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Biorobotic Approaches to the Study of Motor Systems

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Summary

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. There has been a great deal of recent progress in biorobotic studies of locomotion, orientation, and vertebrate arm control.

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Abbreviations

DOF – degrees of freedom; **MEMS** – micro-electromechanical systems.

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 co-evolved and the fact that only the behavior of an entire animal is subjected 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 the joint experimental analysis and modeling of neural activity, peripheral biomechanics, and ecological context [3••]. The 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 quite distinct ways in which robots can be applied to the study of motor systems. First, robots can be employed as physical models of animals that are used to address specific <u>biological</u> 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. Major issues here 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 have either been used to address specific biological questions or have been directly inspired by biological studies.

Locomotion

Locomotion has been a major focus of biorobotics research. Using robots, a variety of modes of locomotion have been explored, including flying (e.g., [7]), swinging from handhold to handhold (brachiation) [8] and serpentine locomotion (e.g., [9]). Recently, Chiel and colleagues developed a three segment worm-like robot that can crawl under water 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) [10•]. Research in legged robotics has been particularly active, and has a long history [11]. Pratt and colleagues have built a number of planar bipedal walking robots whose legs are loosely modeled after turkeys and flamingoes [12•]. Humanoid robots capable of unconstrained bipedal locomotion are a very active area of research, especially in Japan (e.g., [13, 14•]).

A variety of insect-like hexapod robots have also been constructed (e.g., [15, 16]), and a number of reviews of insect walking aimed at roboticists have appeared [17, 18]. Working with Cruse [19], Pfeiffer and colleagues [20] constructed 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 directly based 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 in each middle leg and three 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 smoothly recover 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 biorobotics 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 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 [28]. 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, they have developed a free-swimming robotic fish modeled after the chain pickerel *Esox niger* [29••] (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, Mojarad 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. Based on 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 recently constructed a robot based on studies of chemotaxis in the nematode *Caenorhabditis elegans* [37••]. 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 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 (S. Lockery, personal communication).

Several investigators have examined orientation to auditory signals. Webb 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 [38]. 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 recent robot has demonstrated the viability of this strategy for real cricket songs (recorded from male *Gryllus bimaculatus*) [39••]. 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 species Rhinolophidae and Hipposideridae [40••]. Using an ultrasound transmitter and two receivers, their 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. They 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 locate 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 MIT [44].

Using experiments both with human subjects and with a seven DOF anthropomorphic robot arm, Sternad and Schaal tested two competing hypotheses about the segmented control strategies implied by the observed segmentation of human arm trajectories during rhythmic 3D drawing movements [45••]. 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. These result imply 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 and colleagues have constructed a highly anthropomorphic biorobotic arm that includes fiberglass composite scapula, humerus, radius and ulna bones and surgical total replacement elbow and shoulder joints [46] (Figure 1C). The bones are connected via knit fabric ligaments to fifteen muscle-like actuators that simulate the major muscles in the human arm and shoulder and include artificial muscle spindles. Models of spinal circuitry controlling a simplified model elbow were used to explore the effects of blocking selected afferent pathways on the response of the joint to perturbations [47••]. 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 constructed a robotic model of the human jaw and used it to quantify mastication efficiency [48•]. Takanishi and colleagues developed an anthropomorphic head-eye system with eyelids and eyelashes that blinks, recoils from sudden lights or touch, and tracks moving objects [49]. Using a wheeled robot controlled by models of selected cortical and subcortical visual areas, Sporns and colleagues examined the effects of behavioral and environmental interactions on the development and ongoing adaptation of complex cortical responses to visual stimuli [50••]. They showed that correlated temporal changes in input patterns due to movement of the robot 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 allows hypotheses about a biological motor system to be tested in the same physical environment in which the animal lives. In turn, a biologically-inspired approach to robotic design which 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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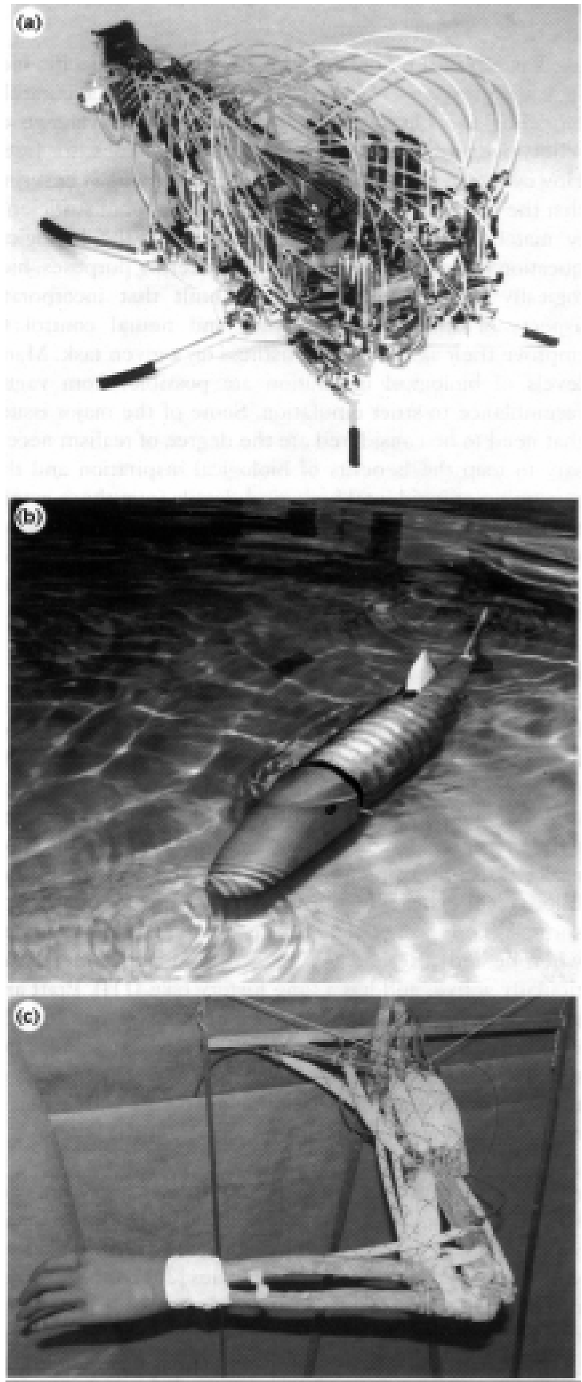

Figure 1: Several recent examples of biorobots. (A) A cockroach-like hexapod robot based on the leg kinematics of *Blaberus discoidalis* [24••]. (B) A robotic fish based on the chain pickeral *Esox niger* [29••]. Photograph courtesy of John Muir Kumph. (C) A biorobotic model of the human arm [46]. Photograph courtesy of Blake Hannaford.

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Recent experimental evidence that the physical properties of bodies and environments are crucial for understanding the operation of neural circuits is reviewed. Recent work in the joint modeling of an animal's neural circuitry, peripheral biomechanics and environment (computational neuroethology) is also reviewed.

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This paper describes the design of a worm-like hydrostatic robot consisting of three fluid-filled bladders connected by sets of four shape memory alloy springs. Using appropriate differential activation of the four springs, the robot was capable of undulatory locomotion underwater and turning around obstacles.

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This paper describes an intuitive approach to controller design called virtual model control, in which control is achieved by simulating the effects of virtual mechanical components attached to

a physical robot. This approach is applied to control support and walking in a planar bipedal robot with two actuated DOF per leg.

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Although only loosely biologically inspired, this bipedal robot is one of the most sophisticated free-walking humanoid robots in existence, with 6 DOF per leg and 7 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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This paper 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/sec 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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This paper describes the mechanical design of a new cockroach-like hexapod robot closely modeled after *Blaberus discoidalis*. The robot is constructed of 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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This paper describes a postural controller for the above cockroach-like hexapod robot based on a virtual model control scheme that uses a single virtual leg model of the robot's mechanics to encourage equal load distribution and minimize joint torques in the supporting legs. With this control scheme, the robot can adjust its posture to commanded body positions and orientations, smoothly recover from substantial postural perturbations, and lift a 30 pound payload.

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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/sec.

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A polyelectrolyte ion exchange membrane-metal composite muscle-like actuator was used as a caudal fin for a robotic swimmer. This material bends due to ion redistribution in response to an imposed electric field. By driving the fin with an oscillatory voltage signal, a travelling bend was produced that propagated along the length of the actuator, shedding vortices that propel the robotic fish.

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This paper describes a 30 mm compound eye with 2 x 30 photodiode receptors based on a fly eye. A piezoelectric actuator rotates the eye about its center of curvature. The authors demonstrate that active scanning enhances the perception of visual motion for such a low

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The authors describe a neural network crash avoidance system for wheeled vehicles based on the neural circuitry controlling the cockroach escape response. The network receives proximity, wheel speed and steering angle inputs and outputs vehicle acceleration and steering angle. The network was trained using backpropagation to produce successful avoidance responses.

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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 mobile robot that performs phototaxis based on studies of chemotaxis in *Caenorhabditis elegans* is described. The robot moves forward at a constant velocity with a controllable steering angle. A single photocell at the front of the robot senses light intensity. Linear dynamic neural networks loosely based on the chemotaxis circuitry of C. elegans were optimized for phototaxis in simulation and then transferred to the robot. The trajectories of the robot closely matched those observed in *C. elegans* and were robust to perturbations in instantaneous speed and steering angle. An analysis of the optimized networks provided insight into its operation.

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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 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 binaural comparison 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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The authors extend the work described in the paper above to investigate the consequences of pinnae movements in bats by allowing the robot's ultrasound receivers to move via servomotors. They find that such movements have two benefits: (1) They produce different viewing perspectives over which interaural intensity disparities can be sampled and (2) They produce amplitude modulations of returning echoes which vary systematically with target elevation.

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This paper examines two hypotheses regarding the motion primitives underlying movement segmentation in three dimensional drawing movements by humans: (1) A stroke-based primitive suggested by abrupt changes in the velocity gain factor of a 2/3 power law relationship between curvature of the drawing path and angular velocity of the endpoint trajectory and (2) A segmentation hypothesis inferred from the piecewise planarity of endpoint trajectories. Using a seven DOF anthropomorphic arm, the authors demonstrate that continuous movements at the level of the biomechanics of the arm can account for the observed segmentation of endpoint trajectories due to nonlinearities in arm kinematics.

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In this paper, 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. They 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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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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