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Numerical investigation of the effect of porous titanium femoral prosthesis on bone remodeling

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ABSTRACT

Porous titanium is a promising orthopedic implant material. As a potential use in total hip replacement, the effect of a porous titanium femoral prosthesis on bone remodeling is investigated in this paper. The stress and strain fields of a post-operative femur with a hip replacement are calculated by applying the three-dimensional finite element method. The effect of the implant material on the bone remodeling is evaluated by analyzing the loss of bone density following a strain magnitude based bone remodeling theory. Different implant materials, including currently used solid cobalt–chrome and solid titanium, potential porous titanium with different porosities, are considered in this study. This investigation confirms that bone loss around the implant strongly depends on the value of the elastic modulus of the prosthesis. There will be a sharp drop of the volume of the bone with density loss if a cobalt–chrome implant is replaced by a porous titanium implant. The numerical results show that both of the bone volume with density loss and the bone density loss rate decrease linearly with the increase of the porosity. However, increasing porosity will reduce the strength of porous titanium. With regard to material design for porous titanium-based femoral prosthesis, stress analysis is required to meet the strength requirement.

1. Introduction

Hip replacement surgery was one of the most surgical advances in the last century. Since the first surgery in 1960, improvements in joint replacement techniques have greatly increased the effectiveness of total hip replacement. Nowadays, it was reported that about 600,000 hip replacements are performed worldwide every year and 90% of recipients are over 65 years old [1]. The femoral prostheses used for hip replacement are made from solid alloys, such as cobalt–chrome and titanium alloys. Following hip replacement, bone loss around femoral prostheses occurs due to the altered post-operative loading environment, particularly due to stress shielding. In some serious cases, bone loss can lead to the loosening of the prosthesis and repeat surgery may be needed [2].

Stress shielding is mainly caused due to the mismatch of the elastic modulus between the implant material and the bone. For example, the elastic modulus of cobalt–chrome alloy is 210 GPa while the elastic modulus of cortical bone is only about 17 GPa [3,4]. Since the implant is much stiffer than the bone, some of the forces applied on the bone have been shielded by the prosthesis, which results in bone density loss. A solution to this problem is to develop new implant materials with the stiffness closing to that of bone, such as composite materials [5] and porous titanium [6,7]. Besides the property of low elastic modulus, open-celled Ti alloy foams allow bone tissue growing in the implant materials [8,9].

To assist the development of porous titanium as implant materials for hip replacement, the effect of a femoral prosthesis made from porous titanium on bone remodeling was theoretically investigated in this study. The bone remodeling, i.e., here, bone density loss, was quantified by applying a strain magnitude based theory. The strain magnitude field was calculated from the three-dimensional finite element modeling of a post-operative femur under typical loading conditions. The three-dimensional finite element simulation plays an increasing role in the development and design of femoral prostheses [5,10,11].

2. Finite element model

2.1. Geometry of the femur

The three-dimensional geometry of a femur can be established from computed tomography (CT) images. The femur geometry varies from person to person and it changes with age even for the same person. From the research standpoint, to simplify the experimental cross-validation of numerical studies, researchers from Rizzoli Orthopaedic Institute, Bologna, Italy, established a database called International Society of Biomechanics Finite Element Mesh

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