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High-strength porous biomaterials for bone replacement: A strategy to assess the interplay between cell morphology, mechanical properties, bone ingrowth and manufacturing constraints

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ABSTRACT

High-strength fully porous biomaterials built with additive manufacturing provide an exciting opportunity for load-bearing orthopedic applications. While factors controlling their mechanical and biological response have recently been the subject of intense research, the interplay between mechanical properties, bone ingrowth requirements, and manufacturing constraints, is still unclear. In this paper, we present two high-strength stretch-dominated topologies, the Tetrahedron and the Octet truss, as well as an intuitive visualization method to understand the relationship of cell topology, pore size, porosity with constraints imposed by bone ingrowth requirements and additive manufacturing. 40 samples of selected porosities are fabricated using Selective Laser Melting (SLM), and their morphological deviations resulting from SLM are assessed via micro-CT. Mechanical compression testing is used to obtain stiffness and strength properties, whereas bone ingrowth is assessed in a canine *in vivo* model at four and eight weeks. The results show that the maximum strength and stiffness ranged from 227.86 ± 10.15 to 31.37 ± 2.19 MPa and 4.58 ± 0.18 to 1.23 ± 0.40 GPa respectively, and the maximum 0.2% offset strength is almost 5 times stronger than that of tantalum foam. For Tetrahedron samples, bone ingrowth after four and eight weeks is 28.6% ± 11.6%, and 41.3% ± 4.3%, while for the Octet truss 35.5% ± 1.9% and 56.9% ± 4.0% respectively. This research is the first to demonstrate the occurrence of bone ingrowth into high-strength porous biomaterials which have higher structural efficiency than current porous biomaterials in the market.

Statement of significance

We present two stretch-dominated cell topologies for porous biomaterials that can be used for load-bearing orthopaedic applications, and prove that they encourage bone ingrowth in a canine model. We also introduce an intuitive method to visualize and understand the relationship of cell topology, pore size, porosity with constraints imposed by bone ingrowth requirements and additive manufacturing. We show this strategy helps to gain insight into the interaction of exogenous implant factors and endogenous system factors that can affect the success of load-bearing orthopaedic devices.

1. Introduction

A biomaterial is a synthetic or natural material intended to interface with a biological system [1]. Porous biomaterials constitute a smaller subsection of the whole field of biomaterials and are particularly relevant for bone interfacing components since they provide a high surface area for bone ingrowth for secondary long term biologic fixation in orthopedic and dental bone implant applications [2]. Porous biomaterials for bone replacement should fulfill specific criteria including: filling bone defect cavities, pore interconnectivity and pore architecture that promote bone formation as well as facilitate the exchange of nutritional components and oxygen to enhance bone ingrowth [3–5], and sufficient

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strength to support physiological loading. In addition, their mechanical properties should ideally be tailored to match the stiffness of the local host bone so as to reduce bone resorption induced by stress shielding [6–9].

Bone ingrowth into an implanted structure is a highly complex phenomenon involving a multitude of factors encompassing a cascade of cellular and extracellular biological events [10]. Among the factors are those that are dependent upon the implanted biomaterial. These include material microarchitecture, e.g. cell topology, porosity, pore shape and size, and properties of the monolithic material among others [11–15]. The function and overall success of a porous biomaterial depend upon the careful selection of a number of morphological parameters, including average pore size and porosity, each affecting the rate of bone ingrowth and interface strength [11,16]. For satisfactory bone ingrowth, porosity should be above 50%, and pore size between 50 and 800 μm [17,18].

For load-bearing applications, porous metallic constructs are predominantly used in bone surgeries because of their severe mechanical strength requirements. A variety of methods have been developed to produce porous metallic scaffolds with a homogeneous pore size distribution that provides a high degree of interconnected porosity for bone ingrowth [2,19]. These processes retain intrinsic limitations, such as an almost uniform distribution of pore size with homogenous porosity. Porous structures with a defined pore shape and size and with a specified porosity distribution, a gradient, or a pattern is very difficult to achieve [20,21]. The thickness of porous coatings might be also insufficient to facilitate effective bone tissue ingrowth [22,23].

Recent advances in additive manufacturing (AM), such as Electron-Beam Melting (EBM) and Selective Laser Melting (SLM), enable to manufacture fully porous structural biomaterials with controlled architecture for bone interfacing applications [17,21,23–26]. AM methods enable scaffolds to be reproduced with controlled topology, porosity, pore shape and size, interconnectivity, and mechanical properties. AM processes allow for the incorporation of gradients of porosity and pore size to tune the performance [20,27]. This allows for a porous biomaterial with an optimum graded microstructure to be designed and manufactured to achieve a desirable mechanical response and functional environment for bone ingrowth.

Among the approaches commonly used to design a porous biomaterial via AM, one consists of selecting the cell topology from a library of unit cells [25,28–30]. The microarchitecture of the unit cell can be tailored to provide sufficient mechanical properties for the porous biomaterial to support physiological loadings with controlled porosity, pore shape, and pore size gradients for an optimum architectural environment for bone ingrowth [15,20,31]. Many studies have shown the use of several AM processes to manufacture unit cells and to evaluate the effect of cell morphology on mechanobiological properties, either *in vitro* and *in vivo* for tissue affinity [24,25,28,32–35]. For implant porous materials, there are currently no quantitative criteria specifying porosity and pore size requirements for bone ingrowth. In particular, there is no study across the length scale that clarifies the role that pore topology, pore size, porosity as well as strut thickness, play in the mechanobiological response of a porous material. The lack of quantitative criteria for understanding such mechanobiological interactions poses challenges to the search of porous materials that can concurrently maximize both mechanical and biological performance. Currently in literature, a common *modus operandi* is to select a cell topology, and with no systematic approach to change iteratively only two of its morphological properties (e.g. cell size, strut thickness, pore size, and porosity) so as to obtain a porous material that is manufacturable. This process, however, does not give a full perspective of the specific property bounds, i.e. the feasible design space, defined by each topology. In addition, this process often leads to the design of porous materials with pore size range much higher than the optimum range for bone ingrowth [31,35]. Moreover, this procedure does not provide any insight into how the morphological properties of the unit cell, such as unit cell size, pore size, porosity, and strut thickness, are interrelated, and how the change of one parameter can influence the others. Furthermore, to the best of the authors' knowledge, there is also no study that shows how manufacturing and bone ingrowth requirements can affect the admissible design range for a given topology.

This paper presents a systematic methodology for understanding the interplay between the morphological parameters and the mechanobiological properties of structural porous biomaterials. The method enables the generation of design maps where morphological attributes of a given cell topology, such as pore size, porosity, cell size, and strut thickness, are conveniently visualized together with both manufacturing constraints and bone ingrowth requirements. The methodology is applied and demonstrated in this paper with two high-strength topologies: the Tetrahedron and the Octet truss. The cells belong to the class of high-strength and stiffness topologies which are stretch dominated, i.e. their struts axially deform under load [36–43], hence their suitability for load-bearing orthopedic applications. Ti6Al4V representative samples are manufactured via Selective Laser Melting (SLM), and micro-CT analyzed to assess their morphological characteristics with respect to the nominal designed values. Uniaxial compression testing is performed to obtain the effective elastic modulus and yield strength of the manufactured samples. Finally, results from *in vivo* clinical experiments using a canine model are given to assess bone ingrowth after 4 and 8 weeks and to evaluate the potential use of structurally efficient topologies in bone replacement implants.

2. Development of cell topology domains

The mechanical and biological properties of a unit cell for a fully porous biomaterial are governed mainly by the topology, nodal connectivity, porosity, pore size, and the monolithic material from which they are made [22,23,25,34,38,44–46]. The way these morphological parameters are related is not necessarily intuitive; neither is how they affect the mechanical properties and biological response. For this reason, we develop a parametric model to describe the geometry of a unit cell, and subsequently use it to visualize its morphological properties on a design chart. This allows us to visually inspect what porosity and pore size combinations exist and are feasible to manufacture.

As archetype topologies, we select herein the Tetrahedron cell and the Octet truss cell (Fig. 1) and used their parametric geometric models to generate their design domains. From the generalized Maxwell rule for static determinacy [36,41,47], both topologies

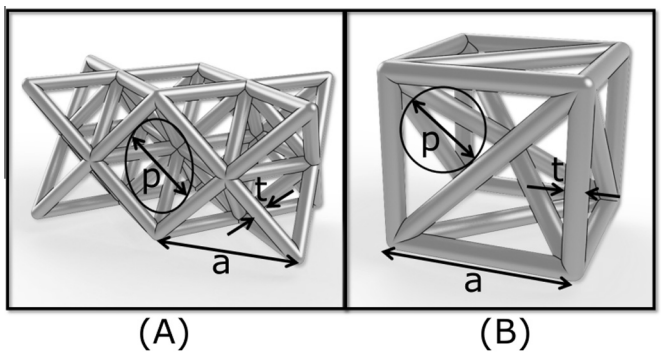

Fig. 1. Parametric models developed for (A) Octet truss unit cell, and (B) Tetrahedron unit cell.