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Spikes alone do not behavior make: why neuroscience needs biomechanics

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Neural circuits do not function in isolation; they interact with the physical world, accepting sensory inputs and producing outputs via muscles. Since both these pathways are constrained by physics, the activity of neural circuits can only be understood by considering biomechanics of muscles, bodies, and the exterior world. We discuss how animal bodies have natural stable motions that require relatively little activation or control from the nervous system. The nervous system can substantially alter these motions, by subtly changing mechanical properties such as body or leg stiffness. Mechanics can also provide robustness to perturbations without sensory reflexes. By considering a complete neuromechanical system, neuroscientists and biomechanicians together can provide a more integrated view of neural circuitry and behavior.

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Introduction

A primary goal of neuroscience is to determine how interactions with the world result in behavior. Before behavior can emerge in response to a sensory stimulus, the signals must be filtered and then sent to act upon the motor circuits that then cause the movements that we observe as behavior. ‘Behavior,’ necessarily, implies movement. However, the connection from the outputs of motor neural circuits to movement is anything but straightforward. The missing link between the two is the mechanical system — the muscles, body, and the external environment. This connection between the sensory stimulus and the resultant behavior is extremely complex, and any sufficient analysis requires an understanding of

not only the neural circuitry but also the mechanics of the body and its interaction with the environment in which the movement is implemented.

Attempting to make inferences about behavior (i.e., movement) based on observations of a neural circuit, without considering mechanics, risks drawing completely incorrect conclusions. For example, a chewing muscle in the marine mollusk *Aplysia californica* has two entirely opposite actions that depend on the configuration of the mouthparts and not on the neural command [1]. Furthermore, an understanding of mechanics is crucial in order to draw conclusions about neural circuits based on behavioral measurements. For instance, the Mauthner circuit that initiates the escape response behavior in fishes was classified as ‘preparatory,’ on the basis of kinematic observations (see review in [2]), but recent measurements of the forces involved indicate that the circuit is important for the overall performance of the escape, not just its initiation [3].

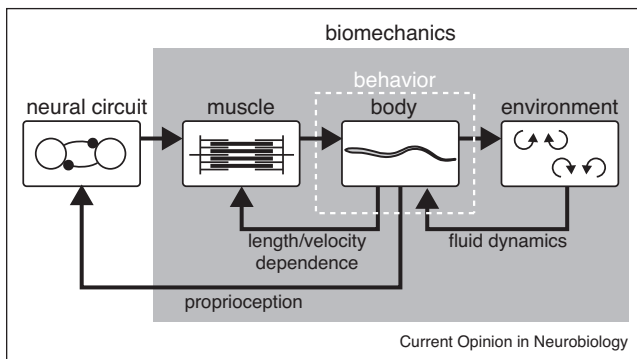
Together, the nervous system, body, external environment, and sensory systems form a set of distributed, nested feedback loops (Figure 1). The effects of feedback can be difficult to predict, but are crucial for understanding behavior. For example, Cowan and Fortune [4] examined electrosensory coding in the weakly electric knifefish, and found that the sensory receptors used to stabilize a low frequency behavior were not themselves sensitive to low frequencies, as one would guess from observing the behavior. Instead, by incorporating a biomechanical model, they predicted that the receptors should respond to high frequencies, as was later observed physiologically [4]. More generally, mathematical models have played a key part in assessing contributions of neural pathways and biomechanics, especially in locomotion studies [5,6].

Here, we describe some ways in which an understanding of biomechanics can lead to better inferences about the functioning of neural circuits. Certain aspects of the interaction of neuroscience and biomechanics have been reviewed recently. Sane and McHenry [7*] examined the role of mechanics in sensory input, and Chiel *et al.* [8*] presented an illustrative set of neuromechanical case studies [see also 9]. In this review, we attempt to build on these ideas to create a more global view.

The role of the mechanical system in generating behavior

Mechanical systems on their own, without neurons, can generate complex motions, as demonstrated by the passive dynamic walkers developed by McGeer [10] and

Figure 1



Schematic of the crucial rôle that biomechanics plays in understanding both behavior and neuroscience. The images depict fish locomotion as an example, but the relationships are true for any circuit with a motor output. In this example, neural circuits activate muscles that produce force to move the body, which then interacts with the environment. The environment produces fluid dynamic forces back on the body, and the muscle force depends on the body motion according to the nonlinear force–length and force–velocity properties of muscle. Finally, the output of the neural circuit is influenced by sensory inputs such as proprioception. The movement of the body (‘behavior’) depends in an intricate way on biomechanical interactions (gray box).

Ruina [summarized in 11] and by Shannon with his classic juggling machine [12]. These devices walk or move stably with no controllers and extremely minimal actuation. The only requirement is a small energy input, usually provided for walking robots by having the robot walk down a slight slope, demonstrating nicely the importance of the environment with everything else stripped away [13].

Of course, animals have nervous systems, but they work together with the body’s mechanics, and in many cases, mechanical effects shape the behavior. Muscles and body can conspire with the external environment to produce complex motions independently of the nervous system, or synergistically with it. A particularly important class of such interactions is resonance. For resonant systems, there is a frequency (or frequency range, for nonlinear systems) at which the system naturally oscillates, so that an input at that frequency evokes a larger output. For example, wings in fruit flies beat at nearly 500Hz: faster than their motor neurons can fire. This motion is primarily due to mechanical resonance between the thorax and stretch-activated muscle [14,15]. Walking and running may also achieve high efficiency due to resonant effects in the Achilles tendon [16,17*].

In fact, it appears that central pattern generator (CPG) circuits, which are often thought to determine oscillation frequency, may instead serve to match mechanical resonant frequencies, a property called ‘resonance entrainment’. This effect has been observed in computer simulations [17*,18*,19,20] and to some extent in experimental

work [21,22]. In both cases, when CPGs are coupled to a resonator such as a pendulum, the coupled system tends to oscillate at the mechanical resonant frequency and not at the preferred frequency of the CPG. This suggests that mechanics may play a decisive role in determining oscillation frequencies, particular in behaviors like running, in which the leg dynamics resemble those of pendula.

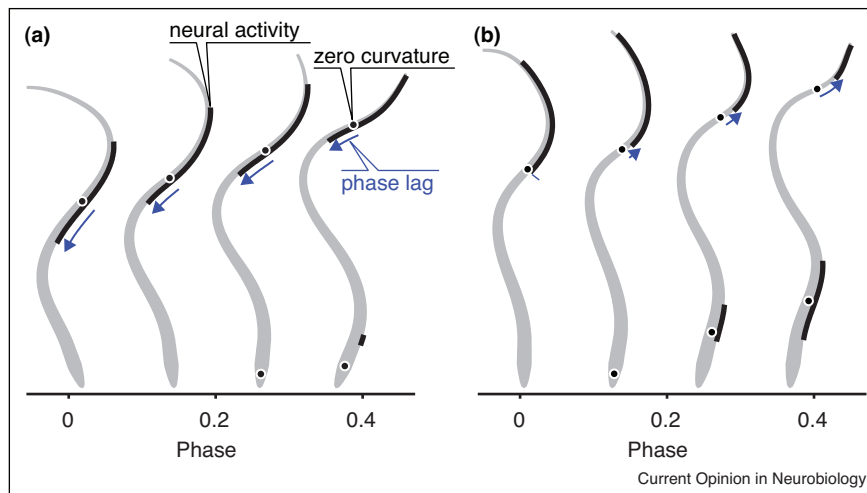
More complex dynamical patterns can also be excited by coordinated muscle activation. Berniker *et al.* [23**] found that matching the activation of groups of muscles called ‘synergies’ [24] to the natural dynamics of the frog hind-limb required the smallest number of independent synergies to produce an accurate and energy-minimizing motion.

Predicting the transformation from spikes in motor nerves to movement can therefore be complex, and requires an examination of body mechanics. Recent work on swimming supports this thesis. CPG circuits in undulatory swimmers including lampreys, other fishes, and leeches produce a characteristic pattern of neural activity that passes from head to tail, activating muscles in a wave along the body [26] to produce a corresponding wave of body curvature. However, the mechanical wave does not, in general, travel at the same speed as the wave of neural activity. Tytell *et al.* [25**] showed that the speed of the mechanical wave depends strongly on the characteristics of the body as it interacts with the fluid. When muscles are relatively strong compared to fluid forces, wave speeds are similar (Figure 2a), but when muscles are relatively weak, the neural wave travels faster than the mechanical wave (see the increasingly long phase lag in Figure 2b). Chen *et al.* [27**] found a similar difference in the speeds of neural and mechanical waves for swimming leeches. In fact, the body–fluid coupling is required for swimming; without it, the traveling wave of neural activity produces a standing wave of curvature [28,29,30*].

To examine this transformation in running cockroaches, Sponberg *et al.* [31**,32**] developed a method for altering the number of spikes in a motor neuron that innervates an extensor muscle. During running, the effect of adding spikes was nonlinear and highly phase dependent [31**]. The nonlinearity is the result of a positive mechanical feedback loop. More spikes produce greater force, which allows the leg to extend for longer and produce even more force [32**]. Supporting our argument that the transformation is difficult to predict, the muscle’s function during running was very different from what had been hypothesized from *in vitro* measurements [31**].

The body’s interaction with the environment is also critical to understanding nervous system function. Flying insects provide a good example of how this coupling between body mechanics and the external environment can generate complex motions. Insect wings must flip

Figure 2



Neural activity and body curvature in a neuromechanical model of a lamprey. The body is shown in gray, with thick black lines to indicate regions where motor neurons are active, and black points to indicate the location of zero curvature. The phase lag between muscle activity and curvature is indicated by a blue arrow. Simulations shown in panel (a) and (b) have identical neural activation patterns, but differ in muscle strength and body stiffness (a), relatively strong muscles and stiff body; (b), relatively weak muscles and less stiff body). Modified from [25**].

over at the end of each wingbeat as the wing reverses direction. The lift force depends sensitively on the timing of the flip [33], so one might imagine that the nervous system would be exquisitely tuned to flip the wing at the right time. In fact, it appears that passive interactions with the air may drive the rotation [34], demonstrating the role of the environmental interactions in defining motor output.

Interactions with moving media, water or air, are clearly important for swimming and flying animals, as described above, but neither can they always be neglected in legged locomotion. Although substrates are often assumed to be rigid, their mechanical properties can couple with, and influence, the body mechanics and nervous system (see examples in [35,36**,37*38*]).

Active tuning of passive properties

In the previous section, we discussed the rôle that mechanical properties like stiffness play in determining an animal's movements. However, in many cases these so-called 'passive' properties are under the animal's control. For example, since muscles activated while being stretched generate considerably more force than a muscle activated while shortening [39], activating a single muscle can change its stiffness [40] depending on the phase of muscle activation relative to body motion. Such a change alters the resultant lengthening and shortening of the respective muscles. It can also dramatically alter effective stiffness [41]; and co-contracting antagonist muscles can change the stiffness of a joint [42]. In addition, muscle activation can also alter effective damping properties [43]. Together, these tunable mechanical properties can affect

many behaviors, including stability in running insects, as we describe below (e.g., Figure 11 in [44]).

For neuroscientists, an important corollary of this fact is that large kinematic changes need not be accompanied by equivalently large shifts in the gross motor output. Relatively subtle shifts, for instance in the amount of co-contraction, may alter the mechanics of the system sufficiently to cause substantial changes in both kinematics and the dynamical responses to perturbations.

An example of changing kinematics comes from experiments on turning in fruit flies. Bergou *et al.* [45**] recently suggested that turning may not require any dramatic change in muscle activation, even though the kinematics change. Instead, it appears that flies alter the effective properties of the torsional spring at the wing-base, so that one wing flips over earlier than the other, causing a difference in forces between the wings and turning the body [45**]. Similarly, small changes in leg stiffness and foot touchdown positions produce turns in running insects [46,47]. Reaching experiments provide further examples of changing dynamics. To reach precisely, humans and other primates increase muscle co-contraction: the resulting stiffer arm is more stable, yielding higher precision in the face of external perturbations or noise in internal motor circuits [42].

In walking or running, phase relationships among different muscle groups or between limbs can change with speed (e.g., the transition from trot to gallop in quadrupeds), or to accommodate changes in the substrate (such as moving up or down an incline). To produce these motions, the brain or

rostral ganglia activate a CPG that produces the periodic muscle activations necessary for the motion [48,49]. However, phase shifts among muscles or gait changes need not be accompanied by dramatic changes in CPG output or descending activation. Instead, these relationships can be adjusted by appropriate tuning of natural frequencies via tonic inputs from the central nervous system, and by phasic inputs from proprioceptive sensors [6,50].

The importance of mechanics in stabilizing behavior

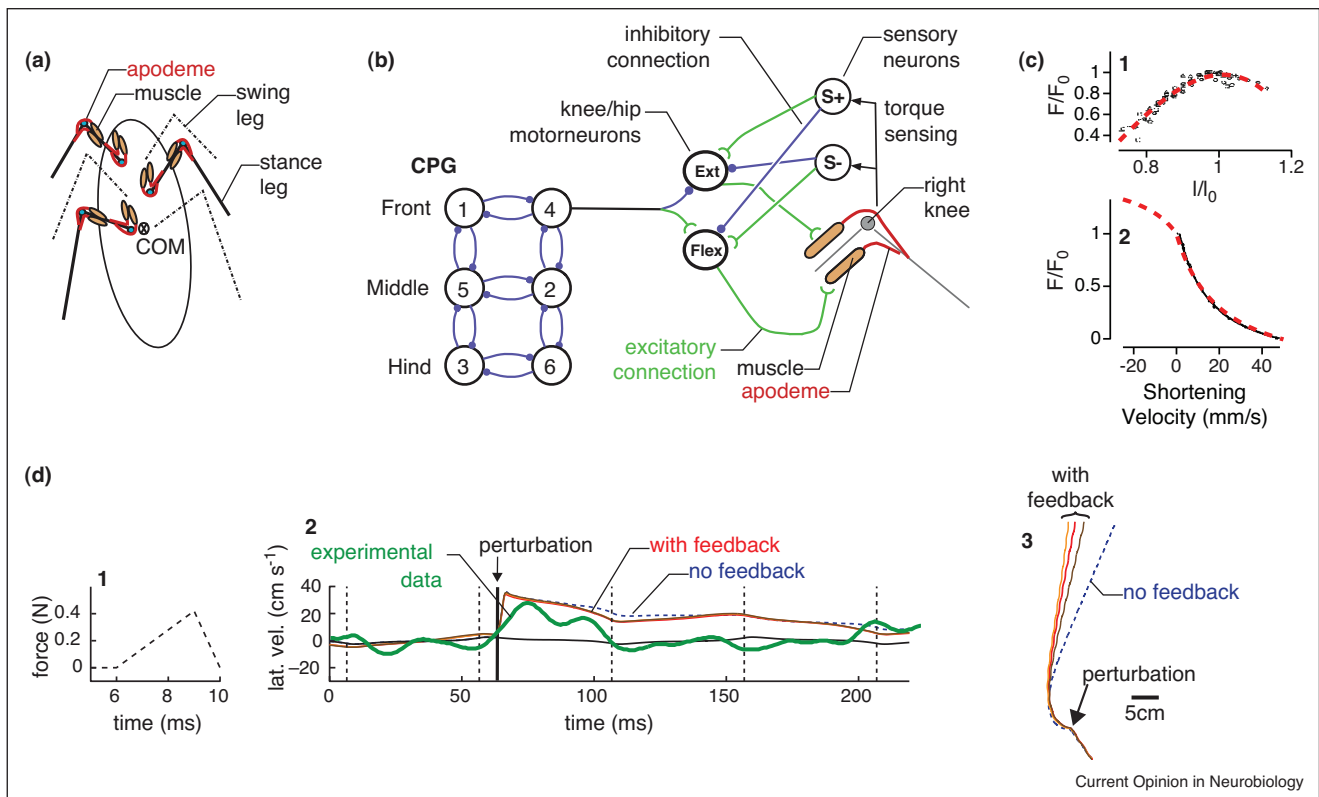
Understanding biomechanics becomes particularly important for neuroscientists when studying how animals cope with unexpected or unpredictable disturbances, called perturbations. Perturbations may include external effects, such as stepping in a hole while running, or internal effects, such as variable or noisy firing rates in motor neurons. Mechanical interactions, such as the stretching of elastic tissues including tendons, start

instantaneously after a perturbation: much faster than sensory information can be processed. These mechanical effects, termed ‘preflexes’ [51], can serve as a first line of defense against perturbations, or can sometimes damp out the perturbation entirely.

In locomotion, preflexes harness mechanical reaction forces, passive stiffness and damping properties, body-limb kinematics, and muscle states in a feed-forward control system driven by the CPG and motor neurons. This is especially important in small, fast animals whose stance periods may be as short as 10–20 ms. Rapid impulse experiments on running insects have shown that recovery begins within 10–15 ms, well before muscle activations can change due to proprioceptive feedback [52].

Models of insect locomotion in the horizontal (ground) plane (Figure 3), drawing on data from cockroaches and reviewed at length in [49], have shown that passive leg

Figure 3



Instantiation of the system of Figure 1 in a model of insect locomotion. (a) Mechanical model. Extensor and flexor muscles actuate simplified ‘hip–knee’ geometry modeling coxa–femur and femur–tibia joints. (b) Six hemisegments constitute a CPG oscillator network that drives motor neurons (MNs) in a feed-forward manner. Joint torques monitored by campaniform sensilla modulate relative phases of MN bursts (via S+ and S– neurons), but primary environmental feedback comes from mechanical reaction forces and stretch and stretch-rate force dependence in muscles. Filled circles and open arcs respectively denote excitatory and inhibitory connections. (c) Forces produced by muscle depend on length (panel 1) and shortening velocity (panel 2). Data from Ahn and Full [53] shown in black; fits shown with red dashed lines. (d) Response of the model as diagrammed in panels a–c to a rapid lateral perturbation. (1) Time course of perturbation force. (2) Lateral velocity after the perturbation. Solid black line shows the unperturbed model. Dashed blue line shows the model with no sensory feedback, while solid orange, red, and brown lines show differing sensory feedback gains. For comparison, experimental data from [52] is overlaid with a thick green line. (3) Trajectory of the model’s mass center in the horizontal plane. Feedback reduces heading change after the perturbation. Modified from [54*,55*].

stiffness alone can provide directional stability [56,57], much as passive machines can walk stably [10,13]. Moreover, incorporation of activation by ‘clock-driven’ mechanical devices [11,58–60] or by periodically-bursting motor neurons and muscles (Figure 3b) [44] preserves feed-forward stability in such models, allowing them to recover from substantial perturbations without feedback (Figure 3d). Insects running across an elastic membrane inserted into a rigid plane distort the membrane, allowing the animal’s center of mass to drop and causing legs to touch down earlier than on a rigid surface [38*]. The resulting increase in double stance duration compensates for slower force production by the compliant surface via purely mechanical feedback, without appeal to reflexes, or need for changes in feed-forward activation. Nonlinearities inherent in muscles (Figure 3c) are important here [61,62]: the fact that muscle forces peak when activated during extension and diminish as contraction speed increases provides active damping and can stabilize force output. Models also help explain the manner in which insects transition from modulating leg cycle frequency to stride length over their speed range [63] in order to maintain stability [58, Figure 14] and [60, Figures 11 and 12].

The addition of proprioceptive feedback can further enhance stability by modulating motor neuron burst timing [54*,64,55*]. Specifically, while both model and animal quickly recover to straight running following an impulsive perturbation [60,52], joint torque feedback can reduce the net heading change [54*,55*] by increasing muscle forces in stance legs to better oppose the impulsive force (see Figure 3d3). Moreover, proprioception can conspire with rhythmic muscle states to enhance corrective motions, as when extensors are activated earlier during the swing phase when they are still lengthening, which produces stronger contractions and prevents overstepping [64, Figure 9]. This and the preceding evidence supports the claim that rapid runners, swimmers and flyers rely on reflexes, even while profiting from reflexive feedback.

All the wonders of neuronal activation of muscle, coupled with the complexity of muscle dynamics conspiring with proprioceptors to stabilize movement, have fascinated and frustrated roboticists for decades [65]. An ambitious Japanese effort has tackled artificial muscle and actuators head on [66], but even though it addressed many of the extremely difficult issues that must be overcome to develop successful actuators, including energy sources, softness and flexibility of materials, and control, it is unclear how much progress was made on the issue of complex compliance. In particular, while artificial actuators may sometimes exceed the abilities of natural muscle in specific categories of performance, muscle performs well across a wide range of different tasks, and no single robotic actuator can yet match this breadth [67].

Conclusions

In this review we have focused on locomotion, in which spinal or thoracic neural circuits generate rhythmic patterns that are coupled to the environment by the body-limb system, producing mechanical work. Here the influence of biomechanics on behavior is clear, but we believe that it can play important, if more subtle rôles in neuroscience at large. Constraints due to muscles and mechanical properties help elucidate the paradox that neuronal activity in motor cortex, thought to generate ‘low-level’ activity of individual motor neurons, correlates with multiple different ‘high level’ kinematic measures of limb movement [68].

In fact, since every behavior involves motor output, neuroscientists neglect biomechanics at their own peril. To understand the activity of any neural circuit that has an input or output, one must be aware of the fact that the circuit is embedded within an organism, and that organism interacts with the physical world. One must consider these interactions in order to deduce which sensory stimuli are relevant to a neural circuit, and what motor outputs produce appropriate movements.

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