Biorobotic approaches to the study of motor systems

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Biorobotics is a promising new area of research at the interface between biology and robotics. Robots can either be used as physical models of biological systems or be directly inspired by biological studies. A great deal of progress has recently been made in biorobotic studies of locomotion, orientation, and vertebrate arm control.

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Abbreviation

DOF	degrees of freedom

Introduction

In recent years, there has been a growing recognition of the crucial roles played by an animal's body and environment in understanding the neural basis of its behavior. According to this view, behavior arises through the interaction of neural activity, the body, and the environment [1], an idea whose roots go back to cybernetics [2]. Given that these three component systems have co-evolved and the fact that only the behavior of an entire animal is subject to selection, it is hardly surprising that animals must be understood as integrated wholes. This is particularly true in motor control, where the behavioral consequences of a given pattern of neural activity can depend on muscle properties, limb geometry and mechanics, and the surrounding media, and where neural activity is often strongly influenced by sensory feedback.

While our understanding of the properties of such coupled neuromechanical systems is in its infancy, a number of researchers have begun to explore these issues through experimental analysis and modeling of neural activity, peripheral biomechanics, and ecological context (see [3••]). Computer modeling of complete neuroethological systems has been termed computational neuroethology to acknowledge its similarities to computational neuroscience and yet emphasize its broader focus on linking neural activity to behavior through the physical properties of the body and environment [4,5]. Given the importance that computational neuroethology places on the embodiment of a neural circuit and the 'situatedness' of that body within an ecological context, it is quite natural to extend this approach to include the use of physical robots [6].

There are at least two distinct ways in which robots can be applied to the study of motor systems. First, robots can be used as physical models of animals to address specific biological questions. Given the difficulty of accurately modeling the physical world, an important advantage of robots over simulation is that the physics comes 'for free'. However, a major difficulty in robotic modeling is ensuring that the relevant physical properties of the robot sufficiently match those of the animal relative to the biological question of interest. Second, for engineering purposes, biologically inspired robots can be built that incorporate aspects of animal biomechanics and neural control to improve their agility and robustness on a given task. Many levels of biological inspiration are possible, from vague resemblance to strict emulation. Some of the major issues that need to be considered are the degree of realism necessary to reap the benefits of biological inspiration and the separation of incidental biological details from those essential to performance on the task of interest. In this review, we summarize selected recent work in which robots either have been used to address specific biological questions or have been directly inspired by biological studies.

Locomotion

Locomotion has been a major focus of biorobotic research. Robots have been used to explore various modes of locomotion, including flying (e.g. [7]), swinging from handhold to handhold (brachiation) [8], and serpentine locomotion (e.g. [9]). Chiel and colleagues [10•] have recently developed a three-segment worm-like robot that can crawl under water by using a hydrostatic design in which fluid-filled bladders are compressed by shape memory alloy springs (i.e. springs that return to their original length when heated). Research in legged robotics has been particularly active, and has a long history (see [11]). Pratt and colleagues [12•] have built a number of planar bipedal walking robots whose legs are loosely modeled after turkeys and flamingoes. Humanoid robots capable of unconstrained bipedal locomotion are a very active area of research, especially in Japan (see e.g. [13,14•]).

A variety of insect-like hexapod robots have also been constructed (see e.g. [15,16]), and a number of reviews of insect walking aimed at robotics have appeared [17,18]. Working with Cruse [19], Pfeiffer and colleagues [20] built a hexapod robot based on the leg geometry of the walking stick insect and controlled by stick insect leg coordination mechanisms [21]. Recent work has focused on neural network implementation of these coordination mechanisms [22]. We have developed a series of hexapod robots whose design and control were based directly on studies of insect walking [23••].

Most recently, Quinn and colleagues [24••] have constructed a robot modeled closely after the leg geometry of the cockroach *Blaberus discoidalis* [25,26], with five degrees of freedom (DOF) in each front leg, four DOF in each

Figure 1

Several recent examples of biorobots. **(a)** A cockroach-like hexapod robot based on the leg kinematics of *Blaberus discoidalis* [24••]. **(b)** A robotic fish inspired by the chain pickerel Esox niger [29••]. Photograph courtesy of John Muir Kumph. **(c)** A biorobotic model of the human arm [46]. Photograph courtesy of Blake Hannaford.

middle leg, and three DOF in each rear leg (Figure 1a). The robot is pneumatically actuated, giving it sufficient power to climb, run and lift a 30 pound payload. A postural controller was implemented [27••] using a virtual model control scheme [12•] and solving the problem of redundant DOF by encouraging equal weight distribution and minimizing joint torques in the supporting legs. This controller allowed the robot to recover smoothly from substantial postural perturbations. The robot has demonstrated the benefits of an insect-like posture for minimizing ground reaction forces, as well as the importance of stiffening joints before ground contact, and the role of higher centers in postural control. In addition, the ability to manipulate a physical model of the insect leg has provided biological insight into insect leg kinematics. Finally, because actuators are expensive, roboticists challenge the biologists to justify the functional importance of each degree of freedom during climbing and rough terrain locomotion.

Swimming has been another major focus of biorobotic research. Most of this work has been motivated by a desire to create autonomous underwater vehicles with the efficiency and maneuverability of fish, but it has also provided important insights into the mechanics and control of fish swimming. Triantafyllou and colleagues (see [28]) developed a suspended robotic fish modeled after a bluefin tuna that was used to explore how fish can reduce drag and create propulsive jets by carefully controlling the development and positioning of vortices. This work demonstrated the significance of the Strouhal number, which quantifies the frequency and spacing of vortex formation, and defined an optimal range for thrust-inducing vortex formation. This led them to examine data from swimming fish, and they found Strouhal numbers that fell within this optimum range.

More recently, Kumph and Triantafyllou [29••] developed a free-swimming robotic fish (called RoboPike) modeled after the chain pickerel *Esox niger* (Figure 1b). RoboPike's main body has two articulations, each controlled by a servo motor. A third servo motor controls the pitch angle of a caudal fin. In addition, there are pectoral fins on each side of the body, each controlled by a small servo. RoboPike is being used to explore fast C-starts (in which a fish makes a C-shaped flexion to initiate escape), forward swimming, and maneuverability. For example, RoboPike has already provided important insights into the effectiveness of the C-start used by the northern pike and trout for rapid acceleration. In addition, Mojarrad and Shahinpoor [30•] have examined the application of muscle-like actuators to a caudal fin, and Kato and Inaba [31] have examined the use of specific kinds of pectoral fin motions to maneuver a robotic fish.

Orientation

Orientation behavior has been another major area of research in biorobotics. On the basis of studies of insect eyes and motion-sensitive neurons in the fly, several investigators have constructed insect-like compound eyes and used them to extract optic flow for obstacle avoidance, object tracking, and pursuit of a visual target in mobile robots [32,33•]. The neural architecture underlying the escape turn of the American cockroach *Periplaneta americana* has been applied to a crash avoidance system for wheeled vehicles [34•]. A small underwater wheeled robot with conductivity sensors was used to test chemical orientation strategies employed by lobsters to locate odor sources [35]. Finally, models of portions of the inferior colliculus and optic tectum underlying auditory localization in the barn owl have been applied to adaptive auditory and visual orientation in a robotic head [36••].

Lockery and colleagues [37••] recently constructed a robot based on studies of chemotaxis in the nematode *Caenorhabditis elegans*. Like *C. elegans*, the robot sensed stimulus intensity at a single point, moved forward at a constant speed, and oriented by controlling steering angle. For simplicity, the robot was wheeled and performed phototaxis rather than chemotaxis. Linear neural networks loosely based on the chemotaxis circuitry of *C. elegans* were optimized for phototaxis in simulation using simulated annealing and then downloaded to the robot and tested. The robot exhibited nematode-like trajectories and was robust to perturbations in instantaneous speed and turning bias. An analysis of the model chemotaxis circuitry led to the formulation of specific hypotheses about the nematode's response to the time rate of change of concentration that were subsequently tested in the animal. Lockery and colleagues (SR Lockery, personal communication) discovered that although chemotaxis was regulated by the rate of change of concentration as expected, concentration changes triggered discrete turning events in the animal rather than the smooth changes in head angle that were observed in the robot.

Several investigators have examined orientation to auditory signals. Webb [38] has developed a robotic model of cricket phonotaxis using a wheeled robot equipped with microphones and phase delay circuitry designed to mimic the effect of the interaural tracheal tube. This robot tested the feasibility of a specific hypothesis about cricket phonotaxis, demonstrating that robust localization can occur by comparing the phases and latencies of the auditory signals at the two ears in a simplified auditory environment. A more recently developed robot [39••] has demonstrated the viability of this strategy for real cricket songs (recorded from male *Gryllus bimaculatus*). A biological implication of the results obtained from this robot is that ear directionality alone can account for much of the frequency selectivity observed in cricket phonotaxis.

Similarly, a robotic model has been developed of binaural echolocation in bats that use constant frequency calls to localize the wingbeats of insects, such as members of the families Rhinolophidae and Hipposideridae [40••]. Using an ultrasound transmitter and two receivers, the robot can orient to an acoustic target by turning so as to null the differences in the acoustic signal at each receiver in frequency channels specific to the rhythmic motions of the target. The biological implications of this result are that rhythmic movements of the insect itself may be used by the bat for target localization rather than a model-based matching scheme. The same authors have also investigated the use of external ear (pinna) movements to improve target localization in bats emitting constant frequency calls [41••]. Their robotic model demonstrated that, by scanning the pinnae, bats can obtain a sequence of signals that unambiguously locates both stationary and moving targets with high accuracy. This work generates testable hypotheses about specific filtering properties of the ear, its movement, and the signal characteristics that are essential for target localization.

Vertebrate arm control

Another area of research within biorobotics concerns the control of posture and reaching movements in vertebrate limbs. For example, based on biologically inspired motion primitives [42], Williamson [43] developed an arm controller for Cog, an upper-torso humanoid robot being built at the Massachusetts Institute of Technology [44].

By studying both human subjects and a seven DOF anthropomorphic robot arm, Sternad and Schaal [45••] have recently tested two competing hypotheses regarding the segmented control strategies implied by the observed segmentation of human arm trajectories during rhythmic three-dimensional drawing movements. Using the robot arm, they discovered that segmentation is observed even with a smooth control strategy, and thus may reflect nonlinearities in arm kinematics rather than an underlying segmented control strategy. The results suggest that in contrast to extrinsic motion planning, which explicitly generates segmented trajectories, continuous pattern generators in joint space can produce the observed segmentation of arm movements.

Hannaford *et al.* [46] have constructed a highly anthropomorphic biorobotic arm that includes fiberglass composite scapula, humerus, radius and ulna bones connected by surgical total replacement elbow and shoulder joints (Figure 1c). The bones are connected via knit fabric ligaments to 15 muscle-like actuators that simulate the major muscles in the human arm and shoulder and that include artificial muscle spindles. Chou and Hannaford [47••] used models of spinal circuitry controlling a simplified model elbow to explore the effects of blocking selected afferent pathways on the response of the joint to perturbations. They found that two efficient ways to increase joint stiffness and damping are muscle co-contraction and Ia afference with gamma dynamic motoneuron excitation. This reduces the mechanical sensitivity of the joint and the length of its transient response to perturbation.

Other motor behaviors

Robot models of a variety of other motor behaviors have also been developed. Takanobu and colleagues [48•] have constructed a robotic model of the human jaw and have used it to quantify mastication efficiency. Takanishi and colleagues [49] have developed an anthropomorphic head-eye system with eyelids and eyelashes that blinks, recoils from sudden lights or touch, and tracks moving objects. Using a wheeled robot controlled by models of selected cortical and subcortical visual areas, Sporns and colleagues [50••] examined the effects of behavioral and environmental interactions on the development and ongoing adaptation of complex cortical responses to visual stimuli. They showed that correlated temporal changes in input patterns resulting from the robot's moving through its environment are crucial for the development of visual invariants.

Conclusions

A variety of recent projects at the interface between biology and robotics have been surveyed. Although robots may differ from animals in the materials that compose them, their relative scale, and in the details of their actuators and sensors, careful analysis of a biologically based robot makes it possible to test hypotheses about a biological motor system in the same physical environment in which the animal lives. In turn, a biologically inspired approach to robotic design that incorporates aspects of animal biomechanics and neural control can improve the agility and robustness of robots performing desired tasks.

A biorobotics approach is likely to be of greatest mutual benefit when biologists and engineers work closely together, generating both new engineering approaches and experimentally testable hypotheses about the original system. In order to maximize the biological utility of this approach, the work we have reviewed suggests that the following sequence of steps is most effective.

First, identify a biological hypothesis that is difficult to address experimentally. Typically, this is a systems question in which the physical properties of the body and/or environment are difficult to simulate on a computer.

Second, design a biorobot that captures the essential physical properties required to address the biological question of interest. This is typically done in conjunction with an experimental program aimed at characterizing the key physical parameters of the biological system. Scaling arguments based on dimensionless quantities such as Reynolds numbers may be helpful in abstracting these parameters. A major obstacle to more biologically realistic robots is the difficulty of matching the sensor densities and actuation power densities available to animals. However, progress in the area of MEMS (micro-electromechanical systems) sensor arrays [51] and muscle-like actuators [30•,46,52•,53] may eventually overcome this obstacle.

Third, test the feasibility of the original biological hypothesis on the biorobot. The biorobot can also serve as a tractable experimental testbed for exploring a broader range of questions related to this hypothesis. In addition, mathematical tools from engineering can often be brought to bear on the analysis of the biorobot (e.g. [54]).

Fourth, the insights gained from experimental study and mathematical analysis of the biorobot can lead to refined questions and new experimental studies of the original biological system. If this sequence is followed, biorobotics has the potential to become a major new tool for the study of motor systems, complementary to both experimental studies and computational modeling.

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Describes an intuitive approach to controller design termed 'virtual model control', in which control is achieved by simulating the effects of virtual mechanical components attached to a physical robot. The authors used this approach to control support and walking in a planar bipedal robot with two actuated DOF per leg.

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Although only loosely inspired by biology, the bipedal robot developed by these authors is one of the most sophisticated free-walking humanoid robots in existence, with six DOF per leg and seven DOF per arm. It can walk forward, backward, or sideways, walk up or down stairs, step over obstacles, turn in any direction, and maintain its posture on uneven terrain.

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Reviews a series of insect-like legged robots whose control is based on experimental studies of leg coordination and local leg reflexes in the cockroach, walking stick, and locust. The most sophisticated robot can walk with a range of insect gaits at speeds up to 14 cm/s and negotiate irregular, slatted and compliant surfaces. The robotic application of dynamical neural circuits for walking that were evolved using genetic algorithms is also briefly described.

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Describes the mechanical design of a new cockroach-like hexapod robot closely modeled after *Blaberus discoidalis*. The robot was constructed from machined aluminum, weighs 30 pounds, and is 17 times the size of the insect. Based on kinematic studies of *Blaberus*, the robot has five DOF in each front leg, four DOF in each middle leg, and three DOF in each rear leg. These joints are actuated by pneumatic cylinders whose valves are driven with 50 Hz pulse width modulation. Potentiometers on each joint provide joint angle feedback.

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The authors describe the design of a free-swimming robotic fish modeled closely on the chain pickerel *Esox niger*. The main body of the robot is made of fiberglass spiral wound spring covered by a skin of latex, lycra and steel mesh. The body is 81 cm long and has two main articulations controlled by servo motors. Additional servo motors control caudal and pectoral fins. To date, open-loop control has been used to produce fast C-starts and forward swimming at speeds up to 1 m/s.

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Using a robotic head with a camera and two lateral microphones surrounded by an array of lights and buzzers, the authors explore the use of visual information to calibrate auditory orientation in a model of plasticity in the inferior colliculus and optic tectum of the barn owl. The robotic head develops spatial registration between auditory and visual maps in the model optic tectum. In addition, the robot can appropriately adapt these maps after the visual image is shifted through prismatic goggles and after the removal of these goggles.

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A small wheeled robot was used to test a model of cricket phonotaxis. The robot includes microphones representing left/right pairs of tympani and spindles and an electronic model of the cricket auditory system. The outputs of this auditory circuit are fed into leaky integrators and whichever side reaches threshold first causes a small turn in that direction. The robot was exposed to a recorded calling song of male *Gryllus bimaculatus.* The authors demonstrate that this simple model can account for both phonotaxis and frequency selectivity due to the frequency dependence of ear directionality.

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A robot is used to test a model of prey localization via binaural echolocation in insectivorous bats that emit long, constant frequency calls. The robot is wheeled and contains an ultrasonic transmitter and a pair of ultrasound receivers. The robot operates by making binaural comparisons of the spectral sideband energy in echoes from periodically moving targets, steering so as to cancel interaural differences. Selectivity is achieved by filtering out all sideband energy except that from the particular sidebands specific to the oscillating targets of interest (e.g. insect wingbeats), allowing robust target localization even in acoustically cluttered environments.

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A robotic model of the human elbow is used to explore the maintenance of human forearm posture by spinal circuitry. The robotic elbow includes two McKibben braided pneumatic actuators whose attachment points mimic those of human elbow flexor and extensor muscles. The model also includes model Golgi tendon organs and muscle spindles. The authors explore open loop stiffness control via co-contraction, closed loop stiffness control with Ia or Ib afferent feedback, and posture maintenance using a model of spinal reflex circuitry. They also demonstrate how gamma dynamic excitation is essential to produce velocity feedback of the Ia signal, which increases closed-loop damping, and how alpha motoneuron activation compensates for the lowpass filtering properties of muscle by acting as a feedforward phase-lead controller.

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The authors use a robotic model of the human jaw to quantify the mastication efficiency of different mandibular motions. The robot consists of an epoxy resin human skull replica with a three DOF jaw actuated by nine motors with force sensors that model the major jaw muscles. Using a small ball-like cookie, they compared the efficiency of two different chewing motions and found a grinding motion to be more efficient than a clenching motion.

49. Takanishi A, Hirano S, Sato K: **Development of an anthropomorphic head-eye system for a humanoid robot.** In *Proceedings of the IEEE International Conference on Robotics and Automation*: 1998 May 16–20. Leuven, Belgium; 1998:1308-1314.

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•• **development of neuronal properties: a cortical model embedded in a real-world device.** *Cereb Cortex* 1998, **8**:346-361.

Using a wheeled robot equipped with a camera and a 'taste' sensor (based on electrical conductivity), the authors explore the development of selective and invariant responses of cortical neurons to complex visual stimuli. When embedded in an environment containing conductive and nonconductive objects with different visual patterns, the robot develops an attraction to visual patterns associated with nonconductive objects and an aversion to visual patterns associated with conductive objects. They found that the robot's movement was essential to the development of selective and translation invariant cortical responses, and that these responses depended on the physical design of the robot and the relative frequency of the various objects in the environment.

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Describes the use of McKibben pneumatic actuators as flexors and extensors for the hip and knee joints of a pair of robotic legs. Standing and striding experiments demonstrate that such actuators are promising artificial muscles that are fast, light, powerful, and compliant.

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