Research Paper

Numerical optimization of open-porous bone scaffold structures to match the elastic properties of human cortical bone

Jan Wieding*, Andreas Wolf, Rainer Bader

Biomechanics and Implant Technology Research Laboratory, Department of Orthopaedics, University Medicine Rostock, Doberaner Strasse 142, 18957/18057 Rostock, Germany

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ABSTRACT

Treatment of large segmental bone defects, especially in load bearing areas, is a complex procedure in orthopedic surgery. The usage of additive manufacturing processes enables the creation of customized bone implants with arbitrary open-porous structure satisfying both the mechanical and the biological requirements for a sufficient bone ingrowth. Aim of the present numerical study was to optimize the geometrical parameters of open-porous titanium scaffolds to match the elastic properties of human cortical bone with respect to an adequate pore size. Three different scaffold designs (cubic, diagonal and pyramidal) were numerically investigated by using an optimization approach. Beam elements were used to create the lattice structures of the scaffolds. The design parameters strut diameter and pore size ranged from 0.2 to 1.5 mm and from 0 to 3.0 mm, respectively. In a first optimization step, the geometrical parameters were varied under uniaxial compression to obtain a structural modulus of 15 GPa (Young's modulus of cortical bone) and a pore size of 800 μm was aimed to enable cell ingrowth. Furthermore, the mechanical behavior of the optimized structures under bending and torsion was investigated. Results for bending modulus were between 9.0 and 14.5 GPa. In contrast, shear modulus was lowest for cubic and pyramidal design of approximately 1 GPa. Here, the diagonal design revealed a modulus of nearly 20 GPa. In a second step, large-sized bone scaffolds were created and placed in a biomechanical loading situation within a 30 mm segmental femoral defect, stabilized with an osteosynthesis plate and loaded with physiological muscle forces. Strut diameter for the 17 sections of each scaffold was optimized independently in order to match the biomechanical stability of intact bone. For each design, highest strut diameter was found at the dorsal/medial site of the defect and smallest strut diameter in the center.

In conclusion, we demonstrated the possibility of providing optimized open-porous scaffolds for bone regeneration by considering both mechanical and biological aspects. Furthermore, the results revealed the need of the investigation and comparison of different load scenarios (compression, bending and torsion) as well as complex biomechanical loading for a profound characterization of different scaffold designs. The usage of a numerical optimization process was proven to be a feasible tool to reduce the amount of the required titanium material without influencing the biomechanical performance of the scaffolds.

*Corresponding author. Tel.: +49 381 494 9343; fax: +49 381 494 9308.
E-mail address: jan.wieding@med.uni-rostock.de (J. Wieding).
scaffold negatively. By using fully parameterized models, the optimization approach is adaptable to other scaffold designs and bone defect situations.

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1. Introduction

By the use of additive manufacturing (AM) processes, both standard and custom-made implants as well as open-porous scaffolds can be fabricated in a wide range of design possibilities (Murr et al., 2009, 2010; Parthasarathy et al., 2010; Schwerdtfeger et al., 2010; Harrysson et al., 2008; Bandyopadhyay et al., 2009). Furthermore, AM offers the possibility to gain control about the geometrical shape and about the mechanical properties in order to cope with various requirements, e.g. in the field of scaffolds for bone regeneration (Wieding et al., 2012). This opens up an entirely new field of unique implants with specific characteristics.

For scaffolds being designated to replace large segmental bone defects, caused by tumors, severe fractures, infections or implant loosening (Attias and Lindsey, 2006; Mavrogenis et al., 2009; Desai et al., 2012) various requirements have to be satisfied. Especially for load-bearing areas of the lower extremity (pelvis, femur, and tibia), these scaffolds are under high mechanical stress. Therefore, in order to act as a bone scaffold, mechanical as well as biological aspects have to be considered for sufficient bone regeneration and long-term stability within large segmental bone defects.

There is a general consensus about the necessity of an open-porous scaffold structure with an interconnecting pore system (Karageorgiou and Kaplan, 2005; Kienapfel et al., 1999; Salgado et al., 2004; Yang et al., 2001). But the specifications vary in a wide range of preferred values for the pore size. Although most studies investigated the pore size between 200 and 500 μm (Ryan et al., 2008; van der Stok et al., 2013; Ponader et al., 2010), there are also studies with much smaller pores (<200 μm) (Itala et al., 2001; Murphy et al., 2010) and larger pores (>500 μm) (Wieding et al., 2012; Lopez-Heredia et al., 2008; Holland et al., 2006) and even with pores up to 2200 μm (Holy et al., 2000) with promising results. Findings obtained from in vitro or in vivo studies provide different specifications for sufficient bone cell ingrowth.

Besides the biological aspects scaffolds must exhibit sufficient mechanical stability for load-bearing areas. Titanium and its alloys are successfully used in clinical application as an implant material due to high biocompatibility and good mechanical properties (Donachie, 1998; Down, 1973; Niinomi, 2008; Mueller et al., 2006). Nevertheless, to be suitable as a bone scaffold, the elastic properties shall be adapted to those of the surrounding bone tissue in order to avoid shielding of mechanical stimuli, which can lead to insufficient bone ingrowth and stress-shielding of the adjacent bone stock (Niinomi and Nakai, 2011; Engh et al., 1992; Merle et al., 2011). As the mechanical properties of titanium (e.g. Young’s modulus of 114 GPa) are lower than other metals like cobalt-chrome (224 GPa) or stainless steel (210 GPa) (Long and Rack, 1998) but still higher than cortical bone (Ohman et al., 2011), open-porous structures are implemented to reduce the stiffness of the scaffolds and to offer an suitable environment for bone ingrowth.

Therefore, the mechanical behavior of open-porous scaffolds has to be adapted for the application area in order to reduce the risk of implant loosening by stress shielding (Bandyopadhyay et al., 2009; Huiskes et al., 1992; Kuiper and Huiskes 1997). Hence, the investigations of bone scaffolds with defined biomechanical properties, suitable for carrying the load within the application field are of great importance.

To cope with all those requirements AM techniques like electron beam melting (EBM) or selective laser melting (SLM) offer a wide range of structural design variations. Thus, scaffolds can be fabricated with specific geometrical shape and subsequently adjustable mechanical properties (Murr et al., 2010; Parthasarathy et al., 2010; Wieding et al., 2012). Moreover, the mechanical properties of AM fabricated dense scaffolds are comparable to those, fabricated with classical fabrication processes like casting and forging (Koike et al., 2011; Wieding et al., 2013). As there are nearly no limits for the fabrication, the question for the mechanical properties becomes more and more important.

Experimental studies for the characterization of the mechanical properties are often time-consuming and cost-intensive and were, therefore, mostly performed under uniaxial loading conditions and for only few design variations. In contrast, by the means of finite element analysis (FEA) the mechanical properties for different structural designs and porosities can be calculated prior to the cost-intensive and time-consuming fabrication (Oliwares et al., 2009; Luxner et al., 2005; Chesh et al., 2004; Chua et al., 2003a, 2003b; Boccaccio et al., 2011; Sanz-Herrera et al., 2010; Wettergreen et al., 2005). In addition with optimization tools the mechanical and biomechanical properties can be directly controlled to match the necessary requirements (Hollister et al., 2002; Chan et al., 2010; Almeida, 2010; Adachi et al., 2006; Challis et al., 2010; Kapfer et al., 2011; Lin et al., 2004). This will lead to optimized scaffolds with desired and suitable mechanical properties.

However, considering the physiological environment, where the scaffolds are designated to be placed in, is essential to judge their ability as bone regeneration scaffold because their biomechanical behavior is different from those determined under uniaxial mechanical testing (Wieding et al., 2013).

Therefore, the aim of this numerical study was to utilize an optimization approach to match the mechanical properties of cortical bone under both mechanical and biomechanical loading with respect to the biological aspects in order to offer an open-porous scaffold structure for sufficient bone ingrowth.

2. Materials and methods

The general investigations of the scaffolds are illustrated in Fig. 1. In a first step the mechanical properties of the open-porous scaffolds have been investigated under uniaxial compression testing in order to determine the influence of the variation of the geometrical parameters (Fig. 1a). (Design