BIOMIMETICS

Metal or muscle? The future of biologically inspired robots

Barry Andrew Trimmer

Biology has inspired the development of agile robots, and it is now teaching us how to grow machines from living cells.

Biology has inspired the development of some amazingly agile robots, but most engineers do not use biology to make robots. Now, as robotics has transformed into a scientific discipline, there is an opportunity to build machines by growing them from living cells. Biological robots are a feature of many science fiction stories, but we now know enough about cell growth and differentiation to consider building them (Fig. 1). How will these robots be different from today's technology, and what are the challenges they present?

Biologically inspired machines have deep origins in the mechanical animals and humanoids described by Al-Jazari in the 12th century (*1*) and in the intricate clockwork mechanisms of the 18th and 19th centuries (*2*). These automatons mimicked living creatures, but they were not robots in the modern sense; they were made to entertain, not to be useful or to extend our capabilities.

Our current concept of a robot as an autonomous entity dates from the 1921 play *R.U.R.* (*Rossum's Universal Robots*) by Karel Čapek. In this play, the robots are humanlike replacements for workers and servants. However, what is often forgotten about Čapek's robots is that they are alive, constructed from "protoplasm," a material that "behaved just the same as living tissue despite being, chemically, quite different." These original robots are grown in factories.

Today, most bioinspired robots are designed using concepts derived from the field of neuromechanics, and they are constructed from traditional mechanical parts. But, as outlined in a recent perspective (*3*), translating biological principles into functional robots raises some major challenges. Foremost among these are the difficulties of developing models at an appropriate level of abstraction and reducing the enormous complexity of biological systems to something that can be fabricated.

One potential solution to this problem is to grow robots directly from engineered cells. Given an appropriate fuel source, a fertilized egg in a suitable environment has enough information to grow into a complete organism. Other pluripotent cells can be stimulated to form complex tissues. Using this self-assembly capability of living systems, bioengineering groups are designing cell-based robots (*4*). Some use cells as microrobots for medical applications (*5*), and others are making devices that can swim or pump fluids using myoblasts grown on biologically compatible structures [e.g., (*6*)]. Although these devices are impressive, groups of engineered muscle cells lack the multiscale organization of natural muscle and are short-lived. We do not know how to grow cells into fully functioning tissues.

This is an extremely important challenge. Although the growth of individual tissues is a reasonable initial goal, biological systems are highly integrated systems with gas and heat exchangers, fuel supplies, waste disposal, and communication networks, all permeating every part of the organism. Biological robots will have to be designed with a level of codependency not usually seen in engineered systems. In addition to growing and coordinating many muscles, we will have to consider how to generate and use thousands of sensors (visual, mechanical, chemical, etc.) for each robot to adapt and interact safely with its environment. This will also involve the development of new interfaces between biological tissues and synthetic materials. We will need huge investments in these areas of research before the first autonomous and useful living robots hit the markets.

Although it is possible that traditional tissue engineering will manage to make useful devices, truly self-sufficient living robots will require a major leap in our understanding of morphogenesis. Knowing which genes are present in an organism does little to explain its shape, nor are differences in gene expression enough to explain morphology. Organismal self-assembly is a dynamic process involving interacting networks across space and time and with effects mediated by chemical interactions, bioelectric potentials, mechanics, electromagnetism, and gravity. Understanding these processes requires combined studies in molecular biology, developmental biology, biophysics, and computational modeling (*7*). We still do not understand how these factors determine the shape and size of an organism. If we are going to design biological machines, we must solve this fundamental problem so that the final form and function of the robot can be encoded in the starting materials and processes. We will need a comprehensive design strategy operating on different scales to grow devices for microscopic applications [e.g., (*8*)] and to make living machines that are useful in our everyday lives.

Why should we grow living robots? For many applications, traditional robots built from metals and plastic will be more than adequate, but living robots will extend robot capabilities. One advantage will be their use of natural hydrocarbons, such as sugars and fats, as a primary fuel source. These biofuels are as energy dense as gasoline but can be converted by tissues into mechanical work at ambient temperature, producing acceptable amounts of CO_2 and water. A biological robot could work all day on the equivalent of one candy bar! Another advantage is that biological robots can be grown in incubators without the massive energy costs of steel and plastics. Last, biological materials can be recycled, making these machines biodegradable and sustainable.

It is important to distinguish living robots from engineered animals. Advances in genome editing mean that animals can be produced with specific genetic changes that are passed on to the next generation (*9*). These living animals are potentially new species, but they are not robots. We can preserve this distinction by designing living robots without a reproductive system or a biological brain.

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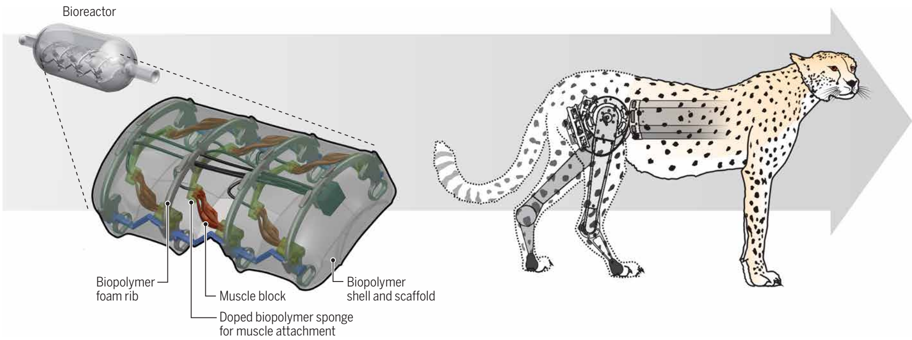

Fig. 1. Biological robots. Currently, bioinspired robots are not made using biological materials or tissues, but future robots will be grown (at least partially) using the intrinsic self-assembling mechanisms of living cells. Actuators, sensors, fuel supplies, and waste disposal capabilities will all be integrated into a living component. These living systems will be combined with biocompatible synthetic materials and interfaced with fast micro-controllers to create truly biomechanical robots.

Living robots should be controlled by computer hardware, and future ethicists will have to decide at what point an entirely synthetic artificial intelligence is protected by legal and ethical constraints.

So, what is the future of biologically inspired robots? Most robots will not be purely biological machines but hybrids that combine the best features of polymer chemistry and bioengineering; cells and tissues will be just another engineering resource. But new technologies have the potential to be harmful, and badly designed biological systems could be devastating to ecosystems and health. Controlling this misuse will be a real challenge. Society must be prepared for a future in which living, breathing machines work alongside us.

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