Animal Models for Non-pneumatic Soft Robots

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Abstract Soft animals can be seen as "living prototypes" to inspire and inform the development of soft robots. However, soft animals are extremely diverse in their biomechanics and neural control systems. These differences should be carefully considered when selecting a biological model to guide robot design. It is also important to consider the technical advantages and limitations that affect the type of information that can be collected from different species. Aside from swimming robots, most soft robots and soft manipulator arms are inspired by annelids and cephalopod mollusks. Both groups are essentially fixed-volume hydrostats that exploit pressure differences to change shape and to gain mechanical advantage. Some robots inspired by these animals mimic their underlying mechanisms (and anatomy), whereas others produce similar movements using entirely different principles. By far the most numerous and diverse group of soft animals are larvae of the holometabolous insects. Because they contain internal air tubes, insect larvae control movements using direct actuation instead of pressure control alone. Insects also have highly stereotypical and modular anatomy and easily accessible neural coding making them excellent prototypes for non-pneumatic robot design. By mapping key features of caterpillar locomotion onto robot design a new class of robots has been fabricated from simple elastomers powered by shape memory actuators and motor-tendons. These robots have proved useful for exploring different control strategies and have the capacity to move quickly. Robots based on these design principles are expected to be useful for climbing in complex 3 dimensional structures and in low gravity environments.

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1 Animal Models for Better Robots

In the quest to make robots function in more diverse environments, many engineers have turned to studies of animal locomotion for inspiration and guidance. However, most studies of animal biomechanics have focused on organisms that have stiff, articulated skeletons such as adult insects, birds and mammals. These animals are attractive prototypes because their basic movements often can be described using simple models composed of springs, dampers and connected rods. This has led to an emphasis on the skeleton itself, largely ignoring the roles of other tissues and structures.

It is becoming increasingly clear that soft structures play an important role in producing the robust and adaptable movements that characterize animal behavior. This realization has led to increasing efforts to incorporate soft materials into robots. In trying to address the challenges of design, fabrication, and control of these robots, some researchers are attempting to build machines that are completely deformable. They have taken inspiration from a variety of soft animals but there has been relatively little attention paid to the distinctions between these different animal groups. In this chapter I will briefly summarize the major groups of soft animals and some of the robots inspired by them. I will then describe in more detail the specializations of lepidopteran larvae (caterpillars) that make them an attractive model system for the design and control of soft climbing robots.

2 Soft Animals as Model Systems

Most animal species are completely soft, or soft for a large proportion of their lifecycle. Of the more than 1 million animal species currently described [1], at least 88,000 (cephalopod mollusks, annelids, nematods, cnideria/ctenophora and platyhelminthes) generally have no stiff skeleton and over 600,000 species (the holometabolous insects) have soft larval stages. The biomechanics of locomotion in these soft animals has only been studied in a relatively small number of species and even fewer have been used as models for robot locomotion. Some of the more novel examples include jellyfish (cnideria/ctenophore) which swim slowly but can rise and descend in a column of water by controlling the way they contract their delicate bell of muscles. This has been replicated in robots with similar structures but the membranes are generally supported on a lightweight articulated frame.

Aside from these aquatic examples, the majority of soft robots have been modeled on annelids (worms) and cephalopod mollusks such as squid and octopus. Both of these major groups are hydrostats; their bodies and limbs are fixed-volume, deformable, cylindrical structures. The internal compartment of worms is largely fluid whereas the arms of cephalopods are predominantly muscular.

Worms as robot prototypes. Annelids (and nematodes) are an attractive biomechanical system because their movements are controlled by regulating the tension in longitudinal and circular muscles. Contraction of the longitudinal muscles shortens the body and increases the radius proportionately. This movement can be antagonized by contracting circular muscles to reduce body radius and increase length. This relatively simple mechanical concept has been exploited in several wormlike robots. A common feature of these devices is a wave of segment contraction from the front (head) to the back of the robot and some sort of differential friction device to promote forward crawling. Many of these modes of locomotion have been modeled mathematically.

Cephalopods as robot prototypes. The arms of the octopus (and elephant trunks) have been inspirational for developing soft manipulator arms [2, 3]. Arm musculature is complicated but in general movements are controlled in a similar way to annelid locomotion. By adjusting the local stiffness through circular and oblique muscle contraction, the arms can be bent into many configurations and the arm can assume different configurations simply by interacting with the surrounding fluid.

Worms and octopus have inspired a variety of robots using similar principles but with quite different body structures. For example, many robots have been constructed with internal body cavities that can be inflated and used as actuators [4]. Using clever combinations of materials and structural stiffness, devices have been designed with directional bending and the ability to inflate in complex shapes such as spirals. Although these pneumatic robots and manipulator arms do not directly mimic any known animals (with a few exceptions, animals do not inflate and deflate to locomote) similar structures are seen in nature, with the duck penis being a notable example. An attractive feature of pneumatic actuators is their ability to sustain very large forces and to produce large displacements [5]. However there are challenges to making pneumatic robots predominantly soft (an untethered device must carry its own compressed gas or pumps) and larger devices require volumes of gas or fluid that move too slowly for many applications.

Flatworms as robot prototypes. Although they are included here for completeness almost nothing is known about the biomechanics of platyhelminth (flatworm) movements. They possess dorsal and ventral muscle bands and are probably hydrostatic in the sense that their tissues can be displaced in all directions but they do not change in total volume in the normal time course of locomotion. Larger species propel themselves through water using waves of contraction of these body muscles but smaller species propel themselves using a ciliated ventral surface.

The remaining group of soft animals, holometabolous insects, constitute the largest number of animal species known. During their larval stages these animals have many features that distinguish them from those already described. In the following Section I will discuss the properties that make insect larvae, particularly caterpillars, useful and interesting model species for understanding soft body locomotion.

3 Insect Larvae as Living Prototypes for Soft Robots

As befitting their diversity, the larval stages of holometabolous insects vary tremendously in ecology and means of locomotion. The larvae of hymenoptera (bees, wasps and ants) in a collective hive can be legless and relatively immobile or in free-living parasitic forms can be highly mobile, digging into the tissues of their host. Dipteran (fly) larvae such as mosquitoes have an entirely aquatic larval phase with a unique wriggling method of swimming, but most fly larvae ("maggots") have rudimentary appendages and move by burrowing through their food. Together with annelids, these legless insect larvae are good subjects for identifying how to move within a supportive substrate.

The remaining major groups of holometabolous insects are the lepidoptera, (butterflies and moths) and coleoptera (beetles) that together are the most numerous species of animals. Depending on their ecological niche, the larvae of beetles and butterflies can be remarkably similar. The majority of beetle larvae have three pairs of thoracic legs but lack any locomotory appendages on the abdomen. Most of these larvae are found burrowing inside plants or underground. Although some lepidoptera larvae also live within leaves and have reduced or absent appendages, most are highly mobile climbing animals called caterpillars.

Caterpillars as robot prototypes. Because they are such ubiquitous and successful climbing animals, caterpillars are an attractive model system for understanding softbodied locomotion [6]. Through detailed studies on the 3-D kinematics of motion, by measuring ground reaction forces on each of their appendages, and through x-ray video imaging of internal tissues, it is now possible to describe caterpillar locomotion in detail. Furthermore, the material properties of the body wall and muscles have been characterized and modeled and the internal pressure changes associated with movements have been monitored. Finally, caterpillars provide a unique opportunity to understand how the central nervous system interacts with biomechanics to control softbodied movements. This is because each muscle is innervated by a single motoneuron. Therefore, by implanting electrodes alongside the muscles it is possible to record the pattern of neuronal spike activity associated with particular movements. Across multiple muscles, this neuronal spike activity constitutes the entire efferent information used to control movements.

The results of these studies can be summarized as a series of "traits" of caterpillar locomotion [7] that can be mapped onto desirable features for a soft robot that can perform similar tasks (Fig. 1). The primary traits are:

1. Caterpillars are hydraulic rather than hydrostatic. Although they have an open body plan and can alter their overall stiffness by pressurization, hydrostatic pressure does not seem to play a major role in the control their movements. This is probably because insect tissues are filled with tubes (trachea) for gaseous exchange making the internal volume variable and compressible.

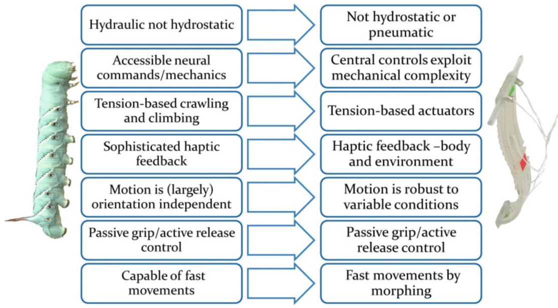

Fig. 1 Mapping caterpillar traits onto features for soft robot design

2. Most neural codes appear to be relatively imprecise; the input to each muscle can vary from moment to moment even during similar movements. This suggests that biomechanical responses are relatively robust and perhaps act as "mechanical computers" to interpret descending activity appropriately.
3. Crawling caterpillars maintain their body in tension for much of the step cycle. Forward movement is achieved by a combination of elastic recoil and active muscle contraction. This allows them to apply compressive forces to the substrate and to keep their body relatively soft and compliant. We have called this strategy the "environmental skeleton."
4. Because they lack long-range sensing, locomotion relies on feedback from mechanosensors. Caterpillars have sophisticated peripheral touch and proprioceptive organs that are accessible for studying the encoding of haptic information.
5. Although they can change their stepping pattern in response to substrate quality and orientation, caterpillars can crawl and climb using the same kinematics. This makes them useful models for robots moving in reduced gravity environments such as space or underwater applications.
6. The success of caterpillars in scansorial environments is largely attributable to their impressive grip. The abdominal prolegs passively attach to substrates and actively release their grip. This appears to be a self-compensating system controlled by a single neuron for each proleg.
7. Although most terrestrial soft animals are slow-moving, caterpillars can exploit shape-change to produce fast movements. They can quickly roll into a circular shape and propel themselves ballistically. This remarkable trait has been replicated in a soft caterpillar-like robot.

4 The Design and Control of Caterpillar-Like Robots (*Softworms*)

With these caterpillar traits in mind we have designed, fabricated and tested, a wide variety of caterpillar-like robots called Softworms [8]. These designs can be 3D printed as molds into which different soft polymers can be cast or printed directly using a multi-material 3-D printer. Direct printing produces robot bodies of any complexity without increasing fabrication difficulty. The body is composed of a soft elastic polymer and stiffer materials can be printed in the same build for motor housings and other components. Most of these devices are tethered so that electrical power and control can be delivered from remote equipment. We have also built an untethered Softworm carrying batteries and a radio receiver. Most of the robots are elongated structures but we have also constructed devices with three, four and six limbs to test hypotheses about the scalability of control structures.

Although it is possible to add actively controlled gripping systems to these robots, we have instead followed the design principles derived from caterpillars and minimized the number of actuators controlling behavior. Softworm grip is achieved by feet each end of the body made of TangoPlus®, a soft and sticky material. When the body bends it changes the substrate contact angle and, beyond a certain threshold, transfers contact to a smooth slippery material allowing the foot to slide. This principle has also been exploited in multi-limbed Softworms and is a key design element for some control systems.

Shape-memory alloy actuated Softworms. For research purposes, the smaller Softworm robots are actuated by shape-memory alloy (SMA) coils attached at specific locations within the body. Passing current through these coils causes resistive heating and contraction strains as much as 100 %. As the SMA cools it is restored to its resting length through elastic recoil or by activating a nearby SMA. This type of actuation resembles muscle in that active force can only be generated in tension and the restorative force comes from other actuators or from stored elastic energy. Different actuators can be placed in the body for steering and 3 dimensional bending [9].

A primary motivation for developing the Softworms is to explore strategies for controlling locomotion in deformable machines. We have explored two approaches that are only briefly summarized here and explained in more detail in several publications [8, 10, 11]. Both methods avoid modeling the physics of the body or its interaction with the environment. The first method is based on autonomous decentralized control. Movements are generated by the interaction of oscillators and feedback adjusts the phase of these interactions. This feedback can be from sensors that monitor tension or a mechanical response through interactions with the environment. The second control approach is based on control primitives in which movements are discretized into simple states (*e.g.*, high or low friction). A series of transitions between these states defines locomotion gaits and the effectiveness of these transitions can be learnt. The system can be described using map based methodologies and by optimizing periodic control sequences. We have shown that different caterpillar gaits such as crawling and inching can be mathematically defined using this approach. One advantage of this model-free method is that multi-limbed robots can still be controlled when one of their limbs is disabled. The large map of possible nodes and transitions of a multi-limbed robot reduces to a much smaller set of effective simple cycles. It remains to be seen how well the method applies to very complex multi-limbed robots or movements in other contexts.

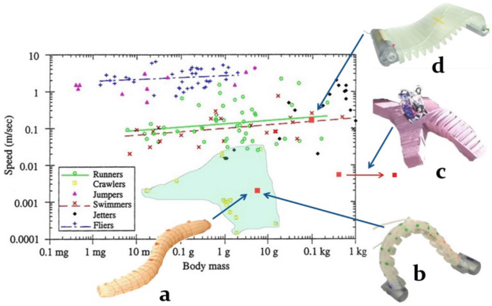

Fig. 2 Soft robots are typically very slow for their size. Most devices (*e.g.*, **a** and **b**) perform similarly to crawling and burrowing animals shown in the *shaded area*. Current pneumatic robots (*e.g.*, **c**) can be made impressively large but they are not faster. The motor-tendon drive robot, M-Bot (**d**), moves ten times faster and is comparable to running and swimming animals of similar size. Adapted from [13], **a** from [14], **c** from [5] and **b** and **d** from [8]

Motor-tendon actuated Softworms. Although the SMA-actuated robots are simple and effective research devices, they are too inefficient, underpowered and slow for most practical applications. As an alternative, we have built Softworms powered by electric motors pulling on tendons [12]. To maintain the flexible and conformable advantages of soft robots the heavy and stiff motors are housed separately from the deformable parts of the robot. A key design aspect of these robots is defining the location and path of tendons. We have shown that the effects of different configurations can be modeled using relatively simple methods and that tendons can be placed to optimize translation or rotation of the robot. We have also demonstrated that these robots can crawl very quickly compared to soft robots powered by other mechanisms. For example, M-Bot, a simple block-like Softworm powered by two rotary motors and employing the simple friction switching mechanism already described, can crawl at half a body length per second (about 10 cm/s). This is an order of magnitude faster than most other flexible crawling robots using SMAs, servos or pneumatic actuators. It is also gratifying to see that this velocity exceeds that of most crawling animals and is comparable to the speed of running or swimming animals when scaled for body size (Fig. 2).

5 Concluding Remarks and the Future

Although the design, fabrication and control of entirely soft robots are relatively new fields, there have been many dramatic advances. The recent Grand Challenge in Soft Robotics competition (sponsored by the RoboSoft Consortium) was an opportunity to see the variety of early-stage conformable machines. Most of these machines are still relatively slow and difficult to control but soft materials are finding their way into hybrid robots that combine the advantages of traditional robot

Fig. 3 The Softworm motor-tendon technology has been applied to power a large (60 cm) robot constructed from plastic foam. A living caterpillar is shown in **a** together with motor housings and the body. **b** shows the robot lifting its "head" and **c** and **d** show stages of a single "step" during the RoboSoft Grand Challenge Competition. Photos curtesy of the Tufts RoboSoft Team

components with the morphability and robustness of deformable structures. From our own research we have been able to demonstrate that caterpillar-like structures, combined with motor-tendon actuators, can be made quite large (60 cm long or larger) and are capable of crawling and navigating through obstacles. These robots can be fabricated from a huge variety of materials including elastomers and compressible foams (Fig. 3).

Although there are still enormous challenges to address, we can now foresee the development of useful and deployable devices. It is important that soft robots are developed for applications that make use of their unique combination of capabilities. Robots based on borrowing animals such as worms and some insect larvae can expand our ability to explore underground and to search for survivors in the debris of an emergency situation. Similarly, robots based on the remarkable climbing ability of caterpillars will help in exploring complex three-dimensional environments such as forest canopies, agricultural applications and electrical wiring. They will also be extremely useful in low gravity situations.

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