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Additively manufactured metallic porous biomaterials based on minimal surfaces: A unique combination of topological, mechanical, and mass transport properties

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ABSTRACT

Porous biomaterials that simultaneously mimic the topological, mechanical, and mass transport properties of bone are in great demand but are rarely found in the literature. In this study, we rationally designed and additively manufactured (AM) porous metallic biomaterials based on four different types of triply periodic minimal surfaces (TPMS) that mimic the properties of bone to an unprecedented level of multi-physics detail. Sixteen different types of porous biomaterials were rationally designed and fabricated using selective laser melting (SLM) from a titanium alloy (Ti-6Al-4V). The topology, quasi-static mechanical properties, fatigue resistance, and permeability of the developed biomaterials were then characterized. In terms of topology, the biomaterials resembled the morphological properties of trabecular bone including mean surface curvatures close to zero. The biomaterials showed a favorable but rare combination of relatively low elastic properties in the range of those observed for trabecular bone and high yield strengths exceeding those reported for cortical bone. This combination allows for simultaneously avoiding stress shielding, while providing ample mechanical support for bone tissue regeneration and osseointegration. Furthermore, as opposed to other AM porous biomaterials developed to date for which the fatigue endurance limit has been found to be ≈20% of their yield (or plateau) stress, some of the biomaterials developed in the current study show extremely high fatigue resistance with endurance limits up to 60% of their yield stress. It was also found that the permeability values measured for the developed biomaterials were in the range of values reported for trabecular bone. In summary, the developed porous metallic biomaterials based on TPMS mimic the topological, mechanical, and physical properties of trabecular bone to a great degree. These properties make them potential candidates to be applied as parts of orthopedic implants and/or as bone-substituting biomaterials.

Statement of Significance

Bone-substituting biomaterials aim to mimic bone properties. Although mimicking some of bone properties is feasible, biomaterials that could simultaneously mimic all or most of the relevant bone properties are rare. We used rational design and additive manufacturing to develop porous metallic biomaterials that exhibit an interesting combination of topological, mechanical, and mass transport properties. The topology of the developed biomaterials resembles that of trabecular bone including a mean curvature close to zero. Moreover, the developed biomaterials show an unusual combination of low elastic modulus to avoid stress shielding and high strength to provide mechanical support. The fatigue resistance of the developed biomaterials is also exceptionally high, while their permeability is in the range of values reported for bone.

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1. Introduction

Porous biomaterials that mimic the various properties of bone are in great demand. That is due to their utility in substituting bone and their application in various types of orthopedic implants that need to avoid stress shielding while offering enough mechanical support and long fatigue life. Moreover, the mass transport properties of bone-mimicking porous biomaterials such as their permeability have to be properly designed [1–3] to allow for nutrition and oxygenation of cells residing in the inner space of the porous biomaterials. Fully porous biomaterials provide multiple advantages as compared to other types of biomaterials [4]. These advantages include greater flexibility in adjustment of mechanical properties [5], increased surface area that could be used for biofunctionalization and infection prevention [6], and a large pore space that facilitates bone ingrowth and drug delivery from within the implants [7].

Design and manufacturing of porous biomaterials that simultaneously satisfy all the above-mentioned criteria in terms of mechanical and mass transport properties, are challenging enough but not necessarily sufficient for the desired level of bone tissue regeneration. Geometry in general, and the curvature of the surface on which cells reside in particular, has recently emerged as an important factor that determines the rate of tissue regeneration [8]. Multiple studies have, for example, shown that tissue regeneration increases with curvature and that tissue regeneration progresses much further on concave surfaces as compared to convex and flat surfaces [8–11]. Design and manufacturing of porous biomaterials whose curvature is most favorable for bone tissue regeneration have therefore received increasing attention to improve bone tissue regeneration. This coincides with recent advances in the additive manufacturing techniques. These advances enable the fabrication of tissue engineering porous biomaterials with arbitrarily complex geometries for an ever-expanding portfolio of biomaterials.

Minimal surfaces are mathematically rigorous concepts from the differential geometry of surfaces (Fig. 1). In non-mathematical terms, minimal surfaces are like soap films. These films span a minimal surface area between given boundaries [12]. The specific property that makes minimal surfaces appealing for bone tissue regeneration is that they have a mean curvature of zero. A mean curvature of zero, as noted by others [13], resembles the mean curvature of trabecular bone, which is also known to be close to zero [14,15]. Moreover, minimal surfaces are frequently found in nature and tissues of a variety of species [16,17]. Examples, as nicely summarized by Kapfer et al. [17], include "beetle shells, weevils, butterfly wingscales and crustacean skeletons" [18–22]. It has been recently hypothesized that porous biomaterials based on minimal surfaces demonstrate enhanced bone tissue regeneration performance [8].

In the present study, we aimed to generate porous biomaterials based on triply periodic minimal surfaces (TPMS) (minimal surfaces with "translational symmetries in three independent directions" [12]) that present a unique combinations of topological, mechanical, and mass transport properties. With these properties they mimic the various properties of bone to an unprecedented level of multi-physics detail. Rational design and additive manufacturing were used to generate these biomaterials. The 'rational' design of biomaterials refers to the process of utilizing physical/biological principles and the established relationships between the topology of biomaterials and their performance to devise certain 'design criteria'. It is assumed that simultaneous satisfaction of relevant design criteria will result in improved bone tissue regeneration performance. The design process started from four different types of TPMSs and took a number of other design condensations into account to produce a large set of variations of porous biomaterials with different dimensions, porosities, and unit cell types. We used selective laser melting (SLM) for production of metallic porous biomaterials at the micro-scale. SLM is an additive manufacturing process in which successive addition of layers based on a computer-aided design (CAD) is used for free-form fabrication of three-dimensional metal parts. The biomaterials fabricated using SLM have precisely-controlled and highly reproducible micro-architectures. Both of those features are essential for realizing the advantages of rationally designed geometries. We studied the topological, quasi-static mechanical properties, fatigue resistance, and permeability of all types of the designed and additively manufactured porous biomaterials to evaluate their success in mimicking the various properties of bone.

2. Materials and methods

2.1. Porous biomaterial design and manufacturing

Four TPMS structures, primitive (P), I-WP (I), gyroid (G), and diamond (D) were generated using *k3DSurf*, a software which provides all the options to produce complex 3D geometries in a finite volume with the use of implicit functions and inequalities. Because

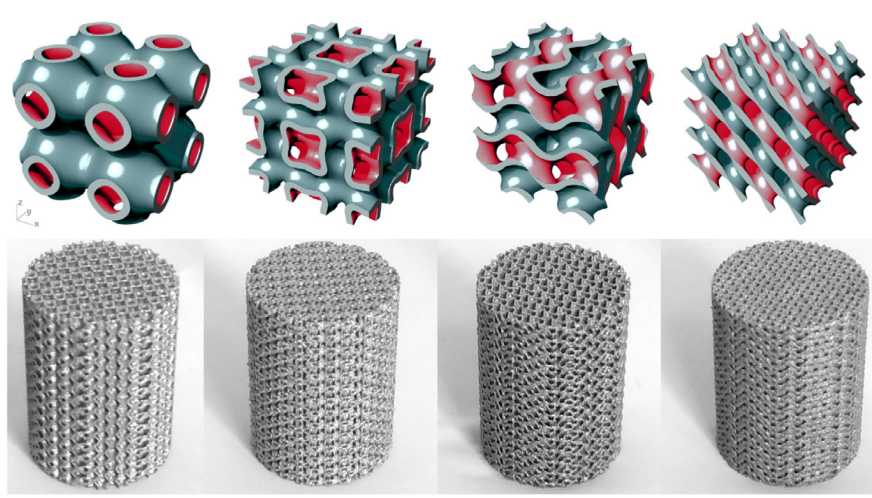

Fig. 1. TPMS porous biomaterials. Top: STL file assemblies of 1.5 mm unit cells, bottom: cylindrical specimens with a height of 20 mm and a diameter of 15 mm manufactured with selective laser melting. From left to right: primitive, I-WP, gyroid, diamond.