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Evaluation of the development of tissue phenotypes: Bone fracture healing using functionally graded material composite bone plates

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ABSTRACT

Long bone fractures are conventionally treated using metallic implants that may be accompanied by complications such as stress shielding, corrosion, poor fatigue life, and loosening. Flexible fixations by reducing the structural stiffness of prostheses or using low modulus materials are promising alternatives to overcome these problems. In this study, different configurations of bone plates developed from functionally graded material (FGM) composites were considered to investigate the effect of bending stiffness on bone fracture healing while maintaining an equivalent bone plate modulus. The healing performance and development of tissue phenotypes were estimated using mechano-regulation theory with deviatoric strain, which was implemented and analyzed with the commercial software ABAQUS 6.10 and a user's subroutine program. The most effective configuration of FGM layers was proposed based on the healing performance.

1. Introduction

The tibia is a weight-bearing long bone that is commonly injured from trauma and falls. A diaphyseal fracture of the tibia is typically treated with a bone plate. Most bone plates are made from metallic materials that have a much higher modulus than that of bones, which causes a stress shielding effect and can lead to bone necrosis, non-union, and delay in bone union followed by stress shielding [1,2]. Moreover, metallic implants induce problems such as corrosion, implant loosening, poor fatigue life, and incompatibility with magnetic resonance imaging (MRI) and computed tomography (CT) scans [3–5]. To overcome the aforementioned problems, composite materials have been considered for biomedical applications because they can be developed with mechanical and biological similarities to bones. Many researchers have studied the mechanical and biological properties of polymer-based fiber reinforced composite bone plates [6–9]. These properties can be tailored by altering the fiber volume fraction, stacking angle, degradation rate, and release rate of bioactive ions to meet the mechanical and biological requirements based on the application. Bones have anisotropic material properties and are exposed to complex loading conditions during walking, running, climbing stairs, and rising from chairs. Therefore, fiber-reinforced composite bone plates have been developed to meet the mechanical requirements and provide adequate stiffness in the plate-bone assembly as well as flexibility to prevent stress shielding effects. Stress shielding is sensitive to the longitudinal modulus [10]. In our previous studies, plates with a longitudinal modulus of 20 GPa were proven suitable for normal fracture configurations; however, the appropriate modulus for the efficient healing of bones depends upon the fracture configuration [11–13]. Plates made of functionally graded materials (FGMs) were introduced to obtain different bending stiffnesses (Nm/degree) while maintaining the tensile properties of the plates [14]. FGMs have a continuous spatial distribution of two or more components through the thickness of a product. The flexural modulus of an FGM plate can be engineered by changing the layer sequence with different fiber volume fractions.

The healing process of a bone fracture can be assessed by various mechano-regulation theories [15–17]. A mechano-regulation theory with deviatoric strain is a simple and efficient theory that can accurately predict the healing process of bone fractures [18,19], and was selected for this study. Bone healing is also affected by the loading history [20–22]. Appropriate loading conditions were selected for this study from previous studies to provide the best healing performance [11,22].

In the present study, finite element analysis (FEA) was employed to investigate the effect of bone plate bending stiffness on the healing performance by changing the spatial distribution of the fiber content along the thickness of the bone plate. The properties of spatially graded composites were altered by changing the layer

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sequence with different fiber contents. Various FGM bone plates were simulated by FEA, and the best FGM sequence was concluded.

2. Material and methods

2.1. Geometry

The tibia, which bears the entire body weight, was modeled using the commercial finite element software ABAQUS 6.10. A male patient, aged 30 years and weighing 70 kg, was analyzed to determine the appropriate dimensions and material properties of the tibia. The 3-dimensional geometry of the simulated tibial diaphyseal section with a smooth circular shaft was developed and the epiphyseal sections were excluded for simplicity. The dimensions of the diaphyseal section were obtained using a digitizer [23,24]. In these studies [23,24] the digitizer was used to measure the dimensions of diaphyseal section of tibia bone and the geometry was simplified to the circular shape. In the current study, the geometry and dimensions of bones suggested in the related studies [23,24] were used to construct the 3D model in ABAQUS. The simplified tibia consists of 5-mm-thick orthotropic cortical bone with an outer diameter of 25 mm that surrounds an isotropic trabecular bone with an outer diameter of 15 mm.

To simulate the simplified representative fracture geometry, a 3-mm-thick smooth transverse fracture was created in the middle of the bone section and was subsequently filled and externally bridged with calluses. The bone fragments were reassembled using a commercial compression bone plate with seven holes (Model 3-642, TREU-Instrumente, Germany), and the assembly was fastened with six bi-cortical screws (Fig. 1(a)). To model the FGM bone plate, each of the ten layers was assigned different material properties based on the fiber content throughout the thickness of the plate (Fig. 1(a)). The eight-node solid element (C3D8R) model was chosen, and the mesh size of calluses was 1 mm to ensure convergence. The number of elements of the bone plate, screws, calluses, cortical bone, and trabecular bone were 10,244, 1728, 5186, 11,736, and 15,752, respectively. The screws were tied to the bone, and a friction coefficient of 0.4 was imposed between the mating surfaces of the bone plate and the bone [23], and between the tapered surfaces of the screw heads and plate holes.

2.2. Material properties

The anisotropic and isotropic material properties of a healthy bone were used for the cortical and trabecular bones [25–27]. Bone plates were designed by a phosphate glass fiber (PGF)/polylactic acid (PLA) composite. The material properties of PGF, PLA, and bone are provided in Table 1. The bone plates were composed of ten layers, each with different material properties. Among the layers, the fiber volume fractions ranged from 5% to 50%, the average fiber volume fraction was 26%, and the orientation of the continuous long fibers was 0°. Fig. 1(a) is a schematic of the different types of FGM bone plates. The healing performance of five types of bone plates was investigated. The healing performance was defined as the ratio of the average Young's modulus of all the tissue phenotypes in the calluses at the 16th week of healing (E_{av}) to the maximum Young's modulus of the mature bone (E_{max} = 6000 MPa) as expressed by Eq. (1).

$$\frac{E_{av}}{E_{\max}} \times 100(\%) \tag{1}$$

One homogenous and four FGM bone plates were introduced in this study, as shown in Fig. 1(a). The average tensile modulus for all of the bone plates was 20 GPa, which is most appropriate for bone healing [11,22]. The bending stiffness (Nm/degree) was varied for the bone plates, and its influence on bone fracture healing was investigated. The FGM bone plates were labeled FGMI, FGMD, FGMS1, and FGMS2 based on the arrangement of the layers. FGMI represents the bone plate whose fiber volume fraction increases (5% to 50%) toward the direction of the bone part, and FGMD represents the bone plate whose fiber volume fraction decreases (50% to 5%) toward the direction of the bone part; FGMS1 has a fiber volume fraction that increases symmetrically outwards, and FGMS2 has a fiber volume fraction that decreases symmetrically outwards (Fig. 1(a) and (b)). The rule of mixture [29] and the Halpin–Tsai model [30] for continuous long fibrous composites composed of PGF and PLA [28] were used to calculate the anisotropic material properties for each layer. Eqs. (2)–(9) were used to calculate the Young's modulus (E) and shear modulus (G) of the composite. The subscripts L and T denote the longitudinal and transverse directions, respectively; the subscripts f and m denote fiber and matrix, respectively; and V_f and V_m denote the fiber and matrix volume fractions, respectively, which were varied as discussed:

$$\eta = \frac{E_f - E_m}{E_f - \xi E_m} \tag{2}$$

$\xi = 2$ for circular fibers

$$E_T = E_m \frac{1 + \xi\eta V_f}{1 - \eta V_f} \tag{3}$$

$$E_L = E_f V_f + E_m(1 - V_f) \tag{4}$$

$$G_m = \frac{E_m}{2(1 + V_m)} \tag{5}$$

$$G_f = \frac{E_f}{2(1 + V_f)} \tag{6}$$

$\xi = 1$ for circular fibers

$$\eta = \frac{G_f - G_m}{G_f + \xi G_m} \tag{7}$$

$$G_{LT} = G_m \frac{1 + \xi\eta V_f}{1 - \eta V_f} \tag{8}$$

The major Poisson's ratio was calculated as

$$\nu_{LT} = \nu_f V_f + \nu_m V_m \tag{9}$$

Fig. 1(b) and (c) shows the Young's modulus and major Poisson's ratio for the layers of the bone plates, which were varied along the thickness and calculated using Eqs. (2)–(9). The gradient pattern for each plate was different, but the average Young's modulus was the same as that of the homogenous bone plate (20 GPa).

2.3. Loading and boundary conditions

The injured leg bears only the anterior and posterior tibial muscle forces which are approximately 10% of the body weight (10% BW) [22,31]. The loading conditions were chosen from our previous study to provide the best bone healing [11,22]. In the FEA, 10% body weight (BW) was applied to the proximal end of the cortical section at 1 to 7 weeks post-surgery; the load was increased to 200% BW at 8 to 11 weeks and progressively increased during weeks 12 to 16 up to a load of 300% BW [32,33], as shown in Fig. 2(a). The load incrementing procedure was executed using the user's subroutine programmed by Python 3.1 with iterative calculations. The opposing end of the bone was fixed in all directions.

To calculate the intact bending stiffness (Nm/degree) of a plate-bone assembly, Eq. (10) was used [34]. The bending stiffness (BS) of the intact plate-bone assembly was calculated at the first day of healing, and the fracture gap was assumed to be filled with granulation tissue (Fig. 2(b)):

$$BS = \frac{F \times L}{\theta} \tag{10}$$