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Featured Letter

Effect of porous structure and pore size on mechanical strength of 3D-printed comby scaffolds

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ABSTRACT

Low mechanical strength is a major challenge for porous scaffolds in bone tissue engineering. Porous scaffold with honeycomb structure, which exhibits excellent mechanical properties, has great application potential in tissue engineering. This study was aimed to explore the influence of structure characteristics on the mechanical properties of the comby scaffolds. The scaffolds were printed by three-dimensional printer, using polylactic acid (PLA) and photosensitive resin (PR) as model material. The effect of structural details (e.g. porosity, pore size and pore interconnectivity) on mechanical properties was discussed in this paper. The results showed that structural design played a critical role in improving the mechanical properties of porous scaffolds. Compared with random structure, the ordered structure constructed by three-dimensional printing (3DP) conferred much higher mechanical strength to the porous materials. And the ordered structure could overcome the negative effects of high porosity on mechanical strength in some degree. Moreover, in the suitable pore size range (50–1000 μm) for cell growth, there was an obvious negative correlation between aperture size and compressive strength. In the condition of fulfilling the requirements of bone repair, smaller pore size might be beneficial for the mechanical strength of porous scaffolds.

1. Introduction

The scaffolds with three-dimensional porous structure are critical for bone tissue engineering to promote cell and/or tissue ingrowth while maintaining the transport of oxygen and nutrition [1] While fabricating a porous scaffold, various structural parameters, like pore size, pore size distribution, pore morphology, orientation, pore interconnectivity, and surface area to volume ratio should be tailored to match the bone mimicking properties [2]. Adding micro- and nanometer details into the scaffolds improves the mechanical properties of the scaffold and ensures better cell adhesion to the scaffold surface [3]. Random processes such as foaming, salt leaching and emulsification are widespread in bone tissue engineering. However, one major drawback of these random processes is the fact that porous scaffolds cannot be produced with full control of the geometrical parameters, such as pore size, pore interconnection size and porosity [4]. Three-dimensional printing (3DP) is an additive manufacturing method, which, upon receiving computer aided designs, methodically constructs three-dimensional structures from successive layers [5]. The greatest advantage of this technology is that it can directly print porous scaffolds with designed shape, controlled pore size and interconnected porosity. Since 3DP was pioneered in the 1980s, it has been widely expected to revolutionize the manufacturing of complex porous materials in bone tissue engineering. It allowed us to produce three-dimensional bone scaffolds with complex geometries and very fine structures.

Low mechanical strength is a major challenge for porous bioceramic bone scaffolds. For the porous material with definite chemical composition, the mechanical strength is primarily controlled by pore volume. Qing Cai [6] fabricated PLA foams with porosity of 90% by using a solution-casting/salt-leaching technique. Compression tests results indicated that the mechanical strength was very poor. The compressive modulus was only 2.91 ± 0.05 MP. Ehsan Rezabeigi [7] fabricated porous PLA monoliths via nonsolvent induced phase separation. The compressive modulus of the porous PLA with porosity of 90.8% was only 1.8 MPa.

A novel comby scaffold, which had excellent strength and high porosity, was designed and fabricated for bone tissue engineering application in our earlier study [8]. It had similar holes as

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honeycomb. The main goal of this work was to study the influence of structural details on the mechanical properties of the comby scaffolds. It would contribute to our understanding of tuning porous structure to improve the mechanical properties of porous scaffolds in bone tissue engineering.

2. Experimental

2.1. Scaffold preparation

The porous scaffolds with honeycomb structure were designed by a computer. The shape of apertures, including main-holes and side-holes, was all regular hexagonal in the comby scaffolds. Then, these scaffolds were printed by a three-dimensional printer. The nozzle diameter, printing speed and temperature were 18 μm, 8 mm/h and 80 °C respectively.

2.2. Morphological and mechanical characterization

The surface microstructure of the scaffolds was observed by an electric scanning microscope (Zeiss Supra 55, Germany). Mechanical testing for the scaffolds was performed by using a Universal Testing Machine (Zwick/Roell Z005, Germany). For each test a minimum of six samples were used.

3. Results and discussion

In this paper, polylactic acid (PLA) and photosensitive resin (RP) were used as model materials. PLA is widely used in bone tissue engineering. PR is a kind of desirable printing material for high-resolution 3DP. Fig. 1a was the computer design image of the comby scaffold. The pore shape was designed as regular hexagonal (Fig. 1b). The scaffolds were all cylindrical shape, with a height of 20 mm and a diameter of 20 mm (Fig. 1c). It had an open, uniform and interconnected porous structure (Fig. 1d). The pore structure was consisted of axial main-hole (Fig. 1e) and interconnecting side-hole (Fig. 1f). The shape of these pores was all regular hexagonal.

Compared with the PLA porous materials prepared by Cai [6] and Rezabeigi [7] as mentioned previously, the PLA comby scaffolds constructed in this paper had much higher mechanical properties. The compressive modulus of the comby PLA scaffolds with porosity of 90% was 70.4 ± 11.4 MPa. The much higher strength could be ascribed to the ordered structure. As shown in Fig. 1, the comby scaffolds had ordered regular hexagon pores. On the contrary, the PLA scaffolds reported by Cai [6] and Rezabeigi [7] had random pores. It demonstrated that the ordered structure conferred higher mechanical properties to the porous materials.

The comby scaffolds with different porosity were designed by changing the comby wall thickness. They had same side length value of main-hole (1000 μm) and side-hole (500 μm). As shown in Fig. 2a and b, there was remarkable negative relation between porosity and strength. When the porosity of the PLA and PR scaffolds increased from 40% to 90%, the compressive strength decreased from 51.3 ± 3.0 MPa to 5.1 ± 1.8 MPa and from 23.2 ± 0.4 MPa to 6.0 ± 0.2 MPa correspondingly. The compressive modulus decreased from 612.7 ± 62 MPa to 70.4 ± 11.4 MPa and from 328.7 ± 7.7 MPa to 119.5 ± 2.7 MPa correspondingly.

Rezabeigi [7] reported that when the porosity of the PLA foams ranged from 40.7% to 90.8%, the compressive modulus decreased from 57 MPa to 1.8 MPa. The latter value was only 3.2% of the former value. The strength decreased very sharply with increasing of porosity. In our works, the comby scaffolds with porosity of 40.7%

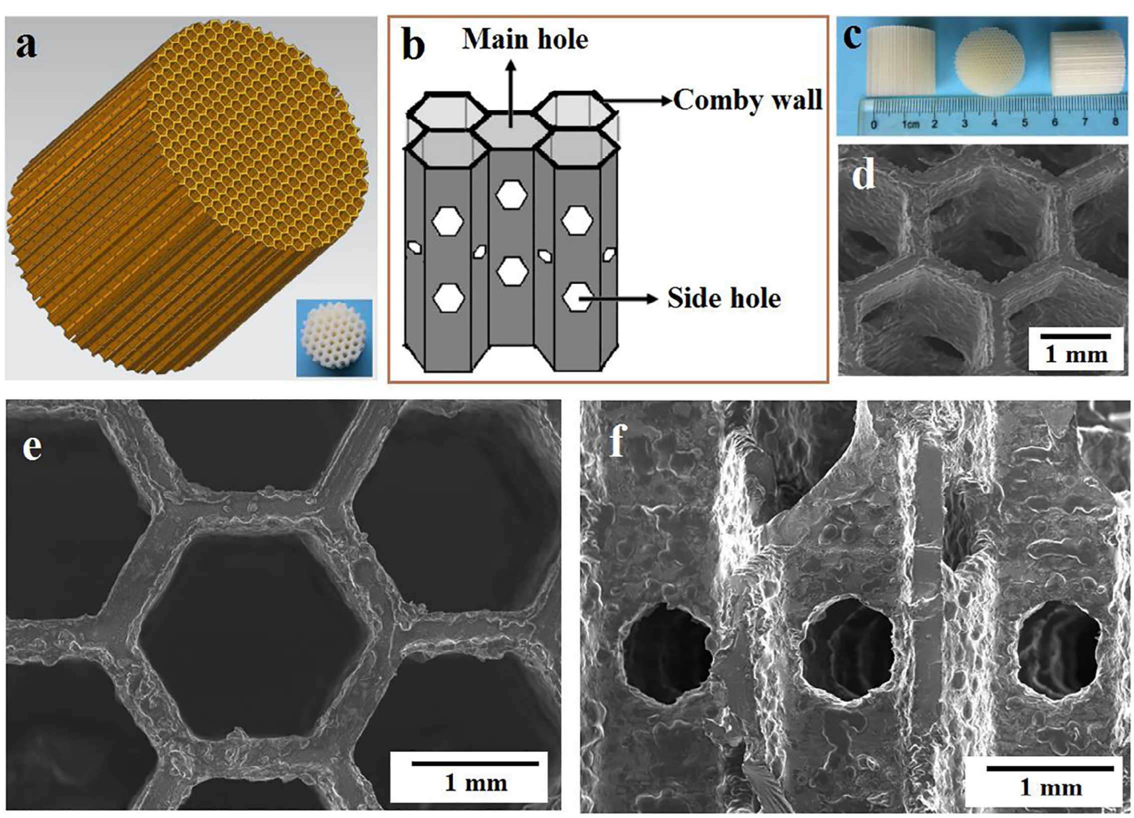

Fig. 1. The Structure of the comby scaffolds, (a) computer aided design image, the inserts in the lower right corner of (a) was a PLA scaffold printed by 3DP, (b) schematic diagram of the comby scaffold, (c) overall appearance of PR scaffold, (d)–(f) were SEM photos of PR scaffold.