Materials challenges for powering miniature bioinspired robots

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To power miniature mobile robots, the body structure must integrate actuators, sensing, wiring, an energy source, power converters, and computing. The system-level performance relies on the interplay among these complementary elements and the fabrication technologies that enable them. While new materials, fabrication, and bioinspired designs are enabling advancements toward insect-scale untethered and autonomous robots, challenges remain in achieving high power efficiency fast actuation and heterogeneous integration. This article overviews the state of the art, opportunities, and challenges covered in this issue of *MRS Bulletin*.

Introduction

In his lecture "Infinitesimal Machinery," Feynman ignited research in miniature robots when he provided an analysis of mobile swimming microrobots and imagined a future where patients can "swallow the surgeon."[1] Today, miniature robots are inspired by the advancements of large-scale bioinspired mobile robots, of which convincing practical demonstrations emerged in the last decade.[2] Examples of such robots include the quadruped Cheetah robots from the Massachusetts Institute of Technology and the quadruped Spot and Humanoid Atlas from Boston Dynamics.[3] These robots are impressive integrated systems, which seamlessly employ advanced materials, bioinspired structural design, computing chips, memory, power sources, power electronic devices, and advanced controls. With this remarkable level of integration, these robots have a wide variety of applications ranging from defense to hospital services.[4] Many YouTube videos demonstrate their impressive agility, which exploit extremely powerful electric motors.[5] These motors offer very large torque density by having a large gap diameter, which makes them particularly suitable for actuating the joints in bioinspired locomotion. Spot's lithium-ion batteries takes on average about 2 h to charge and run for a practical duration of 90 min. The components of larger mobile robots, however, cannot be scaled to insect sizes and require new sets of innovations. Here, we identify areas where advances are revolutionizing the field and where challenges need to be overcome to realize the full vision of microrobots. We invite the readers to explore the perspectives of other authors in detail throughout this issue.

The cost of transport

The actuation and power needs for bioinspired locomotion are more demanding than wheeled locomotion.[6] In particular, walking and running animals are much more agile than wheeled automobiles. They climb, jump, and react to obstacles at a very wide range of speeds and postures. This creates demanding force and torque requirements. For perspective, the maximum output knee torque of a 75-kg walking human is 200 N.m, higher than the motor of a 1200-kg Toyota Corolla, which produces 170 N.m at 4000 rpm! We remind the authors that the latter uses a transmission gearbox to exchange speed and torque. The cost of transport (COT) is the measure used by biologists to gauge the efficiency of moving, be it walking, running, crawling, flying, or swimming.[7,8] Legged animals are typically less efficient than wheeled locomotion and have relatively higher cost of transport. This is attributed to the energetic cost of the cyclic acceleration and deceleration of the center of mass for walking and running, the same feature responsible for their agility. It appears that natural evolution favors agility over efficiency.

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Because this issue is centered on powering bioinspired miniature robots, it is important to examine the scaling of cost of transport as it relates to the actuation and energy-storage materials efficiency. In their articles in this issue, Reynolds and Miskin[9] describe the important topic of actuator efficiencies; while Zhu and Schmidt[10] decribe the current state of the art in microbatteries. COT is defined as[7]

$$COT \equiv \frac{P_{in}}{W.v},$$

where P_{in} is the input power to the animal, $W = mg$ is the weight, and v is the horizontal velocity. **Figure 1** shows the cost of transport for various animals and modes of locomotion. First, because the intrinsic efficiency of the muscles themselves in all animals is similar, on the order of 30% at the peak power,[7] it is initially surprising to see the order of magnitude range of the COT among these animals. It should be a goal for materials scientists to develop actuators with intrinsic efficiency equal to or exceeding the efficiency of natural muscles, that is, >30%. The spread in the COT values points to the critical role of mechanism design and the locomotion gait of the various animals. Some animals have more efficient mechanisms of moving around compared to other animals, even if their muscles have similar biochemical energy-conversion efficiency. Second, because the COT takes into consideration the animals' weight, it is noteworthy that COT is observed to be higher for smaller animals, as illustrated by the negative slopes. This surprising trend can be explained by the effects of the lower inertia, which results in higher accelerations, and the higher friction and drag losses due to the large surface to mass ratio for small animals. Third, running has a higher COT than flying and swimming due to the cyclic vertical accelerations, which do not directly contribute to horizontal locomotion, and hence are considered to be losses in this COT formulation. This scaling has important implications on the requirements for powering miniature robotics: the engineered actuators must be exceptionally efficient and lightweight to enable untethered locomotion. Finally, COT is not exactly equivalent to the inverse of the efficiency and is not bound by the minimum of COT = 1 (i.e. it could give the incorrect impression that animals who have COT < 1 are >100% efficient).[11] To resolve this, the reader is reminded that the weight and the velocity are vectors in two different directions and hence their product is only a qualitative measure of the moving power, unless the animal is moving vertically upward against gravity, which is not the case for these measurements. On the other hand, for wheeled automobiles with a constant horizontal velocity and minimum acceleration in the vertical direction, the horizontal force is due to air drag and friction, which add to less than the automobile's weight. Unfortunately, insect-scale robots cannot use smooth wheels for locomotion because this would greatly restrict their mobility and agility in traversing obstacles and rough terrain. Therefore, insect-scale robots must deal with extremely challenging and demanding efficiency requirements. This will be discussed later in the article.

With these challenges outlined, miniature robots promise applications where large robots cannot reach due to their size. There is no doubt that miniature robots which are capable of carrying sensors, cameras, and tools, such as surgical and biomedical tools, would be useful if they have good reliable untethered performance. Small mobile robots would conduct proximity sensing of temperature, chemical or biological

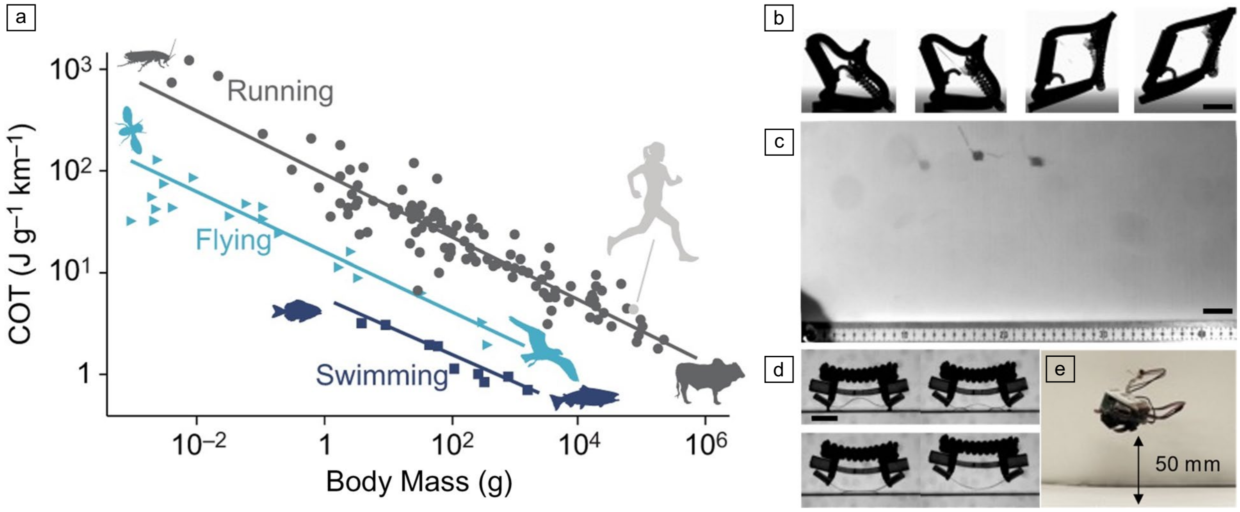

Figure 1. Cost of transport (COT) for various animals and insect-scale jumping robots. (a) Scaling law of COT as a function of mass. Miniature robots are expected to follow this scaling where they must pay the higher energetic COT. This plot sheds light on a roadmap for developing efficient materials and designs for powering insect-scale robots. Reprinted with permission from Reference 8. (© 2019 The Company of Biologists). (b–e) Insects that do not fly use jumping to traverse obstacles or escape. However, jumping is not amenable to COT analysis. (b) Close-up snapshots from a long jumping robot actuated by a nylon-coiled artificial muscle (total duration is 5 ms, scale bar = 10 mm). (c) Full view showing the long jump (scale bar = 30 mm). (d) Close-up snapshots of a vertical jumping robot using nylon-coiled artificial muscle coupled to a snapping steel beam (total duration 4 ms, scale bar = 5 mm). (e) Full view of the vertical jumping robot in (d) jumping while carrying a light sensor, a microcontroller, and a commercial battery.

cues, and be able to send and receive signals wirelessly. These small mobile robots would go in missions whether inside the human brain or intestine, between the branches of a tree, or inside the crevices in an airplane wing.[12] This article is written in conjunction with several relevant review articles published in this same issue of *MRS Bulletin* and hence they will be referenced. These articles present the recent advances in bioinspired designs, actuator materials, and energy-storage devices suitable for bioinspired robots at this scale. Two articles will also focus on applications in brain surgery and in water-jumping robots. The premise of this issue is that there are many future opportunities to enable this vision.

Actuator materials

Actuators are energy transduction elements that produce mechanical motion. Natural muscles are actuators that use metabolic energy to produce motion. Engineers of course prefer to use electrical energy to drive actuators, with the ultimate objective of eventually using onboard batteries. The actuation and fabrication strategies vary widely depending on the size of insect-scale robots from the submillimeter to the 1-cm scale (body length).[9] This is mostly due to the great increase in assembly and integration challenge at smaller scales. For miniature robotic applications, the metrics emphasized in the published work to date are energy density, blocked force, stroke, and power density.[13] These metrics are necessary but not sufficient to enable the practical use of these robots in their intended untethered applications, where power efficiency also plays a critical role, as will be highlighted throughout this article.

Continuous rotation electric motors (walking and jumping)

Although electric motors are outside the scope of this material-focused article, they are mentioned here as the benchmark of size and performance. Materials for actuation, which are discussed next, are expected to address the limitations of continuous rotation motors. In fact, bioinspired centimeter-scale terrestrial robots use miniature electric motors of ~centimeter length for walking and jumping. The use of off-the-shelf electric motors and batteries powering moving legs (hexapods) or bristles is mature, and, in fact, walking centimeter-scale robots are commercially available from the company Hexbug. These robots can be untethered and the batteries last on the order of <0.1 h. Judging by their speed and battery life, the COT of these robots is reasonable because the motor is running continuously, and the gait of the legs is driven by periodic gait mechanisms, such as four-bar linkages. However, as mentioned in the Introduction, while this increases the efficiency, it does not enable the agility needed for small robots in most practical environments. Electric motors also enable storing elastic energy in mechanisms, which can be later released on demand to enable jumping.[14] In their article in this issue, Mathur et al. describe bioinspired design strategies to amplify the power required for impulsive motions.[15] In this case, the COT is irrelevant for a single jump, but these jumping robots driven by motors are expected to be reasonably efficient (>5%).

Piezoelectric actuators (walking and flying)

Piezo actuators used in microrobots are typically bending-mode actuators made from lead zirconate titanate (PZT) driven at ~100–200 Hz.[16] These actuators deliver a notable power density with good mechanical design practices and enable steady walking at small scales.[17] Critical innovations on the material level aim at controlling grain size, geometry, porosity, and grain orientation[16] and on the integration level, including polishing and surface melting to increase the actuator life and suppress fatigue cracks.[18] PZT bending actuators sustain strains typically <0.5% and energy density of <5 J/kg. These are modest values indicating that robots based on piezoelectric actuators will be mechanically fragile. Of course, designs that shield the actuator from the end load and use frequency leveraging, such as inch worm mechanisms, increase the stroke output, while inadvertently increasing the mass, complexity, and decreasing the overall efficiency.[13] For these reasons, the most suitable use of piezoelectric actuators is in applications that actually require >10-Hz frequencies, such as actuating wings for flying microrobots, where their frequency response is simply unmatched, regardless of their performance in other metrics, such as energy density, force output, and efficiency.[19] Piezoelectric actuators were also used to enable miniature water striders walking on the water interface at frequencies of ~40 Hz.[20] In their article in this issue, Kim et al. describe a variety of lightweight water striders that employ piezoelectric actuators to walk on water, whereby these actuators have the suitable size scale, power density, and frequency response.[21]

Shape-memory alloys (SMAs) (walking and jumping)

Shape-memory alloys are used in the form of bending actuators[22] or contracting coils (artificial muscles),[23] typically made from nitinol. The material offers extremely large intrinsic energy density, typically larger than 1 kJ/kg, and for this reason, their power density is acceptable even if their actuation rate is quite small. SMA actuation is typically electrothermal (Joule heating) and therefore, their rate of actuation is <1 Hz and their efficiency is extremely small <1 percent. SMAs can be manually assembled, especially in the coil shape, down to the few millimeters size scale, and this enabled a variety of robots modes of mobility. Bending and folding SMAs also enable a variety of locomotion for millimeter-scale robots.[24] An early example using SMA coils is the robot MEDIC.[25] SMAs are commonly used to actuate jumping due to their extremely high energy density.[26] They were used to also demonstrate jumping on water.[21,27] Compared to a piezoelectric actuator, a single stroke from a SMA can power high jumps, especially when coupled with buckling snap-through.

Swelling, osmotic, and hydrogel (burrowing and jumping)

Swelling hydrogels, surprisingly, have been used with relative success in robotic functions with two different approaches. The first demonstration of a jumping mechanism based on a hydrogel used buckling snap-through, which is inspired by the Venus flytrap.[28] The jumping height is not as impressive as those using SMAs because of the low modulus. A plant-inspired material design truly boosts the actuation performance and speed of hydrogel-based actuators using a multifunctional encapsulating membrane, which exploits the higher modulus to increase the turgor and actuation pressures, and uses electro-osmosis to increase the rate.[29] These actuators can be used for burrowing applications, which do not necessarily require a large rate, but where the environmental-driven stimulation, such as cycles of humidity changes, can be harnessed to minimize the use of external power.[30] In their article in this issue, Shin et al. describe in detail the bioinspired principles of such swelling and turgor pressure actuators, and their potential use in robotics.[31]

Dielectric elastomer actuators (walking)

Extensive work over the last two decades has enabled dielectric elastomer actuators (DEAs) to function as muscles in miniature walking robots.[32] Despite these advancements, DEAs come with many challenges: first, they need large voltages.[33] For a typical thickness, the voltage are ~1 kV.[34] They are also prone to electric breakdown or electromechanical instabilities leading to failure.[35] The very high bonding (VHB) tape from 3M, which is commercially available, must be prestretched for best performance metrics, further complicating their integration. Nonetheless, with new materials that do not require prestretching[33] and the ability to operate with thin films, some current impressive DEA applications have been demonstrated, such as the terrestrial robot.[32] The efficiency of the DEA in this robot is far less than 1 percent.

Coiled artificial muscles (jumping)

Coiled artificial muscles are actuators that store elastic torsional energy during their manufacturing. The most commonly used type is made from nylon fishing lines and referred to as twisted and coiled polymer actuator (TCPA).[36] These actuators are actuated thermally or electrothermally with a wrapped heating wire. They have very large energy density or work capacity of >1 kJ/kg, which is comparable to SMA coils.[37] Nylon fishing lines are commercially available, cheap, strong, and have lower density than SMAs. Due to this extremely high force capability, they are suitable for actuating jumping as shown in Figure 1b–e. Vertical jumping was demonstrated by coupling the coiled muscles to a snapping beam, in a mechanism referred to as a dynamic buckling cascade due to the geometric transformation from the buckling beam bending to the snapping dynamic modes as the muscle is contracted.[38] These jumping robots are likely the first demonstration of jumping without prestored energy in the snapping beam, although the jumping performance is limited in this case. The same study demonstrated very high jumping when the muscles are used only to trigger snap-through, and the beams are preloaded manually before the jump. The same muscles were used to also trigger the long-distance jumping of an additively manufactured elastomeric robot of ~10 mm in body length.[39] These robots can carry a battery, microcontroller, and a light sensor and are untethered. However, the battery does not last more than two jumps due to the extremely low efficiency of the thermal actuation, estimated to be <0.5 percent.

Magnetic actuators (surgical robots)

Magnetic actuators are suitable for remote stimulation whereby a large electromagnetic coil controls the robot by excreting external forces.[40] Clearly, this type of actuation is suitable for biological applications, inspired by Feynman's quote "swallow the surgeon."[1] The advantages of this type of actuation are the ability to scale down without the need to have onboard stimuli generation or power. These magnetically responsive materials are readily 3D-printed by direct ink writing (DIW).[41] In this issue, Noseda and Sakar[42] review the status of the use of these actuators in a variety of real-world applied scenarios in brain surgeries. Importantly, tethered magnetic actuation is more likely to get FDA approval where the external magnetic field controls a catheter.

Bioinspired actuator selection

The type of mobility makes certain actuators more suitable than others. For example, flying microrobots typically use piezoelectric actuators to achieve the required frequency. Similarly, jumping actuators benefit from a power amplification principle, such as latch-mediated spring-actuated (LaMSA) designs,[43] as Mathur et al. describe in their article in this issue.[15] At small scales where motors are impractical, coiled artificial muscles made from nylon or shape-memory alloys are the most used actuators due to their high energy density. Typically, the high energy density is also coupled to a latch-mediated mechanism to achieve the required high-power impulse needed for a jump.[38,39]

Chip-scale extreme miniaturization

Truly chip-scale robots of submillimeter length scales rely on microfabrication technology. In their article in this issue, Reynolds and Miskin describe the material compatibility requirements for microfabrication-based chip scale robotics, such as piezoelectric materials, SMAs, or surface electrochemical actuators (SEAs).[9,44,45] From a performance perspective, the challenge with these actuators is to achieve large strokes, in the form of a bending angle of the bimorph beam, with reasonable voltage. This requires not only high responsiveness to the stimulus, but also thin films that can deform without yielding. Overall, in light of the COT discussion, these microrobots suffer from extremely low efficiencies on the order of $<10^{-9}$ percent.

Fabrication and actuation integration

Great advancements have been accomplished in fabrication technology enabling miniature and microrobots. Fabrication by origami-inspired folding enables centimeter-scale robotic fabrication. A systematic framework is the smart composite microstructure (SCM) process enabling lamination of multimaterials (hence the name composite) and folding or self-folding.[46,47] The approach relies on laser-cutting flat actuation materials such as SMAs, which then are used in bending mode to create static or dynamic hinges. At the microscale, microfabrication combined with pop-up approaches to create origami enable milligram robots, where the actuation material is 2.5-μm nitinol SMA or submicron thickness platinum, which undergoes electrochemical oxygen absorption and swelling to induce actuation.[48] Multimaterial 3D printing capable of depositing both structural and functional materials can play an important role in enabling high-performance and truly 3D microrobots, akin to what has been demonstrated for ~10-cm-scale soft robots.

Energy storage

Although energy density has a constant scaling with device size (L^3/L^3), the high COT of miniature robots ensures that energy storage will critically limit their performance.[10,49] The best commercial microbatteries only power insect-sized crawling robots for about 1 min and only the very best batteries can provide the specific energy and power needed for sustained flight in flapping wing microvehicles.[50] A major challenge is that microbattery energy densities are worse than their macroscopic counterparts because of the poor scaling of critical battery components, such as the packaging and separators, which contribute 30–70% of the total battery volume and mass.[51,52] Yue et al. compared their microbattery advances to the state of the art and showed the dramatic reduction in battery energy density with size.[51] Although there has been much progress in translating macroscale battery advances to small scales, such as integrating high energy density chemistries and 3D architecting the electrodes,[53] significant gains in energy and power can be achieved from novel packaging and integration strategies.[51,54] As batteries shrink to sub-mm^3 volumes, entirely new architectures and manufacturing methods are needed to integrate the necessary anode, cathode, and electrolyte chemistries without shorting the cells.[54–57]

Utilizing primary chemistries and adding additional functionality to microbatteries are promising solutions to their limited energy densities. Primary batteries can achieve higher energy density than rechargeable batteries and are advantageous for applications where the robot is only used once or when there are many swarms of robots and recharging or replacing their batteries is impractical.[58] New primary microbattery designs can stack multiple thick cells to achieve high-voltage outputs, high power densities (>100 mW/cm^2), and energy densities (up to 990 Wh/kg and 1929 Wh/L).[54] A high-voltage output from serially connected cells is important because the output voltage often needs to be boosted to power actuators, sometimes to thousands of volts,[59] and reducing ratio of output to input voltage can significantly increase the efficiency of these electronics. Additional advantages can be achieved with multifunctional batteries that provide power[60,61] or actuation[62] in addition to storing energy. These functionalities reduce the volume or mass needed for other components, or in the case of actuators, can increase the full robot energy density by more than 4x while maintaining the same actuator availability.

An alternative to storing energy is to extract energy from the environment. Applications where tiny robots are confined to specific tasks, such as diagnosing a disease or delivery of a drug, large acoustic, magnetic, or light-based external energy sources can be directed to energy converters on the robot and eliminate the need for onboard energy storage.[44,63,64] It is more challenging to power miniature robots in less structured environments without batteries as energy harvesters cannot provide enough power to operate actuators. With the notable exception of solar panels, which can provide up to 30 mW/cm^2, a typical harvester provides <1 mW/m^2 with many providing <1 $\mu W/cm^2$).[65] A notable exception are electrochemical scavengers that can power centimeter-scale robots by electrochemically oxidizing materials in the environment.[66] In this work, Wang et al. showed that this approach can extract more than 130 mW/cm^2 from various metals to directly power small vehicles for 10x longer than the equivalent weight in batteries. Through advances in catalysis, this approach could be applied to a wide variety of materials and combine the high energy density of harvesters with the power density of batteries. Beyond providing power, electrochemical scavengers can be arranged to follow chemical signals in the environment through electrochemotaxis,[67] allowing miniature robots to navigate through an environment without a computer or battery.

Challenges and outlook

Recent advanced material offer a palette of various high energy density and large stroke actuators suitable for a variety of miniature robots as outlined in this issue. In fact, the energy density of SMAs and coiled artificial muscles is 50x higher than biological muscles.[68] However, with extremely high COT for insect-scale locomotion, these miniature robots can not use thermal actuators to reach the goal of untethered performance with onboard power sources due to their low efficiency (<1%). Hence, there is a strong need to develop high-efficiency actuator materials and high-efficiency locomotion designs. The actuation mechanism and locomotion designs are coupled because most material-based actuators are elastic and hence their performance can only be assessed in conjunction with the specific machine cycle or locomotion gait that they will be employed in, where their mechanical analysis could benefit from concepts developed for electric motors such as series electric actuators.[69]

Similarly, although several high energy density batteries exist, new approaches to powering miniature robots are required to overcome their high COT. By harvesting energy in their environment or through improving battery power output performance while gaining extra mechanical or decision-making functionality, the next generation of miniature robots will be more capable than the swimming surgeons that inspired this field.

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Data availability

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Publisher's note

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