpillars achieve the necessary body contraction via segmental compression and have much more secure body attachment devices [6]. Nevertheless, the climbing gait of InchBot-VII demonstrated caterpillar's robust climbing gait from flat-ground to 45 degrees with the same kinematics (minimal slipping and almost identical step length).

More behaviors can be produced from the same gait pattern by scaling the power and timing. For a soft robot with a loose-climbing gait, increasing the actuator power amplifies the body flexion and reduces the phase difference between posterior and anterior flexions. Further temporal compression of the gait pattern improves the body coordination and produces a fast inching gait (Fig. 5E) which is five times faster than the 3-point climbing gait. However, this speed comes with a cost on stability. Amplified flexion means raising the center of mass much further away from the ground adhesion pad attachments. The probability of tipping over increases dramatically as the adhesion pads are also soft and cannot resist the lateral tipping moments. The two tail struts (Fig. 4D) made of flexible polypropylene (OD = 460±10μm) were added to the body to increase lateral stability. In the absence of an airborne phase (such as hopping or running) the only way to increase locomotion velocity is to increase the step length or the pace frequency. Caterpillars typically perform a fast crawl by cycling the waves of muscle contraction more quickly. However, in some cases, they change from crawling to inching, thereby taking the largest possible steps. Our soft robot experiments suggest that pacing a crawling gait together with higher stimulation intensity could result in a continuous transition to inching gaits.

Interestingly, increasing the actuator power sometimes tipped the robot forward into a tumble. Such a phenomenon prompted us to consider the possibility of creating a rolling motion to boost the locomotion speed. Surprisingly, caterpillars indeed do perform such a rolling behavior but only under special conditions. A group of small caterpillars *Pleuruptya ruralis*, native to the United Kingdom, feed on low nettle vegetations and perform a backward ballistic roll when startled on a flat surface [15]. We found several leaf-rolling caterpillar species in the mountain range of volcano Cacao in Costa Rica that perform comparable escape behaviors (unpublished data, H.T. Lin and B.A. Trimmer). Using this escape behavior as an inspiration and kinematic model, we successfully reproduced ballistic rolling (Fig. 5F) in several versions of GoQBot. The latest version, GoQBot-V was used to characterize the kinematics of ballistic behavior and to measure changes in the ground reaction forces at the head as the robot launches. On a flat level surface, this mode of locomotion boosts the speed over ten-fold. The mechanics and control of ballistic rolling is beyond the scope of this paper and have been previously published [14].

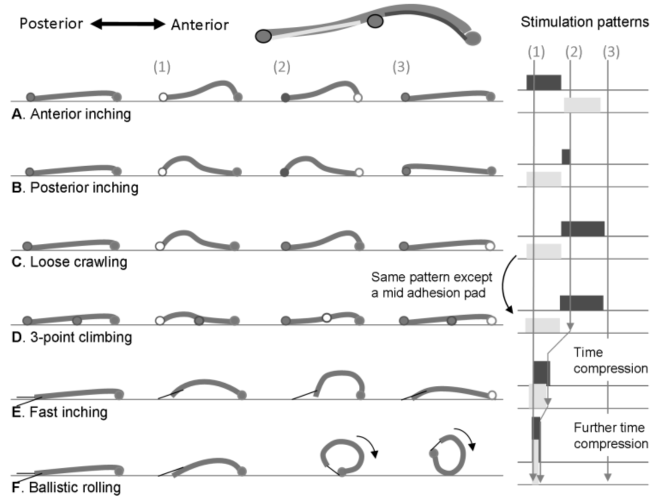

Fig. 5. Schematic gait maps of caterpillar-like soft robots. Six modes of locomotion are shown (top to bottom) with schematic diagrams illustrating the robot body configurations in a given gait pattern (left to right). Most soft robots have mechanisms for locking down the body (noted by solid circle). Open circles represents attachment devices in the retracted state. Gait **E** and **F** involve a pair of tail skids for lateral stability. The right panel shows the patterns of stimulating pulse trains (block height represents power, length represents relative timing) given to the anterior flexor (dark) and posterior (light) flexor respectively.

Development of these soft robot gaits showed that gait transitions can arise from gradual changes by scaling the gait timing and driving power. From partial inching gaits to a loose crawl, the robots can transfer body contraction forward with both ends locked down to the substrate. This body wave then can be secured by the addition of a mid body attachment for climbing. The 3-point climbing gait really resembles the moving principles of crawling caterpillars and illustrates the necessity of mid abdominal prolegs for larger crawling caterpillars. Fast inching can be directly derived from the loose crawling gait by pacing the motor pattern differently and increasing the actuator drives. Pushing this modification to the dynamic regime leads to a ballistic rolling behavior. Indeed, caterpillars performing ballistic rolling escape may only need to drive their typical reverse crawling pattern faster and more forcefully, as suggested by the previous studies [16]. One general finding from these gait transitions is that actuator tuning (SMA length, size, arrangements, preload, etc) becomes increasingly important as we attempt faster locomotion. Clearly, any accurate body co-ordination in a truly soft robot requires muscle-like actuators that can be scaled for different applications and fabricated with intrinsic material.

V. MUSCLE-BASED ACTUATORS

The development of soft robots brings new materials into engineering design and creates opportunities for machines with entirely novel capabilities. One of these important areas exploits biological processes to build biomorphic devices; machines built primarily from biopolymers and living tissues. In addition to being biocompatible and biodegradable they have the potential for self-assembly and cheap scalability. Initially, these devices will be directed by chip-based controllers and flexible electronics interfaces. The primary challenge is therefore to make robust bioactuators. Several studies have demonstrated the potential for explanted muscles in biotic-abiotic hybrid devices [17, 18]. While these studies serve as a valuable proof-of-concept, a tissue engineering approach may be more appropriate to control dimensions, composition, structure and force generation of such constructs. This can be accomplished with mammalian tissues [19-21] but insect cells offer numerous advantages including their easy availability, independence from vasculature and extreme resistance to harsh environmental conditions.

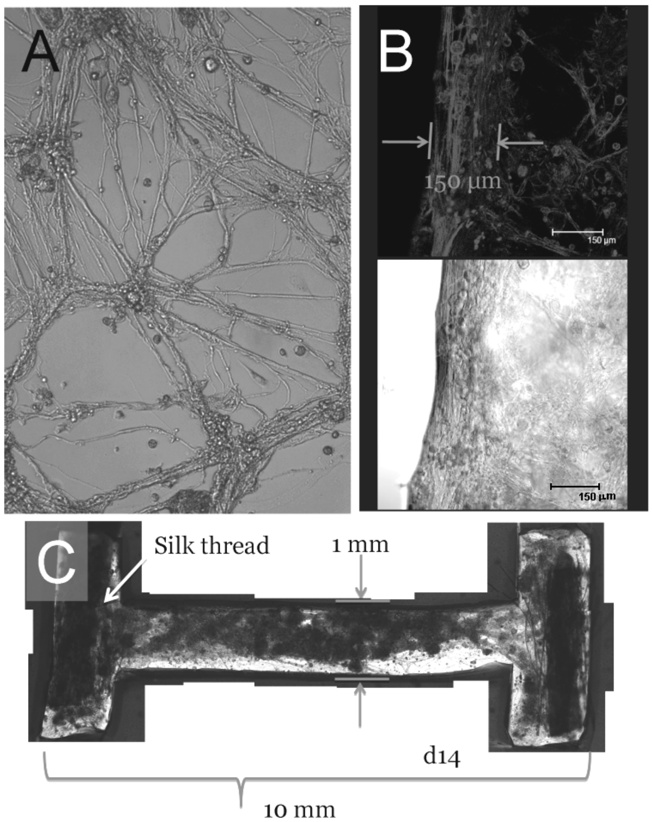

Fig. 6. Cultured insect myocytes and the formation of muscle-based actuators. (**A**) Embryonic *Manduca* myocytes can be grown in culture into networks of spontaneously contracting muscle cells. (**B**). Growing cells on structured substrates helps to organize them into bundles ≈150 µm wide (top, actin filaments stained, bottom muscle construct). (**C**) Cells can be organized into muscle bundles with silk suture attachments at each end. Future work will use tendon precursor cells to engineer tendon-like attachments.

We have isolated and cultured insect myocytes from caterpillar (*Manduca sexta*) embryos and differentiated them into muscle cells using the developmental hormone 20-hydroxyecdysone (Fig. 6A). They spontaneously contract and continue to do so for several weeks without the need for fresh culture medium or special atmospheres [22]. The initial interconnected myotube networks continue to grow and to form bundles of fibers that can be aligned by using structured substrates (Fig. 6B). These bundles of fibers can be directed to grow around attachments point such as silk sutures (Fig. 6C) and the result construct forms a novel muscle-based actuator. These constructs are similar in size to the SMA actuators used in our robots. They survive for many weeks under simple culture conditions at room temperature and we are now characterizing their mechanical properties so they can be incorporated into a small robotic platform.

VI. Discussion and Conclusions

Animals or robots without articulated limbs face a difficult challenge in controlling their body kinematics. It is therefore advantageous to embed useful behaviors into the materials and structures [23]. In this paper, we classify the types of nonlinearity in soft actuators and materials and demonstrate the general concept of tuning soft materials to perform the desired movements. Using only open loop control we show that gait transitions can arise by scaling the gait timing and actuator power. These gaits include partial inching gaits, loose crawls, fast inching and even a ballistic rolling behavior. Because we design the locomotor trajectory into the body itself (*i.e.*, morphological computation) these robots have an inherent robustness allowing variations in the control patterns. For fast movements such as rolling the structure determines a set of initial conditions for dynamic behaviors.

These studies have led to two general strategies for future soft robot implementations. One is to characterize, and then exploit, material complexity in the design of the device. The second is to directly employ biologically derived materials and processes in the construction of new devices. It is our belief that for some critical applications the ability of cells to self-assemble at the nano (actin-myosin interactions) and macro-scale (complete muscle-tendon systems) will provide a revolutionary new approach to robotics, prosthetics and device design. Soft biomorphic and bioinspired robots will play important roles in environmentally sensitive environments, in assisting humans and their health care and in promoting safe, biocompatible and biodegradable technologies.

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