Nano Today (2016) 11, 330—350

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/nanotoday

REVIEW

3D printed bionic nanodevices

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Received 28 January 2016; accepted 6 April 2016
Available online 29 April 2016

KEYWORDS
3D printing;
Bionic devices;
Nanomaterials;
Nanodevices;
Bioelectronics;
Bio-nano hybrids

Summary The ability to three-dimensionally interweave biological and functional materials could enable the creation of bionic devices possessing unique and compelling geometries, properties, and functionalities. Indeed, interfacing high performance active devices with biology could impact a variety of fields, including regenerative bioelectronic medicines, smart prosthetics, medical robotics, and human—machine interfaces. Biology, from the molecular scale of DNA and proteins, to the macroscopic scale of tissues and organs, is three-dimensional, often soft and stretchable, and temperature sensitive. This renders most biological platforms incompatible with the fabrication and materials processing methods that have been developed and optimized for functional electronics, which are typically planar, rigid and brittle. A number of strategies have been developed to overcome these dichotomies. One particularly novel approach is the use of extrusion- based multi-material 3D printing, which is an additive manufacturing technology that offers a freeform fabrication strategy. This approach addresses the dichotomies presented above by (1) using 3D printing and imaging for customized, hierarchical, and interwoven device architectures; (2) employing nanotechnology as an enabling route for introducing high performance materials, with the potential for exhibiting properties not found in the bulk; and (3) 3D printing a range of soft and nanoscale materials to enable the integration of a diverse palette of high quality functional nanomaterials with biology. Further, 3D printing is a multi-scale platform, allowing for the incorporation of functional nanoscale inks, the printing of microscale features, and ultimately the creation of macroscale devices. This blending

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http://dx.doi.org/10.1016/j.nantod.2016.04.007

of 3D printing, novel nanomaterial properties, and 'living' platforms may enable next-generation bionic systems. In this review, we highlight this synergistic integration of the unique properties of nanomaterials with the versatility of extrusion-based 3D printing technologies to interweave nanomaterials and fabricate novel bionic devices.

Introduction

The synergistic integration of biological systems with electronic materials and devices could enable the creation of novel bionic devices. Due to the increasing miniaturization and proliferation of portable electronic devices, the field of bionics has transitioned from science fiction to an area of increasing scientific interest, with particular relevance to the fields of regenerative medicine, smart prosthetics, medical robotics and human—machine interfaces [1—4]. Most research in the field of bionics to date has focused on developing robots which behave increasingly more like humans. Similarly, an equally compelling challenge is integrating electronic and robotic components in a seamless manner with the human body. For example, bioelectronic medicines and devices could potentially be utilized to restore or even augment the complex functionalities of naturally evolved biological systems. At the fundamental level, there are inherent material compatibility challenges associated with integrating functional electronic materials with biology.

The term ''bionics'' is defined by Dictionary.com as, ''utilizing electronic devices and mechanical parts to assist humans in performing difficult, dangerous, or intricate tasks, by supplementing or duplicating parts of the body [5].'' Broadly speaking, ''bionics'' encompasses the functionalities of classes of systems that are formed by merging biological systems, which could be single cellular or multi-cellular systems [2,6—8], with engineered mechanical and/or electronic systems [2]. Our ability to develop tools, which overcome the limitations of human biology, has played a key role in survival and evolution [9]. Utilizing devices for regenerative medicine and as prosthetics can be traced back millennia [1]. Indeed, a very primitive bionic device from the first century AD involved the use of wrought iron for dental replacements [10]. Subsequently, bionic devices such as iron prosthetic hands (1504), contact lenses (1888), and artificial hip replacements (1905) have been used to restore or augment human function [1]. Over the past several decades, the development of active microelectronic devices has enabled the incorporation of sensing modalities [11,12], optoelectronics [13,14], actuators [15] and computational devices [16] into previously passive mechanical constructs. This has enabled an extension of the role of bionic devices toward mimicking or even augmenting the complex functionalities of biological organs. These powerful developments have been leveraged to fabricate active bionic devices such as the cochlear implant [17,18] to restore hearing (Fig. 1A), pacemakers and heart replacements [1] to sustain blood flow (Fig. 1B), locally powered prosthetic devices [19] to provide mobility to amputees (Fig. 1C), retinal implants to provide partial restoration of vision loss due to diseases such as retinitis pigmentosa [20,21] (Fig. 1D), dura mater for the spinal cord [22] (Fig. 1E), and digital skin sensors and electronic skins [12,23—25] (Fig. 1F). Indeed, the ability to merge a diverse palette of materials classes could enable the generation of functional devices that mimic the complex functionalities of grown biological organs [15].

An optimized bionic device should be seamlessly merged with the human body in order to restore or augment human capabilities without causing side effects such as discomfort, infection [26] or rejection due to foreign body responses by the host [27—29]. While the continual discovery of new materials and novel properties will eventually lead to more optimized devices, ideality has been punctuated by challenges in integrating high performance materials and devices with biology. Three key challenges can be identified. First, the mechanical properties of high quality electronic materials are typically disparate from biology. For example, the typical Young's modulus of inorganic electronics is on the order of 1—100 GPa (Si ~ 170 GPa) [30]. By contrast, the Young's modulus of skin is on the order of 0.1—1 MPa [31]. Similarly, inorganic electronic materials typically fracture at strains (ca. 1%) [32] of up to 30× lower than human skin [33]. These significant differences in mechanical properties not only lead to obstacles in the integration of bionic devices with the body, but can cause discomfort, agitation, rejection and injuries.

Second, the processing conditions inherent to high performance electronics are often incompatible with biology. Microelectronics are typically fabricated via ''top down'' approaches which can involve harsh chemical and temperature processing conditions. In contrast, organs and tissues have been grown from the ''bottom up'' under finely tuned physiological conditions [35]. Third and finally, electronic wafers are two-dimensional planar structures, whereas biology possesses intricately complex three-dimensional geometries from the molecular scale to the macroscale. These incompatibilities collectively present significant barriers in grafting independently fabricated bionic devices onto biology in a seamless manner.

A variety of novel strategies have been developed to address these issues, such as integration via intelligent device design [11,32,36,37], transfer printing processes [13,38—41] and/or assembly of prefabricated devices [42] onto three-dimensional constructs to accommodate the geometrical and material incompatibility. This review highlights a relatively new concept in achieving a synergistic integration of bionic devices with biology: by using 3D printing. Extrusion-based 3D printing technologies may overcome the three specific challenges mentioned above. First, the use of