Acta Biomaterialia 8 (2012) 4111-4122

Contents lists available at SciVerse ScienceDirect

Acta Biomaterialia



Mathematical model of mechanical behavior of micro/nanofibrous materials designed for extracellular matrix substitutes

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ARTICLE INFO

Article history: Received 25 January 2012 Received in revised form 17 July 2012 Accepted 19 July 2012 Available online 27 July 2012

Keywords: Electro-spinning Micro/nanofiber Mechanical behavior Extracellular matrix substitutes Fiber structure

ABSTRACT

Electrospun micro/nanofibrous biomaterials are widely used as extracellular matrix substitutes in tissue engineering applications because of their structural and mechanical properties. To explore the influence of microstructure on the mechanical behavior of fibrous material, a mathematical model of the fiber system was developed. The model describes the microstructural properties of a fibrous matrix using a probability density function, and enables study of their mechanical properties. The results from the mathematical model were validated by gualitative comparison with the experimental results of mechanical testing of polystyrene electrospun nanofibrous materials. The analyses show a trend of three-phase load-displacement behavior. Initially, as an increasing number of fibers are recruited for load bearing, the load-displacement curve has a 'J'-shaped toe region, which is followed by a nearly linear load-displacement curve, in which the number of load-bearing fibers remains nearly steady. Finally, there is a phase when the load-displacement curve descends, indicating failure of the material. The increase in flexibility of the fibrous material makes it stronger, but the randomness of fiber orientation makes the fibrous structure more flexible at the cost of lower strength. The measured mechanical properties of a fibrous matrix were also observed to be dependent on sample size. Therefore, the analyses establish a clear link between the structure and strength of fibrous materials for optimized design and fabrication of fibrous biomaterials with targeted use in tissue engineering, regenerative medicine and drug delivery. The model also establishes a need for standardization of experimental protocols for mechanical characterization of fibrous materials for consistency.

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1. Introduction

Fibrous materials are ubiquitous in biological systems because of their unique structural and mechanical properties, arising from the high length-to-diameter ratios of the individual fibers as well as their arrangement in the fiber systems. For example, load-bearing tissues such as the tendon, ligament and the articular cartilage are mechanically reinforced with collagen fibers in the extracellular matrix (ECM), which provide them with adequate tensile strength as well as an appropriate microenvironment for specific cell behavior [1–3]. These tissues achieve a wide spectrum of mechanical properties by the complex hierarchical arrangement of the fibrous system made up of collagen and base matrix composed of proteoglycans, minerals and crosslinking agents [1]. The tissue-specific structural arrangement of the fibers gives rise to the required mechanical strength by frictional sliding of the fibers over one another, followed by their stretching [2]. Inspired by the biological systems, synthetic fibrous materials are being engineered for biomedical applications including, but not limited to, tissue engineering scaffolds and drug delivery systems [3]. Scaffolds designed using the electrospinning technique are the most extensively used fibrous materials in tissue engineering because of their tunable structural properties, e.g. diameter, orientation/alignment, porosity and surface chemical properties, which allow for closer replication of the microenvironment present in the native ECM [4]. Scaffolds designed for load-bearing tissues require not only structural and chemical properties similar to that of the ECM of the tissue of interest, but also appropriate mechanical properties, as mechanical stimuli play a significant role in cell attachment, motility and proliferation in the scaffolds [5–7].

Although there have been multiple studies characterizing fibrous materials based on various geometric and mechanical properties of the fibers [8–14], the relationship between the structural and mechanical properties of fibrous materials remains poorly understood [15–17]. In most studies, the mechanical properties of the fibrous matrices have been characterized using the stress–strain diagram, from which characteristic moduli (elastic or tangential modulus) or characteristic stress and strain values





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