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A simplified application (APP) for the parametric design of screw-plate fixation of bone fractures

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A R T I C L E I N F O

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A B S T R A C T

Screw and plate fixation is commonly used to treat bone fractures. A prototype application (APP) for presurgical simulation was developed and validated by comparing it with current analytical approach and other models. In this APP, alternative plate designs and materials to limit the effects of stress shielding could be tested. In addition, the number and position of screws and the gap between bone and plate that achieved acceptable stability were predicted. The fixation stability providing a situation of interfragmentary strain between 2% and 10% is necessary for callus formation. However, improving the fixation stability leads to a stress shielding effect. The simultaneous alleviation of stress shielding and maintenance of stability are important in fracture healing. In this study, the feasibility of creating a specialized APP to evaluate different screw-plate configurations for diaphyseal femoral fractures was investigated. The ultimate goal is to extend this technique to computer-assisted pre-operative planning for orthopedic surgery.

1. Introduction

Screw-plate fixation is routinely used in the treatment of femoral fractures with the aim of maintaining blood supply to promote rapid healing, reduce the need for bone grafting, and decrease the risk of infection and refracture (Miclau and Martin, 1997). Effective pre-operative planning includes choosing the proper plate length, screw number, and screw position (Mast et al., 1989). A dynamic compression plate (DCP), known as traditional fixation, is compressed directly onto the bone (Allgöwer et al., 1970). However, DCPs are currently being replaced by locking compression plates (LCPs) which have a smaller contact surface that serves to mitigate the interruption of blood supply (Miller and Goswami, 2007). To improve fixation, LCP is designed to contain a combination-hole system that can house either locking or conventional non-locking screws. Whereas conventional non-locking screws function by pressing the plate to the bone, locking screws keep a gap between the bone and plate to protect periosteal vascularity. Recently, non-contact plates (NCPs) have become available for use in the treatment of postoperative infection due to bacterial biofilm formation as well as in the treatment of fractures (Alemdar et al., 2015). Selection of screw-plate fixation depends on bone type and fracture type and is clinically important.

The traditional plating fixations made of metal alloys such as stainless steel, cobalt-chrome, and titanium are accepted as biocompatible materials. Carbon fiber composite can be made more compliant than metal alloys by varying the orientation and number of carbon fiber layers, making its elastic modulus similar to that of cortical bone (Tayton et al., 1982). A plate with high stiffness results in a large portion of the load being carried by the plate rather than by the underlying bone, which is referred to as stress shielding (Ramakrishna et al., 2001). This is a harmful long-term phenomenon that leads to bone loss because the stress in the bone falls below the normal values. Clinical research has shown that strain in the bone decreases when the plate carries the most of external load (Hastings, 1980). Stability determines the amount of strain, which influences the type of bone healing occurring at the fracture site (Egol et al., 2004). A proper strain level stimulates callus formation during fracture healing (Claes et al., 1998). Therefore, specially designed plates combined with novel screws have been proposed to enable interfragmentary motion required for the promotion of callus healing (Doornink et al., 2011; Bottlang and Feist, 2011).

Recently, finite-element APPs have been used to provide new insights into many fields, such as electronic cooling (Segui, 2016), food processing (Carver, 2017), and automotive industry (Marra, 2017). This is the first investigation that uses an APP to demonstrate the presurgical evaluation of various screw-plate fixations for femoral fractures. The goal of this study is to develop an APP to provide information about the screw-plate configuration affecting the mechanical behavior of a hypothetical bone-implant system. This APP enables the parametric study of screw-plate fixation to alleviate the stress shielding and maintain the construct stability. This methodology could, in principle, be extended to computed tomography (CT)-based models and applied to planning and

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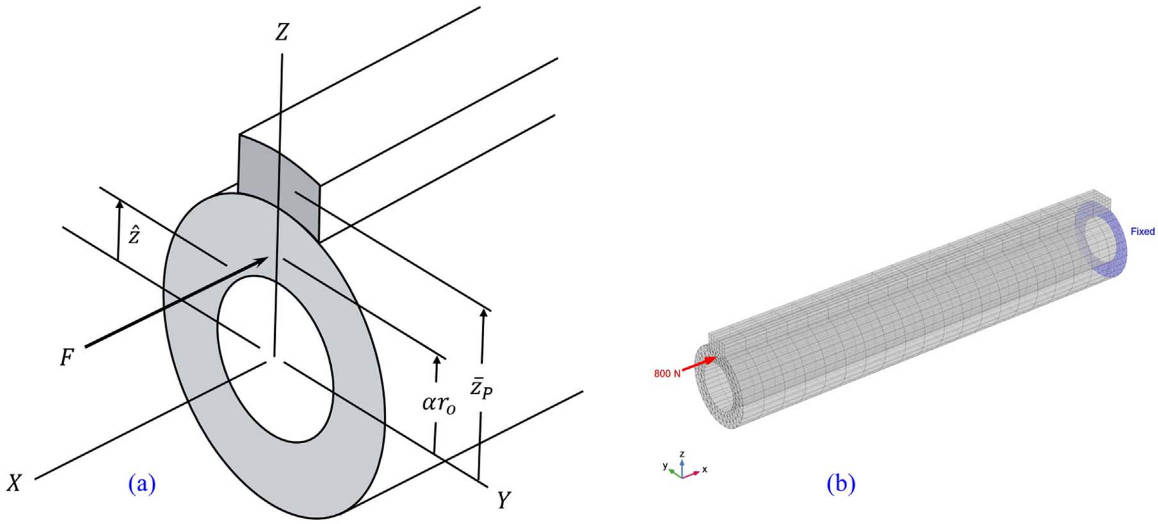

Fig. 1. (a) An idealized model of an implant plate attached to an intact bone. It is assumed that the external forces and moments are reduced to an equivalent axial load F, which acts at a distance αr_0 from the centroidal axis of the bone. The neutral axis of the bone-plate system is located at distance $\hat{z}$ from the centroidal axis of the bone. The centroidal axis of the implant plate is located at distance $\bar{z}_P$ from the centroidal axis of the bone. (b) Finite element representation in Section 2.1 for validation of the analytical model.

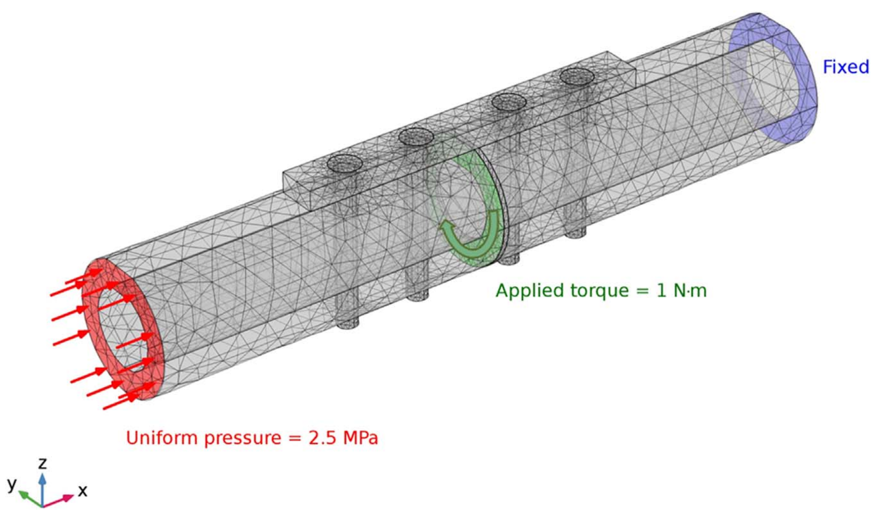

Fig. 2. Representation of finite element model mentioned in Section 2.2 for comparison with Fouad's model (2011). FE mesh of the bone and implant, as well as the applied boundary and load conditions are shown. A uniform pressure of 2.5 MPa, produced by a body weight of approximately 800 N is applied to the end surface of the bone; the opposite end was fixed. In the combined loading condition, a torque of 1 Nm is applied on the fracture site in addition to the pressure.

Table 1
Material properties used in the FE model of bones and implants (Fouad, 2010, 2011).

	Young's modulus (GPa)	Poisson's ratio
Intact bone	20	0.3
Fractured bone (callus) at 1% healing	0.02	0.3
Titanium alloy screws	110	0.3
Stainless steel plate	210	0.3

evaluation before surgery.

2. Methods

2.1. Analytical approach

Fig. 1(a) shows an idealized bone-implant system including a plate attached to an intact femur, which is represented as hollow cylinder (Gray, 1918). The plate can be approximated by a rectangular cross section. Composite beam theory (Gere and Timoshenko, 1997; Carter and Vasu, 1981; Cordey et al., 2000) provides calculation of the stress in the bone at a distance t_B from the neutral axis of the bone-implant system as

$$\sigma_B = -\frac{FE_B}{E_B A_B + E_P A_P} - \frac{M t_B E_B}{E_B I_B + E_P I_P}. \tag{1}$$

The first and second terms of Eq. (1) represent the normal and bending stresses resulting from the axial compressive load and the bending moment, respectively. Here E_B and E_P are the Young's moduli of the bone and the plate, respectively. A_B and A_P are the cross-sectional areas of the bone and the plate, respectively. It is very important to note that I_B and I_P are the area moments of inertia of the bone and the plate, respectively, with respect to the neutral axis of the system. The moment M about the neutral axis produced by the axial load applied at an eccentric distance αr_0 from the centroidal axis of the bone may be written as

$$M = F(\alpha r_o - \hat{z}), \tag{2}$$

and the location of the neutral axis of bending $\hat{z}$ is given by

$$\hat{z} = \frac{\rho_A}{1 + \rho_A}\bar{z}_P. \tag{3}$$

Using these relationships, the stress in the bone can be written as