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Topology Optimization to reduce the stress shielding effect for orthopedic applications

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Abstract

Orthopedic problems are significantly increasing posing pressure to healthcare systems. Traditional clinical procedures for traumatic bone fracture applications comprise the use of high stiffness metallic implants caused by the built-up material and implant design. These implants show a high mechanical mismatch comparing to bone properties resulting in stress shielding phenomena that leads to less dense and fragile bone. This paper follows a design phase by exploring the use of 3D Topology Optimization to create lightweight metallic implants with reduced stiffness, thus minimising stress shielding and bone loss problems.

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Keywords: Topology Optimization; Medical implants, Stress sheilding, Finite Element Analysis

1. Introduction

Bone is one of the few tissues that has the ability to heal itself, through a complex physiological process comprising acute inflammatory responses, cartilage callus formation, endochondral ossification and bone remodelling, without developing a scar [1]. However, in bone fracture events such as high traumatic or pathological fractures, exceeding a critical size defect, bone fracture healing capabilities becomes limited causing delays or non-union problems and requires further interventions (e.g. bone fixation implants) [2-4]. In the United States of America, an estimated 15 million fractures occur annually costing over 60 billion dollars.

Bone fixation is a routine orthopedic procedure. Fracture fixation devices stabilise and immobilise the fracture segments initiating the fracture healing process [5]. Commercially available bone fixation implants (i.e. external fixators, internal fixators and intramedullary pins) are built up with metallic biomaterials like stainless steel, titanium, cobalt and its alloys (e.g. Ti6Al4V and CoCrMo). a large number of cases [6-8], these implants are left permanently in the body leading to long term problems such as possible release of metal ions, inflammatory reactions, risk of infection, screw loosening and most importantly bone resorption due to stress shielding effects.

Additionally, metallic biomaterials have high elastic moduli (e.g. CoCrMo Young's Modulus is around 210 GPa, Ti6Al4V Young's Modulus is around 110 GPa and, Stainless Steel 316 L SS is around 190 GPa) than natural bone (the Young's Modulus of trabecular bone ranges from 0.02 to 2 GPa while for cortical bone the Young's Modulus ranges from 3 to 30 GPa) [9-11]. This large mismatch in mechanical properties between bone and metallic materials causes bone stress shielding, bone instability and bone loss. Stress concentration in the fixation device, which may lead to cracking of plates or screw pullout, is another consequence of the high stiffness of metallic implants.

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Removal of implants after the healing process is an alternative approach, accounting for up to 30% of planned orthopedic operations [12], but often associated with complications like infection, nerve damage, risk of refracture and increased pain at the site of surgery being common.

In order to overcome the current limitations of metallic implants, authors are starting a new research project entitled "Osteofix-novel biodegradable composite implants for osteoporotic bone fractures" partially funded by the government of Saudi Arabia and the UK Royal College of Surgeons. The project aims to reduce the stress shielding phenomena by reducing the equivalent stiffness of the metallic implants through the use of Topology Optimization (TO), and to avoid the need of a second surgery to remove the implant by replacing metallic materials with biocompatible and degradable materials (polymers, ceramics, metals or composites). Fig. 1 illustrates the major research activities behind this research program.

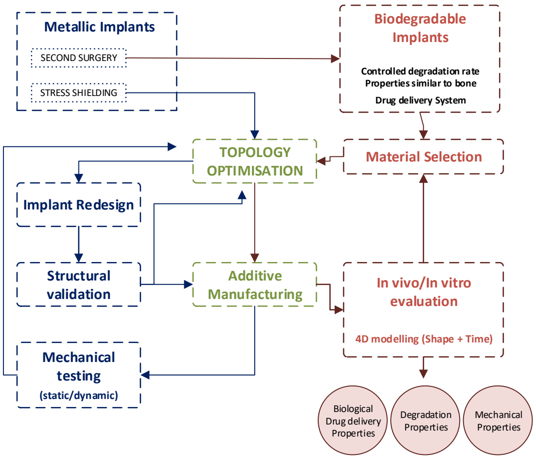

Fig. 1. Research activity flowchart for a novel bone fixation implant.

In a previous paper [13], authors showed that, despite TO seeks to find the optimal load path for a particular load and boundary condition, searching for a minimum compliance design, it is possible to use this mathematical optimization method to obtain implant designs with reduced "equivalent stiffness". Preliminary results were obtained for a Locking Compression Plate (LCP) simulated as a 2D plate. LCP is the most recent developed fracture fixator design with a capability of treating fractures with different healing processes (i.e. secondary bone healing and primary healing) intending to treat juxta-articular fractures (e.g. distal tibia, fibula, olecranon) and in osteoporotic bones [14]. Based on these preliminary results, this paper focus on the topology optimization of 3D LCP plates, considering different loads, boundary conditions and volume reductions. New designs were obtained with reduced "equivalent stiffness" minimising the stress shielding phenomena.

2. Computer Optimisation

A constrained optimisation problem is mathematically described as the minimisation of cost functions subjected to a set of constrains as follows:

$$\text{Find } x = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{Bmatrix} \text{ which minimises } f(x) \tag{1}$$

$$\text{Subject to } \begin{cases} g_i(x) \le o, i = 1,2,..., m \\ h_i(x) = 0, j = 1,2,..., n \end{cases} \tag{2}$$

where x is the vector of design parameters and $f(x)$ is the cost function. The functions $g_i(x)$ and $h_i(x)$ are called the inequality constraint function and the equality constraint function respectively, and they define the constraints of the problem.

Structural optimization is a decision making tool which defines the material distribution according to specific constrains and objective functions. Three methods can be identified. Sizing optimization is the simplest method to optimize truss-like structures including bridges, support bars and frames. In sizing optimization, the structure layout has been defined and the only parameter that can be modified is the size of the component itself or the size of structure element. Shape optimization will not change the topology of the structure and the modified design variables could be the thickness of the wall, radius of holes, width of slot or other complex geometry shape changes.

Topology optimization, the most commonly used structural optimization method, seeking to find the best material distribution for specified Computer Aided Engineering (CAD) structure following the load path from the Finite Element (FE) analysis (i.e. loading and boundary conditions), subject to the objective function (e.g. minimising strain energy), and constraints (e.g. volume).

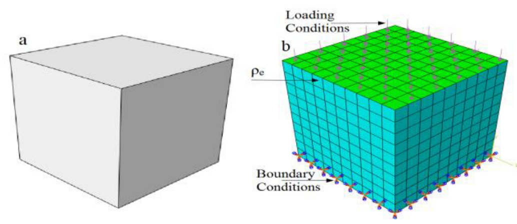

Fig. 2. (a) Initial CAD structure and (b) discretised CAD structure with loading and boundary conditions.

In TO, the initial CAD structure is discretised into discrete divisions (elements) by the FE method (Fig.2). Each element is analyzed and given a certain value of stiffness/strain which defines the stress/displacement of the CAD structure. The TO