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Development and Future Challenges of Bio-Syncretic Robots

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ABSTRACT

Bio-syncretic robots consisting of both living biological materials and non-living systems possess desirable attributes such as high energy efficiency, intrinsic safety, high sensitivity, and self-repairing capabilities. Compared with living biological materials or non-living traditional robots based on electromechanical systems, the combined system of a bio-syncretic robot holds many advantages. Therefore, developing bio-syncretic robots has been a topic of great interest, and significant progress has been achieved in this area over the past decade. This review systematically summarizes the development of bio-syncretic robots. First, potential trends in the development of bio-syncretic robots are discussed. Next, the current performance of bio-syncretic robots, including simple movement and controllability of velocity and direction, is reviewed. The living biological materials and non-living materials that are used in bio-syncretic robots, and the corresponding fabrication methods, are then discussed. In addition, recently developed control methods for bio-syncretic robots, including physical and chemical control methods, are described. Finally, challenges in the development of bio-syncretic robots are discussed from multiple viewpoints, including sensing and intelligence, living and non-living materials, control approaches, and information technology.

1. Introduction

With the expanding requirements of society, robotic technologies have developed rapidly in recent decades alongside electromechanical engineering technology and information technology. Robots are an integral component of human society and play very important roles in various fields. The first industrial robot, based on the fluid drive, was developed in the 1950s. With the development of electromechanical engineering and information technology, industrial robots based on electromechanical systems were then extensively and widely applied [1]. Various types of robots, including medical robots [2], service robots [3,4], bio-inspired robots [5], and humanoid robots [6], have attracted considerable attention from an increasing number of scientists.

However, critical issues that limit the development and application of robots remain to be solved. Most current robots are composed of electromechanical systems. Several energy transformations occur from the available energy to the electricity required for the electromechanical systems, thus greatly decreasing the energy efficiency. As previously reported, traditional electromechanical systems have a low transformation efficiency (< 30%) for mechanical work, leading to large heat losses [7]. In addition, most traditional robots based on electromechanical systems are made of metals, wires, and other hard materials. These artificial materials and structures mean that the robots lack intrinsic safety, flexibility, and adaptability in applications that require human–robot interaction.

Biological entities offer many functional advantages that are difficult to achieve using artificial materials. For example, most biological materials are soft and environmentally safe [8] for human–machine collaboration and integration. Furthermore, biological muscles can be directly driven by chemical energy; therefore, as long as the appropriate nutrients are supplied in the growing environment, these biological muscles can convert chemical energy into mechanical work [9] at much higher efficiencies ($\geq$ 50%) than those of synthetic non-living actuators [7,10]. Biological materials also possess functional environmental compatibility as well as self-repair and self-assembly capabilities. Moreover, biological materials have developed excellent smart sensing, intelligence systems, and actuation systems, which are difficult

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to replicate using artificial materials with the currently available technologies [11].

Therefore, a new type of robot can be developed by merging electromechanical systems with biological materials at various scales of molecules, cells, and tissues, in order to obtain desirable functions that integrate the attributes of living biological materials (e.g., high energy efficiency [10], high power-to-weight ratio [12], and large energy storage [8]) with those of non-living systems (e.g., high accuracy [13], high strength, favorable repeatability, and controllability [14]) (Fig. 1). Due to the advantages of a combined system, compared with living biological materials or non-living traditional robots based on electromechanical systems, developing this new generation of robots—called bio-bots, bio-hybrid robots, or bio-syncretic robots—has been a topic of great interest. Significant progress has been achieved in this area over the past decade.

In this paper, we review existing studies relevant to bio-syncretic robots, including cardiomyocyte-actuated robots, skeletal muscle cell-based robots, and swimming cell-powered robots. We also summarize the development of bio-syncretic robots from various viewpoints. First, we review the performance development of bio-syncretic robots. The capabilities of bio-syncretic robots have been promoted using various materials, fabrication methods, and control strategies. Second, we identify various relevant living biological materials, along with their corresponding characterization. These biological materials provide different properties, such as cellular force, size, and controllability. Third, we identify the non-living materials that are currently used in bio-syncretic robots. The properties and fabrication methods of these artificial materials determine not only the performance of the living biological materials, including differentiation, contractility, and survivability, but also the properties of the bio-syncretic robots, including velocity, force, and manipulation. Fourth, we review the control methods—including electrical stimulation, photic stimulation, temperature stimulation, and chemical stimulation, and magnetic stimulation—that are currently used in bio-syncretic robots, along with their corresponding features. Finally, we examine challenges facing the further development of bio-syncretic robots.

2. An overview of the development of bio-syncretic robots

Over the past decade, many researchers have promoted the development of bio-syncretic robots. One current type of bio-syncretic robot with asymmetric structures can perform simple unidirectional movement actuated by the spontaneous contraction of cardiomyocytes [15]. Bio-syncretic robots with velocity controllability have also been studied with controllable living biological materials. Furthermore, to enable bio-syncretic robots to execute certain functions, controllability of the movement velocity and direction has been developed. Details on the development of bio-syncretic robots based on muscle cells are listed in Table 1 [15–31].

Bio-syncretic robots can implement spontaneous movement that is actuated by living spontaneously contractile bio-actuators, such as cardiomyocytes [15,21,26] and insect heart tissues (also called dorsal vessels (DVs)) [17,19,20]. Xi et al. [15] fabricated the first self-assembled walking bio-syncretic robot that can move autonomously; the movement of this robot was powered by the contractility of beating cardiomyocytes. This bio-syncretic robot was composed of a silicon backbone fabricated with single-crystal reactive etching, a connected chromium/gold (Cr/Au) film fabricated using metallization processes, and a cardiomyocyte tissue growing on the metal film. The leg of the robot was 138 μm long, 40 μm wide, and 20 nm/300 nm (Cr/Au) thick. By taking advantage of the cell growth inhibition of poly (*N*-isopropylacrylamide) (PNIPAAm), the cardiomyocytes were aligned on the patterned metal film. The contraction force of the

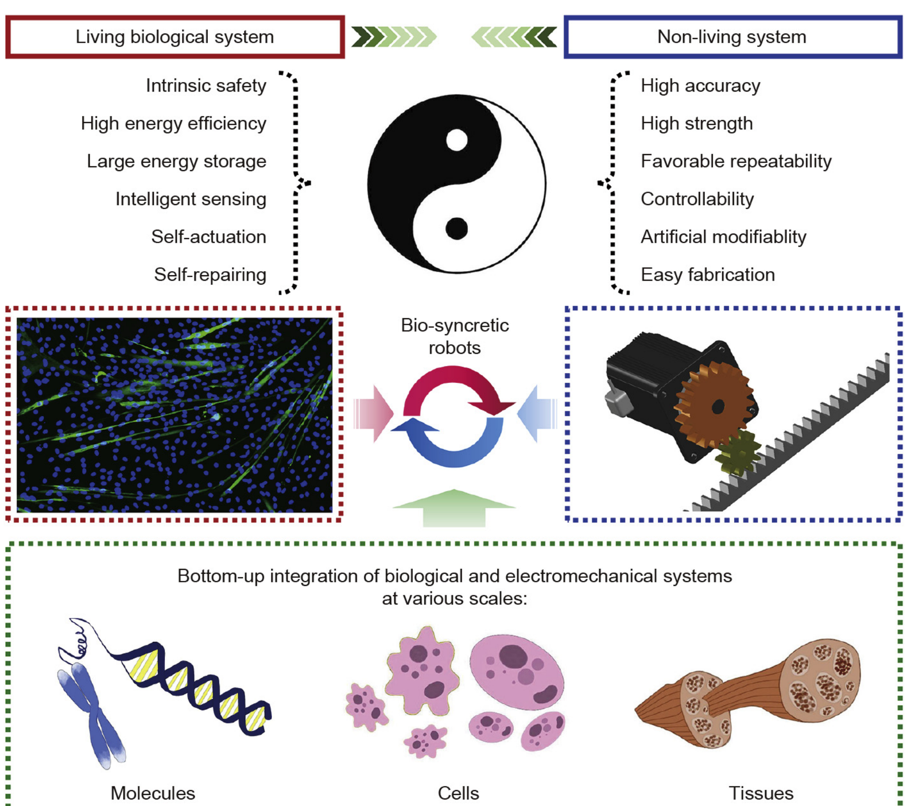

Fig. 1. Bio-syncretic robots consisting of both living biological and non-living systems.

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