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Regenerated silk materials for functionalized silk orthopedic devices by mimicking natural processing

Chunmei Li [a], Blake Hotz [a], Shengjie Ling [a, b], Jin Guo [a], Dylan S. Haas [a], Benedetto Marelli [a, b], Fiorenzo Omenetto [a], Samuel J. Lin [c], David L. Kaplan [a, *]

[a] Department of Biomedical Engineering, Tufts University, 4 Colby St. Medford, MA 02155, USA
[b] Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue Cambridge, MA 02139, USA
[c] Divisions of Plastic Surgery and Otolaryngology, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA 02215, USA

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ABSTRACT

Silk fibers spun by silkworms and spiders exhibit exceptional mechanical properties with a unique combination of strength, extensibility and toughness. In contrast, the mechanical properties of regenerated silk materials can be tuned through control of the fabrication process. Here we introduce a biomimetic, all-aqueous process, to obtain bulk regenerated silk-based materials for the fabrication of functionalized orthopedic devices. The silk materials generated in the process replicate the nano-scale structure of natural silk fibers and possess excellent mechanical properties. The biomimetic materials demonstrate excellent machinability, providing a path towards the fabrication of a new family of resorbable orthopedic devices where organic solvents are avoided, thus allowing functionalization with bioactive molecules to promote bone remodeling and integration.

1. Introduction

The outstanding mechanical properties of natural silk fibers derive from their unique structure, which is determined by spinning process and the nature of the spinning solution. In the natural spinning process of silkworm, *Bombyx mori*, the silk fibroin (hereafter referred to as silk) concentration increases gradually and controllably from ~12% to 30% as the silk molecules move from the posterior to the anterior region of the silk glands [1]. Meanwhile, the chains assemble to micelles, follow by arrange and stack them together in a step-by-step manner, and form the compact solid architecture under regulation of external environments, such as pH, ion concentration, physical shear and/or elongational flow [2]. Many efforts have been explored to regenerate silk materials with mechanical properties comparable to or exceeding those of natural silk fibers [3–5]. Silk fibers stronger and tougher than natural undegummed *B. mori* silkworm silk have been obtained from regenerated *B. mori* silk solutions *via* microfluidic chip [3] and wet spinning [5]. One common feature of those studies is a spinning dope of highly concentrated silk solutions, which is a prerequisite to form a dense, compact solid structure in natural spinning process [1]. However, the focus has mainly been limited to the generation one-dimensional silk fibers in the micrometer range, which significantly hinders their application. There is need to develop three-dimensional silk materials in larger dimensions that can be used to fabricate devices with high mechanical demands, such as orthopedic devices.

Metals like titanium alloys and stainless steel remain the gold standard for orthopedic devices due to their robust mechanical properties and ease of fabrication and implantation, whereas limitations of stress shielding, infections, bone remodeling and second surgical removal have shifted significant interest to degradable devices [6,7]. Resorbable orthopedic devices composed of poly-L-lactic acid and polyglycolic acid reduces the need for hardware removal and improved bone remodeling. However, the degradation of these resorbable devices is associated with inflammatory foreign body reactions due to the acidic degradation products, osteolysis and incomplete bone remodeling [8]. In addition, orthopedic devices are historically designed to provide mechanical stability to the surrounding bone and soft tissue, whereas functionalization of the device to improve the implant integration and mitigate adverse events associated with the foreign body reaction or infection has

* Corresponding author.
E-mail address: david.kaplan@tufts.edu (D.L. Kaplan).

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