The Bionic Man: Restoring Mobility

William Craelius

Science **295**, 1018 (2002);
DOI: 10.1126/science.295.5557.1018

VIEWPOINT

The Bionic Man: Restoring Mobility

William Craelius*

Bionics engineers are making increasingly bold and successful use of their tools to restore mobility to persons with missing or nonfunctional limbs. These tools include the latest materials, minielectronics and megacomputers, advanced robotic mechanisms, and algorithms. With crucial help from their pioneering users, they are learning how and where the residual sensorimotor system can be tapped in order to transmit its intents to replacement or reactivated body parts.

When humans replace a missing body part with an artificial one, they begin an intimate relationship with a partner they barely know. The key to success for such a relationship may be no different than that found in marriage manuals: communication. Unfortunately, for bionic parts, communication is the weakest link in the chain of components that includes electronics, computing, actuators, mechanisms, and materials, all of which are adequate for the application. This situation is perhaps best illustrated by the problem of hand restoration. NASA, for example, has developed a robotic hand that approximates human dexterity, moving up to 22 joints independently (*1*). Available prosthetic technology, however, can control only one joint at a time, leaving amputees with little hope of using the advanced hand. This glaring mismatch between machine and human capabilities clearly reflects the inadequate lines of communication. On the bright side, bionics researchers are opening new vistas for restoring lost human functions as they steadily bridge the gap between human and machine.

Bionics can restore lost mobility to individuals if (i) they can express cognitive control over relevant motor functions somewhere in their residual anatomy and (ii) a device can pick up and decipher that cognition. The first requirement is adequately satisfied by many individuals who have lost function either through paralysis or amputation, and who can both sense and imagine manipulating the nonfunctional or absent joints. These individuals express motor control over their lost parts, including legs, joints, and individual fingers, through nervous and/or muscular activity directed to their residual limbs, and these expressions can be registered by appropriate technology (*2*, *3*). Patients who do not meet this requirement because of damaged residual muscles may soon have a surgical option, whereby their hand motor nerves are rerouted to alternate regions (*4*). This procedure transfers hand-control signals to healthy pectoral muscles, where they can be conveniently accessed and deciphered.

Department of Biomedical Engineering, Rutgers University, Piscataway, NJ 08855–0909, USA. *E-mail: craelius@rci.rutgers.edu

The second requirement is more challenging owing to the complexity of human movement control. Each action originates with a few neurons in the motor cortex that trigger a large neural network that coordinates the activities of several effector muscles after receiving and processing feedback information from thousands of tactile, positional, and visual senses. Transforming this tangled mesh of millions of electrical pulses into graceful movements is a routine accomplishment of our sensorimotor system that bionics engineers can only envy. Its artistry can be appreciated by comparing the elegance and adaptability of human motions with that of the most advanced walking robots, whose latest achievement is the slow climbing of stairs (*5*). Restoration of lost sensorimotor function by robotic assistance is correspondingly challenging, but is steadily progressing, as exemplified by robotic devices such as the RoboWalker, an active exoskeleton that assists walking by motor-impaired individuals (*6*).

The human sensorimotor system, though still far too complex to duplicate, is being invaded by increasingly more versatile bionic interfaces. Our bionic potential was recently demonstrated by a monkey in Brooklyn, whose brain signals, monitored by electrodes, controlled a three-dimensional (3D) robotic arm located in North Carolina, while he watched it on the Internet (*7*). This feat and similar ones were taught to the bionic animals (rats as well as primates) through the presentation of food rewards, and did not require actual movement of the animals' own limbs, because they quickly learned that movement was unnecessary to be rewarded. Cognitive control of artificial limbs, at least for primitive but important motions such as grasping, thus can be achieved with a bionic brain-machine interface (BMI) for individuals with paralyzed or missing limbs.

Humans with motor disabilities can already surpass animal performance when commands from their brains (or spinal cords) are harnessed either noninvasively with the electroencephalogram (EEG) or with implanted electrodes. Paralyzed patients fitted with a brain-implanted chip have learned to move cursors and select letters on a computer (*8*), as well as to direct robotic arm movements using technology known as brain-computer interface (BCI) (*9*). These systems operate by training an algorithmic filter to associate specific movement requests with specific neuronal signal patterns, recorded either directly from neurons or indirectly from EEGs or other noninvasive signals. The filter then directs the appropriate action after recognizing, or decoding, the volition .

How much more function can be restored by advanced bionic systems? Complex activities, such as walking, could probably not be achieved by noninvasive methods such as EEG, owing to their poor resolution of brain activity. The difficulty in extracting volitional requests from the EEG is underscored by the limitations of present technology, which cannot decipher from the brain more than 25 bits of information (three characters) per minute. This rate is many thousands of times too slow to control even the simplest movements. Finer resolution and hence

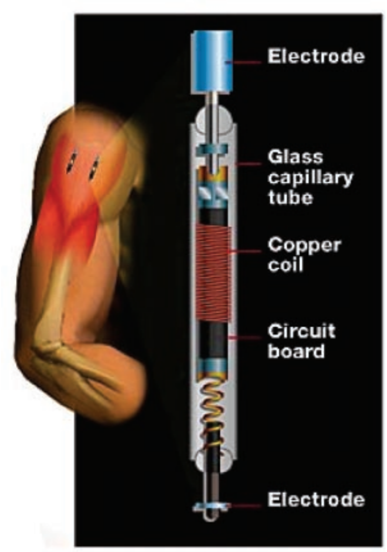

Fig. 1. Bionic restoration of hand mobility. This user, having nerve damage as a result of spinal cord injury, can grasp objects when his forearm muscles are stimulated with Bions. The control computer in his shirt pocket reads his intentions to grasp and activates the wire coils around his arm, to deliver electrical pulses to the Bions (brown rods).

more functionality can be achieved by direct recording with cortically implanted electrodes if a sufficient number of them can be permanently located in the brain. The minimum number of individual neurons required to transform thoughts into a reasonable range of motions probably exceeds 1000 (*10*). This is achievable with microwires in the brain; however, the recording electronics for 1000 channels is currently too bulky to fit in the cranium. For now, the analog electronics of a versatile BCI or BMI would need to be located externally and receive brain signals by wireless transmission. Near–real time operation of such a device is possible, because earlier experiments showed that volitions could be deciphered from monkeys by simply computing the weighted sum of firing rates of several cortical neurons (*7*).

Whereas brain interfaces tap into the head of the sensorimotor system, putting the brain in control of movement, alternative bionic approaches bypass the brain, directly communicating with peripheral nerves and muscles. These peripheral-machine interfaces (PMIs) operate by functional electrical stimulation (FES) of muscles and peripheral nerves and can be programmed for specific movement patterns. A successful example is *FreeHand*, one of the first commercially available and Food and Drug Administration–approved FES devices, pioneered by Peckham (*11*, *12*). *FreeHand* restores grasping to patients with upper-limb paralysis or weakness by giving them control over extrinsic hand muscles through movements of their opposite shoulder that generates radio waves to activate electrodes in the forearm.

Bionic technologies can be adapted for restoring some degree of almost any lost function. Their broader applications are highlighted by a paraplegic who now ambulates by operating switches on his walker that control a stimulator chip implanted in his spinal cord (*13*, *14*). The strictly peripheral approach, however, requires FES to micromanage all actions, much like that of a puppet master. For spinal cord–injured persons, this detail is a welcome remedy for immobility; more natural and graceful control may eventually be possible through developments of hybrid brain-machine interfaces (HBMIs), whereby volitional EEG signals recorded directly from the brain can control the muscles (*9, 10*).

Bionic coordination of muscle movements has been advanced by a new device called *Bion* (Fig. 1) (*15*). *Bions* are single-channel stimulators about the size of a long grain of rice that can be injected into muscles with a 12-gauge needle and controlled by an external radio-frequency coil. Their excellent longevity and functionality in vivo was demonstrated in clinical trials with users for over 1 year. *Bions* can independently control each of the many muscles involved in coordinated movements, given the appropriate motor commands. Direct control over muscles is desirable because human muscles, in contrast to robotic actuators, respond to their natural controller, i.e. neurons, in a highly nonlinear and unpredictable manner, which is not yet understood.

When leaving the brain out of the control loop, bionics engineers must somehow decode volition at the periphery. The most common approach is to train users to execute specific muscle activities to produce surface electromyographic (EMG) patterns recognizable by the decoder. This approach can restore a limited number of activities, such as 1D grasping; however, it does not adequately resolve volition having more than one degree of freedom (*16*). An alternative to control by EMG, developed by Sam Phillips and others in our laboratory, registers volitions by the entire 3D pattern of forces in the residuum (residual limb), known as residual kinetic imaging (RKI) (*17*, *18*). Such patterns can be discriminated by using filters that can be readily trained and retrained as needed. This adaptibility lessens the requirement for precise placement of sensors, an important practical consideration for amputees whose residuum is constantly changing and who must don and doff their prosthesis daily. A key advantage of the RKI method is that it is biomimetic: The original motor pathways can be used to control robotic replacement parts, such as fingers (Fig. 2).

Each approach to bionic restoration of movement is specialized for particular user characteristics (Table 1). For example, BCI is invaluable for severely paralyzed patients, for whom simple communication with the outside world is a primary goal (*8*).

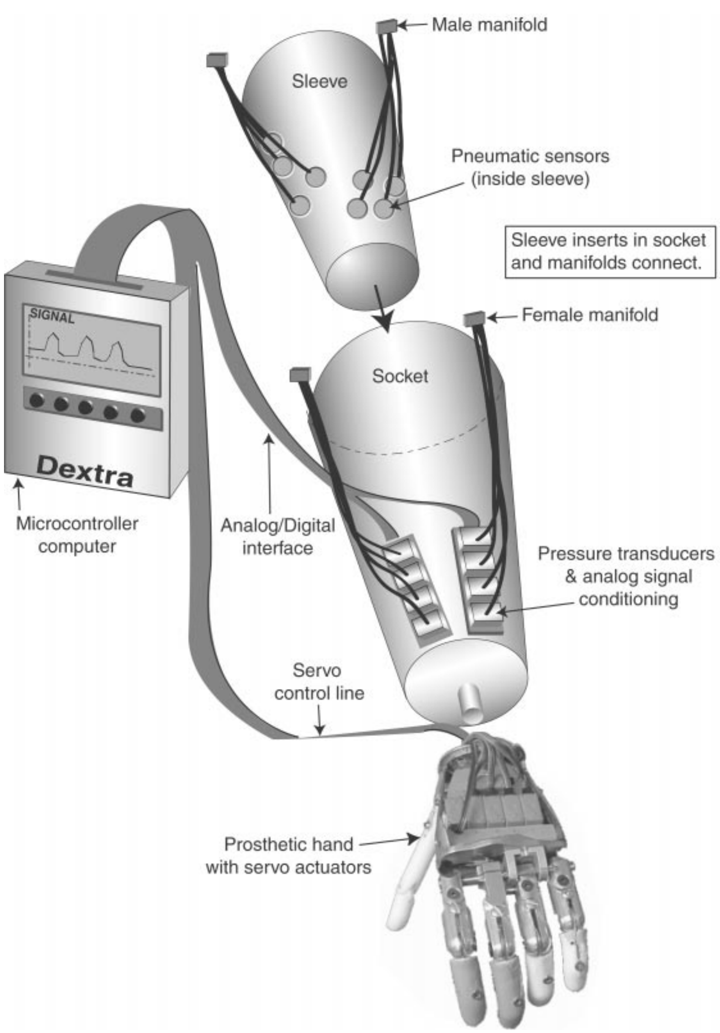

Fig. 2. Biomimetic *Dextra* hand prosthesis. The silicone "smart sleeve" fits snugly over the residual limb and registers 3D forces produced by muscle activity within the hard socket. The pocket computer allows the user to retrain the robotic hand for optimal performance. The hand can flex and extend all five digits in response to commands from the natural motor pathways of the user. [Figure provided by D. Curcie]

CONTINUED ON PAGE 1021

Table 1. Strategies for bionic restoration of movement.

Bionic approach (with electrodes either implanted or external)	Candidate users	Actuator types (with example references)
BMI (brain-machine interface)	Completely paralyzed persons who can benefit from mechanical assist devices	Motors, i.e., robotic arms controlled by monkeys (*7*)
BCI (brain-computer interface)	Completely paralyzed persons who wish to simply communicate	Computer screen, i.e., moving a cursor (*8*)
PMI (peripheral- machine interface)	Amputees and persons with intact central nervous system but weak muscles	Motors, i.e., prosthetic hand (*23*)
HBMI (hybrid brain-machine interface)	Spinal cord–injured persons with intact limb muscles	Muscles, i.e., direct brain control of FreeHand (*9*)
CBI (computer-brain interface)	Parkinson's disease	Muscles (*19*, *20*)

CONTINUED FROM PAGE 1019

The converse of BCI, computer-brain interface (CBI), can treat conditions such as Parkinson's disease, wherein thalamic neuronal activity is substantially impaired, causing tremors. The first commercially available device for this purpose, *Activa Tremor Control* (*19*, *20*), operates from a small computer, located in the chest cavity, that rhythmically stimulates the thalamus to simulate the operation of the diseased neurons.

Persons with an intact central nervous system who have completely lost function of specific muscles can be aided by robotic devices controlled either directly from the brain with HBMI systems or from muscles or peripheral nerves with PMI systems. Strictly peripheral devices, such as the RoboWalker mentioned earlier, can be controlled from muscle activation or movement patterns. Such interfaces, possibly in combination with surgical reinnervation (*4*), could benefit paraplegics, amputees, and those with weak muscles as a result of stroke, spinal cord injury, or neuromuscular disease.

Should progress continue at its present pace, human-machine communication could soon lose its distinction as the number one obstacle to bionics. It is relevant therefore to revisit other technical problems in bionics. First, as noted earlier, the size of electronic devices limits the functionality that may be implanted inside the brain or elsewhere. Analog recording electronics alone for a minimal brain interface (125 electrodes) would occupy board space of at least 60 cm^2, even with very large scale integration electronic technology. Sufficient miniaturization could be reached within a decade, however, as long as "Moore's law" is not repealed. The latter is a remarkably accurate prediction from the year 1965 that transistor density on integrated circuits would double every year (with a slight revision in 1975 to doubling every 1.5 years).

A complication of shrinking size is the difficulty of hermetically sealing small objects and protecting them from corrosion in bodily fluids. Another issue for electronics is susceptibility, especially of digital systems, to electromagnetic interference. This risk is so severe that some bionic systems, such as the Jarvik 2000 heart (*21*), have eliminated all digital electronics. Such precautions may not be an option for bionics that restore mobility, wherein digital processing is fundamental, and hence new anti-interference strategies may be required. Battery energy density and recharging issues will become limiting especially as orthotic and prosthetic devices gain functionality and demand more power. Maximal energy density of implantable batteries is about 1.1 W·hours/cm^3 (lithium ion); however, external battery packs that can use anode air-cells have higher densities. The slight risk of explosion by the latter cells is one willingly borne by users of powered prosthetic devices. The need for more frequent recharging may require more convenient options than radio-frequency transmission, such as optical recharging (*22*).

Computer requirements for a typical PMI hand controller include a relatively high analog I/O throughput of many kilobaud but minimal CPU power and memory. The main processing task is decoding: deriving motor commands from volitions. The task involves a mathematical operation known as pseudoinversion that decodes signals from several sources in near–real time, all of which contain a portion of the code for a complex motion, such as finger flexion (*23*). There are several alternative approaches to decoding, none of which is clearly superior, including neural networks, pattern-recognition algorithms, and hybrid filters.

Although actuators are not yet optimized for bionic use, several commercially available motors and servos are adequate for some advanced applications, including a computer-modulated knee (*24*) and a multifinger hand (*23*). The large sizes and power inefficiencies of present actuators, however, limit functional expansion of robotic assist devices.

A final challenge for bionics is establishing a convenient physical interface between effector devices and the body. Although limb replacement as depicted by Hollywood will likely remain a fantasy, current interfaces, consisting of bulky plastic sockets for limbs, are glaring anachronisms relative to other bionic components. Users who subject themselves to brain implantation of hundreds of electrodes and wearing of transmitters may rightly expect a more versatile and responsive attachment of their arm or leg. To help meet these expectations, much fruitful work is focused on how to integrate prosthetic structural components, such as the titanium pylon, with bone, i.e., osseointegration (*25*). The natural feel, or "osseoperception," of the environment provided by such attachments can complete a sensory link that is crucial to bionic restoration of function.

References and Notes

1. "Compact Dexterous Robotic Hand," U.S. patent number 6,244,644 (12 June 2001).
2. R. Abboudi, C. Glass, N. A. Newby, W. Craelius, *IEEE Trans. Rehabil. Eng.* **7**, 121 (1999).
3. V. S. Ramachandran, *Proc. Natl. Acad. Sci. U.S.A.* **90**, 10413 (1993).
4. T. A. Kuiken, D. S. Childress, W. Z. Rymer, *Brain Res.* **676**, 113 (1995).
5. http://world.honda.com/robot/ (accessed 15 November 2001).
6. www.yobotics.com/
7. J. Wessberg *et al.*, *Nature* **408**, 361 (2000).
8. P. R. Kennedy, R. A. E. Bakay, M. M. Moore, K. Adams, J. Goldwaithe, *IEEE Trans. Rehabil. Eng.* **8**, 198 (2000).
9. J. R. Wolpaw *et al.*, *IEEE Trans. Rehabil. Eng.* **8**, 164 (2000).
10. N. Nicolelis, *Nature* **409**, 403 (2001).
11. B. T. Smith *et al.*, *IEEE Trans. Biomed. Eng.* **45**, 463 (1998).
12. L. D. Maloney, *Design News* **90** (6 March 2000).
13. P. Rabischong, *Bull. Acad. Natl. Med.* **183**, 531 (1999).
14. Reuters, "Chip helps paraplegic walk," 20 March 2000, Strasbourg, France.
15. G. Loeb, R. A. Peck, W. H. Moore, K. Hood, *Med. Eng. Phys.* **23**, 9 (2001).
16. B. Hudgins, P. Paarker, R. N. Scott, *IEEE Trans. Biomed. Eng.* **40**, 82 (1993).
17. S. L. Phillips, W. Craelius, Robotica, in press.
18. S. L. Phillips *et al.*, *Sixth World Biomaterials Congress*, Hawaii, #1343, 15 to 20 May 2000.
19. A. Benabid *et al.*, *Arch. Med. Res.* **31**, 282 (2000).
20. J. Rosengren, *IEEE Spectrum* **35**, 62 (1998).
21. R. Jarvik, V. Scott, M. Morrow, E. Takecuchi, *Artif. Organs* **23**, 487 (1999).
22. K. Goto, T. Nakagowa, O. Nakamura, S. Kawata, *IEEE Trans. Biomed. Eng.* **48**, 830 (2001).
23. D. J. Curcie, J. Flint, W. Craelius, *IEEE Trans. Neural Syst. Rehabil. Eng.* **9**, 69 (2001).
24. J. Michael, *Clin. Orthop. Relat. Res.* **361** 43 (1999).
25. R. Branemark, P. I. Branemark, B. Rydevik, R. R. Myers, *J. Rehabil. Res. Dev.* **38**, 175 (2001).