Composites: Part B 58 (2014) 443–450

Contents lists available at ScienceDirect

Composites: Part B

journal homepage: www.elsevier.com/locate/compositesb

Simulation of the bone healing process of fractured long bones applied with a composite bone plate with consideration of the blood vessel growth

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ARTICLE INFO

Article history:
Received 27 April 2013
Received in revised form 11 September 2013
Accepted 25 October 2013
Available online 10 November 2013

Keywords:
A. Fabrics/textiles
A. Polymer–matrix composites (PMCs)
C. Finite element analysis (FEA)

ABSTRACT

The healing process of long bones such as the tibia was simulated on the basis of a mechanoregulation theory by taking blood vessel growth into consideration. The tissue differentiation process of calluses by taking into consideration blood vessel growth was simulated by a user subroutine program based on the mechanoregulation model and a diffusion equation. Composite bone plates made of a plain weave carbon/epoxy composite (WSN3k) and a plain weave glass/polypropylene composite (Twintex) were applied to the fracture site to investigate the effect of plate modulus on the healing performance. The simulation results revealed that the flexible composite bone plate made of Twintex $[0]_{18}$, which had a slightly higher Young's modulus than a cortical bone, provided the highest healing performance. Moreover, it was found that the effect of the plate modulus on the healing performance reduced when the blood vessel growth at the fracture site was considered, which reflected a more realistic bone healing process.

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1. Introduction

When a fracture occurs in long bones such as a tibia or a femur, the direct bone healing method is usually employed to heal the fractured bones. Further, in such cases, a bone plate – an orthopedic prosthesis – is generally used to stabilize the fractured bones. Currently used bone plates are made of metal, such as a stainless steel, which has a much higher Young's modulus than that of bones; this difference between Young's moduli induces the stress shielding effect [1]. The stress shielding effect induces a stress imbalance between the plate and bone, thereby disturbing the stress transfer through the bone [2,3]. To overcome this problem, flexible implants made of fibrous composites have been developed, and their healing performances have been investigated [2–10]. According to the studies on bone fracture healing via the flexible fixation method, biomechanical behaviors such as tissue differentiation in the fractured part is strongly affected by the mechanical stimulus on the part and this stimulus effect controls the bone healing performance [11–14]. Isaksson et al. [11] carried out a comparative study of mechanoregulation theories to investigate the efficiency of the various types of mechanical stimuli (deviatoric strain, fluid flow, pore pressure, etc.), and concluded that the mechanoregulation theory with deviatoric strain as a single parameter predicts fracture healing well. Kim et al. [12] successfully simulated the tissue differentiation process of calluses at the fractured part by applying the mechanoregulation theory with deviatoric strain as the mechanical stimulus.

Tissue differentiation is affected not only by the mechanical stimulus but also by blood vessel development [15–18]. Claes et al. [15] verified the effect of blood vessel growth on bone healing via animal tests. Hausman et al. [18] studied the relationship between blood vessel growth and bone fracture healing by *in vivo* experiments on angiogenesis inhibitors, which prevent the generation and development of blood vessels. With no blood vessel growth, the bone healing process was retarded.

In this study, the bone healing process of a fractured tibia fixed with a composite bone plate was simulated by taking blood vessel growth into consideration. To verify the validity of the developed simulation code, the results of an *in vivo* test [15] on a sheep leg applied with an external fixator were compared with the simulation results. Finally, this simulation technique was employed to simulate the bone healing process of a tibia applied with a composite bone plate with various material properties.

2. Finite element analysis

To simulate the bone healing process, a commercial finite element code ABAQUS (ver. 6.91) was used. An eight-node thermally coupled solid element (C3D8T) was used to construct a plate-bone

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http://dx.doi.org/10.1016/j.compositesb.2013.10.058

assembly model. For estimating the time-varying material properties of healing tissues, a mechanoregulation algorithm with deviatoric strain and the diffusion equation for calculating blood vessel growth were combined in a user's subroutine programmed by Fortran 11; further, for the post-processing of the strain distribution, the Python code (ver. 3.1) was used.

2.1. Verification of the simulation technique: simulation of bone healing process of a broken sheep leg applied with an external fixator

A finite element model of a fractured sheep leg (see Fig. 1a) applied with an external fixator was constructed using test data [15] to verify the simulation technique. When the flexible fixation method using an external fixator or a bone plate is employed for a fracture site, calluses generate around the fracture site and turn into the bone with the passage of (healing) time; this process is called endochondral ossification. Therefore, the finite element model was composed of a broken bone, a central callus in the fracture gap, and an external callus around the fracture site. Only a small axisymmetric section (5°) of the whole structure was modeled, and a spring element was used to simulate the external fixator, as shown in Fig. 1b. It is known that healing performance varies with the fracture gap thickness [11,19]; therefore, gap thicknesses (1 and 2 mm) were determined by in Claes' study [15] to compare the simulation results with the experimental ones. Moreover, the shape of the finite element model was determined by considering a related study [20]. The external fixator was designed to have multiple spring constants according to the magnitude of the load, as shown in Fig. 1c. The initial spring constant was 4600 N/mm; this value was maintained until the load reached 100 N and then the value abruptly decreased to 10 N/mm. This low stiffness region was determined by the initial interfragmentary strain (IFS) of the external fixator, and position "A" in Fig. 1c was determined on the basis of the IFS. After passing through position A, the spring constant increased back to 4600 N/mm. The initial interfragmentary strain was set to 7%, which was the same as that in a previous study [15]. A constant load of 500 N was applied on the fractured bone.

2.2. Human tibia model with a composite bone plate

A fractured human tibia with a composite bone plate was modeled, as shown in Fig. 2. The tibia was simplified as a coaxial cylinder composed of a cortical bone and a trabecular bone at the center. The shape and dimensions of the external callus were taken from preliminary studies [11,12,21]; the gap thickness was determined to be 3 mm on the basis of Lacroix's research [19]. The shapes and dimensions of the bone plate and screws were taken from previous studies [3,12,21,22]. It was assumed that six screws were tightly fastened to join the bone plate and tibia. A contact condition was applied at the mating surface between the plate and tibia with a friction coefficient of 0.4 [23]. One end of the tibia

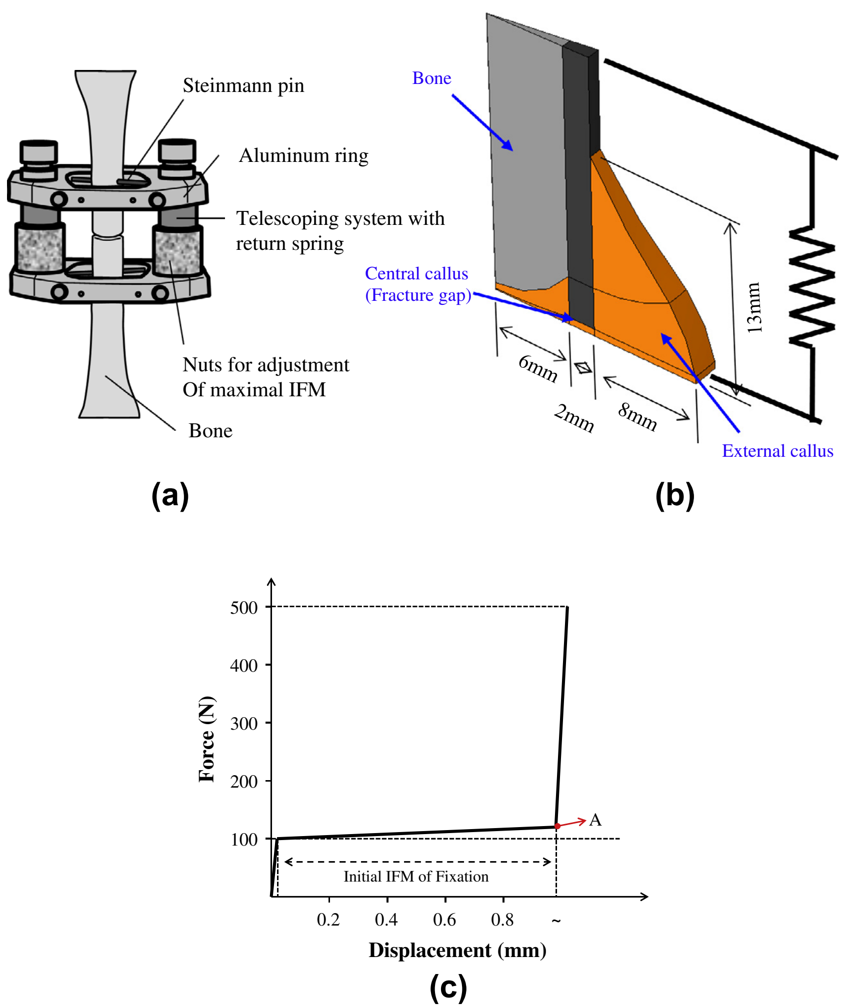

Fig. 1. A fractured sheep tibia with an external fixator; (a) schematic drawing, (b) finite element model, (c) a piece wise spring constant of an external fixator.

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