

## BIOMIMETICS

## Running birds reveal secrets for legged robot design

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Recapitulating avian locomotion opens the door for simple and economical control of legged robots without sensory feedback systems.

Anyone watching a cheetah in pursuit of prey or a mountain goat scaling a cliff will be amazed at their locomotor capabilities. It is not surprising that engineers draw inspiration from animal movements such as these when designing legged robots. To be sure, several legged robots achieve remarkable movement. For example, the MIT Cheetah and Boston Dynamics' SPOT (quadrupedal robots) and Agility Robotics' Cassie (a bipedal robot) each perform impressive autonomous movement over natural terrain. These robots rely heavily on sophisticated sensors, high-capacity actuators, and fast computation. Despite these engineering feats, designing a control framework for agile, stable, and economical movement through unpredictable environments remains a grand challenge for legged robotics. Writing in *Science Robotics*, Badri-Spröwitz *et al.* (1) strategically steer away from computational and actuator "grunt," instead choosing to simplify movement control by emulating the passive mechanics in the legs of animals, with emphasis on specializations found in ground-running birds. The avian-inspired robot leg, BirdBot, has been developed with the potential for self-engagement and disengagement without sensory feedback control. This design approach embeds "intelligence by mechanics," effectively sidesteps computational algorithms vulnerable to assumptions of control objectives, and avoids energy-costly corrective actuation.

Engineers readily adopt new technologies as they become available; lighter and stronger materials, faster computers, and more powerful and efficient motors may well lead to improvements in legged robots. Biological systems, in contrast, are stuck with imperfect components that were simply "good enough" for natural selection to act on. Rather than quickly innovate with novel

structures, as an engineer might, evolution finds hacks to overcome the constraints of inherited morphologies (2). One such imperfection can be seen in the neural control of legged animal locomotion. Animals achieve their remarkable agility and balance despite having a sensory feedback system that is substantially slower than the near-immediate (real-time) correction available to their robotic counterparts. Stubbing a toe, as we too painfully know, is seldom corrected in one step but requires several steps to avoid mishap. This comparatively slow neural control is the result of a speed limit on nerve conduction (axon conduction velocity remains nearly constant across a myriad of species at ~40 to 70 m/s) and delays occurring at the nerve-muscle junction and in muscle excitation-contraction coupling (force generation) (3). In a workaround to this sluggish neural control, animals use tricks that decrease their reliance on it. Through "intelligence by mechanics," self-stabilizing mechanisms embedded in intrinsic limb and muscle properties provide animals with rapid passive control independent of the nervous system (4). Running insects exemplify this self-stabilizing morphology and have inspired robots capable of passively adjusting to even extreme perturbations (5). The realization of self-stabilizing locomotion is perhaps most elegantly demonstrated in passive legged walkers that lack both neural control and actuation (6). These walkers move without falling, purely using passive stability and an exchange of mechanical energies, and are capable of propelling themselves using simple spring-latch mechanisms.

With BirdBot, Badri-Spröwitz and colleagues (1) build on past self-stabilizing robot designs by introducing a passive leg-clutch system based on avian leg morphology. The avian distal leg is characterized by digital

flexor muscles originating on the femur and proximal tibia with tendons running across the entire leg to the end of the toes, crossing multiple (as many as five) joints along the way. The very short strut-like muscle fibers and long elastic tendons of the digital flexors are not ideally suited for producing mechanical energy to drive motion—a good hint that birds use these muscle-tendon systems differently from the typical actuator used to directly drive joints in legged robots. Birds, especially the large flightless ratites that inspired BirdBot, use these multijoint elastic structures to form a "snap-through bistable tensegrity system" (1) to coordinate the storage and subsequent release of elastic energy in their leg to actuate their step (7). This biological mechanism is used by BirdBot, allowing automatic engagement and disengagement of a whole-leg elastic actuator. What is more, this "clutching" emerges from the natural motion of the toes across the step. This bioinspired limb morphology allows for an actuator "on-off" switch that seamlessly initiates the transition between stance and swing without requiring neural control—and a reduction in actuator torque to boot. The same tendon mechanism that BirdBot emulates to achieve self-clutching has similarly been exploited in an avian animal model for passive-elastic limb exoskeletons to overcome the problem of device interference in limb swing (8). Incidentally, this multijoint tendon mechanism provides a near-passive perch grip in birds, a function exploited in a separate class of grasping robots (9).

BirdBot remains a mechanically constrained (planar four-bar) system, and whether similar functionality is possible in autonomous, non-steady-state locomotion remains to be seen. Nevertheless, Badri-Spröwitz and colleagues' avian-inspired design reminds us that a passive, mechanically mediated approach to robot control can be an effective and perhaps essential complement to high-bandwidth sensing for rapid actuator feedback control. Although BirdBot primarily leverages stability arising from specialized structural features, further advances will

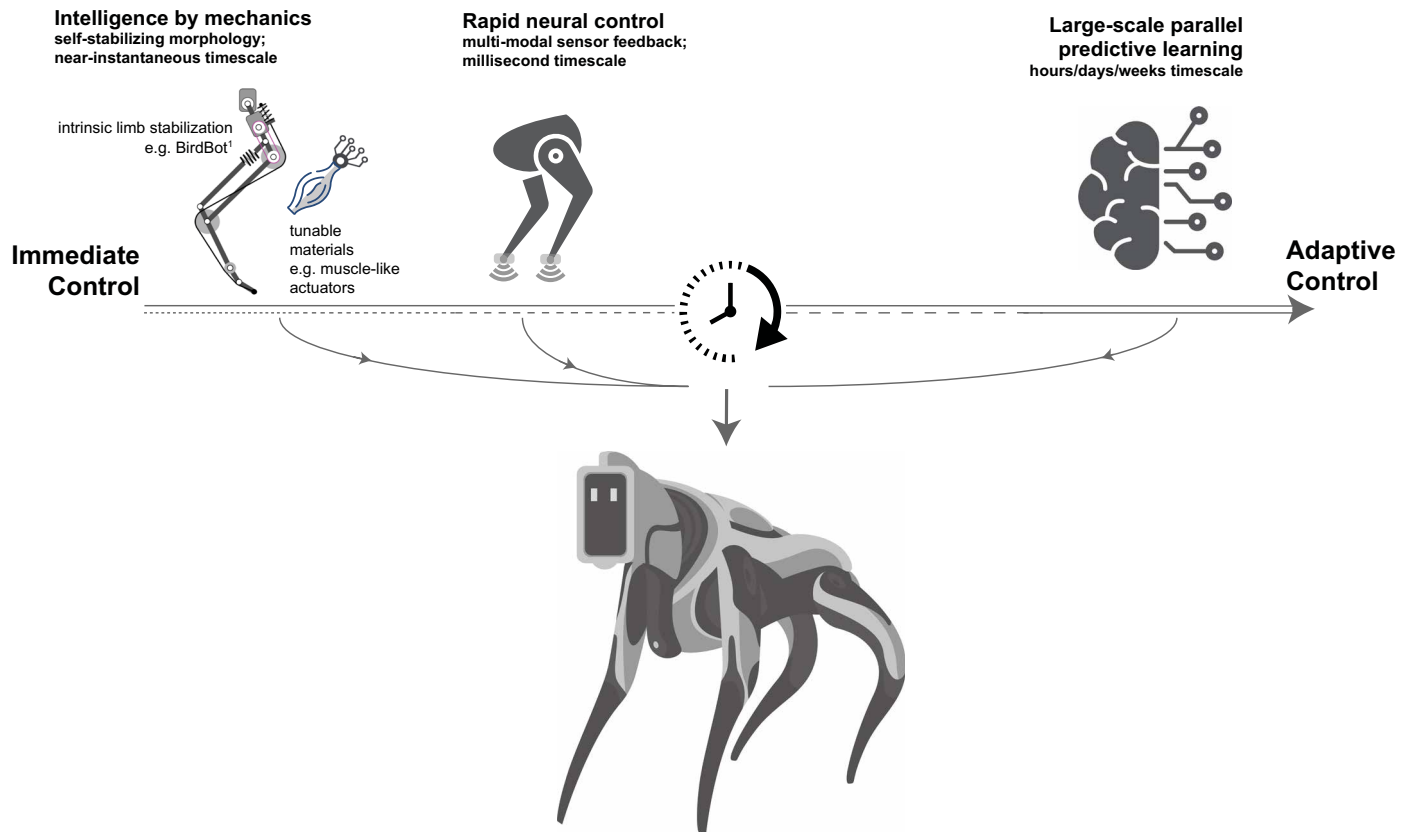
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**Fig. 1. A proposed robot control framework integrating across a range of time scales.** Legged robots typically rely on rapid neural feedback passed back to limb actuators that drive movement. Combining self-stabilizing morphology, such as that applied by Badri-Spröwitz and colleagues (1), and predictive learning (on the other end of the control time scale) provides a neuromechanical framework more akin to biological systems.

come from integrating stabilizing properties of tunable materials (10). For example, materials with tunable impedance (stiffness and damping) derived from modulating electrical or chemical input signals may help layer semi-active control atop passive limb response. Furthermore, limitations in neural response times of animals point toward reliance on a feed-forward, predictive, basis-to-animal locomotor control (11). If computational resources can be freed up through a greater utilization of passive limb control, then it is prudent to allocate surplus bandwidth to iterative reinforcement learning rather than solely investing in a sensor-feedback control schema.

To get us closer to animal-level robot performance, we feel that advantages may come from a neuromechanical framework operating over multiple time scales—from near-instantaneous “intelligence by mechanics” and rapid neural feedback to large-scale parallel computation that enables accurate prediction for short-term adaptation and robust reinforcement learning for long-term planning (Fig. 1) (12). Notably, this strategy

should be equally advantageous when applied to assistive devices worn both outside (exoskeletons and smart prostheses) and inside (endoprostheses) the body.

A future challenge is recognizing when, and under what contexts, to allocate priority to each of these control components—a feature we have not yet gleaned from our animal counterparts. As Badri-Spröwitz and colleagues (1) point out, disentangling the complexity of locomotor control to identify how animals blend passive stabilization and active neural control during natural movement is difficult. To paraphrase the early 20th century physiologist, August Krogh, for every problem, there is an animal on which it is best studied. In this case, the animal might paradoxically be a robot, where these factors can be quickly and systematically manipulated.

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**Funding:** Financial support was provided through seed funding awarded to J.R. and G.S.S. from the Huck Institutes of

the Life Sciences and the College of Health and Human Development, College of Engineering, and College of Medicine at the Pennsylvania State University.

10.1126/scirobotics.abo2147

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*Sci. Robot.*, 7 (64), eabo2147. • DOI: 10.1126/scirobotics.abo2147

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