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REVIEW

Mobile Robots: Motor Challenges and Materials Solutions

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Bolted-down robots labor in our factories, performing the same task over and over again. Where are the robots that run and jump? Equaling human performance is very difficult for many reasons, including the basic challenge of demonstrating motors and transmissions that efficiently match the power per unit mass of muscle. In order to exceed animal agility, new actuators are needed. Materials that change dimension in response to applied voltage, so-called artificial muscle technologies, outperform muscle in most respects and so provide a promising means of improving robots. In the longer term, robots powered by atomically perfect fibers will outrun us all.

In this article, the application of actuator technologies is considered specifically for robots that are humanlike in form. Marc Raibert and his group at Massachusetts Institute of Technology (MIT) showed in the 1980s that robots can walk, run, and do flips (*1*). These robots are not free, however, but rather are attached to their power supplies. The incredible achievements and the limitations of successive lifelike robots provide insight into the challenges of using conventional actuators to drive machines that mimic human form and motion. The focus of this article is on robots and humanoids in particular, but much of the discussion of actuators is relevant to any active mechanical system and particularly those that involve intermittent rather than continuous motion, such as prosthetics, medical devices, valves, locks, and toys.

Combustion Engines: Powerful But Hard to Carry

The power per unit mass achieved in internal combustion engines is 1000 W/kg, about 10 times greater than the continuous power output of our own muscle (*2*). High power makes combustion engines excellent for the propulsion of vehicles, and particularly for highway driving, where abrupt changes in speed or direction are unusual. This power is combined with the long range afforded by the use of gasoline, which has an energy per unit mass that is about 20 times higher than that of a good battery, even after accounting for the ~30% efficiency typical in an internal combustion process. There are two particularly notable challenges to using the combustion engine on a robot, however. The first is that the engine operates best over a narrow range of rotation speeds, providing no torque at all at zero speed. Cars have transmission systems, including clutches and gears, that enable acceleration from a complete stop up to high speed. This transmission is not suited to the abrupt motions required of a robot, such as reaching for an object, then holding it for some time at a fixed position, and then throwing it away. The second challenge is simply carrying the hot, loud, and fuming engine on a robot while operating it efficiently and effectively, with space left for fuel.

Steve Jacobsen and his colleagues have demonstrated particularly impressive use of hydraulics to drive robots (*3*). Hydraulic actuation is a sophisticated version of the system used to drive the shovel on a front-end loader. Jacobsen's hydraulic robotics perform extremely lifelike movements and have been demonstrated in Disney theme park humanoid robots and Jurassic Park dinosaurs. However, these rely on an external power source. The Berkeley Robotics Laboratory has shown that a hydraulic motor can be taken on board (*4*, *5*). Its 75-kg device is not a free-standing robot but rather an exoskeleton with powered ankles, knees, and hips. The robot is attached at the feet and the hips, and it works in parallel with the wearer, allowing an additional 75 kg to be carried. This capability is intended to relieve a foot soldier's burden. The combined hydraulic system, empty fuel tank, valves, actuating pistons, and internal combustion engine exhibit a power-to-mass ratio that is about the same or perhaps a bit lower than that of muscle itself (*6*). Hydraulics are not terribly efficient for walking, which requires high power output only for brief periods of time. For the remainder of the time the system is needlessly shunting fluid. Primarily as a result of this inefficiency, BLEEX expends three times more energy in walking than a human does (*4*). A further drawback is the noise and heat of the combustion engine. The device certainly augments human strength, but so far soldiers are better off building up their own muscle if they can.

One key to reducing weight and increasing efficiency, and thereby making hydraulics more practical, may be to redesign the internal combustion engine to allow for the bursts of power needed during walking, running, or jumping (*7*, *8*). A potential weight-saving measure is to use lightweight pneumatic actuators in place of heavier hydraulic pistons, although this increases the mass of the pump (*9*). Either way, it is very hard to beat muscle.

Electric Motors: Jogging But Not Sprinting

Electric motors are attractive because they feature high continuous power per unit mass [up to 300 W/kg when using rare earth magnets (*10*) and twice that when actively cooled (*11*)] and high efficiency (can be >90%) (*2*). They are also relatively quiet and generate high torques at low speeds, making the transmission easier than it is in the combustion engine. Honda's impressive ASIMO is a battery-powered, untethered humanoid robot driven by electric servomotors (*12*–*14*). There is a motor for each of the 34 joints, including arms, legs, hips, hands, feet, head, and fingers. The fast rotary motion of the electric motors (which deliver maximum power at high speed) is converted to slower joint rotation by using a compact reduction system known as a harmonic drive. The drive has the same effect as going into very low gear on a bicycle. This transmission system, however, is heavy, bringing the overall power per unit mass down to or below that of muscle. Honda's latest robot, shown in Fig. 1, is able to do a slow run (6 km/hour, equivalent to a 16-min-mile pace), with both feet leaving the ground simultaneously between steps, clearing the ground by about 3 cm (*13*). It can also do light work, picking up 1 kg (about four coffees) when using both hands. Similar complexity and performance are demonstrated in other battery-powered servomotor-driven robots, including Sony's QRIO robot (*15*, *16*), which is much smaller than ASIMO and was the first to run, and Kawada's HRP-2 (*16*, *17*), which is about the same size as ASIMO but does not run.

Fig. 1. Honda's humanoid robot ASIMO on the run. Reproduced from (*13*) with the permission of the Honda Motor Company.

Why can't ASIMO and the others go faster, jump higher, or carry a larger load? Speed is limited by the peak power output. Peak power requirements triple in the progression from walking to sprinting (*18*), so ASIMO's motors need to be three times heavier to achieve a fast run

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than they do for a moderately paced walk. In a human the size of ASIMO, the peak power at the ankle is about 200 W (*4*). At a sprint pace, the power rises to 700 W (*18*). Factoring in the inefficiency of the transmission, the power needed from an electric motor is more than 1000 W in each ankle. With transmission included, the power density of the motor is roughly halved, so when using a high-performance uncooled electric motor and gearhead the output is 150 W/kg (*10*), resulting in the need for a 6.5-kg motor on each ankle. Imagine the effect on the quadriceps of carrying an extra gallon of milk on each calf during a sprint: The actuator is simply too heavy.

Mammalian skeletal muscle, the form of muscle we use to move our limbs, has a peak power to mass of about 300 W/kg for fast twitch muscle and lower in aerobic forms (*19*). On the basis of the 700 W required at the ankle during sprinting and optimistically assuming fast twitch performance, 2.3 kg or about 2 liters of calf muscle are required. That is a very large calf muscle, particularly for a person the size of ASIMO (54 kg). Nature gets away with significantly smaller muscles. This is achieved by shunting more than 50% of the energy in a stride in to tendon extension, muscle stretching, and flexion of the foot (*18*). The running motion has been likened to the travel of a pogo stick, and the legs each modeled by a spring in series with muscle. This approach is being mimicked in robotics by inserting springs in series with actuators (*20*) and has been used in several bipedal robots (*9*). In time these may be able to match our own mechanical performance, particularly if metal springs are avoided (the small strains of metals make them low in energy density compared to tendons and rubbers).

Can the electric motors used in robots be improved? The Lorentz force used to drive these motors produces a force that is proportional to current. Current is limited by the heat generated due to resistive losses. Power output can be doubled by adding cooling. One means of improving ASIMO's performance is to add a water circulation system that enables perspiration. In expending 1 kW of energy continuously (a strenuous activity level in a human), little more than 1.5 liters of water per hour would be evaporated. The addition of water cooling is not trivial because it adds complexity, weight, and cost, but making robots that drink to keep cool should dramatically improve agility.

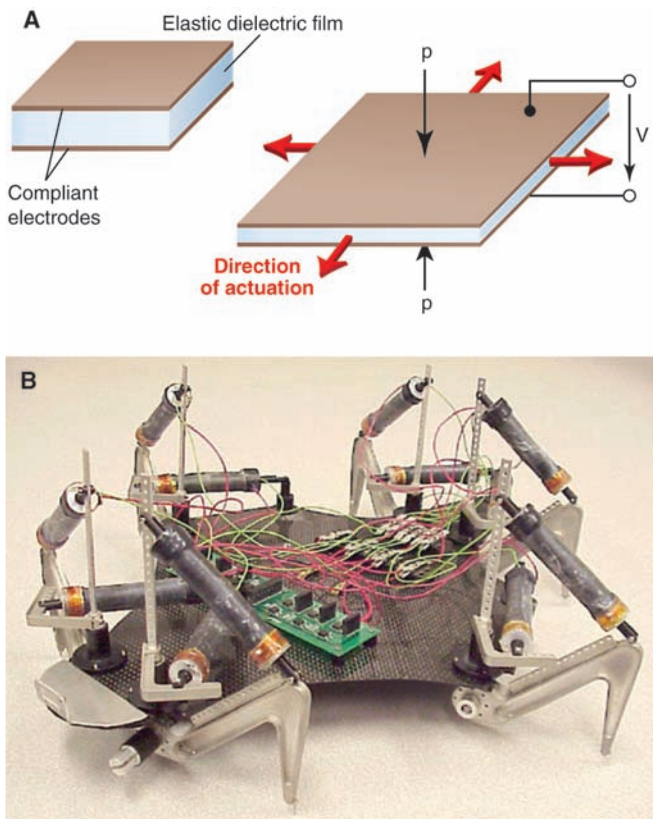

Fig. 2. (**A**) Mechanism of actuation of dielectric elastomers (*21*) and (**B**) SRI's FLEX 2 six-legged robot operating with sheets of dielectric elastomers rolled around a spring to form tubes. Two spring rolls drive each leg. Figure reproduced from (*29*) with permission of the SPIE.

Batteries, hybrids, or fuel cells? ASIMO has a 51.8-V lithium ion battery pack, which can sustain it for 1 hour and takes 4 hours to recharge. Humans can continue for days on their reserves. Our fat, when combined with oxygen, generates enough adenosine triphosphate (ATP) (*21*) (the molecule used to power muscle and other processes) to provide 15 MJ/kg, 30 times more usable energy than the same mass of lithium ion battery. At present ASIMO, with its image and voice recognition abilities, can act as a receptionist, sitting plugged in between making small deliveries or after guiding visitors to their meetings. How can endurance be improved?

Some reduction in energy expenditure may be possible. HRP-2 runs its 11-kg batteries down in about 1 hour, corresponding to an average power expenditure of about 300 W. A person walking at a moderate pace burns about 3.3 W/kg of body mass, a 220-W expenditure for someone weighing the same as the robot (58 kg). The comparison suggests that there are opportunities to reduce power consumption in robots, but what is really needed is a high energy density storage method.

One option is to create the robotic version of a hybrid car. A portable combustion engine driving a 1-kW generator weighs about 15 kg including fuel for up to 8 hours. The effective energy density of the fuel plus the generator over 8 hours is about five times better than that of a battery, but still about five times worse than storing energy as fat. The key to matching fat is to make the motor smaller and lighter. In the long run, the development of turbine generators on a chip could solve the energy challenge. These are millimeter-scale turbine blades, combustion chambers, and electric generators microfabricated in silicon. Fuel-driven microfabricated turbines exhibit power densities that are more than 100 times larger than those in traditional combustion engines, making their size negligible compared to the stored volume of fuel and thus enabling a 20-fold longer running time than is possible with batteries (*22*). Some fabrication challenges remain, however, before these devices are fully demonstrated.

Fuel cells are a promising option but are not sufficiently developed. A commercial portable hydrogen fuel cell (*23*) can provide the same power output per unit mass as the portable gas generator, but the space required is larger because of the fuel volume needed, making it more cumbersome.

Muscle: hard to surpass. The skeletal muscle used to actuate our limbs (*24–26*) is a beautifully refined linear actuator, typically capable of contracting by 20% of its length. This large linear contraction is transmitted to bones via tendons, creating a torque about joints that in turn rotates limbs. Cycle life is high, reaching more than 1 billion activations in the heart. The source of energy is chemical and, as with fossil fuels and hydrogen, is very high in energy density in large measure because oxygen is freely available in the atmosphere. The ~45% energy conversion efficiency between ATP and mechanical work is not as good as in a high revving electric motor but is better than that of the combustion engine. A special feature of muscle is that it can selectively activate subsets of fibers within a single muscle. It is also capable of changing stiffness by a factor of 5, a characteristic made possible in part by muscle's ratchetlike actions at the molecular scale. When the ratcheting mechanism is released, the stiffness drops. These properties enable us to grade force depending on load, thereby increasing efficiency and improving control. Imagine trying to catch a baseball with your arms completely stiff or totally relaxed. In the first case, it would bounce out of your glove before you could grasp it, and in the second the ball would move right through you. The same property enables us to cushion our landing when jumping from a height.

So why not use muscle in robots? Muscle operates optimally when associated with a circulation system that provides oxygen, glucose, and nutrients and can carry away heat, CO_2, and other waste. It also has relatively fine control from nerves that enable rate, force, and speed control. Additionally, the digestive and circulatory systems provide amino acids that enable muscle to build up, repair itself, and regenerate, allowing it to adapt to demand and to last a lifetime. Our technology is not yet ready to interface with such a complex system.

Artificial Muscle

Many materials have been investigated as candidates for artificial muscle (*26*–*28*), including gels that swell and contract by more than 100% in response to changes in pH and temperature; shape memory alloys, whose change in crystal structure with changes in temperature or applied magnetic field produce relative changes in length of up to 10% at high loads; intrinsically conducting polymers that charge and discharge like batteries and swell or contract by about 8% in the process; ionically conductive polymers in which ions and solvent are shuttled from one side of the material to another, producing a bending motion; and liquid crystals, whose change in alignment with temperature or electric field leads to displacements. The two most immediately promising technologies are dielectric elastomers and relaxor ferroelectric polymers. Both are electric field–driven, and they feature high work per unit volume [reaching ~1 J/cm^3, compared to 0.04 J/cm^3 in muscle (*26*)]. The high work density compared with muscle means that less volume and mass are needed (because densities are similar to that of muscle), enabling lighter and thus more agile devices. The relatively good coupling between the electrical input energy and the mechanical work performed (20% to 90%) enables them to operate with efficiencies that are comparable to or better than that of muscle. Dielectric elastomers in particular are ripe for application, having been demonstrated in multilegged robots (*29*) (Fig. 2B) and an arm-wrestling device (*30*), as well as being commercially available from the start-up Artificial Muscle Incorporated of Menlo Park, California.

Electrically driven rubber. Dielectric elastomers (*31*) are thin sheets of rubbery materials (typically silicones or acrylics) whose top and bottom surfaces are coated with flexible electrodes, as depicted in Fig. 2A. The devices are capacitors with compliant dielectrics. When the electrodes are charged, the opposite charges on each electrode attract, leading to a reduction in the distance between capacitor plates and an expansion in the plane. The actuator can more than double in length. These materials outperform muscle in nearly every respect but have their limitations.

Strains increase in proportion to the square of the magnitude of the applied field, so ensuring that breakdown occurs only at very high fields (~100 MV/m) is critical. High dielectric strength is achieved by prestretching films by up to 500%. The problem is that maintaining this prestretch requires a mechanical structure that is generally much bigger and heavier than the elastomer film itself (*26*, *32*). This makes the effective work density much lower, similar to that of muscle. The performance may not be good enough for use in humanoid robots because of additional electronics required to produce the high voltages (>1 kV) that are needed. There are materials solutions that help eliminate the need for prestretching, however, and thereby greatly improve performance. Recent work has shown that, by interpenetrating a stiff, cross-linked polymer between the rubbery chains of the elastomer when in a stretched state, much of the extension is maintained when the load is released (*32*). This eliminates the need to prestrain, improving the work density. The actuators can also be fast, with nearly constant amplitude of displacement having been demonstrated at more than 1 kHz in one form of dielectric elastomers. Important challenges in the application of dielectric elastomers to robotics are finding an effective and compact method of generating high voltages and ensuring safety.

Electric fields that move molecules. Ferroelectric polymers such as polyvinylidene fluoride (PVDF)–based materials generate substantial anisotropic deformations when an electric field is applied (*33*, *34*). The backbone of this polymer is partially fluorinated. The fluorine atoms attract electrons, making the polymer polar. Fields act to change the orientation of the polar groups, altering the conformation of the polymer chains, resulting in displacements. A disadvantage had been the relatively large hysteresis in these materials, similar to that seen in permanent magnets, leading to high switching losses and poor control of displacement. In order to reduce these losses, defects are introduced, which disrupt the formation of large polar domains. In these disordered materials, known as relaxor ferroelectrics, the application of a field to an oriented polymer leads to changes in length of up to 7%. The strain is smaller than that in muscle, making larger mechanical amplification necessary in order to displace limbs. However, stiffness and force per cross-sectional area are higher than in muscle (20 MPa operating stress versus 0.35 MPa in muscle), leading to a much larger work density (about 25 times higher than that of muscle).

Further development is needed in order to determine cycle life and scale the size of these devices up to that needed to run a large robot. As in dielectric elastomers, high voltages are used. There are opportunities to reduce voltages needed in ferroelectric polymers and dielectric elastomers by using thinner layers of materials with a higher dielectric constant and lower stiffness, but these solutions are not as simple as they appear. Increasing dielectric constant can lead to higher stiffness and lower breakdown potential, for example. Another challenge is ensuring that these and other materials can go through the needed number of cycles before failure, because regeneration is

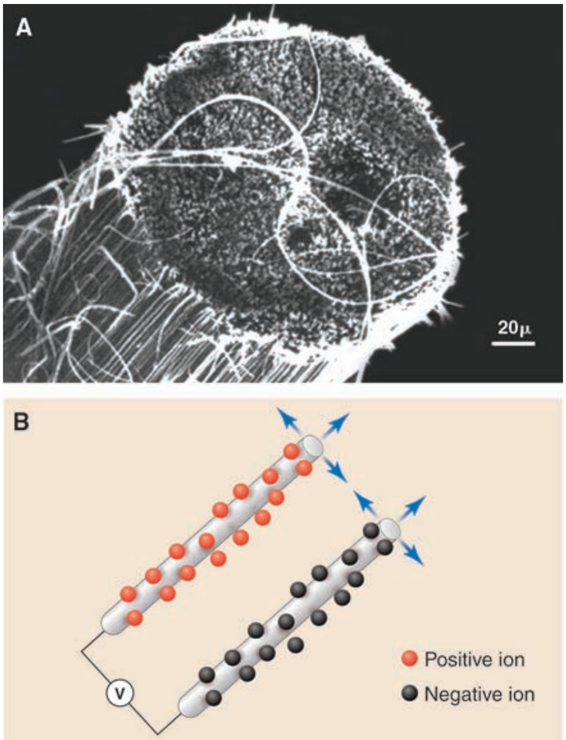

Fig. 3. Actuation of metal nanofibers. (**A**) Scanning electron micrograph of niobium nanofilaments formed by drawing a copper-niobium composite. Reprinted from (*39*). [Copyright 1978 American Institute of Physics] (**B**) A depiction of how such fibers might be actuated, showing two individual fibers to which voltage has been applied through an electrolyte. The charging of the surfaces of the fibers is expected to lead to both expanding relative to their neutral states when charging levels are sufficiently high.

not currently possible. At present, the cycle number is in the tens of millions in dielectric elastomers, adequate for continuous operation once a second 8 hours a day for 1 year.

New Approaches

Can we emulate muscle itself? One approach is to design molecules that undergo reversible shape-changing interactions and to harness these shape changes in order to create musclelike materials. Synthetic motors relying on molecular-scale interactions have been developed (*35*) that could eventually mimic muscle. These include molecules that fold and unfold as a function of applied voltage, single molecule rotary motors, and molecules that slide past each other in response to ion insertion. Creating assemblies of motor proteins is another option. In these cases, a key challenge is not only designing the appropriate molecular-scale interactions but also producing the meso- and microscale structure that enables effective operation on the macroscale. The molecules-to-mechanisms approach has been successfully demonstrated in azobenzene, a molecule that reversibly changes bond shape in response to interactions with photons. Atomic force microscopy measurements show that these molecules exhibit molecular-level length changes in response to light, and similar strains are observed macroscopically (*36*). Light actuation is not always practical. A challenge for the synthetic chemistry and materials communities is to develop molecular mechanisms that are activated directly or indirectly by high energy fuels [e.g., hydrogen and oxygen (*37*)].

An exciting new actuator technology that is currently being explored employs nanotubes. Carbon nanotubes are essentially perfect in their atomic structure. Defects help atoms to slip with respect to each other, causing irreversible deformation. The absence of defects enables these filaments to deform elastically by several percent or more, instead of the 0.1% typical of metals and ceramics. The elastic energies stored in these materials are huge, approaching 10 J/cm^3 in metals, based on elastic strain and modulus. About one-fourth of this energy can readily be extracted (*38*). A sphere 7.5 cm in diameter could contain the active material needed to perform the same work as all of our muscles put together. Our biceps could be replaced by an 8-mm-diameter wire. Such compact muscle would be enormously enabling for robots, making them far lighter and more agile.

In order to extract the energy from nanowires or nanotubes, there needs to be a mechanism of stretching them in the first place. In a cross-bow our muscle provides the stretching, but what can we use to stretch these tiny filaments? Also, if they are to be used in robots, the size needs to be scaled up substantially without producing defects. The stretching can be done electrostatically, as has been shown in carbon nanotubes (*38*), platinum nanoparticles (*39*, *40*), and most recently nanowires (*41*). Charging is achieved by submerging films of these materials into an electrolyte and applying an electrical potential through the solution, as depicted in Fig. 3B. The resulting charging of the surfaces of the nanotubes, wires, and nanoparticles is sufficient to expand these stiff materials because of their high surface area–to–volume ratios.

At present, however, the problem is that the coupling between input electrical energy and output mechanical work is low. Spun nanotube yarns show charge-induced strains of 0.5%, and stresses can exceed 100 MPa. However, the electromechanical coupling is less than 1%. The problem is that a lot of energy is expended stretching the nanotubes, but very little is extracted because the stiffness of the yarn is far lower than that of the individual nanotubes.

How can the coupling and the strain be improved? The conceptually simple but practically challenging answer is by making the macroscopic structures as stiff as the microscopic ones. It has been known for some time that bundles of superstrong nanowires (*42*–*44*), as shown in Fig. 3A, can be as strong as the individual wires from which they are composed. If the bundles can be made porous, then it may be possible to ionically charge them in order to induce deformation.

No actuator technology yet matches the muscular system's combination of high energy density fuel, relatively efficient operation, scaleable force, elastic energy storage, and power output. Developments in transmissions, series elastic elements, and energy storage and generation mechanisms should make it possible to equal muscle's performance using traditional motors. Electric field–driven polymers outperform muscle in most respects but need creative solutions for delivering the electrical power in a safe and compact manner. If the incredible properties of nanofibers can be extended to macroscopic scales in actuators, as has been achieved for passive mechanical structures, then artificial muscle will enable robots to outrun and outjump us all.

References and Notes

1. J. K. Hodgins, M. H. Raibert, *Int. J. Robot. Res.* **9**, 115 (1990).
2. J. Hollerbach, I. W. Hunter, J. Ballantyne, in *Robotics Review 2*, O. Khatib, J. Craig, P. Lozano, Eds. (MIT Press, Cambridge, MA, 1991), pp. 301–345.
3. S. C. Jacobsen *et al.*, *Int. J. Robot. Res.* **23**, 319 (2004).
4. A. Zoss, H. Kazerooni, A. Chu, in *Proceedings of the International Conference on Intelligent Robots and Systems 2005 (IROS 2005)*, IEEE/Robot Society of Japan (RSJ), Edmonston, Canada, 2 to 5 August 2005, pp. 3465–3472.
5. H. Kazerooni, Berkeley Robotics Laboratory, http://bleex.me.berkeley.edu/bleex.htm (accessed 2007).
6. K. Amundson, J. Raade, N. Harding, H. Kazerooni, in *Proceedings of the International Conference on Intelligent Robots and Systems 2005 (IROS 2005)*, IEEE/RSJ, Edmonston, Canada, 2 to 5 August 2005, 3453–3458.
7. G. T. Huang, *Technol. Rev*. **2004**, 24 (2004).
8. S. C. Jacobsen, M. Olivier, U.S. patent 6,957,631 (2005).
9. R. Van Ham, thesis, Vrije Universiteit Brussel, Brussels, Belgium, 2006. Accessible at http://mech.vub.ac.be/multibody/publications.htm.
10. C. Maxon Motor, *RE40 Graphite Brushes DC Motor 150 W*, www.maxonmotor.co.uk.
11. Powertec, www.powertecmotors.com/pactorq.html.
12. Y. Sakagami *et al.*, in *Proceedings of Intelligent Robots and System 2002 (IROS 2002)*, IEEE/RSJ, Lausanne, Switzerland, 30 September to 4 October 2002, pp. 2478–2483.
13. C. Honda Motor, http://world.honda.com/ASIMO/.
14. K. Hirai, M. Hirose, Y. Hajikawa, T. Takenaka, in *Proceedings of the International Conference on Robotics and Automation 1998*, IEEE, Leuven, Belgium, 16 to 20 May 1998.
15. Y. Kuroki, M. Fujita, T. Ishida, K. Nagasaka, J. Yamaguchi, in *Proceedings of the IEEE Conference on Robotics and Automation, 2003* (IEEE, Taipei, 2003), vol. 1, pp. 471–476.
16. K. Kaneko *et al.*, in *Proceedings of ICRA '04 IEEE International Conference on Robotics and Automation* (IEEE, New Orleans, 2004), vol. 2, pp. 1083–1090.
17. N. Kanehira *et al.*, in *Proceedings of the International Conference on Intelligent Robots and Systems 2002,* IEEE, Lausanne, Switzerland, 30 September to 4 October 2002, vol. 3, pp. 2455–2460.
18. T. F. Novacheck, *Gait Posture* **7**, 77 (1998).
19. R. K. Josephson, *Annu. Rev. Physiol.* **55**, 527 (1993).
20. D. W. Robinson, J. E. Pratt, D. J. Paluska, G. A. Pratt, in *Proceedings of 1999 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (IEEE, Atlanta, 1999), pp. 561–568.
21. G. M. Cooper, R. E. Haussman, *The Cell: A Molecular Approach* (Sinauer, Sunderland, MA, ed. 2, 2000).
22. C. Lee, M. Liamini, L. G. Frechette, paper presented at Solid State Actuator, Sensor and Microsystems Workshop, Hilton Head, SC, 4 to 8 June 2006.
23. I. Ballard Power Systems, Nexa power module, www.ballard.com.
24. A. M. King, D. S. Loiselle, P. Kohl, *IEEE J. Ocean. Eng.* **29**, 684 (2004).
25. I. W. Hunter, S. Lafontaine, in *Proceedings of the Solid State Actuator, Sensor, and Microsystems Workshop*, IEEE, Hilton Head, SC, 21 to 25 June 1992, pp. 178–185.
26. J. D. W. Madden *et al.*, *IEEE J. Ocean. Eng.* **29**, 706 (2004).
27. Y. Bar-Cohen, Ed., *Electroactive Polymer (EAP) Actuators as Artificial Muscle* (SPIE, Bellingham, WA, ed. 2, 2004), p. 765.
28. M. Shahinpoor, K. J. Kim, M. Mojarrad, *Artificial Muscles: Applications of Advanced Polymeric Nanocomposites* (Taylor and Francis, New York, 2007).
29. R. Pelrine *et al.*, *Proc. SPIE* **4695**, 126 (2002).
30. G. Kovacs, P. Lochmatter, M. Wissler, *Smart Mater. Struct.* **16**, S306 (2007).
31. R. Pelrine, R. Kornbluh, Q. Pei, J. Joseph, *Science* **287**, 836 (2000).
32. H. Soon Mok, Y. Wei, P. Qibing, P. Ron, S. Scott, in *Proceedings of Smart Structures and Materials 2006: Electroactive Polymer Actuators and Devices* (SPIE, San Diego, 2006), vol. 6168, pp. 08-1–08-12.
33. Q. M. Zhang, V. Bharti, X. Zhao, *Science* **280**, 2101 (1998).
34. Q. Zhang, C. Huang, F. Xia, J. Su, in *Electroactive Polymer Actuators as Artificial Muscle*, Y. Bar-Cohen, Ed. (SPIE Press, Bellingham, WA, 2004), pp. 95–170.
35. P. A. Anquetil, J. D. Madden, H.-H. Yu, T. M. Swager, I. W. Hunter, in *Handbook of Organic Electronics and Photonics*, H. S. Nalwa, Ed. (American Scientific, Los Angeles, 2007), vol. 1, pp. 447–483.
36. T. Hugel *et al.*, *Science* **296**, 1103 (2002).
37. V. H. Ebron *et al.*, *Science* **311**, 1580 (2006).
38. R. H. Baughman *et al.*, *Science* **284**, 1340 (1999).
39. J. Weissmüller *et al.*, *Science* **300**, 312 (2003).
40. R. H. Baughman, *Science* **300**, 268 (2003).
41. S. Lu, B. Panchapakesan, *Nanotechnology* **17**, 888 (2006).
42. V. Vidal, L. Thilly, F. Lecouturier, P. O. Renault, *Scripta Mater.* **57**, 245 (2007).
43. J. Bevk, J. P. Harbison, J. L. Bell, *J. Appl. Phys.* **49**, 6031 (1978).
44. C. W. Sinclair *et al.*, *J. Cryst. Growth* **276**, 321 (2005).

10.1126/science.1146351