Composite Structures 159 (2017) 307–315

Contents lists available at ScienceDirect

Composite Structures

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

How post-operative rehabilitation exercises influence the healing process of radial bone shaft fractures fixed by a composite bone plate

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ARTICLE INFO

Article history:
Received 30 July 2016
Revised 25 September 2016
Accepted 26 September 2016
Available online 28 September 2016

Keywords:
Composite bone plate
Glass/polypropylene composite
Finite element analysis
Bending stiffness

ABSTRACT

Radial bone shaft fractures are commonly treated with bone plates. Flexible bone plates made of fiber-reinforced polymer composites have advantages over complications, such as stress shielding, corrosion, harmful ions, X-ray artifacts, resulting from metallic bone plates. Postoperative rehabilitation exercise is an important factor influencing the healing outcomes of radial bone fractures. A finite element model of radial shaft fracture was treated with Twintex $[0]_{2nT}$ composite bone plate and six stainless steel bicortical screws. Axial compression (10 N), bending moment (0.1 Nm), and torsion (0.1 Nm) as single, combined, and alternative loads (10% loads of daily activities) were used in the finite element study. A mechano-regulation algorithm based on deviatoric strain was used to predict the healing of bone fractures. The healing performance and bending stiffness were evaluated and compared to estimate the healing status of bone fractures. The best exercise mode, which gave the highest healing performance (68%) and bending stiffness (89%), was suggested. These results can be successfully utilized for the design of healing devices for the rehabilitation of fractured bones.

1. Introduction

Radius fractures are one of the most common injuries in long bone fractures, accounting for almost 20% of all fractures [1–3]. The key to successful bone unions is to use the appropriate fixation devices and postoperative physiotherapies. Many fixation devices are used to restore diaphyseal fractures, including external fixation, intramedullary nails, bone plates, wire, pins. [4–6]. Compared with other surgical interventions internal fixations using bone plates show promising results [5]. Metallic bone plates lead to several complications such as a mismatch of mechanical properties, stress shielding, X-ray artifacts, the release of harmful metallic ions, etc. [7–9]. Therefore, fiber-reinforced polymer composite materials were studied to overcome the aforementioned complications and flexible composite bone plates were introduced to improve bone healing [10–17]. Biomechanical stability of such a bone plate is very important in determining the union or non-union of the bone fractures. The healing process of bone fractures is influenced by the biomechanical environment supplied by the stiffness of the plate-bone structure and applied loads to the forearm [18]. Intramembranous ossification (primary healing) is followed by the rigid fixations, and callus is not generated in this healing process; however, endochondral ossification (secondary healing) is followed by flexible fixations where inter-fragmentary movement occurs at the fracture site that promotes callus formation and tissue differentiation. Endochondral ossification (secondary healing) process can be predicted using mechano-regulation algorithms and finite element analyses (FEA). The loading condition in the forearms, which includes axial compression, torsion, and bending moment according to the hand movement pushing/gripping, pronation/supination, and flexion/extension, is relatively complex compared to that in the other long bones. In daily activities, the forearm of an adult is subjected to approximately 100 N of axial compression, 1 Nm of torsion, and bending moment [19–21]. Immediately after surgery, patients are not allowed to use their forearm normally and suggested special rehabilitation exercises are necessary to improve the healing of bone fractures [18]. However, the amounts of loading during rehabilitation exercises are not as severe as in daily exercise. Generally, therapists advise the patient to move the fingers, grip a ball lightly, and perform flexion/extension and pronation/supination. These loadings during these exercises are, however, much smaller than the loadings in daily activities, but awareness of the appropriate forces for successful healing of bone fractures and proper combinations of loading types is necessary. Even these small forces generate stress

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http://dx.doi.org/10.1016/j.compstruct.2016.09.081
0263-8223/

and strain at the fracture site and affect the healing process of bone fractures. Moreover, investigating the mode of exercise that includes axial compression, bending moment, and torsion is necessary. Each type of load may lead to a different healing status of bone fractures. To the best of our knowledge, no research has been carried out to estimate the healing outcomes of radius bone fractures by using different types of exercises. This may aid surgeons/therapists in advising their patients on appropriate exercises according to the type of fracture and help engineers to invent new types of bone-healing devices.

In this study, a simplified radius bone of a healthy adult male with a 3-mm simple transverse fracture was modeled using finite element code ABAQUS 6.10. A composite bone plate and six screws were used to fix the bone fragments. Immediate after surgery, 10% loadings of axial compression, torsion, and bending moment in daily activities were used to estimate the healing of the radius bone fractures using a mechano-regulation algorithm. The healing performances and bending stiffness of the fractured bones were evaluated and compared when single and various combinations of the three types of loads were applied to mimic the different modes of rehabilitation exercises.

2. Methods

2.1. Finite element model construction

A diaphyseal section of a healthy adult male radius bone was simplified to the cylindrical shape and modeled by finite element code ABAQUS 6.10 as shown in Fig. 1. The radius bone consists of an outer shell of cortical bone 2 mm thick and filled with a 10-mm diameter of trabecular bone [20]. The length of the bone was 180 mm, with a simple transverse fracture gap of 3 mm in the middle of the bone to simulate diaphyseal shaft fracture. The fracture was filled and bridged with central and external calluses, respectively, and these calluses were filled with a soft tissue called granulation tissue (the initial state of the healing process). The dimension of the calluses at the radius fractures was projected from the tibia to calluses ratio in our previous studies [15,16]. Six bicortical holes were created in the bones to insert the screws. A six-holed commercially available non-locking compression bone plate (Smith & Nephew, Inc., USA) was modeled and assembled with bone fragments, with the help of six bicortical screws. The bone plate bridged the bone fragments and kept enough space between the screws and fracture site to prevent interaction with injured tissues. The detailed dimensions of bones, fracture site, calluses, bone plate, and screws are given in Table 1.

Mesh models of bone/calluses/plate/screw system were generated with an eight-node solid element (C3D8R). The size of elements was controlled to 1 mm for calluses and fracture site for accurate convergence. Table 1 shows the number of elements and nodes used in the finite element (FE) models. Anisotropic material properties were used for the cortical bone, and a composite bone plate made of glass/polypropylene (Twintex $[0]_{2nT}$, *jb* martin, France), and isotropic material properties were used for the trabecular bone, calluses, and screws (stainless steel) as listed in Table 1 [22]. To simulate realistic interfacial conditions, the friction coefficient of 0.3 was defined between the tapered screw collar and bone plate holes, and between the bone plate and cortex [23] as shown in Fig. 2. The surfaces of the simplified screws were tied to the bone holes.

2.2. Physiological loading in FEA

Generally, in active wrist and forearm motion (see Fig. 1a), three types of loadings are applied in daily activities which are axial compression (100 N), bending moment, and torsion (1 Nm) [19] as shown in Fig. 1c. Immediately after surgery, surgeons suggest that patients rest and start nominal exercises that can heal the bone fracture efficiently. The magnitudes and directions of the rehabilitation exercises are still unknown for efficient bone healing. In this study, 10% of daily activities loads were used to simulate the muscular forces around the bone fractures [24]. Our assumption is based on minor movements of the hand such as

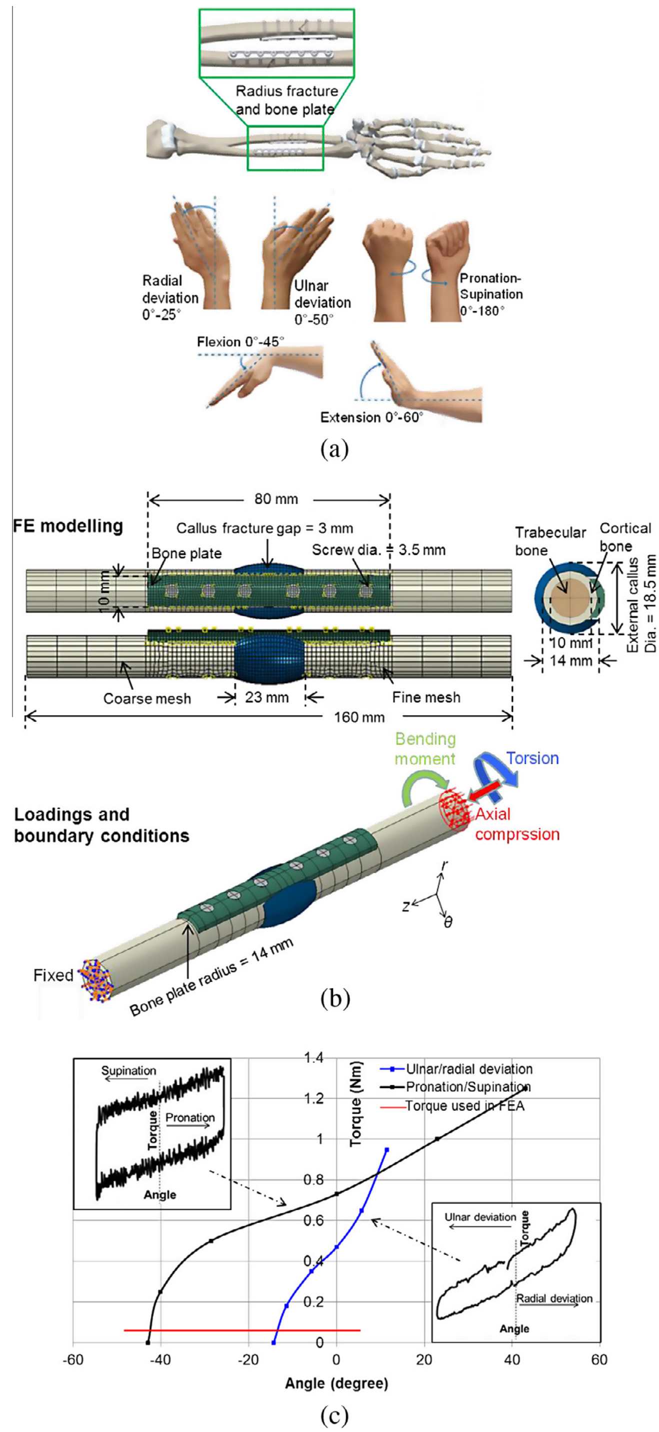

Fig. 1. Forearm movements, finite element modeling and load types of radial bone; (a) different movements of forearm generating different types of loads, (b) details of finite element model of a fractured bone fixed by a bone plate, (c) magnitude of loads generated in the forearm according to the movement of the hand [19].